“Influence of Overexploitation and Seawater Intrusion on the Quality of Groundwater in Greater Beirut”

Von der Fakultät Georessourcen und Materialtechnik der

Rheinisch-Westfälischen Technischen Hochschule Aachen

zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften

genehmigte Dissertation

vorgelegt von

Master of Science

Mark Saadeh

aus Beirut, Lebanon

Berichter:	Prof. Dr. rer. nat. Rafig Azzam Prof. Dr. rer. nat. Thomas Rüde Prof. Dr. ing. Hamed Assaf
Tag der mündlichen Prüfung:	12. Februar 2008

Abstract

The phenomena of seawater intrusion is the most prominant process that degrades the quality of groundwater along coastal aquifers. In Lebanon, it has already increased the salinity of groundwater to such concentrations that it has very little use domestically, industrially or agriculturally. With a total population of nearly 5 million, a third live in Greater Beirut and its suburbs, thus placing a tremendous stress on the limited amount of supplied freshwater, the consequence is groundwater overabstraction leading to the hydraulic gradient to reverse and encourage seawater encroachment. As such, this investigation was undertaken in the Lebanese capital of Beirut and its suburbs between 2004 to 2006, in order to assess the degree of seawater intrusion. With groundwater samples exhibiting salinities in the thousands of milligrams per liter in some areas, this significant and potentially irreversible deterioration of the quality of groundwater in Greater Beirut may potentially lead to an inevitable conclusion, namely searching for an alternate source of freshwater other than groundwater abstraction.

Kurzfassung

Die Phänomene des Meerwassereindringens ist der auffallendste Prozeß, der die Qualität des Grundwassers entlang Küstenwasserleiter vermindert. Im Libanon hat sich bereits die Salzigkeit des Grundwassers auf solche Konzentrationen erhöht, sodass sie sehr wenig Gebrauch inländisch, industriell oder landwirtschaftlich hat. Mit einer Gesamtbevölkerung von fast 5 Million, leben ein Drittel davon in Beirut und die Vororte. Dies setzt einen enormen Druck auf die begrenzte Menge von geliefertem Frischwasser, der zu einem Grundwasserüberpumpen führt, welches ein Gefälle des Wasserspiegels ins Inland führt, und ruft Meerwassereingriff hervor. So wurde diese Untersuchung im libanesischen Kapital von Beirut und ihren Vororten zwischen 2004 bis 2006 aufgenommen, um den Grad des Meerwassereindringens festzustellen bzw. zu bewerten. Wenn die Grundwasserproben ein Grad an Salzigkeit in den Tausenden von Milligrammen pro Liter zeigen, kann diese bedeutende und möglicherweise irreversible Verschlechterung der Grundwasserqualität im Groß Beirut zu unvermeidlichen Konsequenten führen, nämlich eine andere Alternative für Frischwasserquellen zu suchen, als das Grundwasserpumpen.

Acknowledgements

I would like to take this opportunity to thank Prof. Dr. R. Azzam my first supervisor and head of the Lehrstuhl für Ingenieurgeologie und Hydrogeologie (LIH) RWTH Aachen, Prof. Dr. T. Rüde my second supervisor and head of the Lehrstuhl für Forschungsgebiet für Hydrogeologie (LIH) RWTH Aachen, and my second supervisor, Professor H. Assaf at the Engineering Department of the American University of Beirut for their unwavering guidance and encouragement throughout this research.

I also extend my sincerest gratitude to all who have contributed to this research, by deed or by word, throughout these past few years.

lastly, I owe everything to my wife, Jana, and my parents who made all this come true.

In loving memory to my mother, Inge.

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1 Introduction

A hydrogeological investigation was undertaken in the Lebanese capital of Beirut and its suburbs (2004/6), as part of a Ph.D. dissertation submitted to the RWTH Aachen University, in order to assess the degree of seawater intrusion, and consequently the quality of the affected groundwater. The lack of any national database or monitoring program for surface or groundwater has made this study all the more pertinent.

The study employed physico-chemical tests of groundwater pertaining to dozens of private and public wells selected throughout Greater Beirut seen from the satellite image in Figure 1.1, and sampled on a monthly as well as seasonal basis in order to assess the level and extent of salinization of the coastal aquifers.

Seawater intrusion in the coastal aquifers of Greater Beirut has been largely a direct consequence of years of water mismanagement further exacerbated by a civil war which devastated the country for more than fifteen years. Significant and potentially irreversible deterioration of the quality of groundwater in Greater Beirut continues, due to extensive aquifer over-abstraction by a population that probably exceeds one and a half million, causing the hydraulic gradient to reverse and encourage seawater encroachment.

Concurrent urban growth, and repeated natural drought conditions has amplified this phenomena. Seawater intrusion into Beirut's aquifers has mainly rendered the groundwater unsuitable for any purpose (raising the salinity in some monitored wells to thousands of milligrams per liter).

In 2004, the World Bank published the Cost of Environmental Degradation (COED) report for Lebanon. The report indicates that the costs in the year 2000, was in the range of USD 565 million or 3.4 % of the GDP. Furthermore, the degradation of the country's coastal zone is the highest in the Mediterranean region.

The Ministry of Energy and Water (MoEW) is the authority responsible for the management

Figure 1.1: Satellite Image of Greater Beirut (Google Earth, 2005, not to scale)

of water resources in Lebanon, including coastal aquifers such as Greater Beirut. This ministry should set a clear strategy for developing solutions to mitigate the phenomenon of seawater intrusion along the entire Lebanese coast and not just Beirut.

The strategy for a sustainable exploitation of groundwater, should lay out a long-term plan that provides direction for government authorities and private institutions to work in tandem to combat seawater intrusion.

2 Background

2.1 Meteorological Data

In general, the wind trajectories in Lebanon can be grouped into four categories (Saad and Kazpard, 2005):

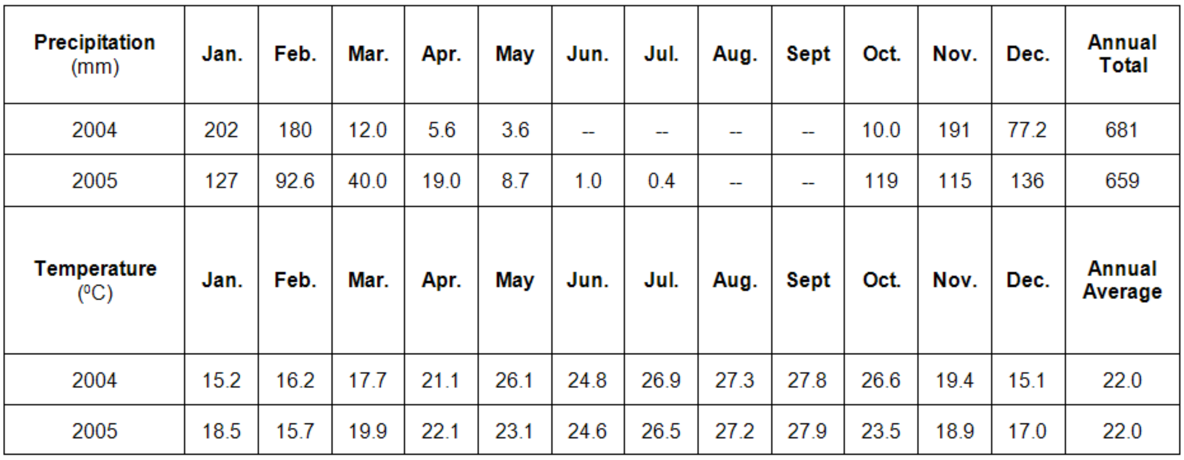
1. The trajectory originates from Eastern Europe (humid and cold air masses) and turns into the Mediterranean Sea and then towards northeast Lebanon;
2. The trajectory that is originating from the southern Mediterranean Sea turns southeast passing over Northern Africa towards southwest Lebanon (windy rain) and southeast Lebanon (warm wind);
3. The trajectory that is originating from the central Mediterranean Sea (humid and mild) turns southeast over the Mediterranean Sea and then towards west Lebanon;
4. The trajectory that is passing over the Syrian desert (warm wind) turns towards east and southeast Lebanon.

A strong correlation was observed between Na^+ and Cl^- in coastal precipitation as well as a strong correlation between sulfate and other elements of marine origin, which indicates that the Mediterranean Sea is the origin of these aforementioned elements in rain (Saad and Kazpard, 2005).

The annual average precipitation in Beirut ranges from 800 to 900 mm between November and February (Majdalani, 1997), yielding about 495 million cubic meters (MCM) with nearly half lost to evapotranspiration (Shaban, 2003). The rest of the country receives more or less the same amount of precipitation depending on the local geomorphology.

The average monthly precipitation and temperature data for the years 2004/05, are presented in 2.1, and obtained on-line from the Central Administration for Statistics in Lebanon. This

Table 2.1: Average Monthly Precipitation and Temperature in Beirut (Central Administration for Statistics, 2004/5)



Precipitation (mm)	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept**	**Oct.**	**Nov.**	**Dec.**	**Annual Total**
2004	202	180	12.0	5.6	3.6	--	--	--	--	10.0	191	77.2	681
2005	127	92.6	40.0	19.0	8.7	1.0	0.4	--	--	119	115	136	659
Temperature (ºC)	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept**	**Oct.**	**Nov.**	**Dec.**	**Annual Average**
2004	15.2	16.2	17.7	21.1	26.1	24.8	26.9	27.3	27.8	26.6	19.4	15.1	22.0
2005	18.5	15.7	19.9	22.1	23.1	24.6	26.5	27.2	27.9	23.5	18.9	17.0	22.0

public service site includes meteorological data prepared by the Beirut International Airport as well as other locations throughout the country.

As can be noticed from Table 2.1 of temperature versus precipitation variations in Beirut during 2005, the relative dry period would be between the months of March to September when the temperature curve exceeds the precipitation one for a reasonable period of the year. It is during this period, that the phenomena of seawater intrusion is magnified. It is noteworthy to mention that the dry months according to some sources (Koumair, 2005) extend between July and October. However, it is evident from said table that dry months for 2005, extended longer, between April and October.

2.2 Geology

The unique coastline of Lebanon is characterized by low relief with a sharp increasing altitude as the western mountain range in the east is rapidly approached. The length of the entire coast of Lebanon stretches to about 200 km with about nearly 70 % of the population concentrated there and placing enormous stress on the limited available coastal water budget. The exposed aquifers of Lebanon cover an area of about 7,000 km^2 or 70 % of the total area, of those aquifers, 51 % are of the Cretaceous period, 15 % to the Jurassic and the remaining 4 % to the Eocene Period (Ghattas, 1975).

Limestone karstification along the coast of Lebanon occupies about 70 % of the area (or nearly

3,500 m^2) and is heavily dissected with dense fault systems. The relatively high precipitation rate (average 900 mm) coupled with seaward dipping steep slopes and bedding planes, are conducive of a high loss rate in surface and ground water resources (Shaban, 2003).

Elevations in the study area vary between zero at the seashore and increases towards the interior where a maximum relief of 900 mm is reached in the southeast part of Beirut known as Aley.

Lebanon in particular is dissected by numerous fractures which include faults, fissures, and joints tending in various directions as can be clearly seen in Figure 2.1. Several principal and minor fault systems exist, they include normal faults with varying apparent dextral strike slip displacement, as is the case for the fault south of Naher el Kalb (to the north of Greater Beirut) trending E-W, the two faults cutting Naher el Mot (to the north of Beirut proper) trending NE-SW, and the fault cutting Damour river in the south. The central Beirut river and Beirut harbor faults have a direction NE and run parallel to each other with a Miocene graben in between (Ukayli, 1971).

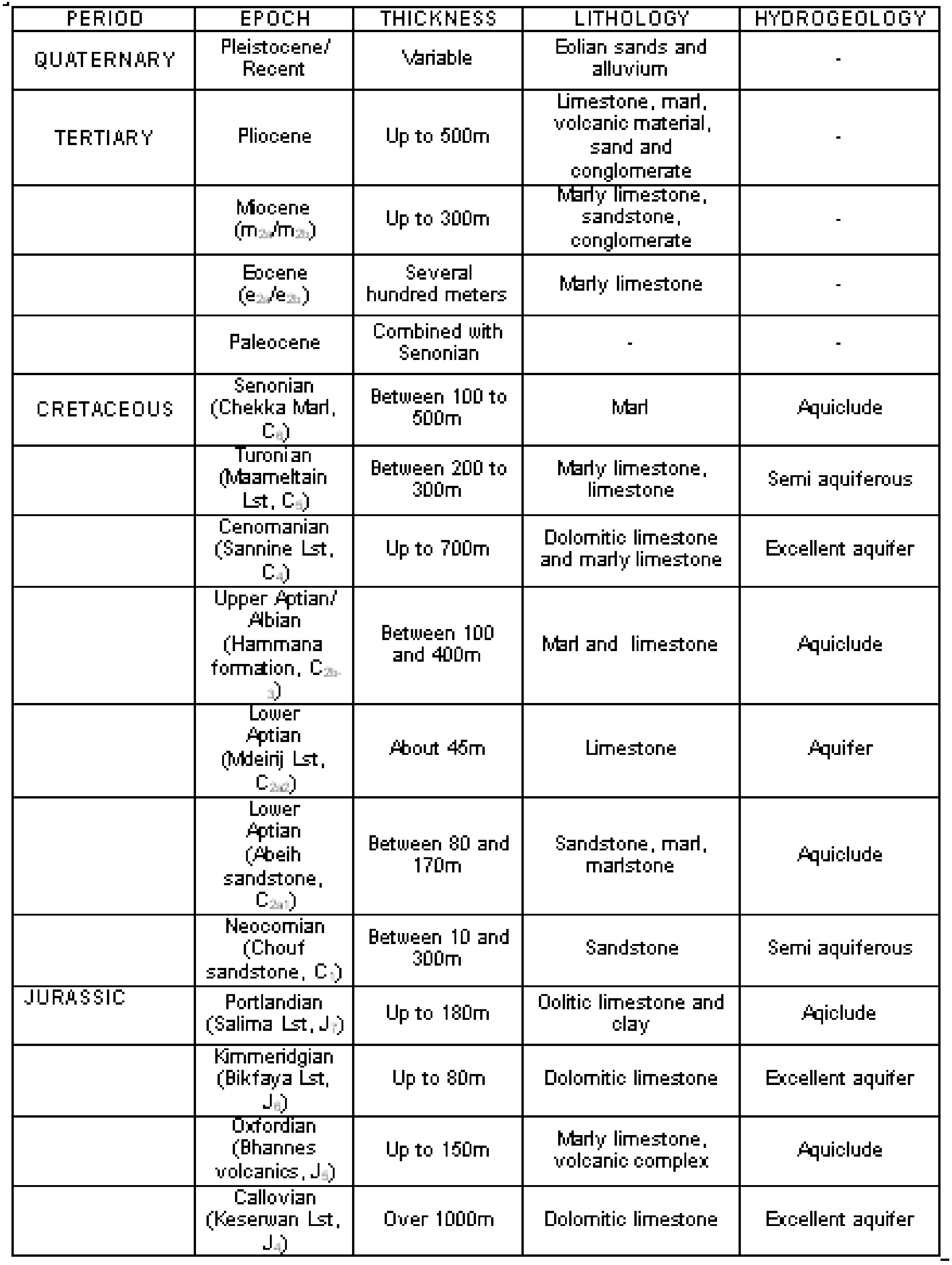
Among the seventeen different geological formations known in Lebanon, three are considered excellent aquifers, three are generally classified as being aquiferous to semi aquiferous, while the remaining formations are aquicludes. The aquifers of Lebanon are generally composed of dolomitic limestones to limestone while the aquicludes vary in composition from sandstone to marlstone as in 2.2.

The karstic aquifers prevalent in Lebanon, mainly consist of calcium carbonate and dolomitic rocks formed by the deposition of marine shells and corals. The primary porosity and permeability are low to moderate. Subsequent fractures and fissures make up the so called secondary porosity and permeability which is much more considerable.

Due to large the openings in karstic aquifers, the response to recharge is generally very rapid. This does not only hold for the response to natural recharge or human activities such as groundwater abstraction, but also for the effects of tides, and storm surges. The latter greatly effects seawater intrusion. Depending on the system, with or without submarine springs, and more in particular the levels of outflow, seawater intrusion can take place at the outlets or more inland at greater depths. (Cotecchia, 1997).

Variability is introduced in both space (space differences linked to the position of the conduits) and time since temporal variation induced by sometimes strong head variations caused by sudden floods, are characteristic of karst (Arfib, 2007).

Table 2.2: Stratigraphic Column of Lebanon (Aker, 2006)



PERIOD	EPOCH	THICKNESS	LITHOLOGY	HYDROGEOLOGY
QUATERNARY	Pleistocene/ Recent	Variable	Eolian sands and alluvium	-
TERTIARY	Pliocene	Up to 500m	Limestone, marl, volcanic material, sand and conglomerate	-
	Miocene (m_{2a}/m_{2b})	Up to 300m	Marly limestone, sandstone, conglomerate	-
	Eocene (e_{2a}/e_{2b})	Several hundred meters	Marly limestone	-
	Paleocene	Combined with Senonian	-	-
CRETACEOUS	Senonian (Chekka Marl, C_6)	Between 100 to 500m	Marl	Aquiclude
	Turonian (Maameltain Lst, C_5)	Between 200 to 300m	Marly limestone, limestone	Semi aquiferous
	Cenomanian (Sannine Lst, C_4)	Up to 700m	Dolomitic limestone and marly limestone	Excellent aquifer
	Upper Aptian/ Albian (Hammana formation, C_{2b-3})	Between 100 and 400m	Marl and limestone	Aquiclude
	Lower Aptian (Mdeirij Lst, C_{2a2})	About 45m	Limestone	Aquifer
	Lower Aptian (Abeih sandstone, C_{2a1})	Between 80 and 170m	Sandstone, marl, marlstone	Aquiclude
	Neocomian (Chouf sandstone, C_1)	Between 10 and 300m	Sandstone	Semi aquiferous
JURASSIC	Portlandian (Salima Lst, J_7)	Up to 180m	Oolitic limestone and clay	Aqiclude
	Kimmeridgian (Bikfaya Lst, J_6)	Up to 80m	Dolomitic limestone	Excellent aquifer
	Oxfordian (Bhannes volcanics, J_5)	Up to 150m	Marly limestone, volcanic complex	Aquiclude
	Callovian (Keserwan Lst, J_4)	Over 1000m	Dolomitic limestone	Excellent aquifer

In general, the greater the outflow of karst springs, the lower the salinity of the outflow water. Mixing of fresh and saline water takes place rapidly, rendering the out-flowing fresh water unfit for use. Mixing of fresh and saline water in karst regions takes place under a completely different regime compared to a homogeneous and isotropic porous media. Connective flow of fluids, not hydrodynamic dispersion, dominates the physical mixing. Thus the fresh-saline relationship in karstic regions only partly follows the Ghyben-Herzberg principle discussed in later sections. Altogether, description of this feature with mathematical formulas is complex or even impossible,

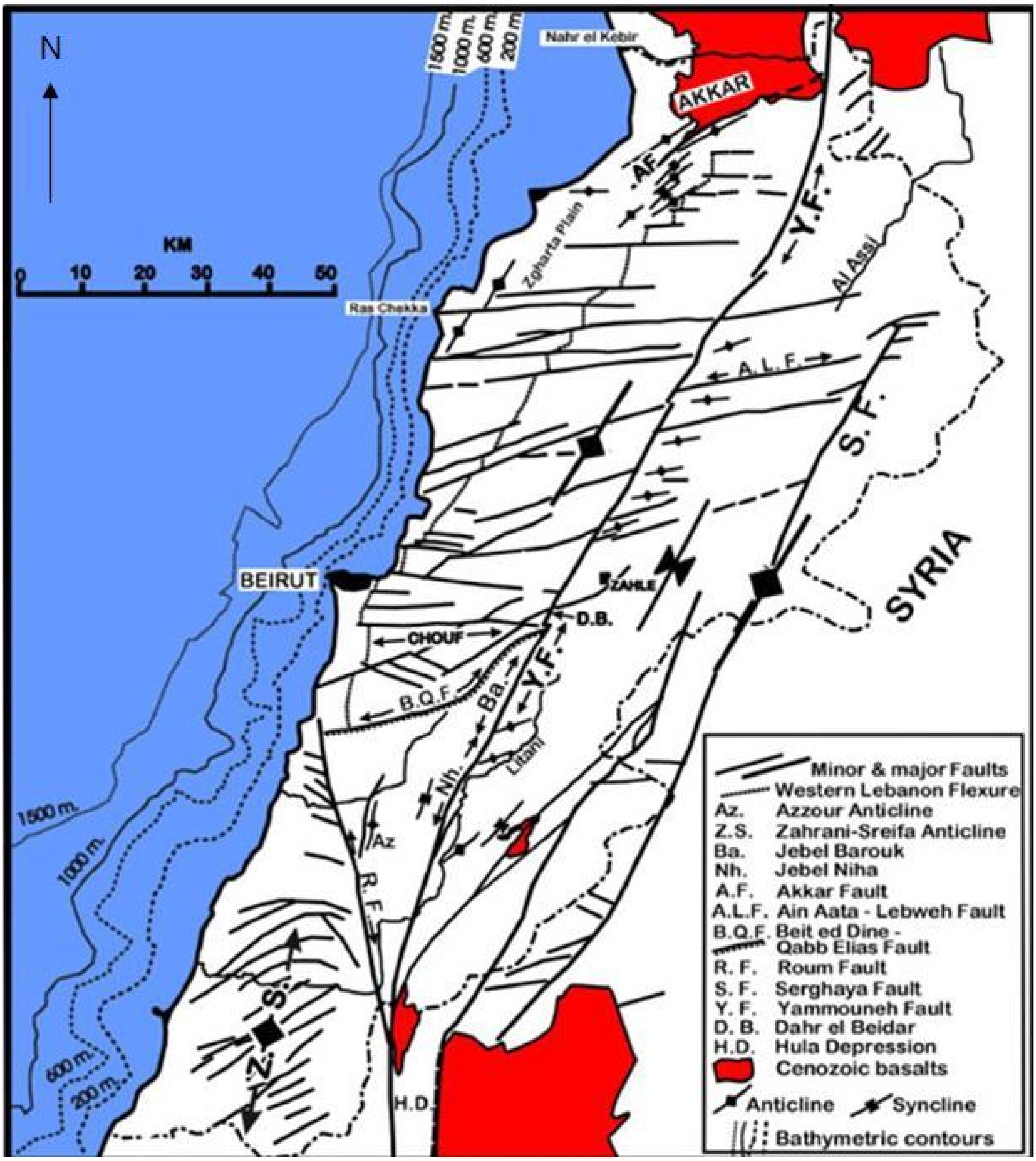


Figure 2.1: Geological Faults of Lebanon (Walley, 2003)

Table 2.3: Rivers of Greater Beirut (Agency-JICA, 2003)

River	Length (km)	Average Discharge (million m^3/year)	Catchment Area (km^2)	Spring Source
Kalb	35	117	260	Jeita, Asal, Laban, Sannine, Kashkoush, Manbouk, Jouzat
Beirut	48	65	231	Aar, Saidi, Habrouk, Fawar, Hasa, Ghab, Ramta
Damour	45	157	288	El Safa, Barouk

unless very rough assumptions are permitted .

Beirut river in the center, forms the largest river course and drains much of the study area. The sources of Beirut river consist of springs around Hammana and Ain el Delbe in the mountains outside the study area. In the summer period, the river dries up and all that remains is the concrete canal. The other rivers of Beirut include Naher el Mot, Ghadir, Naher Yabes and Naher Antelias. All of which are non perennial except for the latter.

2.3 Springs

The springs that issue from the limestone and dolomite formations of Lebanon (about 1250 million m^3/year according to (Khair, 1992) are of two major types:

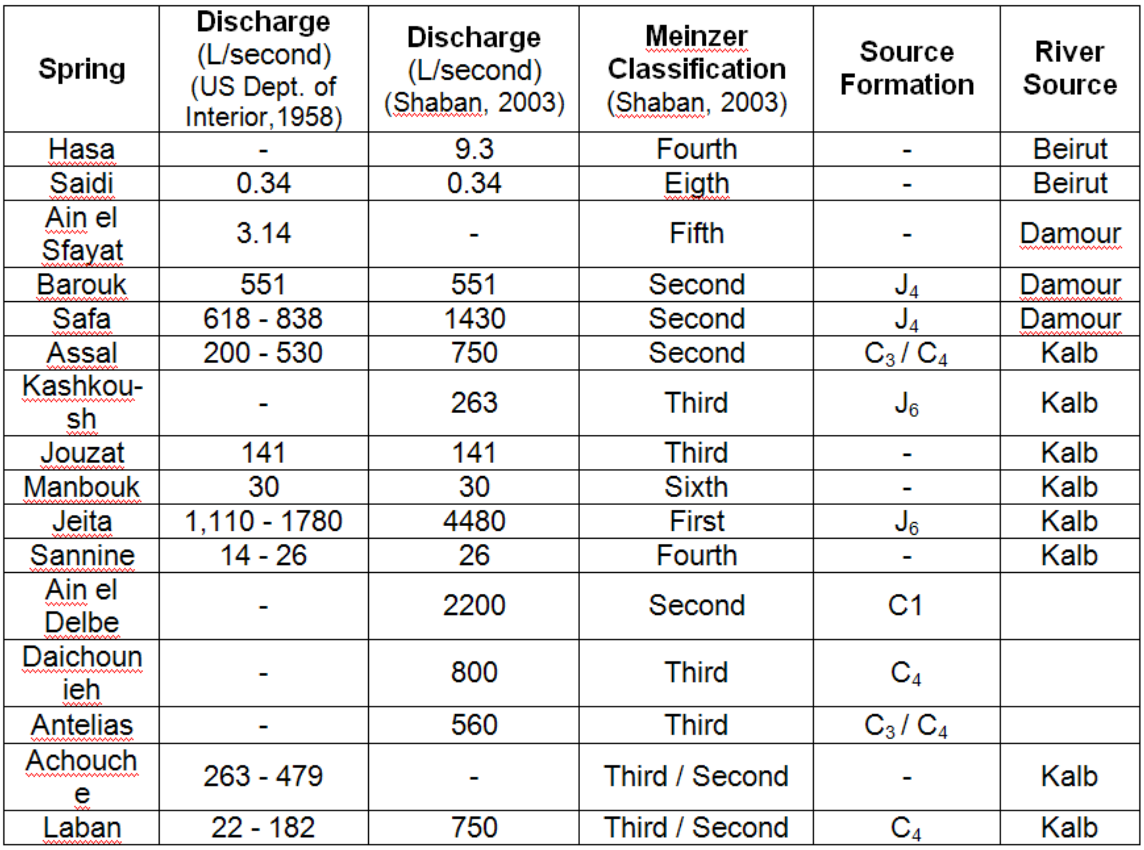
1. Karstic springs
2. Overflow springs

As for the study area, the three permanent rivers; Kalb, Beirut, and Damour are fed by a myriad of springs summarized in Table 2.4.

Other important types of springs in Lebanon are submarine with an estimated total yield of about 620 MCM/year. The following table includes a list of the submarine springs that are found in the study area of Greater Beirut but require further scientific investigation for verification.

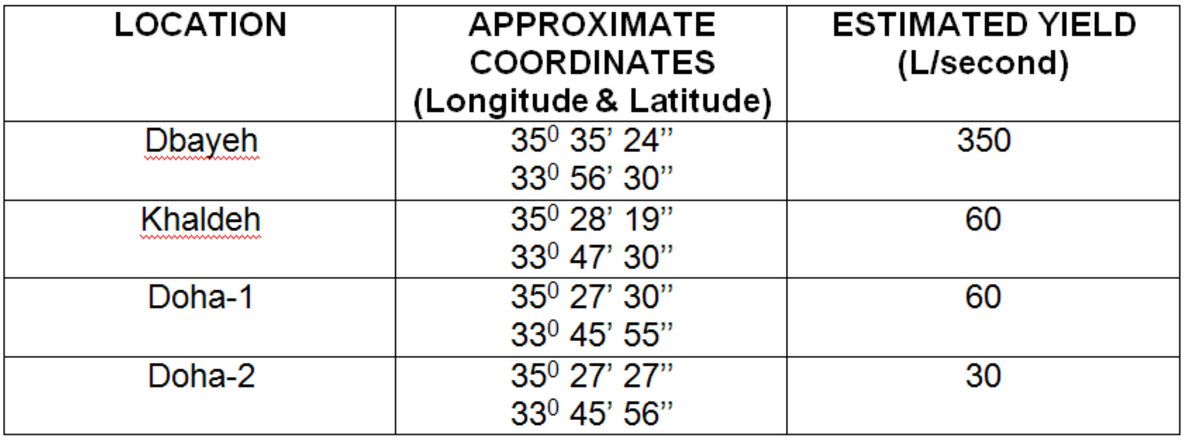
Further inquiry into the validity of these springs has revealed that the Dbayeh submarine spring has been since 1988, buried under the construction debris of a large marina.

Table 2.4: Springs of Greater Beirut



Spring	Discharge (L/second) (US Dept. of Interior, 1958)	Discharge (L/second) (Shaban, 2003)	Meinzer Classification (Shaban, 2003)	Source Formation	River Source
Hasa	-	9.3	Fourth	-	Beirut
Saidi	0.34	0.34	Eigth	-	Beirut
Ain el Sfayat	3.14	-	Fifth	-	Damour
Barouk	551	551	Second	J$_4$	Damour
Safa	618 - 838	1430	Second	J$_4$	Damour
Assal	200 - 530	750	Second	C$_3$ / C$_4$	Kalb
Kashkou-sh	-	263	Third	J$_6$	Kalb
Jouzat	141	141	Third	-	Kalb
Manbouk	30	30	Sixth	-	Kalb
Jeita	1,110 - 1780	4480	First	J$_6$	Kalb
Sannine	14 - 26	26	Fourth	-	Kalb
Ain el Delbe	-	2200	Second	C1	
Daichounieh	-	800	Third	C$_4$	
Antelias	-	560	Third	C$_3$ / C$_4$	
Achouche	263 - 479	-	Third / Second	-	Kalb
Laban	22 - 182	750	Third / Second	C$_4$	Kalb

Table 2.5: Suspected Submarine Springs of Greater Beirut (Shaban, 2003)



LOCATION	APPROXIMATE COORDINATES (Longitude & Latitude)	ESTIMATED YIELD (L/second)
Dbayeh	35^0 35’ 24” 33^0 56’ 30”	350
Khaldeh	35^0 28’ 19” 33^0 47’ 30”	60
Doha-1	35^0 27’ 30” 33^0 45’ 55”	60
Doha-2	35^0 27’ 27” 33^0 45’ 56”	30

As for the Khaldeh and Doha springs, they were identified back in 1973 thru a study undertaken by the Food and Agricultural Organization (FAO) using infrared imaging. They have since never been corroborated, apart from a study by the Lebanese Atomic Energy Commission in 2004, which does not even indicate any submarine springs near Beirut except in Chekka about 30 km north of Beiut and Saida/ Sour also about 30 km to the south, as evident in the following figure.

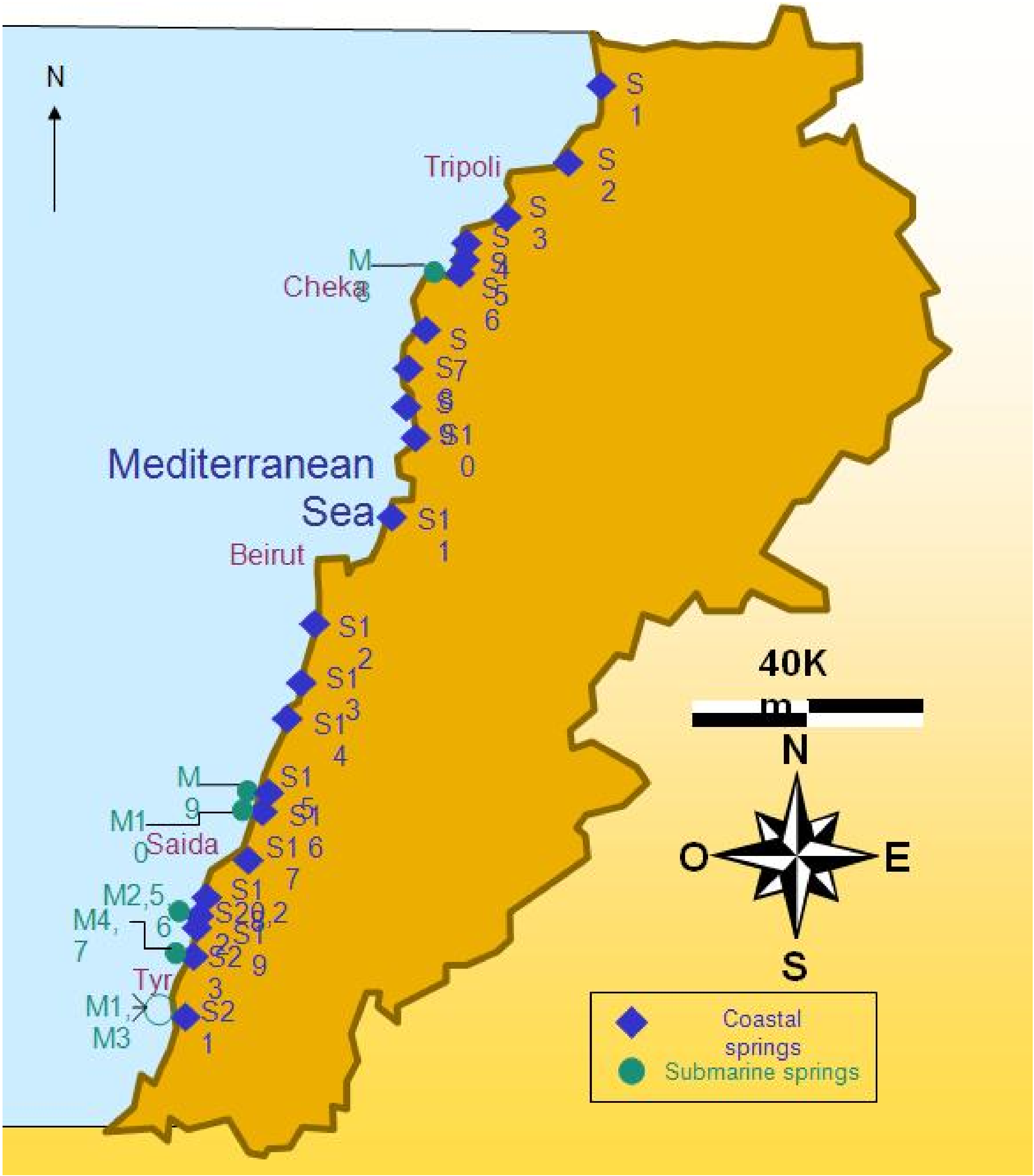


Figure 2.2: Submarine Springs Along the Coast of Lebanon (Saad and Kazpard, 2004)

2.4 Hydrogeology

Groundwater in Beirut occurs in two principal aquifers: sand aquifers, and carbonate aquifers.

2.4.1 Sand Aquifers

Sand aquifers are represented by the Basal Cretaceous sandstones of the Lower Cretaceous (Gres de Base) and the Quaternary sands. The lithographic characteristics of the Basal Cretaceous sandstone succession classify this stratum as a poor aquifer.

The Basal Cretaceous sandstone of the study area is exposed mainly at Mkalles, east of Antelias and Hazmieh, Dekouane and Mazraet al Shaab in the Beirut municipality of Metn to the north, and is composed mainly of quartz grains, loosely cemented with metal oxides, calcite, or clay. The grains range in size from fine grained to coarse.

The Quaternary sandstone deposits in many places directly overly the Cenomanian carbonates, which in turn extend westwards beyond the coast to outcrop on the sea floor. The Quaternary deposits in the study area are represented by mainly three types of deposits:

- Alluvial deposits (mix of sands, pebbles, and cobbles of limestone and basalt),
- Beach deposits (loose littoral sand deposits mixed with shells and loosely consolidated limestone conglomerates),
- Eolian deposits (sand dunes with high content of calcareous material)

These Quaternary deposits extend almost over about half of the area of Beirut and especially so to the south, Baabda municipality, as well as the coastal plain between Dorah and Naher el Kalb, in some parts of the Raouche area, along the coast from Ramlet el Baida to Khalde (south of Beirut), Forn el Shebak, Bir Hassan, Shiah, Burj Barajneh, and Choueifat.

The infiltration rate is the highest over the deposits due to presence of weak or partial cementation between the grains of sand allowing for moderate permeability. These two formations constitute important aquifers in the Beirut area and have the largest number of wells tapping them (Khair, 1992).

2.4.2 Carbonate Aquifers

In the study area, the following carbonate aquifers can be identified:

1. J_6 (Bikfaya Limestone) is highly fractured with consequent permeability and having a small exposure to the east of Dbaiye and Antelias to the north of Beirut,
2. C_2b (Jezzine Cliff limestone), also has a small and scattered outcrop at Sin el Fil, Jdeide and Antelias. The cliff thickness of about 50 m limits the availability of water in this aquifer,
3. C_4 (Cenomanian limestone), which along with the Quaternary deposits covers almost 75 % of the study area.

At present the Cenomanian-Quaternary aquifer is the only extensively tapped aquifer in the Greater Beirut area. It extends from Damour, Naameh, Choueifat, Khaldeh, and Hadath to Hazmieh, Sin el Fil and Jal el Did in the north. This thick and extensive formation consists mainly of limestone and dolomite as well as some intercalations of marl. The limestones and dolomites are mostly thick, hard and compact with interbedding of chert.

The total estimated area of the Cenomanian-Quaternary aquifer is about 47 km^2 (as roughly outlined in black, in the Figure 2.3), with an estimated thickness of about 700 m in the area of Beirut. In Beirut, the Cenomanian forms an isolated block cut by the Quaternary marine terraces. Some literature indicates that this aquifer is capable of discharging water at 20,000 m^3/ day/ well (Rammal, 2005). The accessibility and relatively high transmissivity of the C_4 aquifer, have encouraged the Beirut Water Authority to exploit it extensively. However, its proximity to the coast coupled with the fact that it is heavily jointed and faulted make it very susceptible to the phenomena of seawater intrusion.

Official estimates place the current number of groundwater wells found in Beirut at approximately 4,000, about 95 % of which may be without permits (Rammal, 2005), and tapping mainly the Cenomanian (C_4) and Quaternary (Q) formations which share a high degree of hydraulic conductivity between them and are the most susceptible to salt water intrusion (Ukayli, 1971). Other sources such as (Khair, 1992) place the number of existing wells for Beirut well beyond 10,000.

Unlike the aforementioned and accessible aquifers, the aquiferous C_{2a2} is sandwiched and isolated between the impermeable C_{2a1} and C_3. Furthermore, the aquiferous Jurassic formation on the

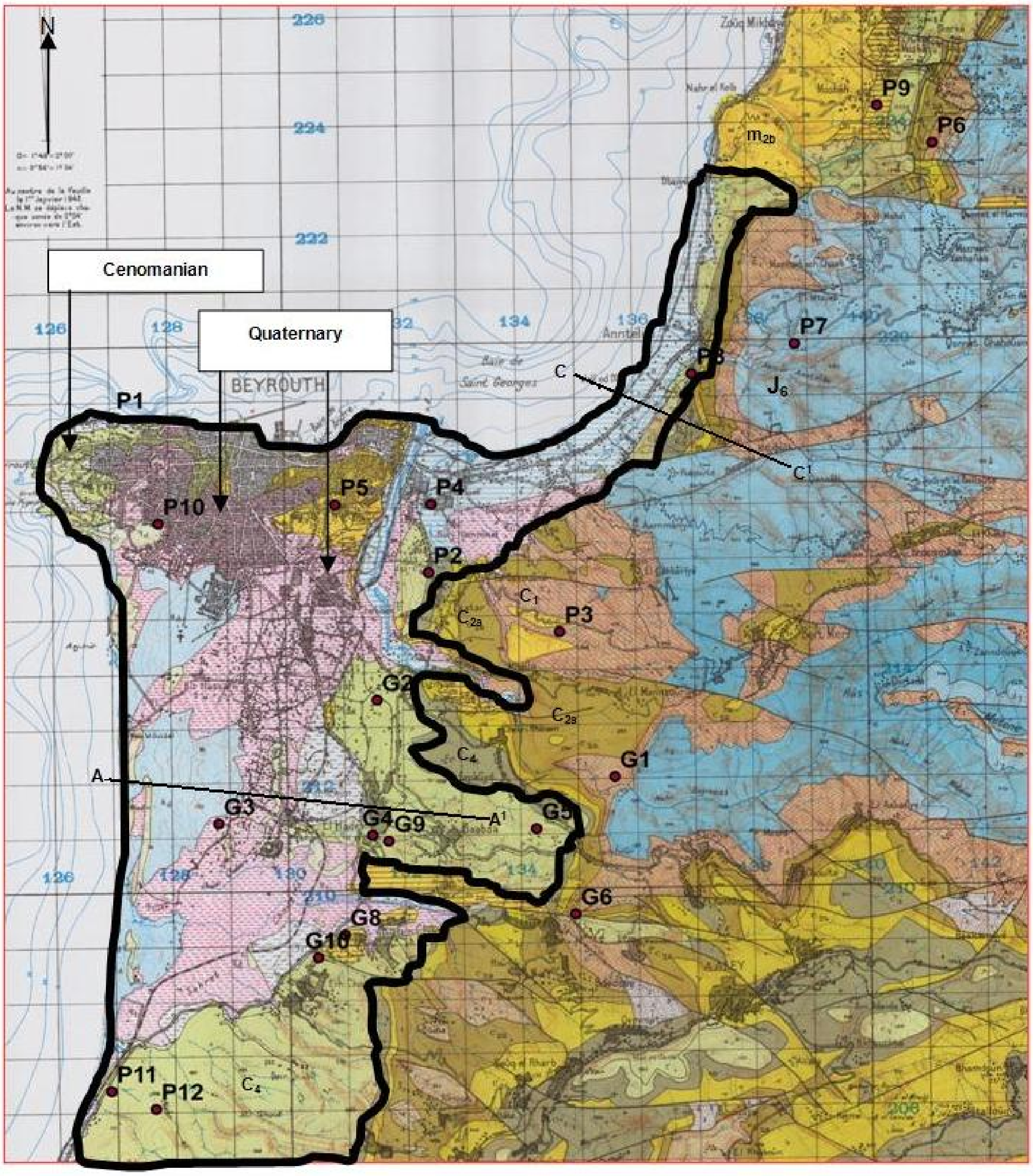
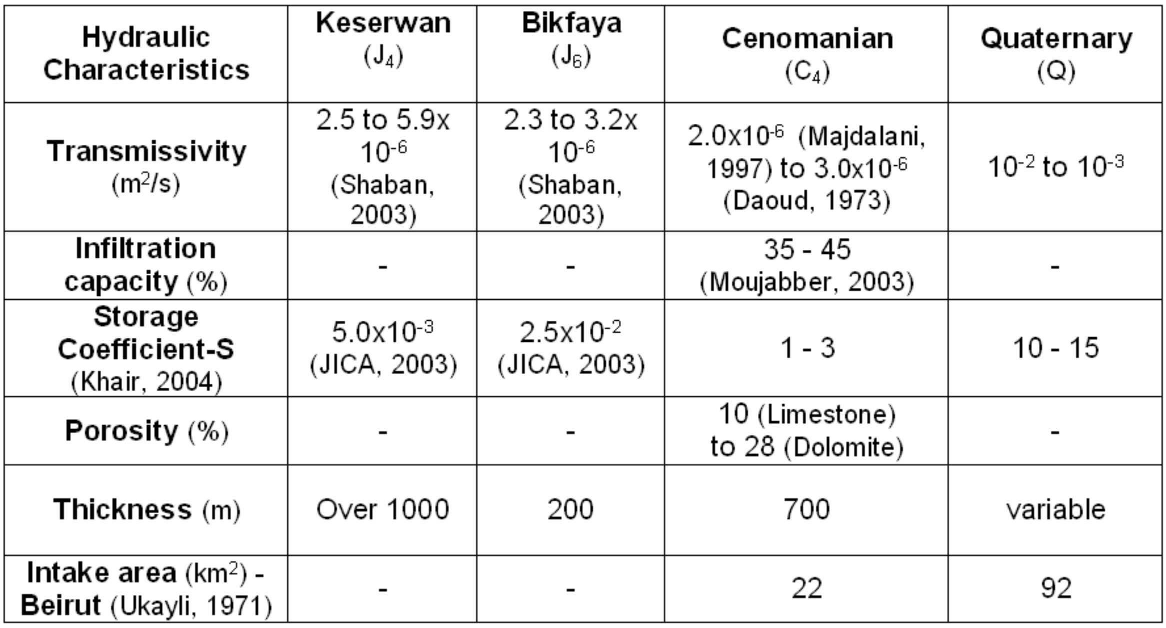


Figure 2.3: Geology of Greater Beirut and the Locations of Sampled Wells (Dubertret, 1945). NB: Each square represents 1 km^2

Table 2.6: Hydraulic Characteristics of Coastal Aquifers



Hydraulic Characteristics	**Keserwan** (J_4)	**Bikfaya** (J_6)	**Cenomanian** (C_4)	**Quaternary** (Q)
Transmissivity (m^2/s)	2.5 to 5.9x 10^{-6} (Shaban, 2003)	2.3 to 3.2x 10^{-6} (Shaban, 2003)	2.0x10^{-6} (Majdalani, 1997) to 3.0x10^{-6} (Daoud, 1973)	10^{-2} to 10^{-3}
Infiltration capacity (%)	-	-	35 - 45 (Moujabber, 2003)	-
Storage Coefficient-S (Khair, 2004)	5.0x10^{-3} (JICA, 2003)	2.5x10^{-2} (JICA, 2003)	1 - 3	10 - 15
Porosity (%)	-	-	10 (Limestone) to 28 (Dolomite)	-
Thickness (m)	Over 1000	200	700	variable
Intake area (km^2) - **Beirut** (Ukayli, 1971)	-	-	22	92

other hand remains too deep to be exploited in Beirut. See Table 2.6 for a summary of properties of the mentioned aquifers.

Lastly, in an attempt to determine firsthand the depth of the water table in a heavily populated part of eastern Beirut, some public wells were sampled on 23 March 2005 by the author, using a dip meter to assess seasonal fluctuations.

Repeat measurements were not possible due to the fact that the author was not granted, by the relevant authorities, further permission to take same measurements, and hence the project was discontinued.

3 Water

3.1 Water Budget

Lebanon, also known during the French Mandate as “Chateau d’eaux,” has a surface area of 10,452 km^2, with a typical Mediterranean climate, and is considered among the most water rich countries in the Middle East. However, there is a conflict in the estimations of this precious resource, but most would agree that Lebanon’s water reserve is under stress incurred mainly by a population that is growing at an average rate of 2%.

According to many sources (ECODIT-LAURIF, 1997) and others, the renewable water resources in Lebanon (about 9,000 MCM/ year from precipitation) are broadly classified as follows:

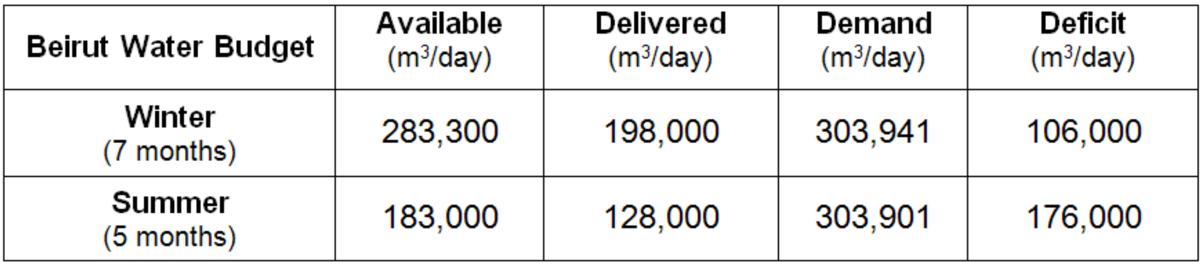
- 3,500 MCM/ year flowing waters in 15 perennial rivers,
- 1,250 MCM/ year flowing waters issuing from about 850 springs,
- 1,350 MCM/ year estimated groundwater resources.

Koumair (2005) estimated the total amount of water which Beirut and surroundings would require by the year 2030 will be in the range of 778 MCM (for domestic, industrial and agricultural purposes), however, these water requirements would be divided between agricultural consumption (15%), industrial (20%), and domestic (65%).

During the dry period, the water need for domestic and other purposes are generally estimated to be between 200 to 250 L/capita/day, whereas during the rainy season, the estimated average could drop to about 220 L/capita/day or less. Considering that Beirut’s current population is estimated at 1.5 million, then the total required amount would be no less than 110 MCM annually. As for agricultural and industrial demand for water, the quantities required by Greater Beirut are insignificant in comparison to the total current domestic requirements.

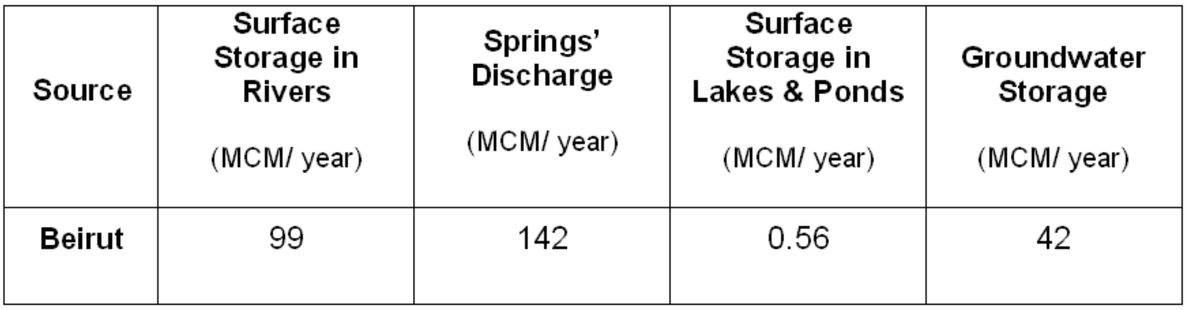
The Beirut Water Authority has issued the following estimates for Beirut’s water budget in

Table 3.1: Water Budget in Beirut (Beirut Water Authority)



Beirut Water Budget	**Available** (m^3/day)	**Delivered** (m^3/day)	**Demand** (m^3/day)	**Deficit** (m^3/day)
Winter (7 months)	283,300	198,000	303,941	106,000
Summer (5 months)	183,000	128,000	303,901	176,000

Table 3.2: Water Storage in Beirut (Shaban, 2003)



Source	**Surface Storage in Rivers** (MCM/ year)	**Springs' Discharge** (MCM/ year)	**Surface Storage in Lakes & Ponds** (MCM/ year)	**Groundwater Storage** (MCM/ year)
Beirut	99	142	0.56	42

recent years, summarized in Tables 3.1 and 3.2:

3.2 Water Sector in Lebanon

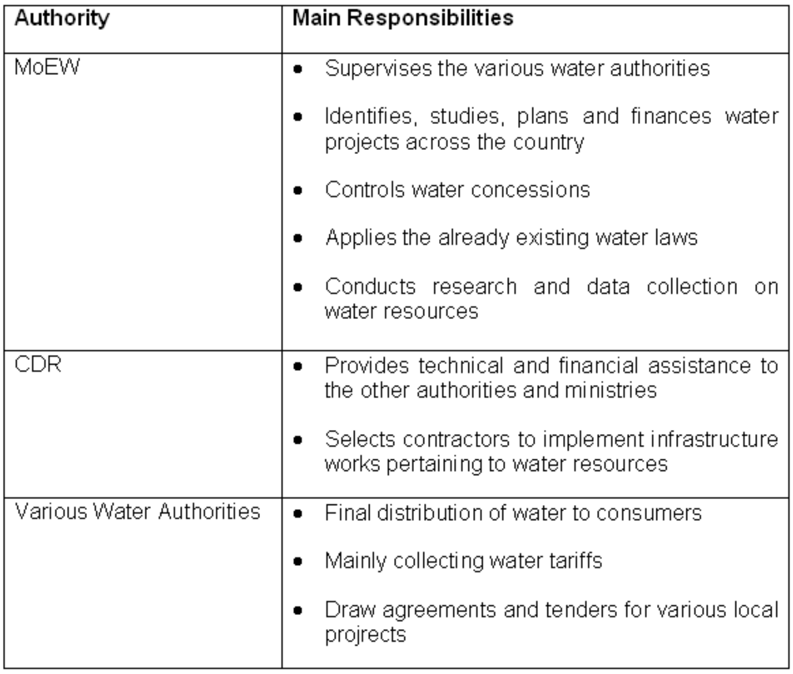
The management of water resources in Lebanon falls primarily under the responsibility of three entities:

- Ministry of Energy and Water (MoEW)
- Council for Development and Reconstruction (CDR)
- Various Autonomous Water Authorities (such as the Beirut Water Authority)

Table 3.3 summarizes the responsibilities of the aforementioned water sector authorities.

Water delivered to the consumers are abstracted from surface and groundwater sources. Surface sources comprise the majority of delivered water during the wet season, while boreholes provide much needed additional supplies during the predominating dry season (Semerjian, 2004).

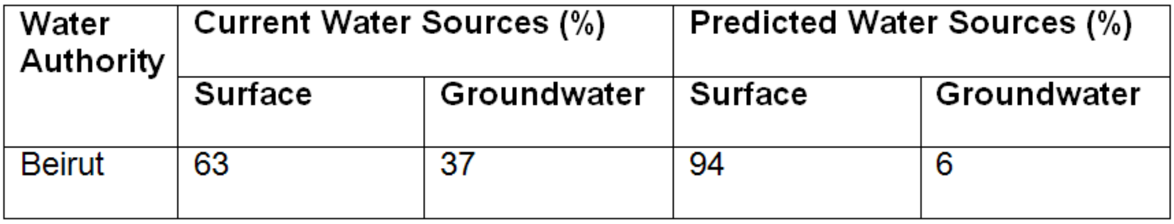
Table 3.3: Water Sector Agencies in Lebanon (Semerjian, 2004)



Authority	**Main Responsibilities**
MoEW	• Supervises the various water authorities • Identifies, studies, plans and finances water projects across the country • Controls water concessions • Applies the already existing water laws • Conducts research and data collection on water resources
CDR	• Provides technical and financial assistance to the other authorities and ministries • Selects contractors to implement infrastructure works pertaining to water resources
Various Water Authorities	• Final distribution of water to consumers • Mainly collecting water tariffs • Draw agreements and tenders for various local projrects

Future projects aim at relying more on surface waters as opposed to groundwater abstraction in to alleviate shortages pollution and seawater intrusion problems as depicted in the following table.

Table 3.4: Current and Future Water Sources Dependability (Semerjian, 2004)



Water Authority	**Current Water Sources (%)**		**Predicted Water Sources (%)**	
	Surface	**Groundwater**	**Surface**	**Groundwater**
Beirut	63	37	94	6

With the current population of Greater Beirut estimated in the range of 1.5 million (about a third of the total population) a tremendous strain is placed on the aquifers to meet the current water demand. Unless all wells are equiped with meters, any attempt at estimating the groundwater budget would entail a considerable margin of error. Figure 3.1 provides a glimpse of the average domestic water supply network in Lebanon.

Covering an area of about 130 km^2 (Ukayli, 1971), Greater Beirut is circumscribed by Kalb River in the north, Damour River to the south, and the Lebanon Mountain range to the west up to an altitude of about 400 m. The Ministry of Energy and Water is solely responsible for supplying Greater Beirut with its water needs relying mainly on the following sources (Rammal, 2005):

- Dbaye Water Treatment Plant: supplying nearly 350,000 m^3 per day of domestic water to Greater Beirut and the Metn.
- Daishunieh Spring: supplying on average 10,000 m^3 per day during the summer, to about 140,000 m^3 during the winter.
- Ain El Delbe Spring: supplying on average 12,000 m^3 per day during the summer, to over 100,000 m^3 during the winter.
- Public Wells: estimated to be around 40, spread all over Greater Beirut, and supplying a total of about 110,000 m^3 per day.

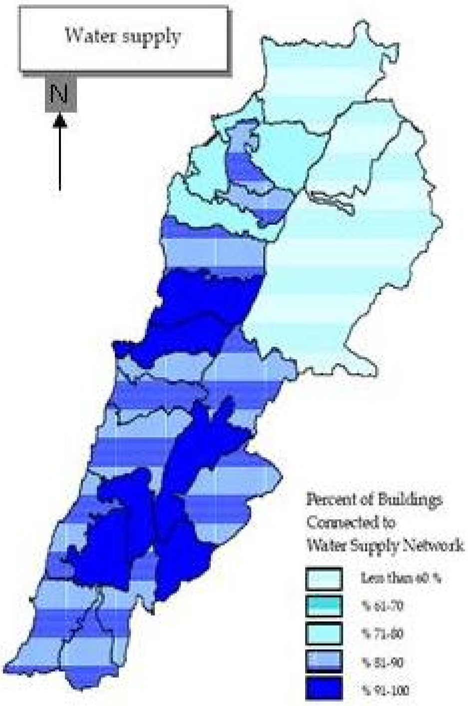
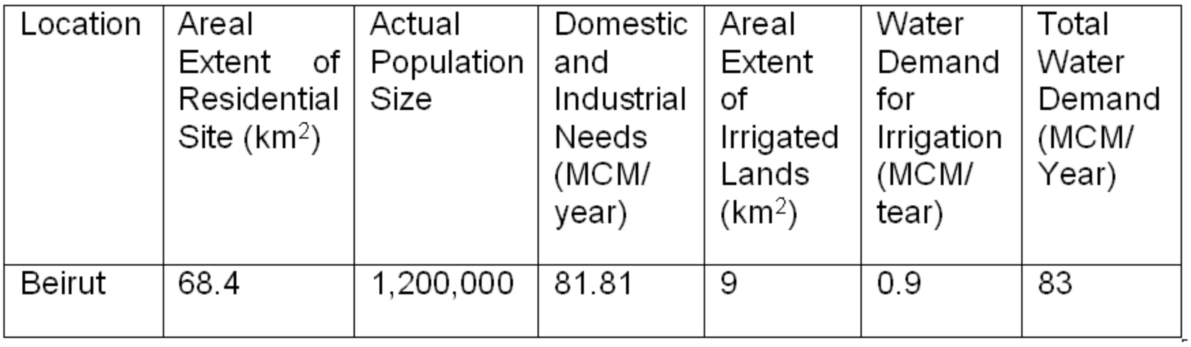


Figure 3.1: Water Supply Network of Lebanon, not to scale (Ministry of Environment/LEDO, 2002)

The current average domestic water needs of Greater Beirut is in the range of 330,000 m3 per day (assuming 220 liters per capita per day). The water delivered by the aforementioned sources varies between 200,000 m3 per day during the summer, to about 450,000 m^3 per day during the winter. Hence, the water deficit during the summer is over 130,000 m^3. Table 3.5 provides an idea of the estimated water demand for Beirut based on a PhD thesis completed by Amin Shaban in 2003.

Table 3.5: Water Demand in Beirut (Shaban, 2003)



Location	Areal Extent of Residential Site (km^2)	Actual Population Size	Domestic and Industrial Needs (MCM/ year)	Areal Extent of Irrigated Lands (km^2)	Water Demand for Irrigation (MCM/ tear)	Total Water Demand (MCM/ Year)
Beirut	68.4	1,200,000	81.81	9	0.9	83

A recent survey of Beirut's domestic water supply network was conducted during 2005. The survey concluded that losses in water quantity from supply pipes were up to 40% in some areas with an estimated one leak for every 2 km of network length, out of a total of 400 km for Beirut (Maalouf, 2005). With such a deficit during the summer time, the affected population of Greater Beirut is consequently forced to resort to groundwater exploitation through abstraction by thousands of existing wells promoting further ingress of seawater.

3.3 Wastewater

Some 2.3 million people live in the coastal zone, and they release approximately 950,000 m^3 of wastewater a day, most of it ending up in the sea (LEDO, 2002).

While improvements are being made to sewer networks, wastewater treatment plants are non existant except in Ghadir (southern Beirut suburbs). However, several wastewater treatment plants are expected to become operational in the near future.

3.3.1 Wastewater Network

Since 1997, improvements in wastewater works have been achieved, which has presumably increased the wastewater collection capacity. The current extent of buildings connected to sewer networks in Greater Beirut is higher than the rest of the country estimated at around 90% (LEDO, 2002). The remaining buildings either use cesspools and septic tanks or simply release raw sewage directly into the environment, including rivers and streams, dry river beds, and underground (through dry wells) as inferred from Figure 3.2 .

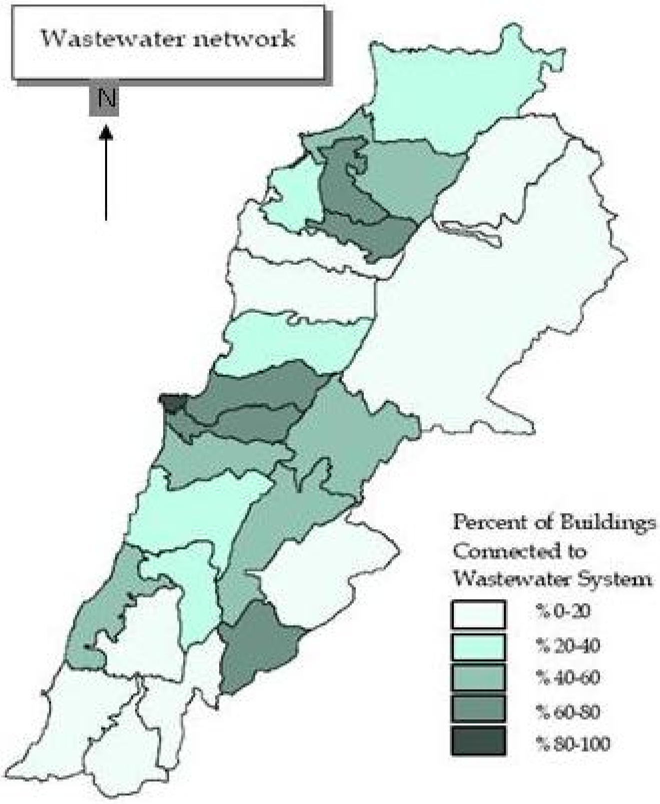


Figure 3.2: Wastewater System of Lebanon (LEDO, 2002)

In the Greater Beirut area, wastewater, from Beirut as well as parts of the Cazas of Metn, Baabda and Aley is mainly collected and transported to a series of coastal collectors. The northern main collectors comprise two lines that converge on Dora, where a wastewater treatment plant and associated outfall will be constructed. Specifically, these lines extend from the Manara area in Ras Beirut to Dora, and from Dbaye to Dora. Together, these northern collectors extend over about 17 kilometers and are designed for a future population of only 891,000 people (LEDO, 2002).

Likewise, the southern collectors comprise two lines converging on the Ghadir plant, where a preliminary wastewater treatment facility already exists. These converging lines originate from the Manara area and Naameh, respectively. The two southern collectors are about nine kilometer long and will serve an estimated population of 784,000. Figure 3.3 illustrates the overall design for wastewater collection and treatment in the GBA (design capacity 1.68 million people), (LEDO, 2002).

Although works on the northern coastal collectors were completed in 2001, the collectors will remain out of operation until the proposed Dora wastewater treatment plant is constructed. To date, no funding is foreseeable for the construction of the Dora plant, which means that the

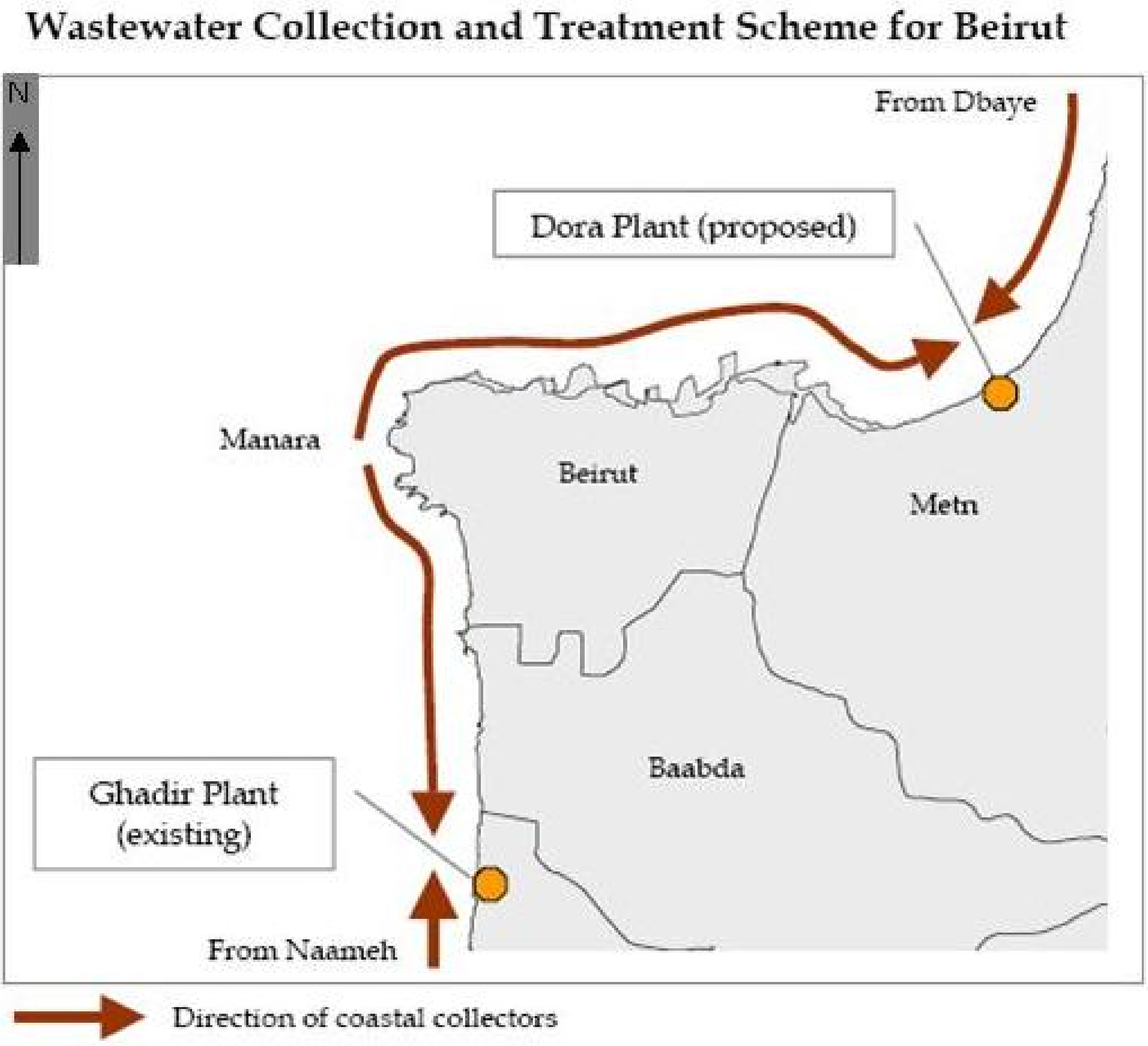


Figure 3.3: Wastewater Collection Scheme of Beirut (Ministry of Environment/LEDO, 2002)

collectors will remain idle for several more years to come. Meanwhile, the newly built collectors would eventually require routine maintenance and repairs. The Council for Development and Reconstruction (CDR) is currently contracting out the construction of the southern coastal collector from Ras Beirut to Ghadir.

The only wastewater treatment plant in Greater Beirut (and Lebanon for that matter) is currently in Ghadir.

This plant however provides only preliminary treatment (i.e. grit and scum removal). The Ghadir outfall is a 1,200-mm diameter submersed pipeline which extends 2.6 km into the Mediterranean Sea. The outlet point is approximately 60 meters deep thereby achieving some dilution of the disposed wastewater (LEDO, 2002).

Other studies are exploring the economic feasibility of upgrading the Ghadir wastewater treatment plant to provide secondary treatment before discharge into the sea. The other proposed Beirut wastewater treatment plant located in Karantina, will also become operational once funds for construction are secured.

3.3.2 Wastewater Disposal

In the absence of operational wastewater treatment plants, effluents from coastal communities are discharged into the sea while effluent from inland communities are disposed in rivers, streams, on open land or underground. Usually, approximately 80% of the house or per-capita domestic water demand is accounted for as wastewater, but other sources such as infiltration and industrial discharge for example, often result in wastewater flow that is greater than the water demand rates (Tchobanoglous and Schroeder, 1987).

In addition to the aforementioned wastewater discharge outfalls of Ghadir and Karantina, of Beirut proper (each discharging over 50 m^3 per day), there are an estimated 15 minor outfalls (50 m^3 per day) serving the remaining population of Greater Beirut and extending along the entire coast.

Most outfals extend only a couple of meters or terminate at the surface of the water (i.e., no submersed outfall and therefore no effective dilution of wastewater). See Figure 3.4 for a typical outfall in Beirut.

The conclusion drawn here is that there is negligible mixing of raw sewage with the aquifers of Greater Beirut, primarily due to the aforementioned fact that about 90% of the total population of Greater Beirut is served by the municipal sewer network (Rammal, 2005).

Figure 3.4: Typical Image of Raw Sewage Discharging on the Coast of Beirut (2006)

4 Understanding Seawater Intrusion

The global phenomena of seawater intrusion is the most important process that degrades the groundwater quality of coastal aquifers by increasing the salinity to such concentrations that render them unacceptable for drinking, irrigation or even engineering purposes (were concrete is involved).

Seawater can contaminate freshwater aquifers thru several routes, including lateral intrusion from the sea, and by downward intrusion from coastal waters. Some authors use the term seawater encroachment to refer to lateral movement of seawater within an aquifer and the term seawater intrusion to refer to vertical movement of seawater.

Another term that has been used to describe a specific type of vertical seawater intrusion is seawater upconing, which refers to the movement of seawater from a deeper seawater zone upward into a freshwater zone in response to pumping wells (Kumar, 2003). Seawater intrusion extent depends on several factors working alone or in tandem. They mainly include the following parameters:

- Rate of total groundwater abstraction (or withdrawal) versus aquifer recharge,
- Hydraulic properties of the aquifer such as permeability, and storativity,
- The potential presence of aquicludes that act as barriers hindering seawater intrusion,
- The distance of wells and drainage canals from the source of seawater intrusion.

The freshwater and seawater zones within coastal aquifers are separated by a transition zone within which mixing between freshwater and seawater. The transition zone is identified most commonly by measurements of total dissolved-solids concentration and of the chloride concentration of ground water sampled at designated observation wells.

Transition zones of mixing usually range from several hundred meters to several kilometers laterally, with typical chloride concentrations ranging from 250 to 20,000 mg/L, and TDS from

1,000 to 35,000 mg/L.

Within the transition zone, freshwater mixing is caused by heterogeneities in the geologic structure and the hydraulic properties of an aquifer and by dynamic forces that operate over a range of time scales, including daily fluctuations in tide stages, seasonal and annual variations in ground-water recharge rates, and long-term changes such as sea-level rise.

The interplay of these forces cause the freshwater and seawater zones to move seaward at times and landward at other times. The mechanism of movements and dispersion are not well known, but some experimental facts provide a theory; it has been noticed that near seas which have no tide (such as the Mediterranean), the transition zone is usually very narrow and sometimes non-existent, however, near seas with tides (the Atlantic Ocean), the transition zone may be rather considerable (Fried, 1975).

The theory is then the following: without tides and without pumping, and neglecting seasonal recharges due to rains (especially valid assumption in the semi-arid climates), the mean seawater-freshwater interface does not move. The only movement is freshwater flowing to the sea on the seawater which generates a probably small transverse dispersion, as it is linked to the vertical permeability. Also, seawater dispersing in the aquifer will be carried away by the freshwater (Fried, 1975).

There is a relatively simple equation that has been used in areas to estimate the depth to seawater and the thickness of freshwater in a water-table (unconfined) aquifer. The equation "Ghyben-Herzberg" relates the elevation of the water table to the elevation of the boundary of the interface between the freshwater and underlying seawater zones of an aquifer, and is based on the balance of the height of two columns of fluids of slightly different densities.

As a word of caution, classically the depth of the saline intrusion in an aquifer is roughly estimated by the Ghyben-Herzberg equation, but it applies only to porous systems and not karstic ones like those of Lebanon (Arfib, 2007).

In the equation, the thickness of the freshwater zone above sea level is represented as h and that below sea level is represented as Z. The two thicknesses are related by:

$Z = (\rho_f/\rho_s - \rho_f)/h$

Where;

- ρ_f is defined as the density of freshwater (mass/volume)

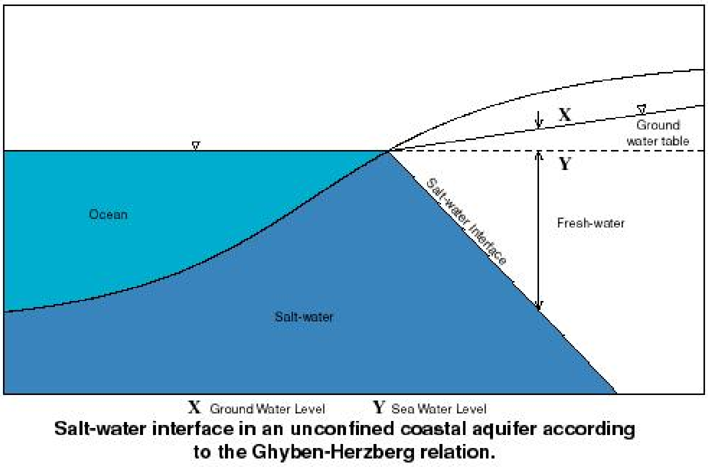


Figure 4.1: Seawater Intrusion in a Typical Coastal Aquifer, not to scale (Spechler, 1994)

- ρ_s is defined as the density of seawater (mass/volume)
- h is defined as the height of the groundwater table above sea level (meters)
- Z is defined as the depth to seawater interface from mean sea level (meters)

Freshwater has a density of about 1.000 grams per cubic centimeter (g/cm^3) at 20°C, whereas that of seawater is about 1.025 g/cm^3. Although the difference between the density of freshwater and seawater is small, this density contrast results in 40 m of freshwater below sea level for every 1 m of freshwater above sea level (Fetter, 1994), that is:

$Z = 40h$

Due to these minute differences in densities, small changes in fresh water level or head can induce large changes in the transition zone. It states that for every meter drop in head (water table), the seawater-freshwater interface immediately beneath will theoretically rise 40 meters. Therefore even very small changes in the water level (whether they are caused by drought or over abstraction).

In Figure 4.1 , freshwater and seawater mix at the boundary between the two waters, which results in a zone of dispersion at the interface.

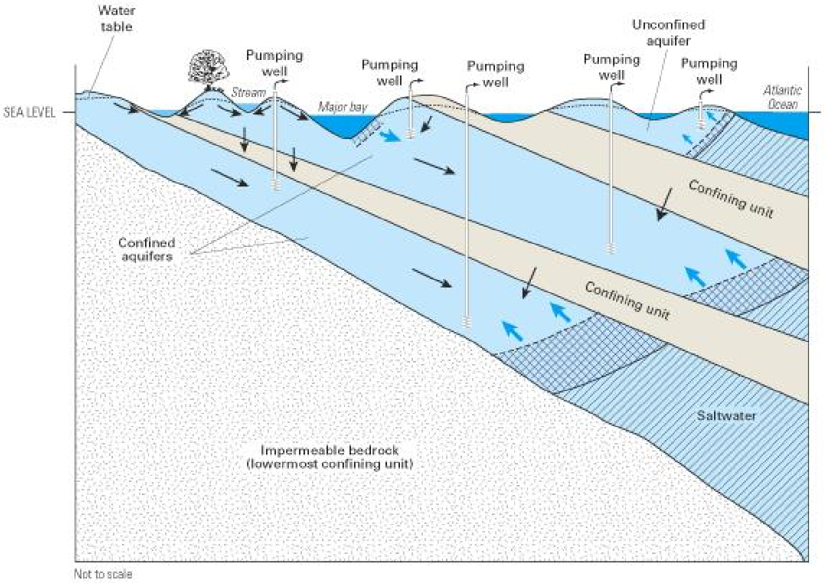


Figure 4.2: Modes of Seawater Intrusion in a Multilayer, Regional Aquifer System Caused by Ground-water Pumping, not to scale (Kumar, 2003)

This natural and delicate balance between freshwater and seawater in coastal aquifers is affected by prolonged ground-water abstractions and other human activities that lower the water table, reduce fresh ground-water flow to coastal waters, and ultimately leading to seawater intrusion. With ground-water pumping being the primary cause of seawater intrusion, the coast of Lebanon is no exception. Other hydraulic stresses that reduce freshwater flow into coastal aquifers, such as lowered rates of ground-water recharge in sewered or urbanized cities, also could lead to intrusion. The different modes of seawater intrusion are depicted in Figure 4.2.

4.1 Sources of Seawater in Coastal Aquifers

In order to discuss the various sources of seawater in coastal aquifers, it is pertinent to first define salinity and classify according to Total Dissolved Solids (TDS) the different types of waters, according to the definition set by the United States Geological Survey.

- Slightly saline: 1,000 to 3,000 mg/L
- Moderately saline: 3,000 to 10,000 mg/L

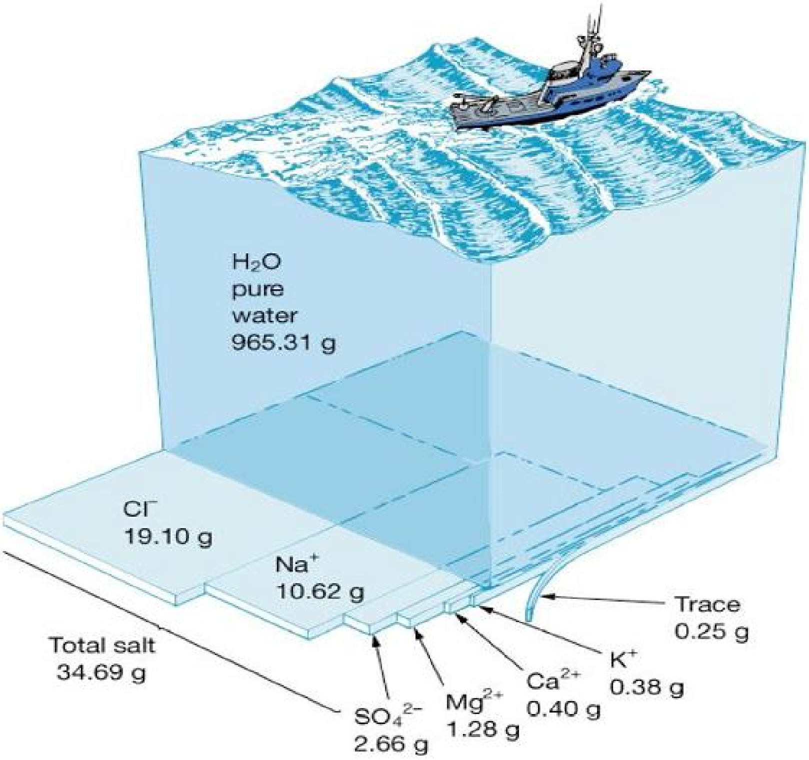


Figure 4.3: Chemical Composition of Seasalts (UCSC, 2000)

- Very Saline: 10,000 to 35,000 mg/L
- Brine: more than 35,000 mg/L

The upper concentration limit of saline water is normally set at the approximate concentration of seawater, with the largest concentration of salts being sodium chloride as evident in Figure 4.3
.

Because of the high concentration of chloride in seawater (19,000 mg/L), less than a 2-percent contribution of seawater mixed with fresh ground water would render the water unsuitable for public supply using the USEPA guideline (Barlow, 2003). A mixing of only 1% would triple the groundwater salinity, while a 5% mixing would increase salinity to over 1000 mg/L in chloride (Bear, 1999).

Although seawater is by far the primary source of saline water in coastal ground-water systems, a number of other sources can affect coastal ground-water quality. These sources include:

- Precipitation: seawater is the largest source of salts in the atmosphere, with sodium chloride being the most abundant of the these salts (Hamdy, 2001). Chloride and sodium concentrations, therefore, are high in air masses near sea coasts but decrease rapidly with increasing distance inland. These airborne salts are delivered to coastal watersheds by precipitation. Chloride concentrations in precipitation, however, are still relatively small compared to seawater.

- Sea-spray accumulation, tides, and storm surges, which can be local sources of increased ground-water salinity in low-lying coastal areas.
- Entrapped fossil seawater in ancient parts of an aquifer: Such water either was trapped in sedimentary formations when they were deposited (connate water), or flowed into the formations during elevated sea levels.
- Dissolution of evaporitic deposits such as halite (mineral sodium chloride), and gypsum (calcium sulfate).
- Pollution from various anthropogenic sources including sewage, industrial effluents, and irrigation water, just to name a few.

4.2 Effect of Seawater Intrusion

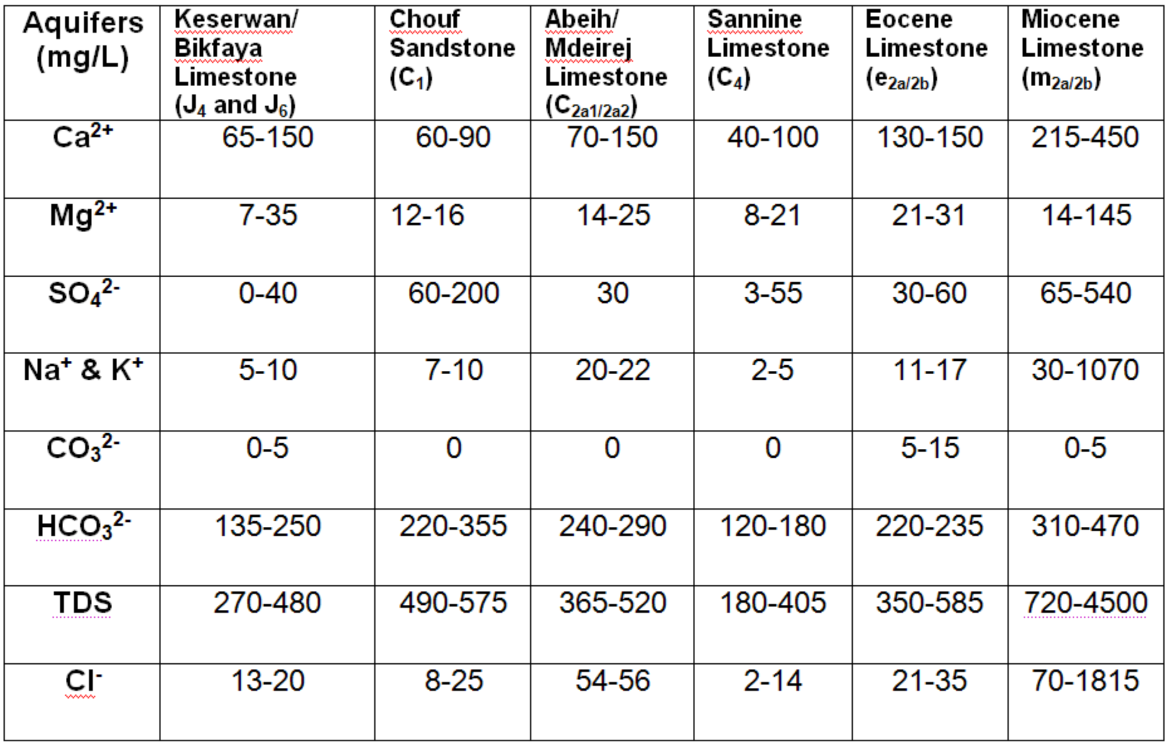
As already mentioned, the devastating effect of seawater intrusion on a coastal urban center that relies heavily on its coastal aquifer is threefold, drinking water, irrigation, and construction. As for Lebanon, the most severe of the aforementioned three being the contamination of potable ground-water. Lebanon's coastal seawater contains approximately 22,000 mg/L of chloride. Therefore, it is evident that even a small amount of seawater intrusion can cause drinking water problems when mixed with fresh water aquifers such as the Quaternary and Cretaceous which predominate in Greater Beirut.

A thesis completed by (Abbud, 1986), entitled “The Aquiferous Formations of Lebanon through the Chemistry of their Typical Springs,” states that of all the aquiferous formations, the Miocene limestone (which is a coastal aquifer) has the highest chloride content reaching 1,800 mg/L. Furthermore, all coastal aquifers of Lebanon are brackish, contaminated by sea water intrusion attested by elevated salinity concentrations.

Table 4.1 summarizes the aforementioned work that was carried out in order to determine typical spring waters issuing from aquifers across Lebanon.

Calcium is abundant in waters which are in contact with limestone, dolomite and gypsum. Mag-

Table 4.1: Typical Hydrochemistry of Lebanon's Aquifers (Abbud, 1986)



Aquifers (mg/L)	Keserwan/ Bikfaya Limestone (J_4 and J_6)	Chouf Sandstone (C_1)	Abeih/ Mdeirej Limestone ($C_{2a1/2a2}$)	Sannine Limestone (C_4)	Eocene Limestone ($e_{2a/2b}$)	Miocene Limestone ($m_{2a/2b}$)
Ca^{2+}	65-150	60-90	70-150	40-100	130-150	215-450
Mg^{2+}	7-35	12-16	14-25	8-21	21-31	14-145
SO_4^{2-}	0-40	60-200	30	3-55	30-60	65-540
Na^+ & K^+	5-10	7-10	20-22	2-5	11-17	30-1070
CO_3^{2-}	0-5	0	0	0	5-15	0-5
HCO_3^{2-}	135-250	220-355	240-290	120-180	220-235	310-470
TDS	270-480	490-575	365-520	180-405	350-585	720-4500
Cl^-	13-20	8-25	54-56	2-14	21-35	70-1815

nesium is mainly associated with dolomitic formations. In Lebanon, groundwater contains high concentrations of calcium and bicarbonate ions due to the abundance of limestone formations. (Bear, 1999) states that groundwater in Lebanon is either of the calcium bicarbonate or calcium sulfate type imparting temporary hardness.

Drinking water standards established by the United States Environmental Protection Agency (Agency, 2006) require that drinking water contain no more than 250 mg/L for chloride (commonly measured as salinity) and sulfate each, and 500 mg/L of Total Dissolved Solids (TDS). Yet, several public and private wells sampled in the study area of Greater Beirut have revealed salinities and Total Dissolved Solids (TDS) above 5,000 mg/L especially in the heavily populated areas of the southern suburbs. Even back in 1986, during Abbud's study, the coastal Miocene formation also revealed high TDS values attested by seawater intrusion.

Accordingly, since the demand of water needs in Lebanon is allocated mainly to agricultural use (estimated at over 65%), the first and major victim of seawater intrusion and thus elevated groundwater salinity are crops (Moujabber, 2002). Water with a TDS over 500 mg/L will begin to have detrimental effects on crops. And a TDS over 1,000 mg/L, will have adverse effects on most crops.

Furthermore, elevated concentrations of sulfate in groundwater associated with seawater intrusion, also has a definite laxative effect on humans. In this way, it can be troublesome especially to infants. In addition to its laxative properties, sulfate water can induce water hardness.

Chloride-rich water will also corrode metal pipes, causing leaching and will reduce the lifespan of household plumbing. According to the American Society for Testing and Materials, ASTM C-94 standard (ASTM, 2007) , water used for concrete mixing and curing places very stringent restraints on chloride, sulfate and TDS concentrations. Non compliance with said concrete standard has adverse repercussions by reducing strength and durability of concrete mainly through corrosion of embedded reinforcement. Many apartment buildings inspected by the author along the coast of Beirut, have exhibited corrosion of household plumbing and concrete reinforcement within as little as three years of construction, in most cases due to uncontrolled abstraction from brackish wells.

The ready mix concrete industry in Lebanon is very likely using saline water in its supplied concrete since there is no readily accessible alternative to pertinent fresh water sources.

4.3 Detecting Seawater Intrusion

The major obstacle faced with the author of this study was collecting data investigating the phenomena of seawater intrusion, which at best are scarce and random. Normally, this phenomena is monitored and hence diagnosed in time by the emplacement of a network of monitoring wells to track the location and movement of seawater in freshwater aquifers. A direct method for measuring seawater concentrations in coastal aquifers includes measuring water parameters such as TDS or Total Dissolved Solids, EC or Electrical Conductivity, and chloride or salinity, as well as Br, which are known to behave conservatively (Bear, 1999). Indirect methods, includes resorting to geophysical means to locate the freshwater/seawater interface.

Reports indicate that salinity of coastal wells have been on the rise since it was seriously investigated for the first time in 1964 by a UN study entitled: Report on Geoelectrical Investigations in the South of Beirut. Said report forewarned of a detected seawater-freshwater interface progressing evermore inland if left unchecked. Other numerous, but random studies, have since then investigated seawater intrusion and have also forewarned of rising levels of salinity in aquifers along the Lebanese coast. Some notable are: (Peltekian, 1980), (Khair, 1992), (Majdalani, 1997), and (Moujabber, 2002), to name a few.

Generally, most academicians and engineers believe that there are well over 10,000 wells tapping into the coastal aquifers of Beirut. As such, a study on seawater intrusion of Beirut indicated that chloride concentrations from 125 randomly sampled wells, have steadily risen from 340 mg/L in 1970/1, to 1200mg/L in 1979, to over 4200mg/L in 1985 (Khair, 1992). It should be emphasized that the presence of elevated concentrations of chloride alone is not by itself definitive proof of active seawater intrusion. Seawater intrusion is however indicated by increase in the chloride concentration of water samples collected periodically over time, rather than by a single or several measurements at one point in time. In addition, increase in sulfate concentrations is another reliable indicator of seawater intrusion.

This research of Greater Beirut's groundwater, reports salinities of over 5,000 mg/L in some public and private wells being utilized for various domestic, industrial and limited agricultural purposes. With such high levels of salinity in coastal wells, seawater intrusion would theoretically indicate a mixing of no less than 10%, placing it way past the 2% irreversible contamination limit (Barlow, 2003) which would render groundwater unsuitable for public supply.

Increasing chloride (or salinity) concentrations may well be the first indication of the approach of a seawater contamination front. In an area where no other source of saline contamination exists, high chloride concentrations in groundwater can be considered rather definitive proof of seawater contamination. Furthermore, the following ratios used in tandem with chloride measurements, offer further evidence of seawater intrusion. These ratios remain conservative throughout the world's seas and are known as the "law of constant proportions."

These ratios include sodium to chloride (Na/Cl), which is a useful tool for detecting seawater intrusion. Ratios usually lower than 0.86, combined with other geochemical parameters (Bear, 1999), and indexes such as Ca/Mg ratio, and Br/Cl are used as indicators in this study.

5 Investigation

5.1 Geostatistical Analyst

The purpose of geostatistics, in general, is to calculate a continuous ppredictionßurface using field measurements for the purpose of estimating values at locations where no measurements are available. Statistical methods have become an indispensable tool for environmental monitoring in general because it is practically impossible to cover a study area by direct observation of each and every point. By way of example, it would be economically unrealistic and impractical to analyze the entire aquifer water to decide if it is polluted or not.

For this reason, geostatistical analysis is a well established method used to estimate continuous surfaces from specific point measurements. It has been used in several groundwater contamination studies including the seminal works entitled: "Geostatistics Applied to Groundwater Contamination" as well as "Geostatistics Applied to Groundwater Pollution," (Cooper and Istok, 1988).

In said articles, the authors adopted Kriging as a geostatistical technique to obtain estimates of comtaminant concentrations at points within a groundwater contaminant plume from just a limited set of field measured concentrations. That is why, geostatistical analyst is a useful tool that creates a tightly integrated geostatistical approach with GIS software as illustrated in a typical predictive surface such as Figure 5.1.

In general, GIS is able to provide two different perspectives of the world

- The first perspective illustrates the world visually (spatial representation).
- The second perspective depicts the world in numbers and figures (attribute characteristics such as measured concentrations).

Surfaces generated during Geostatistical Analyst process can be used within the Geographic

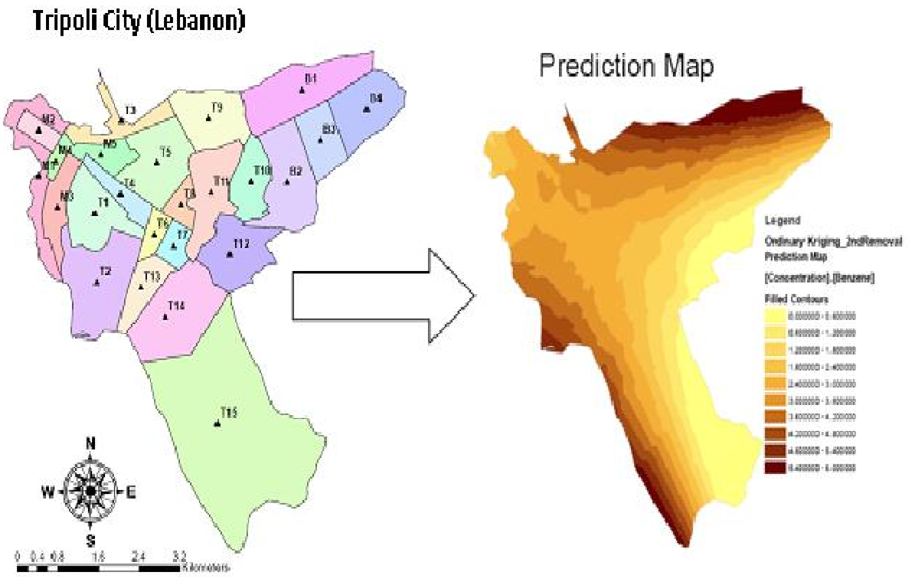


Figure 5.1: Generation of a Predictive Surface using Geostatistical Analyst (ESRI, 2002)

Information System (GIS) models and consequently can be visualized using ArcGIS extensions from Spatial Analyst to ArcGIS 3D Analyst in addition to other applications as for example in the following figure. The methodology of geostatistical analysis of contaminant concentrations from a source plume in groundwater consists basically of four steps:

- Determining if the measured contaminant concentrations are additive and normally distributed and to make appropriate transformations if they are not,
- The second step is to estimate the spatial correlation of pairs of measured concentrations as a function of the distance and direction of their separation, otherwise known as the calculation of the semivariogram,
- The third step is the structural analysis, in which a theoretical model is fitted to the experimental semivariogram,
- The fourth step is using a fitted model in an interpolation procedure known as Kriging to estimate expected values of contaminant concentrations for unmeasured points within the plume.

There are mainly two Geostatistical techniques used to create predictive Analysis: Deterministic Analysis and Geostatistical Analysis. Both methods rely on similarity of surrounding sample

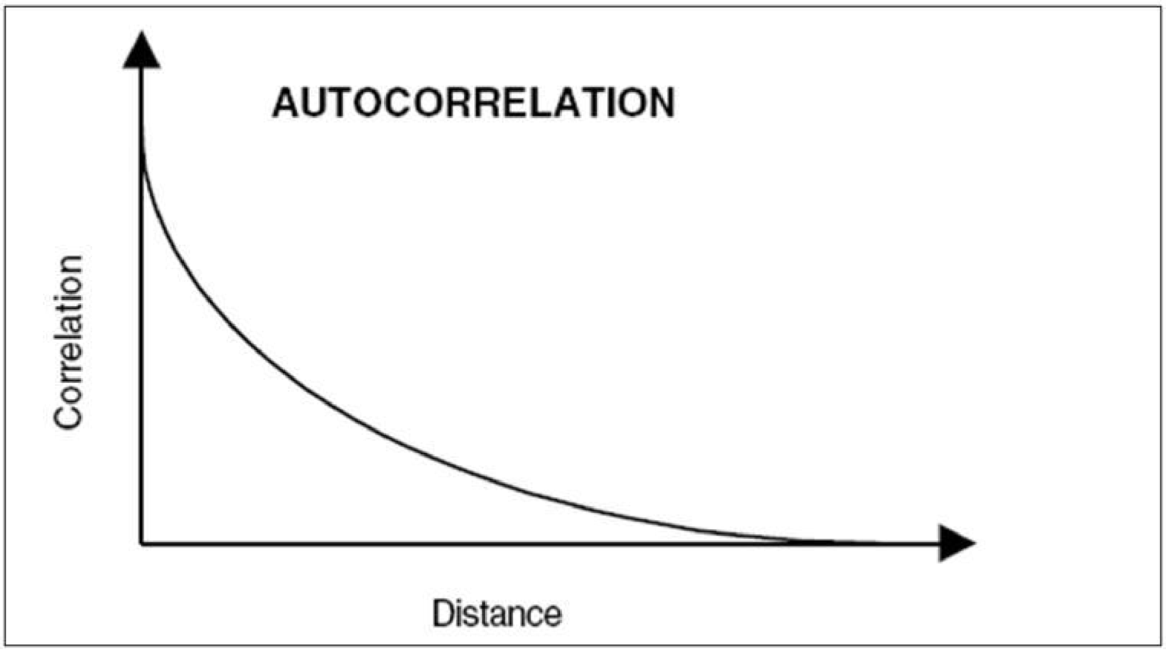


Figure 5.2: Example of One Dimensional Data Interpolation by Kriging (ESRI, 2002)

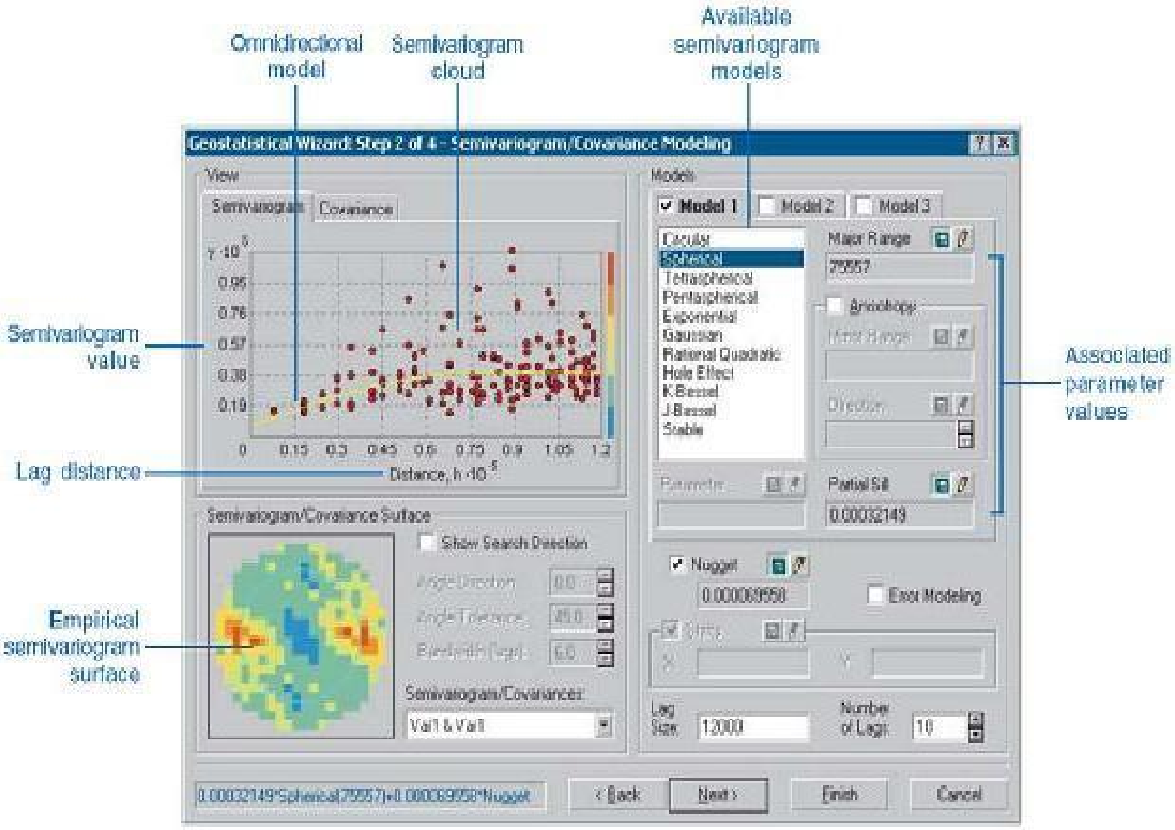
points during the prediction phase. The difference between the given techniques is that Deterministic method relies on mathematical functions while Geostatistical method relies on statistical and mathematical functions that take into account autocorrelation between points.

Deterministic methods include Inverse Distance Weighted (IDW), Radial Basis Functions (RBF) and global & local polynomial interpolators. These techniques are controlled by the degree of similarity between parameters without taking into account random spatial processing models (ESRI, 2002).

Geostatistical methods are based on several statistical approaches, but the one employed in this study is Kriging. These techniques assume that some of the spatial variation of the studied phenomena is attributed to spatial correlation and thus can be modeled using random spatial processes. In fact, Kriging methods rely on the autocorrelation which is defined as the tendency for two types of variables to be related. In the Kriging approach, this dependency can be expressed in function of distance as shown in Figure 5.2.

The method of Ordinary Kriging involves basically two processes, namely, variography and the prediction surface

1. Variography: determination of spatial-dependency (spatial structure) of data. This process involves fitting a function of correlation vs. distance.



☑ Model 1 ☐ Model 2 ☐ Model 3

Spherical

Major Range: 75557

☐ Anisotropy

Partial Sill: 0.00032149

☑ Nugget: 0.000069958

☐ Exact Modeling

☐ Show Search Direction

Angle Direction: 0.0

Angle Tolerance: 45.0

Bandwidth (lags): 6.0

Semivariogram/Covariances: Var1 & Var1

Lag Size: 1.2000

Number of Lags: 10

0.00032149*Spherical(75557)+0.000069958*Nugget

Figure 5.3: Semivariogram Modeling Dialog Box (ESRI, 2002)

2. Using the variography results, to generate prediction and probability surfaces.

Variography relies on spatial correlation estimated using the empirical semivariogram. The empirical semivariogram is a plot of $\frac{1}{2}$ the square of difference between pairs of data points vs. the distance between pairs of data points (ESRI, 2002). Pairs of data points are grouped according to common average distances as well as directions in clear steps of dialogue boxes as seen in Figure 5.3 .

Ordinary kriging principle formula is defined as follows (All Formula are taken form "Using ArcGIS Geostatistical Analyst", (ESRI, 2002):

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

where:

$\hat{Z}(s_0)$ is predicted value

N is number of points in the "searching neighborhood" used in calculating the average

λ_i weight for point i, based on distance and spatial correlation

$Z(s_i)$ is the observed value at the location i

Geostatistical Data can be expressed as:

$$Z(s) = \mu(s) + \epsilon(s)$$

where:

$Z(s)$ is the variable under consideration

$\mu(s)$ deterministic trend

$\epsilon(s)$ random and autocorrelated errors

Assumptions about random errors:

- Equal to zero on average
- Autocorrelation between $\epsilon(s)$ and $\epsilon(s+h)$ is on h and not s

Ordinary kriging assumes a polynomial mean as follows :

$$\begin{aligned} \mu(s) &= \mu \\ \mu(s) &= \beta_0 + \beta_1 x + \beta_2 y + \beta_3 x^2 + \beta_4 y^2 + \beta_5 xy \text{ (}2^{nd}\text{ order polynominal)} \end{aligned}$$

Ordinary Kriging was used in this study to generate prediction curves for chloride parameters superimposed on a georeferenced satellite image of the Greater Beirut. The chloride values used to generate said prediction curves of groundwater salinity were done carried out every month between October 2004 to December 2005, as well as a follow up on August 2006.

The next step was to select the Semivariogram Model as opposed to covariance with 2 to 5 neighbors included in the elliptical search shape.

Finally, for cross validation, a “predicted” chart type was used to check for prediction errors, by displaying prediction error indicators in the form of:

1. Mean,
2. Root mean square,
3. Mean standardized, and
4. Root mean square standardized.

On account of the large amount of data collected from the study area, a GIS database together with a geographic database was created, so as to enable integrated methods to be adopted for modeling seawater intrusion in the coastal aquifer system. The database, created with Microsoft Access, is implemented according to relational database principles. The information gathered in the monitoring network over the years of measuring campaigns were organized into files containing well coordinates and elevations, and results of chemical analyses for each month of measurement during this study. Each file is composed of fields containing the information gathered for each well and records pertaining to the well designation.

To facilitate input, modification and above all display of the information contained in the database, “masks” were created for “coordinates and elevations”, and “chemical analyses” for each month of measurement.

In each mask it is possible to:

1. search for information concerning a specific well;
2. access the other masks;
3. print the report of the data, after preview;

The geographic database of Greater Beirut consists of a number of views and themes:

1. a view that contains levels of general information that have been created from .DXF files

and imported and converted into ArcInfo coverages and ArcView shape, i.e., geology, elevation, and well locations;

2. a view containing the levels of information created from the seawater intrusion modeling results including the two-dimensional equipotential and equiconcentration lines.

5.2 Geochemical Investigation

5.2.1 Water Quality Testing Products

The water testing equipment used during this study were from LaMotte, USA. The following tests, pH, salinity, and Total Dissolved Solids (TDS) were completed on site with portable pocket-testers, while others were analyzed within a 24 hour period in a laboratory using the latest spectrophotometer.

The portable pocket-testers were calibrated at the beginning of every sampling day. Other parameters such as sodium, potassium, calcium, total hardness, magnesium, salinity, chloride, sulfate, bromine, nitrate phosphate, fluoride and alkalis were tested using the titrimetric method in tandem with the spectrophotometer.

5.2.2 Sample Collection

For chemical analyses, opaque PVC bottles were used purchased from LaMotte specifically produced for water quality sampling. Upon use, they were rinsed a few times with the water to be collected and examined. Commonly, at least three well volumes were removed or "purged" to ensure standing well water was discarded prior to sampling (Fetter, 1993). Well volume or casing is defined as the water standing in the well prior to pumping (Artiola, 2004).

pH was immediately performed in situ to avoid errors due to gas exchange using a portable pH measuring unit. For the remaining tests, samples were kept in coolers with ice packs at 40C before reaching the laboratory for storage in fridges until the relevant time of testing (Harter, 2003).

Prior to every sampling trip, all equipment was calibrated in order to ensure reliability of the test results. Furthermore, samples were duplicated during certain months and tested independantly in order to ensure quality control.

The following is a summary of the groundwater sampling protocol that was adopted throughout the duration of the field work (Triplett, 1997):

- Inspect the well for damage, missing parts, and evidence of tampering.
- Review equipment list, prepare area around well for sampling.
- Calibrate equipment within specified operating limits.
- Collect samples for laboratory analysis only after a minimum of three water column volumes has been purged.
- Record field parameters (air temperature, wind speed, precipitation, moisture, dust) while simultaneously purging the well. Specific conductance, temperature, and pH are measured in the field.
- Consult parameter list, adequately label sampling containers (site name, container ID, collection date, collection time, persons collecting sample).
- Don protective gloves. Replace gloves with a new pair when soiled and between each sampling site.
- Fill bottles to be analyzed in the following order: major and minor ions, nitrogen.
- Place the samples in a chilled shipment cooler at approximately 4 0C during transport to laboratories.
- Prepare quality control samples where applicable. One replicate (duplicate) semi annually.
- Decontaminate any reusable equipment and proceed to the next well.
- Ship the samples to the laboratory for analysis.

5.2.3 Field Quality Control Samples

Field quality control samples measure the effectiveness of field quality control activities in ensuring that data meet stated limits of precision and accuracy. There are two main types of FQC:

- Field quality control blanks;

- Field duplicates;

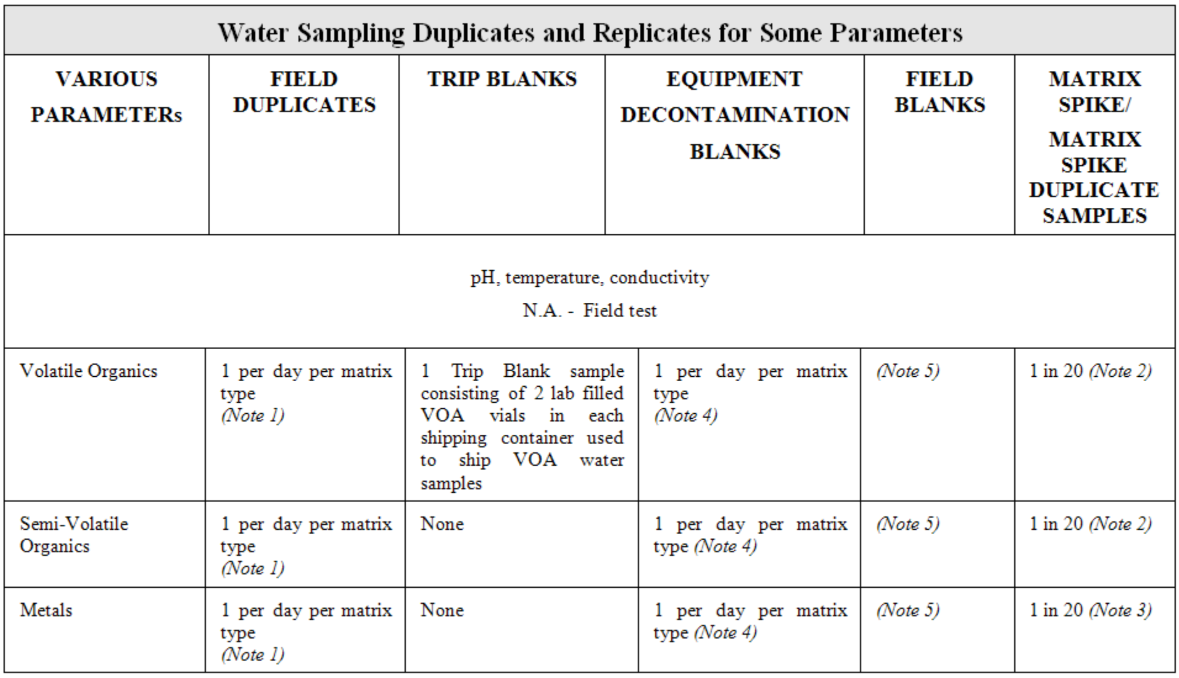
Field Blanks Blank samples are taken to ensure that the environmental samples have not been contaminated by the data collection process. Any measured value in a blank sample for any parameter that was absent in the blank solution is then due to contamination.

However, field blanks are used if there are concerns of environmental contamination during sample collection and processing, especially if testing for organics, volatile inorganics, hydrocarbons, oils and greases, which is not the case for this study.

Field Duplicates Field duplicates (FD) measure the variability in the sampling process. Duplicates are collected by repeating (simultaneously or in rapid succession) the entire sampling regime method that was used to obtain the initiall sample.

The field duplicates were collected, preserved, transported and documented in the same manner as the originals. They were analyzed for the sample parameters as the associated samples in an independent laboratory (SANA Engineers, Beirut) in order to cut down on the transit time.

Table 5.1: Sample Duplicates and Blanks (Navy, 2004)



Water Sampling Duplicates and Replicates for Some Parameters					
VARIOUS PARAMETERs	FIELD DUPLICATES	TRIP BLANKS	EQUIPMENT DECONTAMINATION BLANKS	FIELD BLANKS	MATRIX SPIKE/ MATRIX SPIKE DUPLICATE SAMPLES
pH, temperature, conductivity N.A. - Field test					
Volatile Organics	1 per day per matrix type *(Note 1)*	1 Trip Blank sample consisting of 2 lab filled VOA vials in each shipping container used to ship VOA water samples	1 per day per matrix type *(Note 4)*	*(Note 5)*	1 in 20 *(Note 2)*
Semi-Volatile Organics	1 per day per matrix type *(Note 1)*	None	1 per day per matrix type *(Note 4)*	*(Note 5)*	1 in 20 *(Note 2)*
Metals	1 per day per matrix type *(Note 1)*	None	1 per day per matrix type *(Note 4)*	*(Note 5)*	1 in 20 *(Note 3)*

Note 1 Water samples: For some projects and methods, 1 water sample in 10 may be required. Preparing a Field Duplicate Sample, minimum one per day per matrix type for RCRA.

Note 2 Water samples for organic analyses: Collecting an additional 4 sample containers for one sample in 20 for each matrix type per method.

Note 3 Water samples for inorganic analysis: One additional sample containers may be required Testing Sample should include enough material for lab MS/MSD samples to be run at the rate of 1 per 20 Test Samples (minimum of 1 MS/MSD per matrix per method or 1 per batch of samples).

Note 4 Submitting one per type of analysis for each type of sampling equipment used for each day of sampling and each matrix sampled. Project specific requirements may eliminate or increase the frequency of equipment decontamination blanks.

Note 5 Submitting one per type of analysis for each batch of sample containers and preservatives used.

The average of the differences between the actual field sampling results and the duplicates carried out in tandem done randomly during May, June and November 2005, in an independent laboratory (SANA Engineers Ltd, Beirut) resulted in differences usually not exceeding 11.0%.

On the other hand, if the only anomalous reading that exceeds 50% deviation is excluded (Ras el Nabaa well, in June 2005 for salinity), then the average difference between the two sets of results would drop to only 9%.

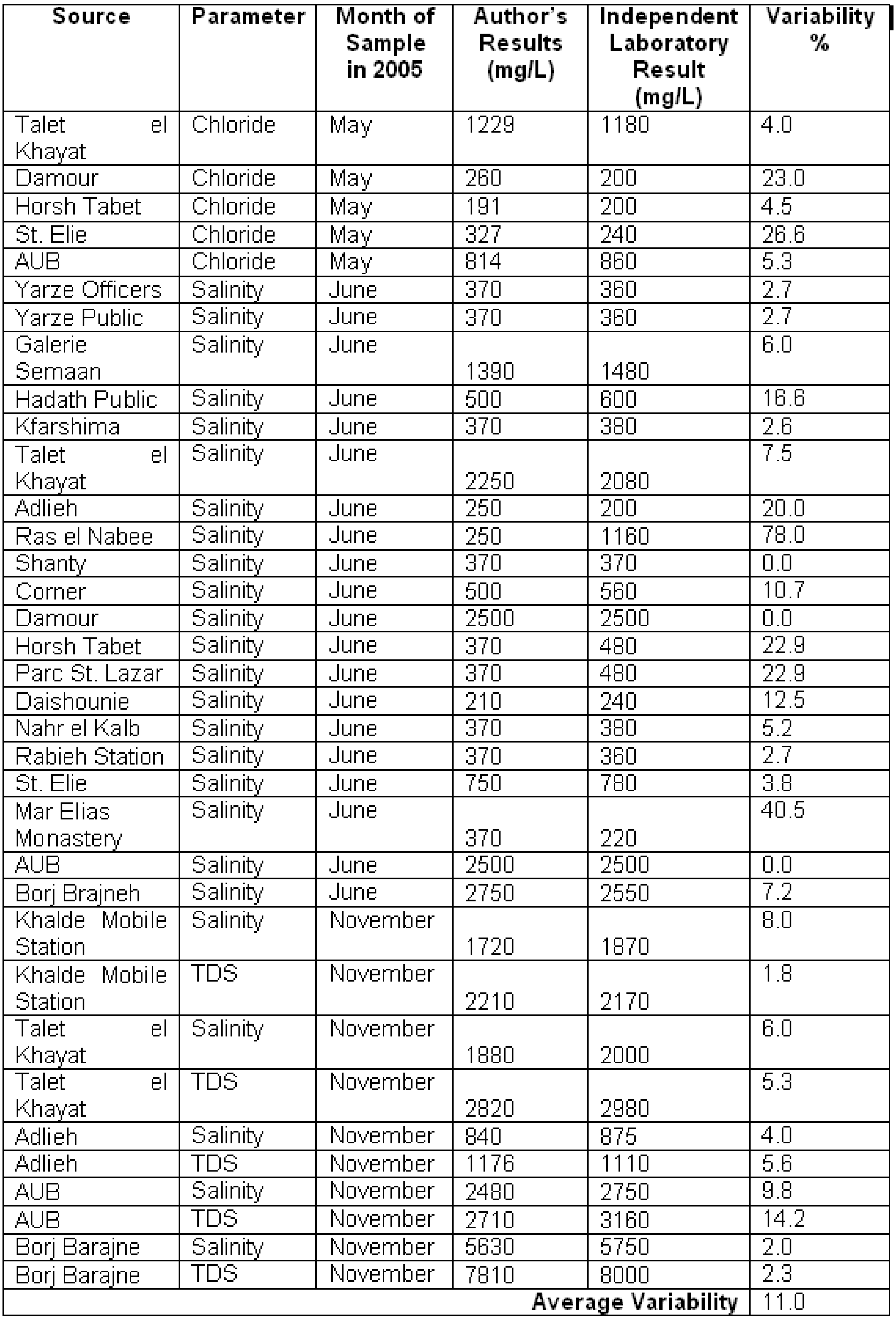
Chemical Parameters

Following is a brief summary of the relevant water parameters (analytes) that were tested from the sampled wells. Based on the abundance of the following parameters in groundwater, they can be classified as being major constituents (1,000 to 1 mg/L) such as sodium, calcium, magnesium, bicarbonate, sulfate and chloride, or secondary constituents (10 to 0.01 mg/L) such as potassium, carbonate and nitrate, or even minor constituents (0.1 to 0.0001 mg/L) such as phosphate (Chapman, 1996).

All results were reported as mg/L rather than the equivalent but outdated, parts per million (ppm). The two aforementioned units are equivalent so long as the Total Dissolved Solids (TDS) of water does not exceed 7,000, otherwise density corrections are necessary (Fetter, 1994).

Monthly: parameters tested on a monthly basis, and in situ.

Table 5.2: Quality Control of the Sampled Wells



Source	Parameter	Month of Sample in 2005	Author's Results (mg/L)	Independent Laboratory Result (mg/L)	Variability %
Talet el Khayat	Chloride	May	1229	1180	4.0
Damour	Chloride	May	260	200	23.0
Horsh Tabet	Chloride	May	191	200	4.5
St. Elie	Chloride	May	327	240	26.6
AUB	Chloride	May	814	860	5.3
Yarze Officers	Salinity	June	370	360	2.7
Yarze Public	Salinity	June	370	360	2.7
Galerie Semaan	Salinity	June	1390	1480	6.0
Hadath Public	Salinity	June	500	600	16.6
Kfarshima	Salinity	June	370	380	2.6
Talet el Khayat	Salinity	June	2250	2080	7.5
Adlieh	Salinity	June	250	200	20.0
Ras el Nabee	Salinity	June	250	1160	78.0
Shanty	Salinity	June	370	370	0.0
Corner	Salinity	June	500	560	10.7
Damour	Salinity	June	2500	2500	0.0
Horsh Tabet	Salinity	June	370	480	22.9
Parc St. Lazar	Salinity	June	370	480	22.9
Daishounie	Salinity	June	210	240	12.5
Nahr el Kalb	Salinity	June	370	380	5.2
Rabieh Station	Salinity	June	370	360	2.7
St. Elie	Salinity	June	750	780	3.8
Mar Elias Monastery	Salinity	June	370	220	40.5
AUB	Salinity	June	2500	2500	0.0
Borj Brajneh	Salinity	June	2750	2550	7.2
Khalde Mobile Station	Salinity	November	1720	1870	8.0
Khalde Mobile Station	TDS	November	2210	2170	1.8
Talet el Khayat	Salinity	November	1880	2000	6.0
Talet el Khayat	TDS	November	2820	2980	5.3
Adlieh	Salinity	November	840	875	4.0
Adlieh	TDS	November	1176	1110	5.6
AUB	Salinity	November	2480	2750	9.8
AUB	TDS	November	2710	3160	14.2
Borj Barajne	Salinity	November	5630	5750	2.0
Borj Barajne	TDS	November	7810	8000	2.3
				Average Variability	11.0

- pH
- Temperature (°C)
- Salinity and chlorinity (mg/L)
- Total Dissolved Solids (or TDS in mg/L)

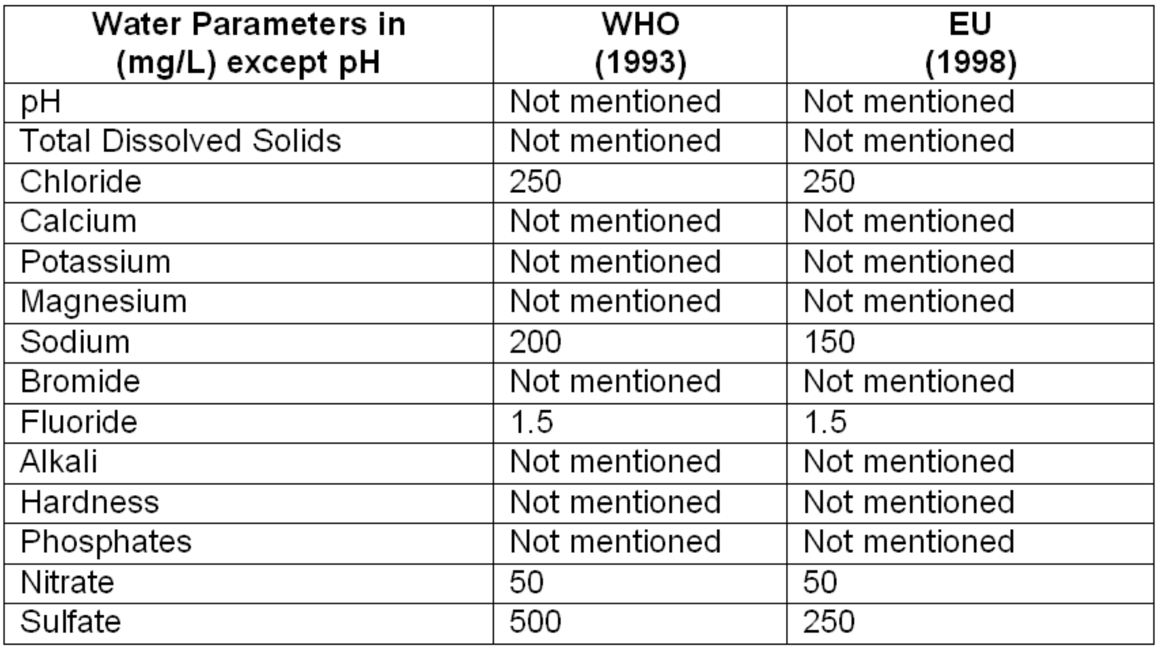
Seasonal: in addition to the aforementioned monthly parameters, the following were also sampled once per season. All expressed in mg/L as well.

- Sodium
- Potassium
- Calcium
- Nitrate
- Phosphate
- Sulfate
- Bromine
- Alkalinity
- Hardness
- Magnesium
- Fluoride

Chlorides

For drinking water, most standards recommend a maximum chloride content of 250 mg/L. See Table 5.3 for drinking water standards in Lebanon and from the EU and WHO. Although chlorides in drinking water are generally harmless to human beings, until concentrations exceeding 500 mg/L are surpassed, potentially affecting people with hypertension. Restrictions on chloride concentrations in drinking water are generally based on palatability requirements rather than on health.

Table 5.3: Worldwide Drinking Water Guidelines (Lenntech, 2004)



Water Parameters in (mg/L) except pH	WHO (1993)	EU (1998)
pH	Not mentioned	Not mentioned
Total Dissolved Solids	Not mentioned	Not mentioned
Chloride	250	250
Calcium	Not mentioned	Not mentioned
Potassium	Not mentioned	Not mentioned
Magnesium	Not mentioned	Not mentioned
Sodium	200	150
Bromide	Not mentioned	Not mentioned
Fluoride	1.5	1.5
Alkali	Not mentioned	Not mentioned
Hardness	Not mentioned	Not mentioned
Phosphates	Not mentioned	Not mentioned
Nitrate	50	50
Sulfate	500	250

Chlorides are found in all natural waters or may originate from the following sources if found in elevated concentrations:

1. Seawater intrusion,
2. Agricultural application of fertilizers,
3. Wastewater discharge,
4. Industrial wastewater.

Chlorides in excessive amounts in water supplies exert a significant effect on the rate of corrosion of steel and aluminum pipes if in excess of 500 mg/L (ASTM, 2007). In irrigation, they are considered to be among the most troublesome anions, considered to be toxic to crops such as lemons, fruit trees and potatoes if abound in concentrations in excess of 100 mg/L. In livestock, chloride concentrations in excess of 4000 mg/L have been reported to cause injury to livestock.

Salinity

Salinity is defined as the concentration of all ionic constituents present including halides and all bicarbonates being converted to carbonate. Sea water contains about 20,000 mg/L chloride and has a salinity of approximately 35,000 mg/L.

By measuring chlorinity, salinity can be determined using the following fixed ratio (University, 2006):

$\text{Salinity}_{ppt} = (1.805 \times chlorinity_{ppt}) + 0.03$ (ppt stands for parts per thousand)

A caveat regarding the use of the aforementioned equation, since it is best applied to waters with relatively constant major cations, where the ratios to one another are relatively constant such as the case of salts dissolved in seawater (Stumm and Morgan, 1996).

Nevertheless, the use of this equation was used prudently during this study only through continual quality control and assurance, by obtaining field replicates as discussed in the previous section.

Hardness

Total hardness is attributed principally to calcium and magnesium ions, expressed as an equivalent amount of calcium carbonate ($CaCO_3$) . When the hardness of water is greater than the sum of the carbonate and bicarbonate alkalinity, the amount in excess is called nnon-carbonate hardnessänd such waters may contain considerable amounts of chloride and sulfate ions. The sum of carbonate and non-carbonate hardness is commonly termed general hardness (Chapman, 1996).

Total hardness is commonly expressed in mg/L of calcium carbonate ($CaCO_3$), degrees hardness (dH) or, more properly, the molar concentration of $CaCO_3$. One German degree hardness (dH) is 10 mg of calcium oxide (CaO) per liter. In the U.S., hardness is usually measured in mg/L of $CaCO_3$. A German dH is 17.8 mg/L $CaCO_3$ (Chapman, 1996).

Note that most test kits give the hardness in units of $CaCO_3$; this means the hardness is equivalent to that much $CaCO_3$ in water but does not mean it actually originates from calcium carbonate.

Carbonate hardness (KH) is the measure of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions in the water. In freshwater of neutral pH, bicarbonate ions predominate and in seawater, carbonate ions begin to dominate.

Alkalinity on the other hand is the measure of the total acid binding capacity (all the anions

```
100% base             ,---------      ,----------
                     /               /
             H2CO3  |     HCO3-     |      CO3--
 50% mix     + CO2  |<- pH=6.37     |<- pH=10.25
                    |               |
                    /               /
100% acid  --------`       --------`

      pH   ...5...6...7...8...9...10..11..12...
```

which can bind with free H+) but is comprised mostly of carbonate hardness in freshwater systems. Thus, in practical freshwater usage, the terms carbonate hardness, acid binding, acid buffering capacity and alkalinity are used interchangeably. Carbonate hardness acts as one of the main buffering agent in stabilize the pH of limestone aquifers.

When groundwater has some carbonate buffering it, the bicarbonate ions will combine with the excess hydrogen ions to form carbonic acid (H_2CO_3) which then slowly breaks down into CO_2 gas and water. Since the excess hydrogen ions are used in the reaction, the pH does not alter very much. Over time, as the carbonate ions are used up, the buffering capacity will drop and larger pH changes are measured.

In more detail, the pH of a buffered solution can be expressed by the Henderson-Hasselbach equation:

$pH = pK + log(base/acid)$

where pK is one or more equilibrium dissociation constants of the weak acid. In the bicarbonate and carbonate buffering cases, this is:

$pH = 6.37 + log(HCO_3^-/H_2CO_3) and pH = 10.25 + log(CO_3^{2-}/HCO_3^-)$

pK values are affected considerably by temperature and chlorinity. Plotting the pH versus the ratio of the conjugate base to acid, a logarithmic graph as following is obtained:

Drinking water quality standards usually set the limits of calcium hardness at 200 mg/L and magnesium to 150 mg/L. Waters with a total hardness in the range of 0-60 mg/L are termed soft, from 60-120 mg/L are medium hardness, from 120-180 mg/L are hard, and above 180 are termed very hard.

The main detrimental effect of hardness is the formation of scales in boilers, hot water heaters, pipes and other similar utensils. As such, the major impact of water hardness is of economical value.

Total Dissolved Solids

Total dissolved solids is an expression for the combined content of all inorganic and organic substances contained in a liquid which are present in a molecular, ionized or suspended form. Generally the definition of TDS is that the solids must be small enough to pass a filter sieve size of 0.45 micrometres. Although TDS is not considered a primary pollutant (e.g. it is not deemed to be associated with health effects), but it is rather used as an indication of aesthetic characteristics of drinking water.

Primary sources for TDS in receiving waters are usually agricultural runoff, leaching of soil contamination and point source water pollution discharge from industrial or sewage treatment plants. The most common chemical constituents are calcium, phosphates, nitrates, sodium, potassium and chloride, which are found in nutrient runoff, general and stormwater runoff. These elements may be cations, anions, or molecules. More exotic and harmful elements of TDS are pesticides arising from surface runoff. Total dissolved solids also arise from the weathering and dissolution of rocks and soils.

Dissolved solids in natural water are usually composed of the sulfate, bicarbonate, and chlorides of calcium, magnesium and sodium. The recommended secondary limits for potable water are usually set at 500 mg/L. Table 5.4 classifies water according to TDS values, in general and in Lebanon specifically.

Table 5.4: Total Dissolved Solids Water Classification (Barlow, 2003)

TDS (mg/L)	Designation	Uses
0-1,000	Fresh	Most purposes
1,000-3,000	Slightly saline	Drinking if fresh water unavailable
3,000-10,000	Moderately saline	For livestock and limited irrigation
>10,000	Very saline to brine	Oil and gas production

Total dissolved solids are differentiated from total suspended solids (TSS), in that the latter cannot pass through a sieve of 0.45 micrometres and therefore are indefinitely suspended in solution.

Sulfates

Sulfates occur naturally in waters as a result of leaching from gypsum and other common minerals. Calcium sulfate and magnesium sulfate contribute significantly to the hardness of water. They also may be discharged in numerous industrial wastes such as tanneries, pulp mills, steel mills, municipal waste and textile mills. The standards normally set a limit for sulfate in potable water at around 250 mg/L. In irrigation waters, sulfate are less toxic than chlorides, yet in high concentrations, sulfate ions may cause the precipitation of calcium and may themselves become toxic to plants (Peltekian, 1980).

People unaccustomed to drinking water with elevated levels of sulfate can experience diarrhea and dehydration. Infants are often more sensitive to sulfate than adults. As a precaution, water with a sulfate level exceeding 400 mg/L should not be used in the preparation of infant formula.

Sulfate is derived principally from evaporate deposits such as gypsum. Minerals that contain sulfate include magnesium sulfate (Epsom salt), sodium sulfate (Glauber's salt), and calcium sulfate (gypsum). Sulfate may also result from the oxidation of reduced forms of sulfur (sulfite and sulfide), from wastes of various industries, or from seawater intrusion.

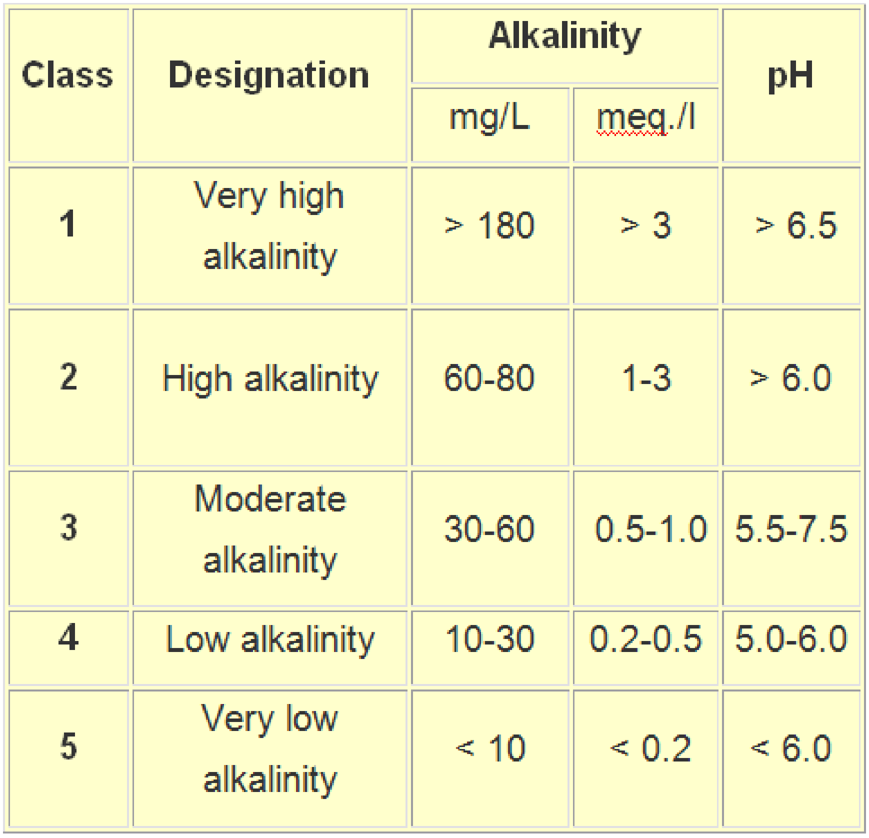
Under anaerobic conditions and pH levels below 8, sulfate reducing bacteria convert the sulfates into hydrogen sulfide gas (H_2S) which causes odor problems in ground water. When this gas is dissolved in the water, bacteria capable of oxidizing hydrogen sulfide convert the gas into sulfuric acid which is highly corrosive and attacks metallic and concrete pipes.

Alkalinity

Alkalinity is a measure of the acid neutralizing capacity (ANC) of a solution. This neutralizing capacity is equal to the sum of the bases in solution. The normal conditions of alkalinity of natural waters are associated with the dissolved carbon dioxide, bicarbonate, carbonate, and hydroxide components. These factors are characteristic of the source of water and the natural processes taking place at any given time. Natural groundwater however seldom contains hydroxide unless there is a considerable influx from alkaline wastes.

Incorrectly, alkalinity is sometimes used interchangeably with basicity. For example, the pH of a solution can be lowered by the addition of CO_2. This will reduce the basicity; however, the alkalinity will remain unchanged. Classification of water by alkalinity concentrations is summarized in Table 5.5.

Table 5.5: Alkalinity Water Classifcation (Agency, 2002)



Class	Designation	Alkalinity		pH
		mg/L	meq./l	
1	Very high alkalinity	> 180	> 3	> 6.5
2	High alkalinity	60-80	1-3	> 6.0
3	Moderate alkalinity	30-60	0.5-1.0	5.5-7.5
4	Low alkalinity	10-30	0.2-0.5	5.0-6.0
5	Very low alkalinity	< 10	< 0.2	< 6.0

The dissolution of carbonate aquifers in Lebanon overwhelmingly supplies groundwater with the carbonate and bicarbonate ions. Since measured groundwater pH values are usually in the range of 7 to 8.5, this would simply imply that bicarbonate ion predominates. At higher pH values, bicarbonate would dissociate into carbonate ions, and conversely, at low pH values ($<$ 4.5), bicarbonate are converted to carbonic acid.

Fluoride

Fluoride exists fairly abundantly in the earth's crust and can enter groundwater by natural processes such as erosion and weathering.

Water is a major source of fluoride intake. Most guidelines from around the world keep fluoride content in drinking water to a maximum concentration of 1 mg/L. The differentiation derives from the fact that we perspire more in hot weather and consequently drink more water. It should be noted that fluoride is also found in some foods, so the amount of fluoride people actually ingest may be higher than assumed.

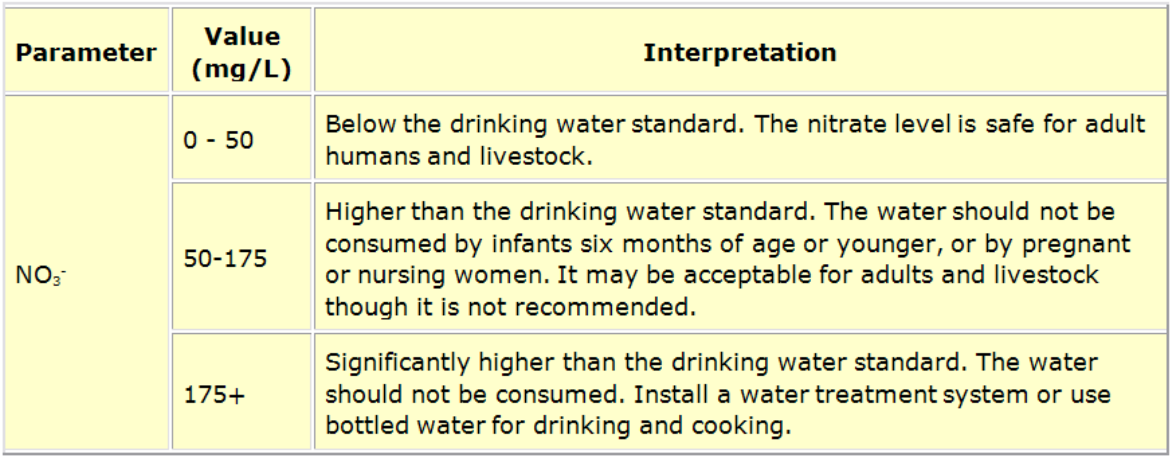
Fluoride may be present in natural water supplies as well as industrial and municipal effluents. Many municipal water supplies are supplemented with up to 1 mg/L of fluoride to strengthen teeth and reduce dental cavities. An excessive amount causes unsightly mottling of teeth enamel. The limits for domestic uses are usually set between 0.8 and 1.7 mg/L.

Chronic intake of excessive fluoride can lead to the severe and permanent bone and joint deformations of skeletal fluorosis. The next stage is osteosclerosis (hardening and calcifying of the bones), and finally the spine, major joints, muscles and nervous system are damaged.

Nitrate

Nitrate is a problem as a contaminant in drinking water (primarily from groundwater and wells) due to its harmful biological effects. High concentrations can cause methemoglobinemia, see Table 5.6.

Table 5.6: Nitrate Classification of Portable Water (District, 2002)



Parameter	Value (mg/L)	Interpretation
NO_3^-	0 - 50	Below the drinking water standard. The nitrate level is safe for adult humans and livestock.
	50-175	Higher than the drinking water standard. The water should not be consumed by infants six months of age or younger, or by pregnant or nursing women. It may be acceptable for adults and livestock though it is not recommended.
	175+	Significantly higher than the drinking water standard. The water should not be consumed. Install a water treatment system or use bottled water for drinking and cooking.

Anthropogenic activities have a major impact on the levels of nitrogen compounds that are found in both rain water and the atmosphere. Many of the major sources of nitrate and ammonium come from the use and production of fertilizers and the burning of fossil fuels.

Although there are many sources of nitrogen (both natural and anthropogenic) that could potentially lead to the pollution of the groundwater with nitrates, the anthropogenic sources are really the ones that most often cause the amount of nitrate to rise to a dangerous level.

Waste materials are one of the anthropogenic sources of nitrate contamination of groundwater. Many local sources of potential nitrate contamination of groundwater exist such as, disposal sites of human and animal sewage; industrial wastes, and sites where handling and accidental spills of nitrogenous materials may accumulate as well as from septic tanks.

In densely populated areas, septic systems can represent a major local source of nitrate to the groundwater. However in less populated areas septic systems pose a lesser threat to groundwater contamination.

The main source however, of nitrate pollution in the groundwater results from the agricultural application of fertilizers. The United States Environmental Protection Agency established the current drinking water standard and health advisory level of 10 mg/L nitrate-nitrogen (equivalent to 10 mg/L nitrate-nitrogen or 45 mg/L nitrate) based on the human health risks (District, 2002).

Sodium

Sodium is the most abundant of the alkali metals in natural waters. Nearly all sodium compounds are readily soluble, and since it does not precipitate, sodium generally remains in solution. The limit for potable water standards is usually 150 mg/L. There is some evidence that sodium can increase blood pressure.

The principal source of sodium in groundwater is mainly evaporate sediments, although sewage and industrial wastes contribute significant amounts. Sea water intrusion is another considerable source of sodium. As groundwater moves slowly through an aquifer (or water-bearing formation), it dissolves many minerals from the soil and rock.

Higher than normal levels of sodium in groundwater may indicate pollution. Salt, widely used as a de-icing agent, can enter both ground and surface waters by surface runoff. The most common source of sodium in drinking water is from the treatment of the water with an ion exchange water softener. A water softener exchanges the sodium ions in the water for the calcium and magnesium ions that cause water hardness. A water softener usually contributes an additional 100 to 150 milligrams per liter (mg/L) of sodium to the amount already present in groundwater.

Potassium

Potassium is another alkali metal similar to sodium in many respects. It is normally present in water in smaller amounts than sodium. Potassium in most natural waters is generally found in concentrations less than 10 mg/L. Standards for potable water limit potassium to 10 mg/L.

Sodium remains in solution persistently once liberated from silica mineral structures. The principal potassium minerals of silicate rocks are some feldspars. Potassium is released with difficulty from silica minerals and exhibits a strong tendency to be reincorporated into solid weathering products especially clays (Hem, 1992).

In most freshwater aquifers, if the sodium concentration substantially exceeds 10 mg/L, the potassium concentration is then commonly half of sodium.

Potassium is also an important element for both plants and soils. Maintenance of optimum soil fertility entails providing a supply of available potassium. The element is present in plant material and is lost from agricultural soil by crop harvesting and removal as well as by leaching and runoff acting on residues (Hem, 1992).

pH

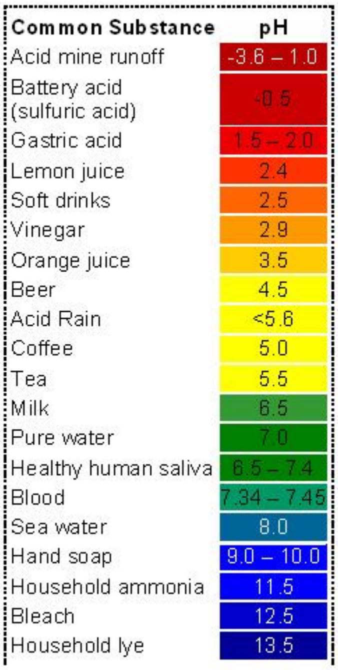
The term pH (or negative logarithm of the proton activity) can be considered to be an index of the amount of hydrogen ions present in a substance. Most natural waters will have pH values from 5 to 8.5. Natural sea water will have a pH value of 8.0 and changes from this value indicate that water from an inland source is entering the body of sea water.

In homogenous waters, the hydrogen ion activity is dictated by the dissociation constant of water ($Kw = 1.011 \times 10 - 14at25°C$) and interactions with other ions in solution. Due to this dissociation constant, a neutral solution (hydrogen ion activity equals hydroxide ion activity) has a pH of approximately 7. Aqueous solutions with pH values lower than 7 are considered acidic, while pH values higher than 7 are considered basic as summarized in Figure 5.4.

The reaction of dissolved carbon dioxide with water which is one of the most important, establishing pH in natural water systems, is represented by three steps:

$CO_2 + H_2O == H_2CO_3$

$H_2CO_3 == H^+ + HCO_3^-$



Common Substance	pH
Acid mine runoff	-3.6 – 1.0
Battery acid (sulfuric acid)	-0.5
Gastric acid	1.5 – 2.0
Lemon juice	2.4
Soft drinks	2.5
Vinegar	2.9
Orange juice	3.5
Beer	4.5
Acid Rain	<5.6
Coffee	5.0
Tea	5.5
Milk	6.5
Pure water	7.0
Healthy human saliva	6.5 – 7.4
Blood	7.34 – 7.45
Sea water	8.0
Hand soap	9.0 – 10.0
Household ammonia	11.5
Bleach	12.5
Household lye	13.5

Figure 5.4: Common pH Values

$$HCO_3^- == H^+ + CO_3^{2-}$$

Even when no other solutes are present, a few of the water molecules in liquid water will split into hydrogen and hydroxide ions.

Phosphates

Phosphates enter waterways from human and animal waste, phosphorus rich bedrock, laundry, cleaning, industrial effluents, and fertilizer runoff. These phosphates over enrich water systems with nutrients ultimately leading to eutrophication.

Soil erosion however may contribute considerable amounts of suspended phosphate to streams. The most important mineral source of phosphorous is apatite, which is calcium phosphate with variable amounts of hydroxide, chloride, fluoride.

The amount found in water generally is not more than 0.1 mg/L unless the water has become polluted from waste sources or excessive drainage from agricultural areas, but the latter seems to be rather a minor factor as phosphates are not very mobile in soils or sediments. Waste waters contain excessive amounts of phosphate as a result of the demand for household detergents.

When phosphorous is present in excess of the concentrations required for normal aquatic plant growth, a process called eutrophication takes place. This creates a favorable environment for the increase in algae and weed nuisances. This “cultural eutrophication” is an unnatural speeding up of this process because of man’s addition of phosphates, nitrogen, and sediment to the water. Bodies of water are being aged at a much faster rate than geological forces can create new ones.

Phosphorus is one of the key elements necessary for growth of plants and animals. Phosphates PO_4^{3-} are formed from this element. Phosphates exist in three forms: orthophosphate (M_3PO_4, where M can be potassium for instance), metaphosphate (or polyphosphate, $H_XP_YO_Z$) and organically bound phosphate. Each compound contains phosphorous in a different chemical formula. Ortho forms are produced by natural processes and are also found in sewage. Poly forms are used for treating boiler waters and in detergents. In water, they change into the ortho form. Organic phosphates on the other hand may result from the breakdown of organic pesticides.

The following criteria for total phosphorus were recommended by (Agency, 2006):

1. no more than 0.1 mg/L for streams which do not empty into reservoirs,
2. no more than 0.05 mg/L for streams discharging into reservoirs, and
3. no more than 0.025 mg/L for reservoirs

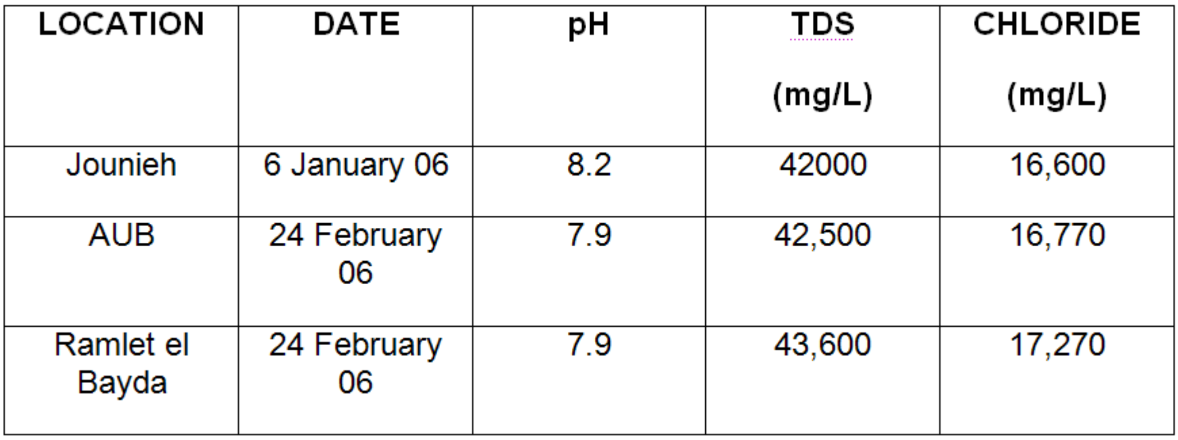
5.2.4 Sampling Coastal Waters

Coastal waters were tested along Greater Beirut in order to ascertain pertinent parameters mainly pH, TDS, and chlorinity for verification of previous studies which focused on seawater. Summary of the results are presented in Table 5.7 affirming that Beirut’s coastal waters range in 17,000 mg/L chloride.

5.2.5 Groundwater Sampling

The following wells were sampled during the duration of the study. Half of these wells were privately owned and hence designated as “P,” and the rest were drilled by the Ministry of Energy and Water and thus fall under the jurisdiction of the Beirut Water Establishment, designated as “G” for government. They are summarized in the following two tables:

Table 5.7: Chemical Characteristics of Beirut's Coastal Waters



LOCATION	DATE	pH	TDS (mg/L)	CHLORIDE (mg/L)
Jounieh	6 January 06	8.2	42000	16,600
AUB	24 February 06	7.9	42,500	16,770
Ramlet el Bayda	24 February 06	7.9	43,600	17,270

Many more wells were initially screened as part of the selection process for the specific purpose of monitoring seawater intrusion. Said process was time consuming and trying, since no monitoring network is in existence to this date in Lebanon to carry out any groundwater monitoring.

The main criteria for the well selection process was sufficient depth in order to sample water at or just below sea level and to ensure that all the major coastal aquifers of Greater Beirut were covered taking into consideration any unique geological structures such as faults, joints, and unconformities. Furthermore, wells were selected to ensure that all aquifers were adequately monitored.

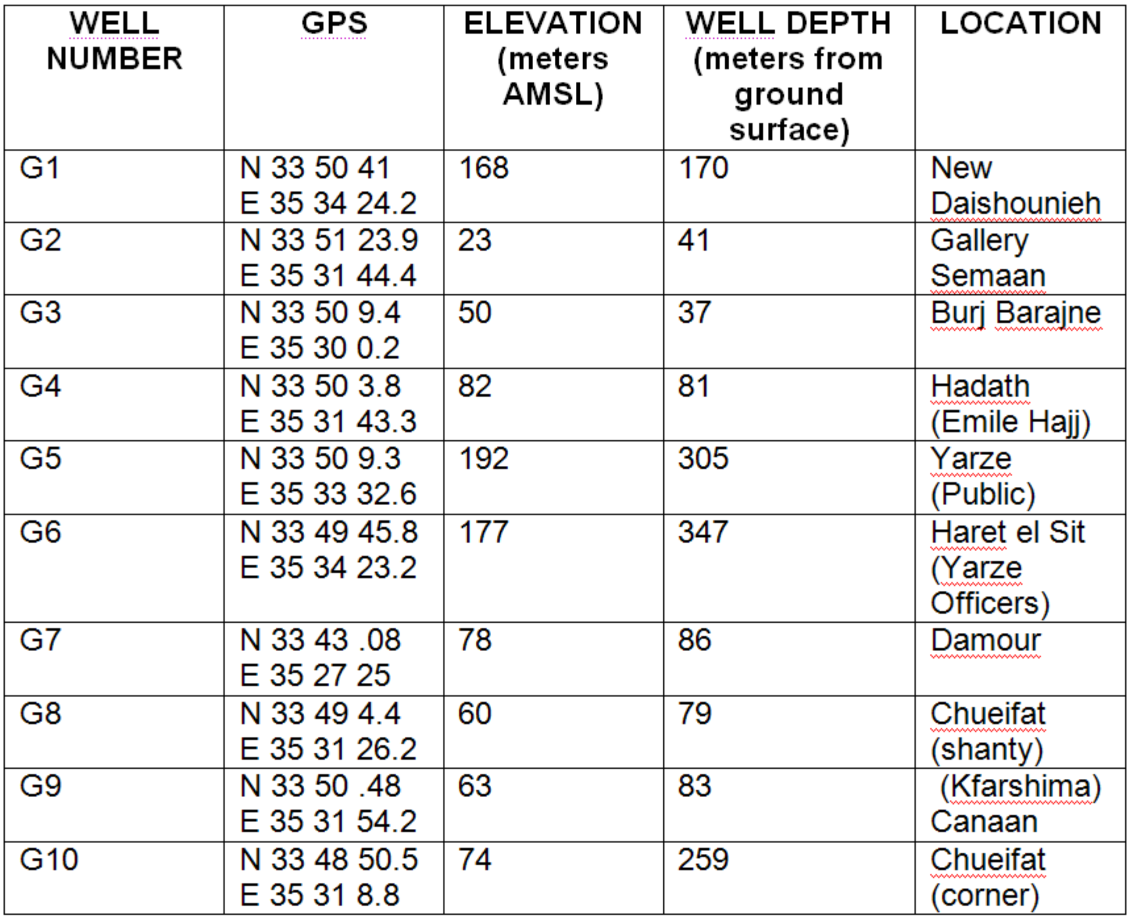
For comparison's sake, the United States Geological Survey has in existence along the Atlantic coast monitoring networks for seawater intrusion, as illustrated in the USGS report entitled: Ground Water in Freshwater-Seawater Environments of the Atlantic Coast, (Barlow, 2003). Accordingly, South Carolina for instance has a coastline exceeding 300 km with 80 monitoring wells in place. Fourty of which are monitored continuously and all are sampled twice a year. Calculating the density of wells per linear km of coastline, yields on average one monitoring well for every 4 km of coastline.

If the coastline of Greater Beirut is assumed to be in the range of about 35 km, according to the aforementioned density, the study area would require no more than 9 observation wells strategically located along the coastal aquifers. As such, more than twenty wells were carefully selected for monitoring purposes to ensure sufficient coverage during this study.

Table 5.8: Private Wells Sampled

WELL NUMBER	GPS	ELEVATION (meters AMSL)	WELL DEPTH (meters from ground surface)	LOCATION
P1	N 33 54 8.4 E 35 28 43.2	4	75	American University of Beirut (AUB)
P2	N 33 52 40 E 35 32 17.2	70	55	Horsh Tabet
P3	N 33 52 30.3 E 35 33 45.5	130	130	Hazmieh (Lazare)
P4	N 33 53 20.5 E 35 32 17.8	67	65	Adlieh
P5	N 33 53 19.2 E 35 31 13.8	56	105	Ras Nabaa
P6	N 33 56 60 E 35 37 48	41	130	Nahr Kalb
P7	N 33 54 97 E 35 59 15	223	125	Rabieh
P8	N 33 55 40 E 35 35 38	12	9	Jdeideh (St. Elie)
P9	N 33 57 21.3 E 35 37 34.9	134	320	Jeita
P10	N 33 53 5.9 E 35 29 15.9	103	320	Talet Khayat
P11	N 33 47 29 E 35 28 52.7	6	40	Khalde (Mobile Station)
P12	N 33 47 19.2 35 29 22.6	87	70	Aramoun

Table 5.9: Public Wells Sampled



WELL NUMBER	GPS	ELEVATION (meters AMSL)	WELL DEPTH (meters from ground surface)	LOCATION
G1	N 33 50 41 E 35 34 24.2	168	170	New Daishounieh
G2	N 33 51 23.9 E 35 31 44.4	23	41	Gallery Semaan
G3	N 33 50 9.4 E 35 30 0.2	50	37	Burj Barajne
G4	N 33 50 3.8 E 35 31 43.3	82	81	Hadath (Emile Hajj)
G5	N 33 50 9.3 E 35 33 32.6	192	305	Yarze (Public)
G6	N 33 49 45.8 E 35 34 23.2	177	347	Haret el Sit (Yarze Officers)
G7	N 33 43 .08 E 35 27 25	78	86	Damour
G8	N 33 49 4.4 E 35 31 26.2	60	79	Chueifat (shanty)
G9	N 33 50 .48 E 35 31 54.2	63	83	(Kfarshima) Canaan
G10	N 33 48 50.5 E 35 31 8.8	74	259	Chueifat (corner)

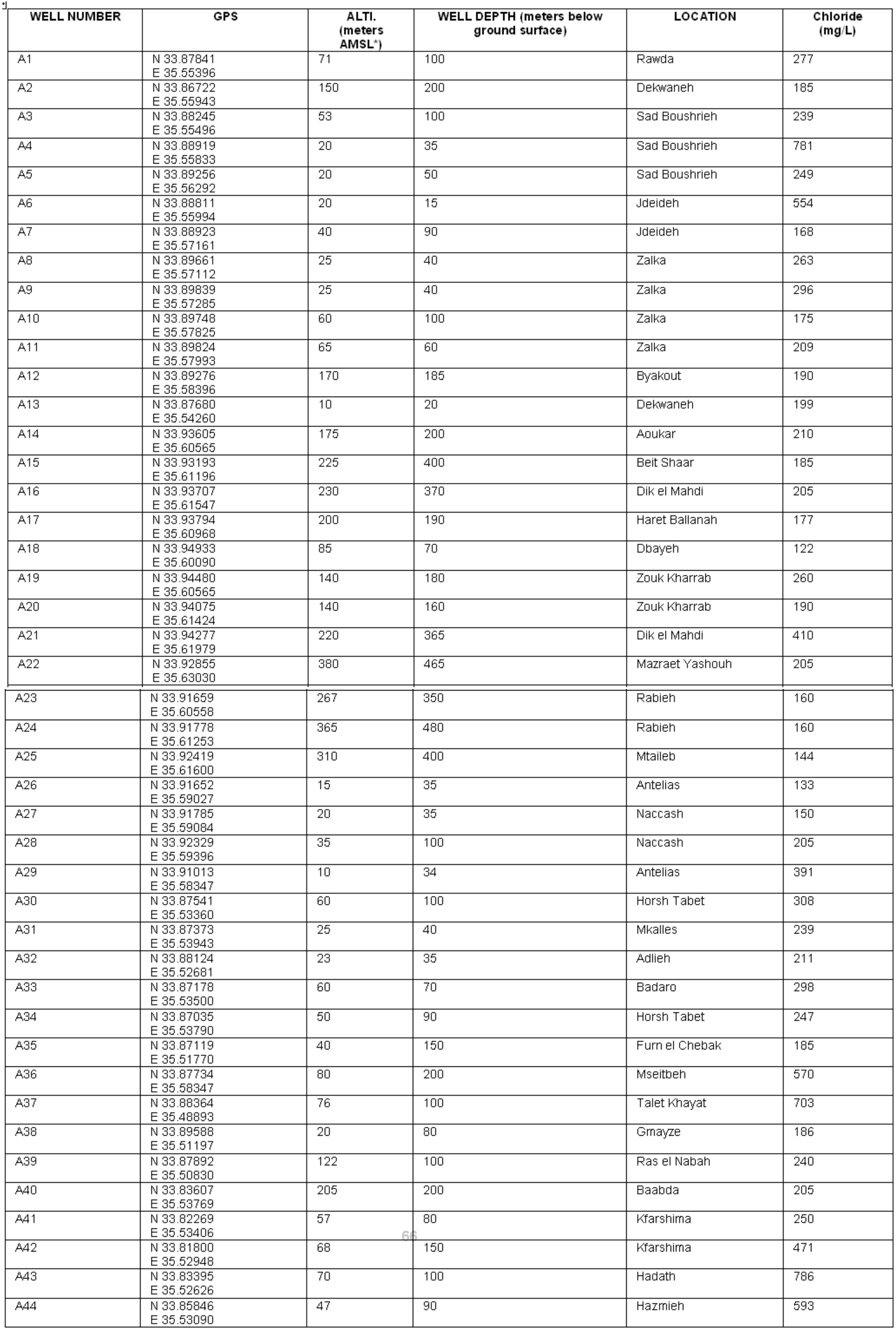
5.2.6 Additional Well Sampling

The following 44 additional wells were sampled during August 2006, as summarized in Table 5.10, nearly six months after the completion of the initial field survey. These privately owned wells were sampled for chlorinity, to serve the following purposes;

- Obtain a snapshot of the continued deterioration of groundwater during the dry period of 2006,
- Validate the outcome of the Geostatistical Analysis for the interpolated values of groundwater salinities in locations which were not covered during the initial survey of 2004/5.

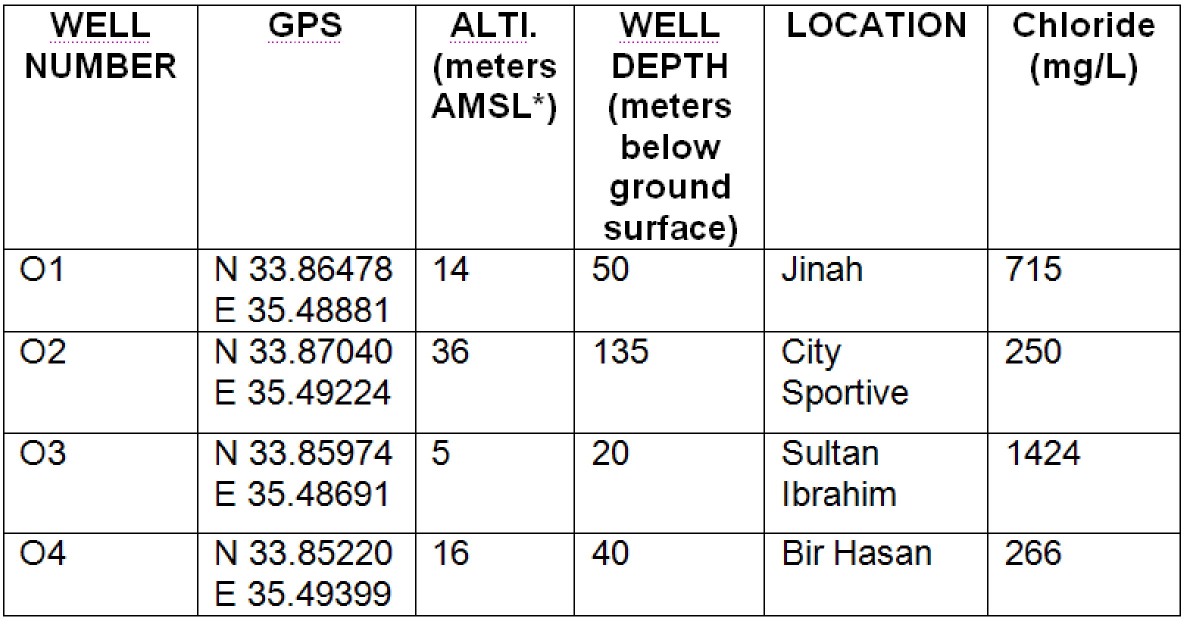
Additional wells were selected and sampled for salinity values on 14 October 2006 in the Dahia (southern suburbs) area of Beirut. The selection of these four wells was based on the fact that said area was most devastated by the conflict with Israel in August 2006. The descriptions of the aforementioned wells are summarized in Table 5.11.

Table 5.10: Additional Sampled Wells



WELL NUMBER	GPS	ALTI. (meters AMSL*)	WELL DEPTH (meters below ground surface)	LOCATION	Chloride (mg/L)
A1	N 33.87841 E 35.55396	71	100	Rawda	277
A2	N 33.86722 E 35.55943	150	200	Dekwaneh	185
A3	N 33.88245 E 35.55496	53	100	Sad Boushrieh	239
A4	N 33.88919 E 35.55833	20	35	Sad Boushrieh	781
A5	N 33.89256 E 35.56292	20	50	Sad Boushrieh	249
A6	N 33.88811 E 35.55994	20	15	Jdeideh	554
A7	N 33.88923 E 35.57161	40	90	Jdeideh	168
A8	N 33.89661 E 35.57112	25	40	Zalka	263
A9	N 33.89839 E 35.57285	25	40	Zalka	296
A10	N 33.89748 E 35.57825	60	100	Zalka	175
A11	N 33.89824 E 35.57993	65	60	Zalka	209
A12	N 33.89276 E 35.58396	170	185	Byakout	190
A13	N 33.87680 E 35.54260	10	20	Dekwaneh	199
A14	N 33.93605 E 35.60565	175	200	Aoukar	210
A15	N 33.93193 E 35.61196	225	400	Beit Shaar	185
A16	N 33.93707 E 35.61547	230	370	Dik el Mahdi	205
A17	N 33.93794 E 35.60968	200	190	Haret Ballanah	177
A18	N 33.94933 E 35.60090	85	70	Dbayeh	122
A19	N 33.94480 E 35.60565	140	180	Zouk Kharrab	260
A20	N 33.94075 E 35.61424	140	160	Zouk Kharrab	190
A21	N 33.94277 E 35.61979	220	365	Dik el Mahdi	410
A22	N 33.92855 E 35.63030	380	465	Mazraet Yashouh	205
A23	N 33.91659 E 35.60558	267	350	Rabieh	160
A24	N 33.91778 E 35.61253	365	480	Rabieh	160
A25	N 33.92419 E 35.61600	310	400	Mtaileb	144
A26	N 33.91652 E 35.59027	15	35	Antelias	133
A27	N 33.91785 E 35.59084	20	35	Naccash	150
A28	N 33.92329 E 35.59396	35	100	Naccash	205
A29	N 33.91013 E 35.58347	10	34	Antelias	391
A30	N 33.87541 E 35.53360	60	100	Horsh Tabet	308
A31	N 33.87373 E 35.53943	25	40	Mkalles	239
A32	N 33.88124 E 35.52681	23	35	Adlieh	211
A33	N 33.87178 E 35.53500	60	70	Badaro	298
A34	N 33.87035 E 35.53790	50	90	Horsh Tabet	247
A35	N 33.87119 E 35.51770	40	150	Furn el Chebak	185
A36	N 33.87734 E 35.58347	80	200	Mseitbeh	570
A37	N 33.88364 E 35.48893	76	100	Talet Khayat	703
A38	N 33.89588 E 35.51197	20	80	Gmayze	186
A39	N 33.87892 E 35.50830	122	100	Ras el Nabah	240
A40	N 33.83607 E 35.53769	205	200	Baabda	205
A41	N 33.82269 E 35.53406	57	80	Kfarshima	250
A42	N 33.81800 E 35.52948	68	150	Kfarshima	471
A43	N 33.83395 E 35.52626	70	100	Hadath	786
A44	N 33.85846 E 35.53090	47	90	Hazmieh	593

Table 5.11: Additional Sampled Wells (October 2006)



WELL NUMBER	GPS	ALTI. (meters AMSL*)	WELL DEPTH (meters below ground surface)	LOCATION	Chloride (mg/L)
O1	N 33.86478 E 35.48881	14	50	Jinah	715
O2	N 33.87040 E 35.49224	36	135	City Sportive	250
O3	N 33.85974 E 35.48691	5	20	Sultan Ibrahim	1424
O4	N 33.85220 E 35.49399	16	40	Bir Hasan	266

6 Results

The subsurface intrusion of seawater into the Greater Beirut aquifers is the primary focus of this thesis. This seawater, being more dense, moves inland below the freshwater, forming a wedge-like interface with the freshwater aquifer, mainly in the Miocene and the Cenomanian (C_4) and perhaps, the deeper Jurassic formations.

This interface is always dynamic, moving laterally in response to changes in water levels such as overabstraction of groundwater by wells. Generally, there would be time lag in the movement of this interface in response to changes in water levels, with regional long-term changes having a greater effect than any seasonal ones.

As such, the only approach to monitor this lateral movement is by directly taking measurements of this interface. For the purpose of this study, hydrochemical parameters were selected to achieve this objective. The following results are elaborated as individual measured chemical parameters as well as combined indeces, and summed up graphically in the form of figures rendered possible using Arc GIS's Geostatistical Analyst.

6.1 Geostatistical Analysis

Since little information was available about the vertical distribution of contaminant concentrations, only two dimensional analyses were performed. It was assumed that the contaminants were uniformly distributed vertically in their respective plumes. Because the analysis was two dimensional, the thickness of each plume at each well location was required to convert volumetric contaminant densities into areal contaminant densities as seen in the following figures. Furthermore, these ArcGIS prediction surface figures presented in the following discussions indicate various concentrations of salinity off the coast of Greater Beirut. This is not to be taken literally. Predictive values only apply to areas in Greater Beirut adjacent to actual groundwater measurements. The Mediterranean seawater salinity on the other hand is generally considered to be homogenous.

Though the number of monitored wells at the beginning of the survey was about 20, more wells were added in an effort to continually modify and improve the ongoing monitoring program and ArcGIS Geostatistical prediction figures.

The two following figures indicate that the mixing front or seawater-freshwater interface continues to ingress from a south westerly to a north easterly direction penetrating the southern suburbs of Beirut otherwise known as Al Dahia.

Overall, values of measured chloride concentrations in the southern suburbs of Beirut (Baabda Municipality) were among the highest of all the monitored wells as will be discussed in following chapters. Said area exhibited a staggering 2,500 mg/L salinity in one case, nearly twofold the average concentrations of the monitored wells from other municipalities.

The aforementioned figures again support the main observation that the Dahia suburbs (Baabda Municipality) is the area most affected by seawater intrusion. Furthermore, these figures also act as a template in order to gain insight into some areas of Greater Beirut that were not covered by monitoring wells.

As such, Figure 6.1, which is a composite figure of the data compiled from August 2005 and August/October 2006, provides valuable insight into the effect of groundwater salinization in Beirut, that was not apparent in the previous figures. The apparent conclusion drawn from this figure is that seawater ingression in the Beirut municipality is approaching from the northern coastline heading south along the Beirut river, totally different than what is occuring in the Dahia were the intrusion is from a southwesterly to a north easterly direction.

Hence, seawater intrusion is not just ingressing into the Baabda municipality, but to a lesser degree, into the Beirut municipality area as well, but from a northern front as opposed from the south-west. More Geostatistical Analyst images are found in Appendix C covering all the months between October 2004 to December 2005.

Figure 6.2, was generated by subtracting the groundwater chloride values beween the monthly readings taken during October of 2004 and October 2005, in order to determine spatial variations in the intensity of seawater intrusion during a one year period.

Said figure, indicates that the Dahia suburbs (Baabda municipality) has in general, steadily increased in groundwater chlorinity between 2004 and 2005. These chlorinity increments in said area are in the range of 50 to 100 mg/L in a peiod of just one year. Note the said figure does not include a legend because the focus of this illustration is simply to present the areas of salinity changes as numerical values.

While in other parts of Greater Beirut, such as Beirut municipality in the center, chlorinity in groundwater appears to be generally also on the rise, but less in intensity than Baabda municipality. Increments here are in the range of 25 to 50 mg/L between fall of 2004 and fall of 2005.

Finally, in the last of the three municipalities, the Metn to the north of Beirut, is showing slight increments in groundwater chlorinity in some wells but decrements in others. Said municipality also has the lowest population density of all the three municipalities of Greater Beirut.

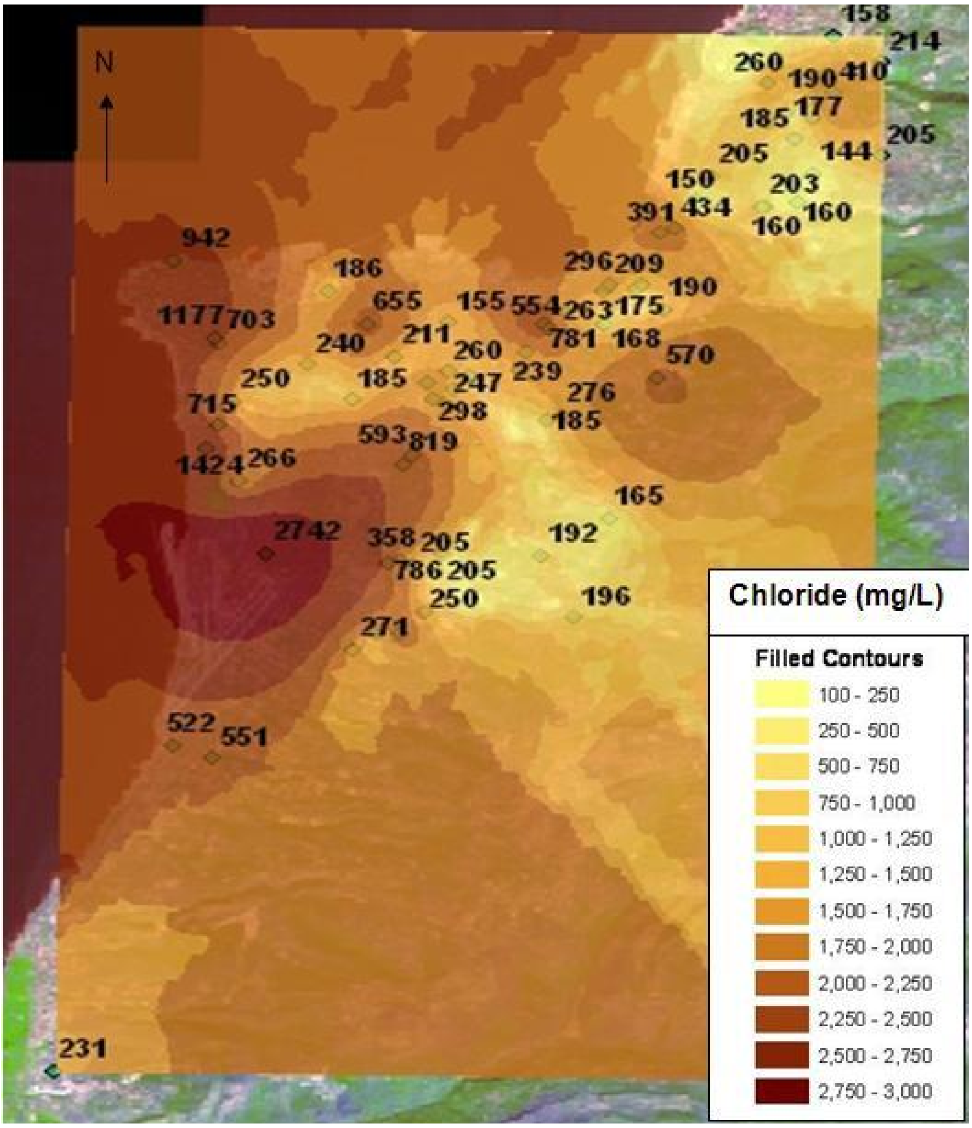


Figure 6.1: Seawater Intrusion (mg/L) in Greater Beirut during August 2005 and August/October 2006, not to scale (ArcGIS 9, Geostatistical Analyst, ordinary kriging)

Hence, it would be fair to assume that the Metn is the least affected by the phenomena of seawater intrusion. However, it would at the same time, prudent to continue to monitor this area closely in the future, in order to take some preemptive measures to combat the ingress of the seawater-feshwater interface.

In conclusion, the Kriging variance for each of the monthly Geostatistical Analyst image, was produced and can be found as tables in Appendix D. The differences between the measured chlorinity values and those predicted hold up well for most of the sampled wells.

Only in the case of two to three wells, where measured chlorinity values were exceptionally high (over 1,000 mg/L), did the difference between measured and predicted values increase. Nevertheless, wells with continual high chlorinity, such as G2 and G3, are government wells which are repeatedly over-abstracting large quantities of groundwater to serve the heavily populated surroundings, and as such, should be considered deleterious in any case.

6.2 Hydrochemical Findings

The hydrochemical findings in this section will deal with individual chemical parameters measured over the course of the study period, as well as calculated proven indexes that will help in elucidating the phenomena of seawater intrusion.

Secondly, all these results will be combined into Trilinear diagrams, otherwise known as Piper diagrams, in order to generate more comprehensive seasonal pictures of the groundwater chemistry determined by the input of monthly data from individual wells.

But in order to accomplish that, the accuracy of the aforementioned analyses have to be elucidated are estimated using the electrical balance (EB) method for major water ions, as stated in the formula below:

Electrical Balance (EB) = (Sum of cations-Sum of anions)/(Sum of cations+Sum of anions) × 100

Differences up to 2% are inevitable, but deviations in excess of 5% should be examined (Appelo and Postma, 2005). The electrical balance method could not be determined for all the analyses, because in several instances, the analyte concentration was so high that during titrimetric testing, several dilutions had to be made. These very high results would be roughly estimated by multiplying the measured concentration by the pertinent dilution factor, and therefore the

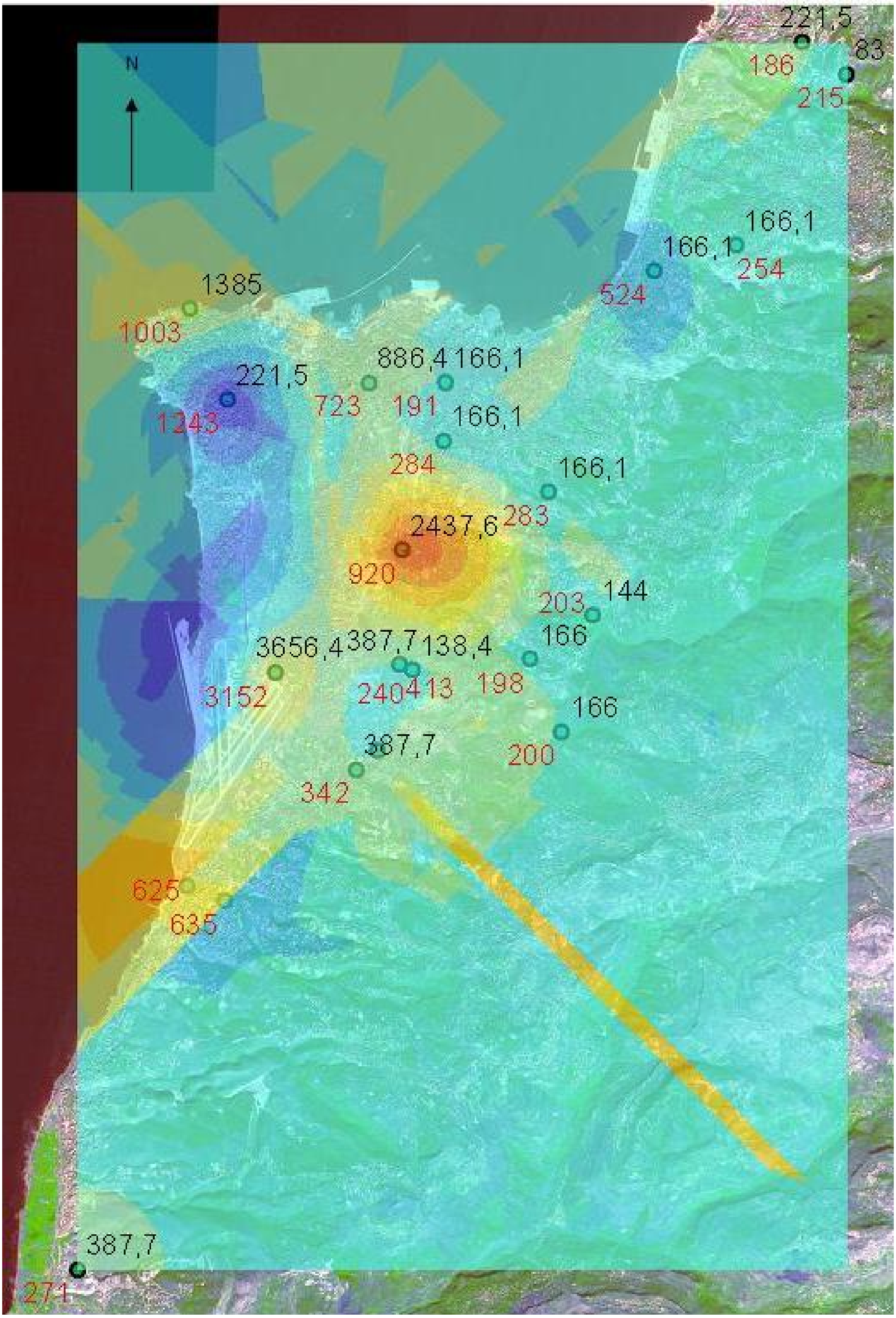


Figure 6.2: Seawater Intrusion Variations (mg/L chloride) in Greater Beirut between October 2004 (values in black) and October 2005 (values in red) not to scale

final result would inherently have some degree of error. This method was applied to wells with very high chlorinity values.

Results for electrical balances are summarized in Appendix F.

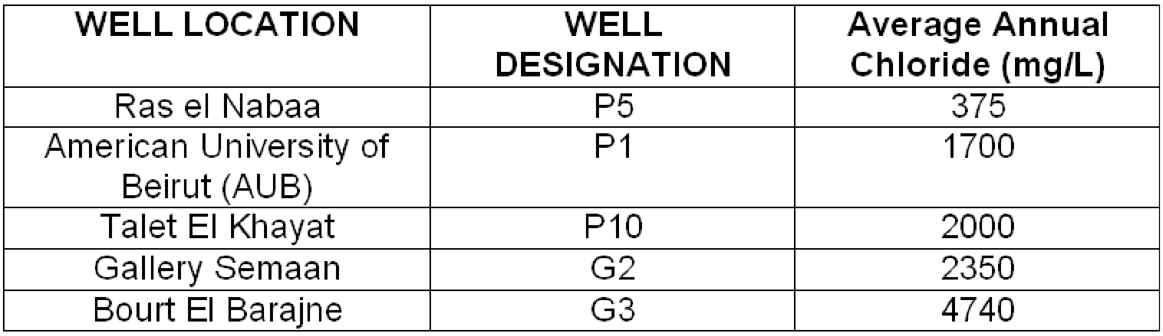
6.2.1 Chloride

The element in the forefront of seawater intrusion detection is, unequivocally chloride. Any rise in groundwater salinity is always a cause for concern, and subsequent remediation measures.

When seawater intrudes into coastal aquifers, a transition zone of fresh and seawater mixing emerges. The boundary between the freshwater and seawater is not a sharp interface, but a transition zone with a width controlled, in part, by the aquifer properties. The Greater Beirut aquifer were mixing is occuring, this zone is no exception.

Chloride concentrations exceeding 500 mg/L are generally considered to be evidence of contamination with seawater. Throughout the study, four wells have consistently stood out over the rest with chloride concentrations exceeding the 500 mg/L threshold, they are summarized in Table 6.1:

Table 6.1: Wells Most Affected by Seawater Intrusion by Chloride



WELL LOCATION	WELL DESIGNATION	Average Annual Chloride (mg/L)
Ras el Nabaa	P5	375
American University of Beirut (AUB)	P1	1700
Talet El Khayat	P10	2000
Gallery Semaan	G2	2350
Bourt El Barajne	G3	4740

These wells have repeatedly exhibited advanced signs of seawater intrusion as attested by very elevated concentrations of salinity (chloride), Total Dissolved Solids (TDS), and pertinent values of the indicative index ratios, namely: calcium/ magnesium, non carbonate hardness/ carbonate hardness, sodium/ chloride, bromine/ chloride, chloride/ sulfate and chloride/ alkalinity which will be elaborated in the coming sections.

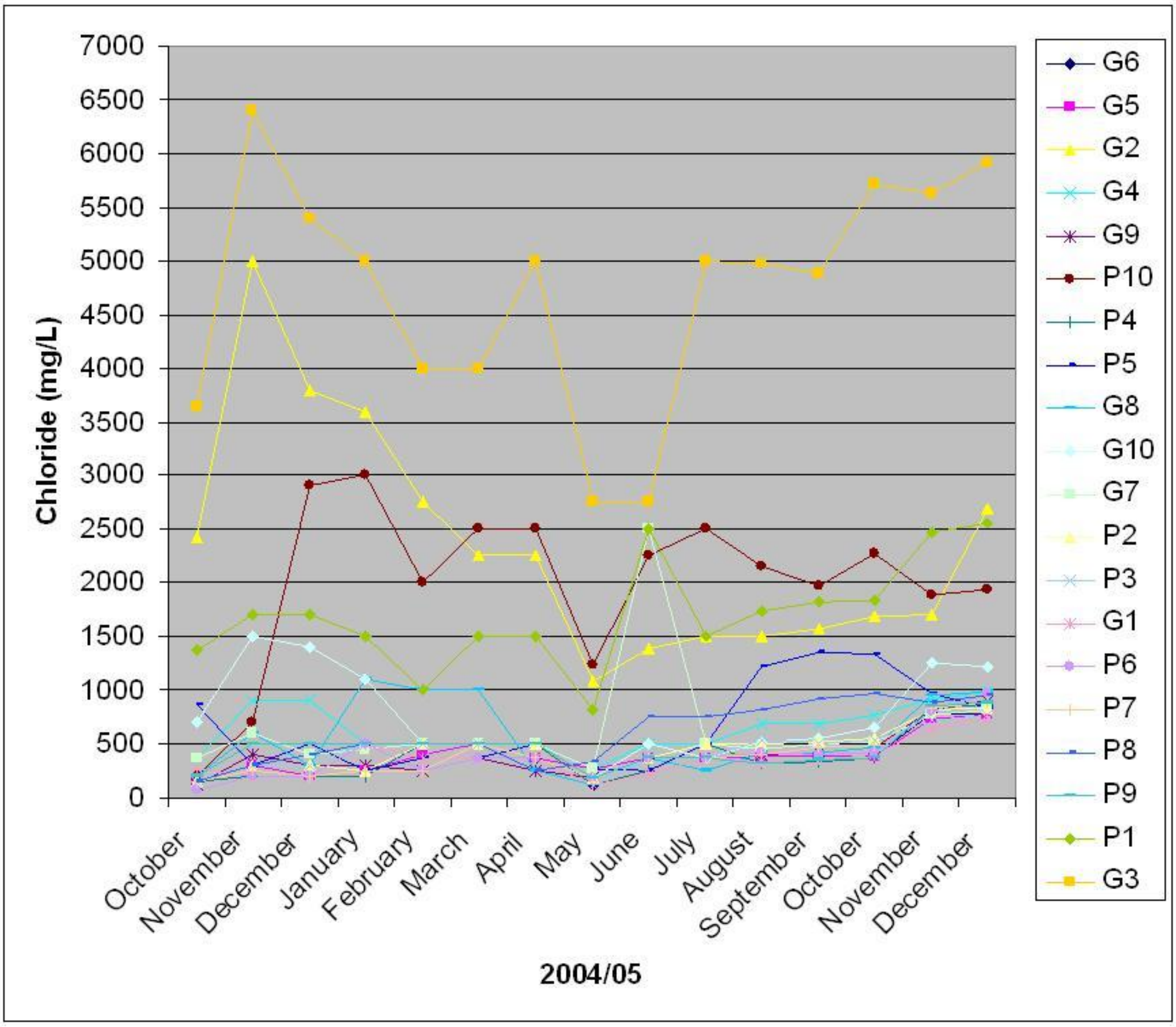
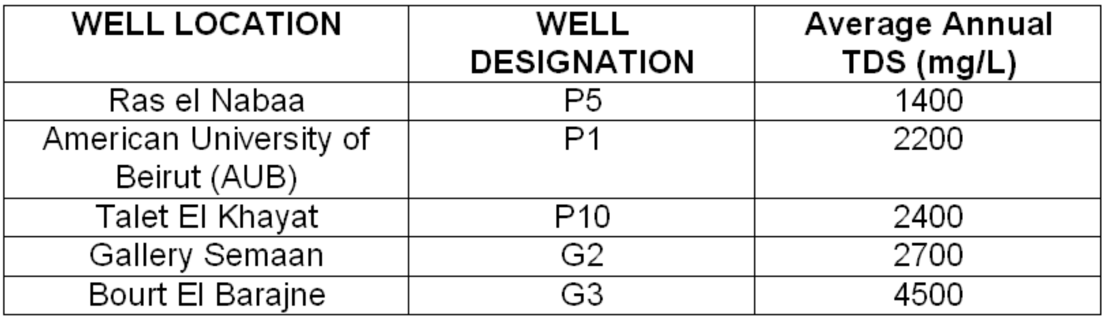


Figure 6.3: Chloride Variations in Greater Beirut Wells

Furthermore, Bear et al, states that a 5% contribution of seawater intrusion would raise the salinity of groundwater to over 1000 mg/L in chloride. As such, since the Burj el Barajne (G3), Gallery Semaan (G2) and Talet el Khayat (P10) wells have continually exhibited salinity concentrations over 2000 mg/L, this would simply imply that seawater intrusion may very well have exceeded 5% mixing in the aquifers tapped by these wells.

Table 6.2: Wells Most Affected by Seawater Intrusion by TDS



WELL LOCATION	WELL DESIGNATION	Average Annual TDS (mg/L)
Ras el Nabaa	P5	1400
American University of Beirut (AUB)	P1	2200
Talet El Khayat	P10	2400
Gallery Semaan	G2	2700
Bourt El Barajne	G3	4500

6.2.2 Total Dissolved Solids

Other measured parameters corroborate the presence of an advanced mixing front between salt water and fresh water. Namely these parameters include measured values of Total Dissolved Solids (TDS), sodium and sulfate. From Table 6.2, for measured TDS values, the fluctuations in said values closely conform to the previous ones on chloride concentrations especially true for the Burj Barajne (G3), Gallery Semaan (G2), and Talet el Khayat (P10), AUB (P1) wells which would provide further indication of potential mixing of seawater with fresh groundwater.

The Burj el Barajne well would be classified with respect to the TDS average concentration as moderately saline, rendering it suitable only for limited irrigation and livestock. The Gallery Semaan well with its average TDS in the range of 2,700 mg/L, would classify it as being slightly saline bordering on the moderately saline. Caution should be exercised when using said water for human consumption. The same would also hold true for the Talet el Khayat and AUB wells having similar TDS ranges.

Most of the remaining wells that were monitored during the study period are bordering on the fresh to slightly saline waters rendering them for the moment potable and useful for most domestic purposes.

6.2.3 Total Hardness

Calcium is abundant in waters which are in contact with limestone, dolomite and gypsum as is the case in most of Lebanon's aquifers.

Waters with a total hardness in the range of 0-60 mg/L (as $CaCO_3$) are termed soft, from 60-120

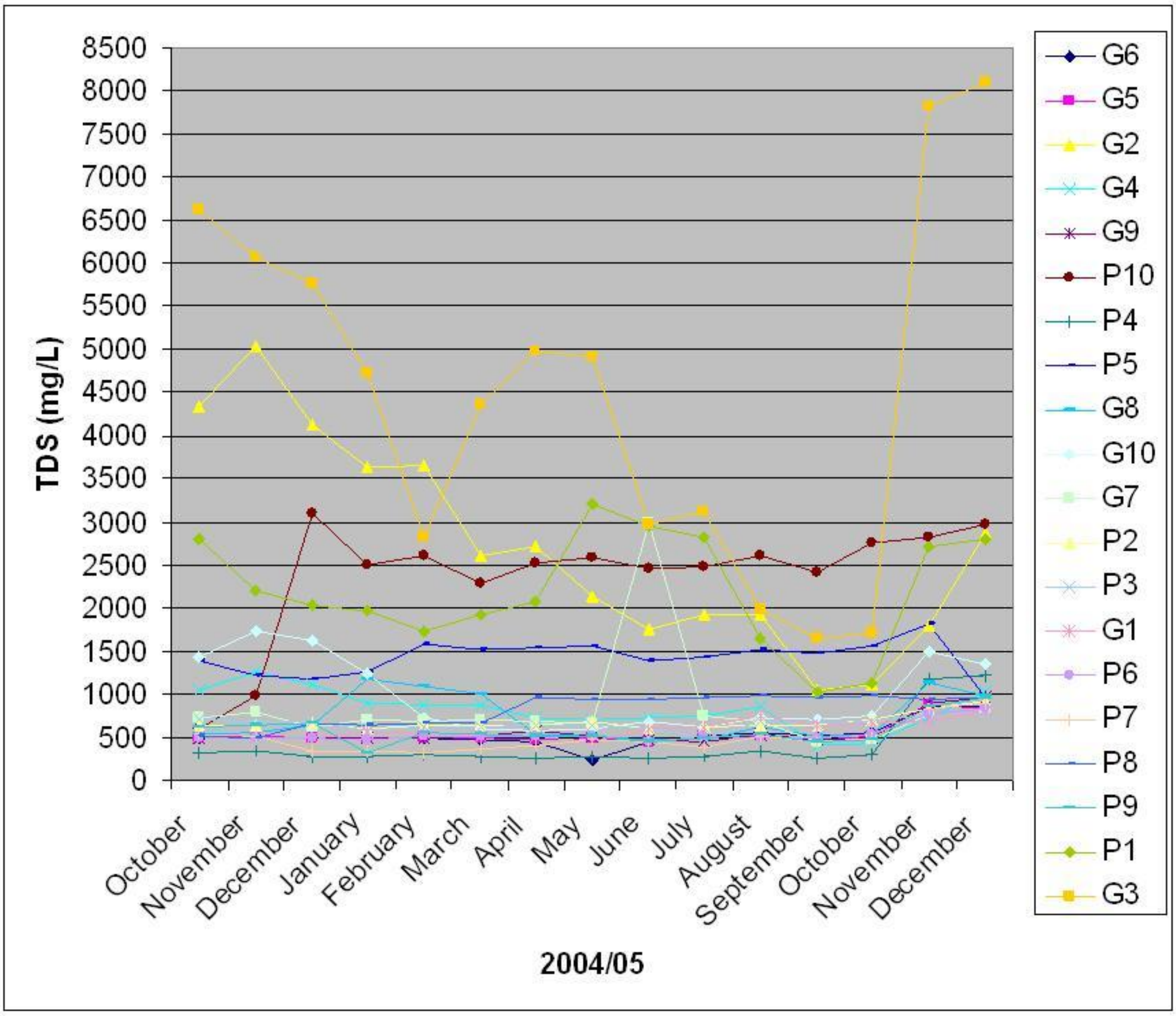


Figure 6.4: TDS Variation in Greater Beirut Wells

mg/L are medium hardness, from 120-180 mg/L are hard, and above 180 are termed very hard (Hudak, 2005).

From Figure 6.5, it is evident that groundwater in the study area is classified as very hard water with the yearly average of the sampled wells in the range of 500 mg/L, meaning that the groundwater has had considerable transit time in limestone aquifers leaching them of calcium and magnesium cations before having reached the coast.

Such hard waters may not have any adverse effects on health which may limit their use for drinking water. However, they are of concern because these waters will form scales in boilers, hot water heaters, pipes and cooking utensils imparting an economic impact. The following figure summarizes the results of the water hardness for the sampled wells in the study area.

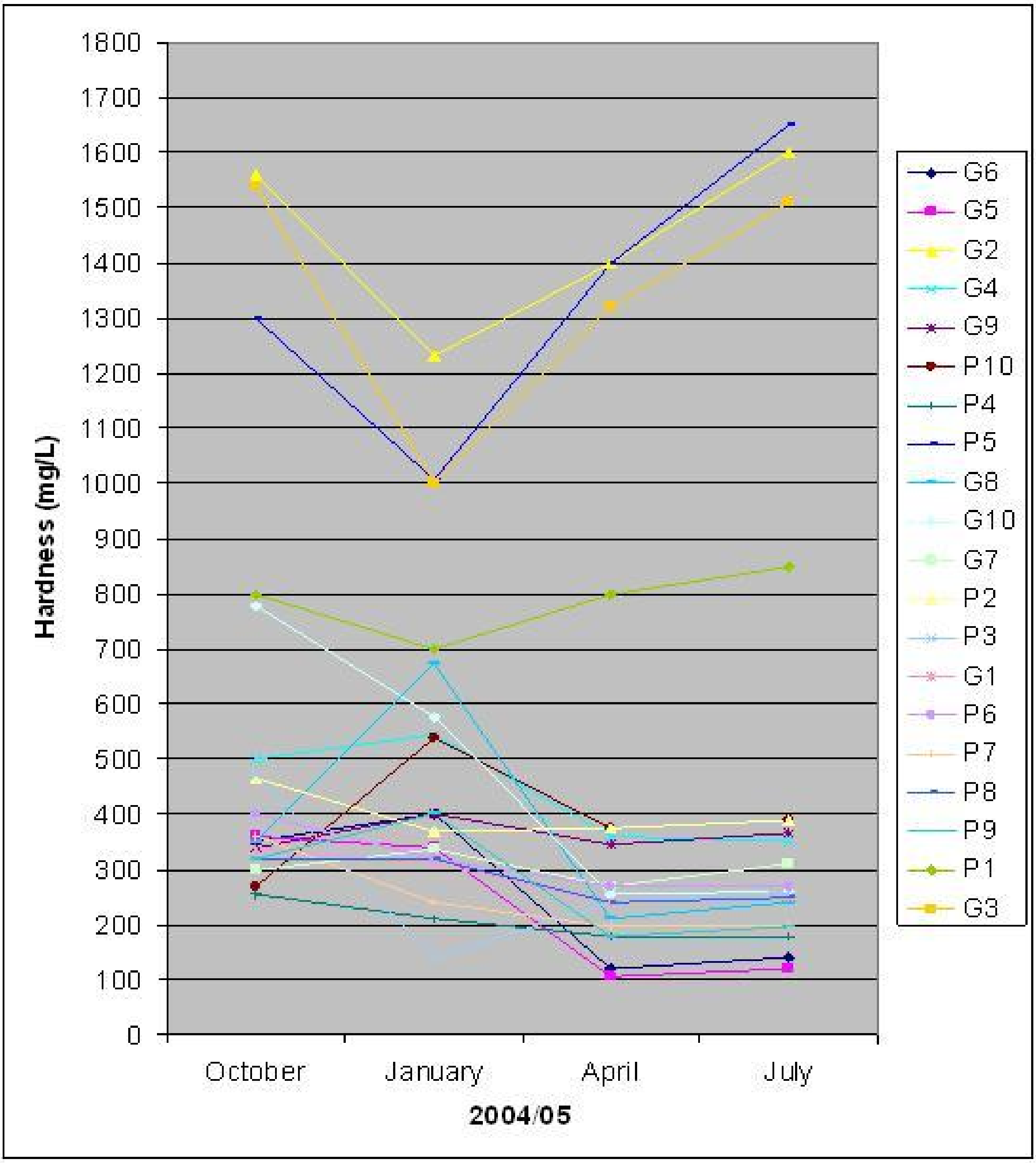


Figure 6.5: Water Hardness Variation in Greater Beirut Wells

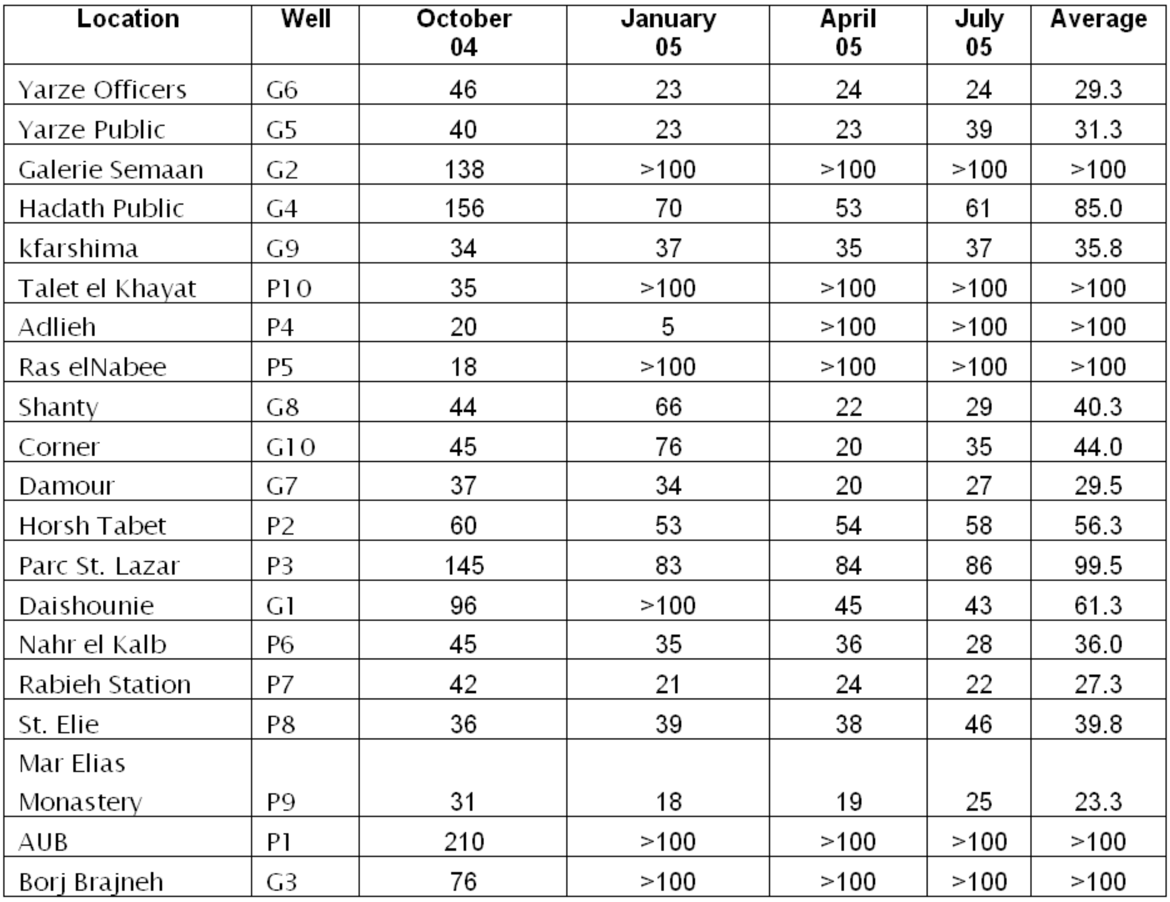
6.2.4 Sulfate

The geological formations of Lebanon give little indication of the presence of gypsum or similar deposits especially in the study area of Greater Beirut that could contribute significantly to elevated concentrations of sulfates in groundwater. Thus the high concentrations of sulfate found most notably in the following wells, could only attest to mixing of fresh groundwater with seawater through the process of intrusion (Bear, 1999) as summarized in Table 6.3:

- Gallery Semaan (G2)
- Talet el Khayat (P10)
- Adlieh (P4)
- Ras el Nabaa (P5)
- Burj el Barajne (G3)

The aforementioned wells are consistent with the previous elevated results of chloride and TDS concentrations, which point to only one thing, and that is seawater intrusion. It is noteworthy to mention that, of these six heavily saline wells, half are coastal except for Gallery Semaan, Adlieh, and Ras el Babaa. The Gallery Semaan well lies along the strike plane which intersects the coast of Beirut to the north, which potentially acts as a direct conduit to seawater.

Table 6.3: Sulfate Values of Greater Beirut Wells



Location	Well	October 04	January 05	April 05	July 05	Average
Yarze Officers	G6	46	23	24	24	29.3
Yarze Public	G5	40	23	23	39	31.3
Galerie Semaan	G2	138	>100	>100	>100	>100
Hadath Public	G4	156	70	53	61	85.0
kfarshima	G9	34	37	35	37	35.8
Talet el Khayat	P10	35	>100	>100	>100	>100
Adlieh	P4	20	5	>100	>100	>100
Ras elNabee	P5	18	>100	>100	>100	>100
Shanty	G8	44	66	22	29	40.3
Corner	G10	45	76	20	35	44.0
Damour	G7	37	34	20	27	29.5
Horsh Tabet	P2	60	53	54	58	56.3
Parc St. Lazar	P3	145	83	84	86	99.5
Daishounie	G1	96	>100	45	43	61.3
Nahr el Kalb	P6	45	35	36	28	36.0
Rabieh Station	P7	42	21	24	22	27.3
St. Elie	P8	36	39	38	46	39.8
Mar Elias Monastery	P9	31	18	19	25	23.3
AUB	P1	210	>100	>100	>100	>100
Borj Brajneh	G3	76	>100	>100	>100	>100

pH

As mentioned earlier, most natural waters will have pH values ranging from 7 to 8.5. Natural sea water will have a pH value of about 8.1, and any changes from this value indicate that fresh water from an inland source is entering the body of sea water or conversely.

The measured pH values for the sampled wells between October 2004 and December 2005 were in the range of seven to eight, which is considered within the most standards set for drinking waters from around the world. Furthermore, waters were a pH range between 7 and 8.5 would indicate that the alkalinity was predominantly composed of bicarbonate ions.

It is noteworthy to mention that a spike in recorded values was observed around September 2005 for most monitored wells in the study area seen in Figure 6.6. The explanation for this phenomenon could lie in the ingress of seawater into the aquifers at a point when natural groundwater recharge is at its lowest by the end of summer. With seawater having a pH value in the range of eight, it is no surprise that groundwater pH values have shifted to that of seawater during the month of September.

6.2.5 Phosphate

The amount of phosphate generally found in water is not more than 0.1 mg/L unless the water has become polluted from waste sources or excessive drainage from agricultural areas.

The measured phosphate values during the months of October 2004, April 2005 and July 2005 were on the average recorded at 0.41, 0.12 and 0.13 mg/L, with the annual average of the measured wells at 0.44 mg/L. Clearly, measured phosphate values are within the aforementioned drinking norms with no indication of drainage from any agricultural activities or potential pollution from raw sewage into the groundwater aquifers.

6.2.6 Nitrate

As evident in Figure 6.7, nitrate concentrations in groundwater from the sampled wells were generally below the acceptable 50 mg/L normally set for drinking water indicating the absence of potential sewage or agricultural runoff contaminating the aquifers of Greater Beirut.

The only exceptions were the Borj Barajne (G3) and the Talet el Khayat(P10) wells which

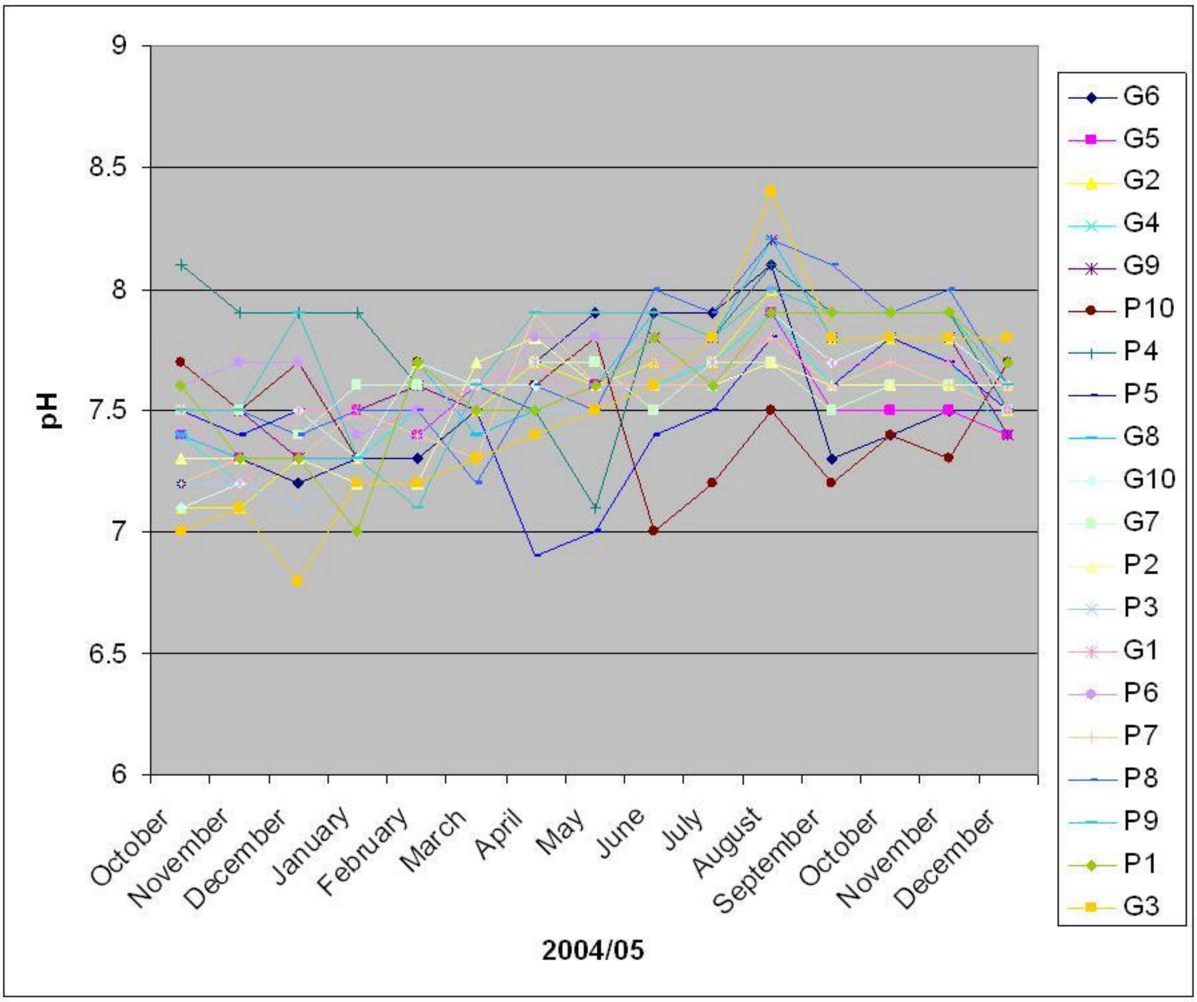


Figure 6.6: pH Variation in Greater Beirut Wells

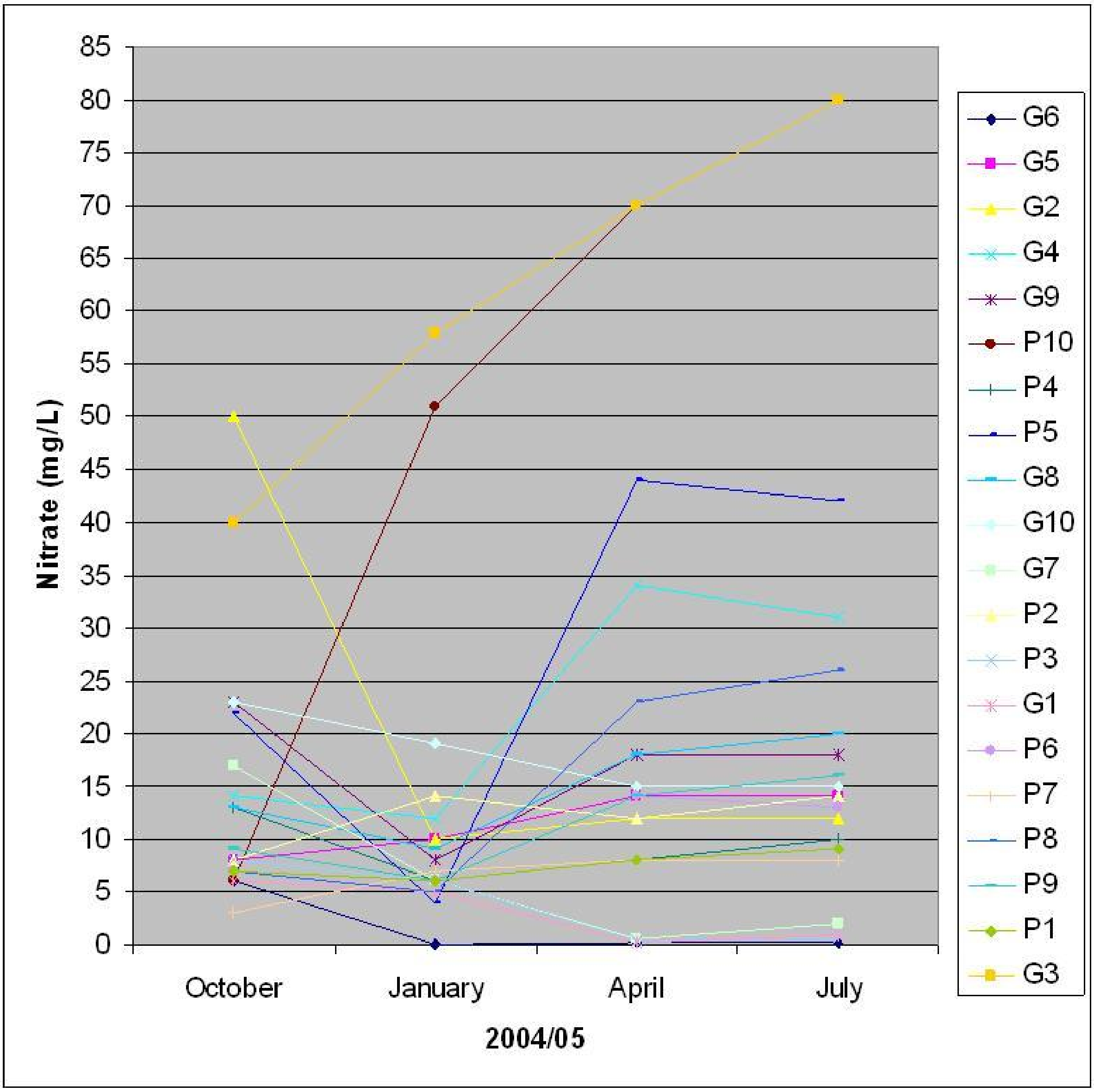


Figure 6.7: Nitrate Variation in Greater Beirut Wells

spiked only occasionally at 70 and 80 mg/L during the months of April and July 2005 respectively, possible due to improper wastewater discharge rather than agricultural activity, since the locations of these aquifers are in heavily urbanized areas.

A possible explanation for the elevated nitrate concentrations would be the close proximity of several sewer outfalls along the coastline intersecting the very formations that supply said wells, mainly the Quaternary and Cenomanian aquifers respectively. Seawater contaminated with sewage effluent rich in nitrates, nitrites and ammonia, is somehow finding its way back into coastal aquifers along with the intruding seawater. Leakage from sewer system networks is potentially a minimal source of nitrates for the Greater Beirut area as claimed by the Ministry of Environment (LEDO) report.

6.2.7 Seawater Intrusion Index Ratios

In all of the following index ratios, values are calculated as milliequivalent (meq) which is defined as the amount of substance in moles multiplied by the valence of the substance, unless specified otherwise. The letter r before an element denotes the unit of equivalency.

Calcium/Magnesium Index Ratio

Components of seawater other than chloride may be used to identify seawater contamination mainly magnesium. Magnesium is present in seawater in much greater concentrations than is calcium, hence one of the most conspicuous features of seawater intrusion is the enrichment of the latter over calcium (Majdalani, 1997). Hence, a low calcium to magnesium ratio (in the range of 0.2) is very often indicative of seawater intrusion. With ageing of seawater in aquifers, this ratio can exceed 30 (Hamdy, 2001).

The Mediterranean seawater calcium to magnesium ratio has been analyzed independently by several authors and found to be on the average of about 0.2 in equivalent ratio (Bear, 1999).

This ratio is however expected to increase as the distance from coastline increases due to enrichment of calcium over magnesium originating from the limestone rich aquifers of the study area as summarized in Table 6.4. This increase in the calcium to magnesium index ratio is also generally in tandem with other parameters such as chloride, TDS, sulfates, chloride to alkalinity and the non carbonate to carbonate hardness ratios.

Table 6.4: rCa/rMg Index Ratio of Greater Beirut Wells

Location	Well	October 04	January 05	April 05	July 05	Average
Horsh Tabet	P2	0.74	2.57	0.10	0.13	0.88
Galerie Semaan	G2	0.60	1.33	1.27	1.53	1.18
AUB	P1	0.44	3.60	0.53	0.50	1.27
Nahr el Kalb	P6	0.55	2.60	1.20	1.20	1.39
Hadath Public	G4	1.07	1.10	2.49	2.20	1.71
Ras elNabee	P5	1.46	4.13	0.69	0.91	1.80
Damour	G7	1.20	1.92	1.71	3.53	2.09
Adlieh	P4	1.17	1.85	3.00	3.00	2.25
Rabieh Station	P7	0.99	3.00	7.20	3.40	3.65
Borj Brajneh	G3	0.65	3.40	6.00	5.44	3.87
Yarze Officers	G6	1.73	1.58	6.60	7.80	4.43
Corner	G10	1.07	3.00	8.00	7.20	4.82
Mar Elias Monastery	P9	1.32	0.60	10.20	7.20	4.83
Shanty	G8	1.73	0.98	12.00	5.16	4.97
Parc St. Lazar	P3	1.26	3.60	13.80	2.00	5.17
Yarze Public	G5	0.60	2.80	12.00	6.60	5.50
Talet el Khayat	P10	1.71	15.60	5.83	6.09	7.31
Daishounie	G1	1.74	18.00	6.60	14.40	10.19
kfarshima	G9	1.44	0.90	40.80	4.27	11.85
St. Elie	P8	1.00	9.00	13.80	29.40	13.30

The large excess of magnesium over calcium in seawater is characteristic and can be used to ascertain whether or not brackish water may be marine in origin. Calcium is easily added or subtracted by mineral dissolution and precipitation at the zone of mixing. Evaporite formations rich in gypsum may easily produce magnesium rich water after calcium reaches saturation. In that case, high sulfate content will help in identifying the origin.

The aforementioned table and figure for the calcium to magnesium ratio, clearly point to the wells with elevated salinity concentrations, by a indicating a low rCa/rMg ratio for several ones, most notably:

1. Ras El Nabah (P5),
2. Hadath (G4),
3. Naher el Kalb (P6),
4. AUB (P1),

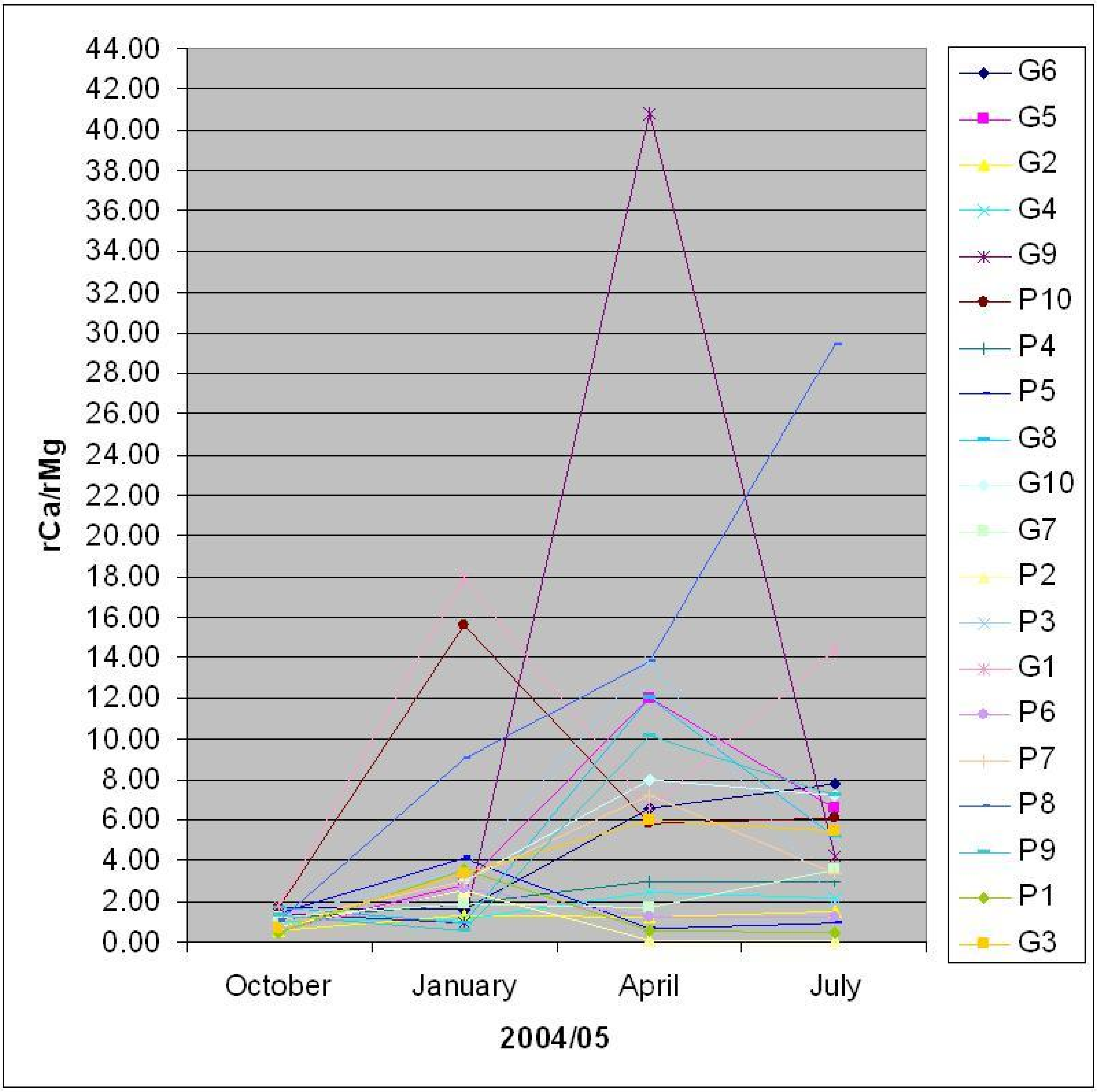
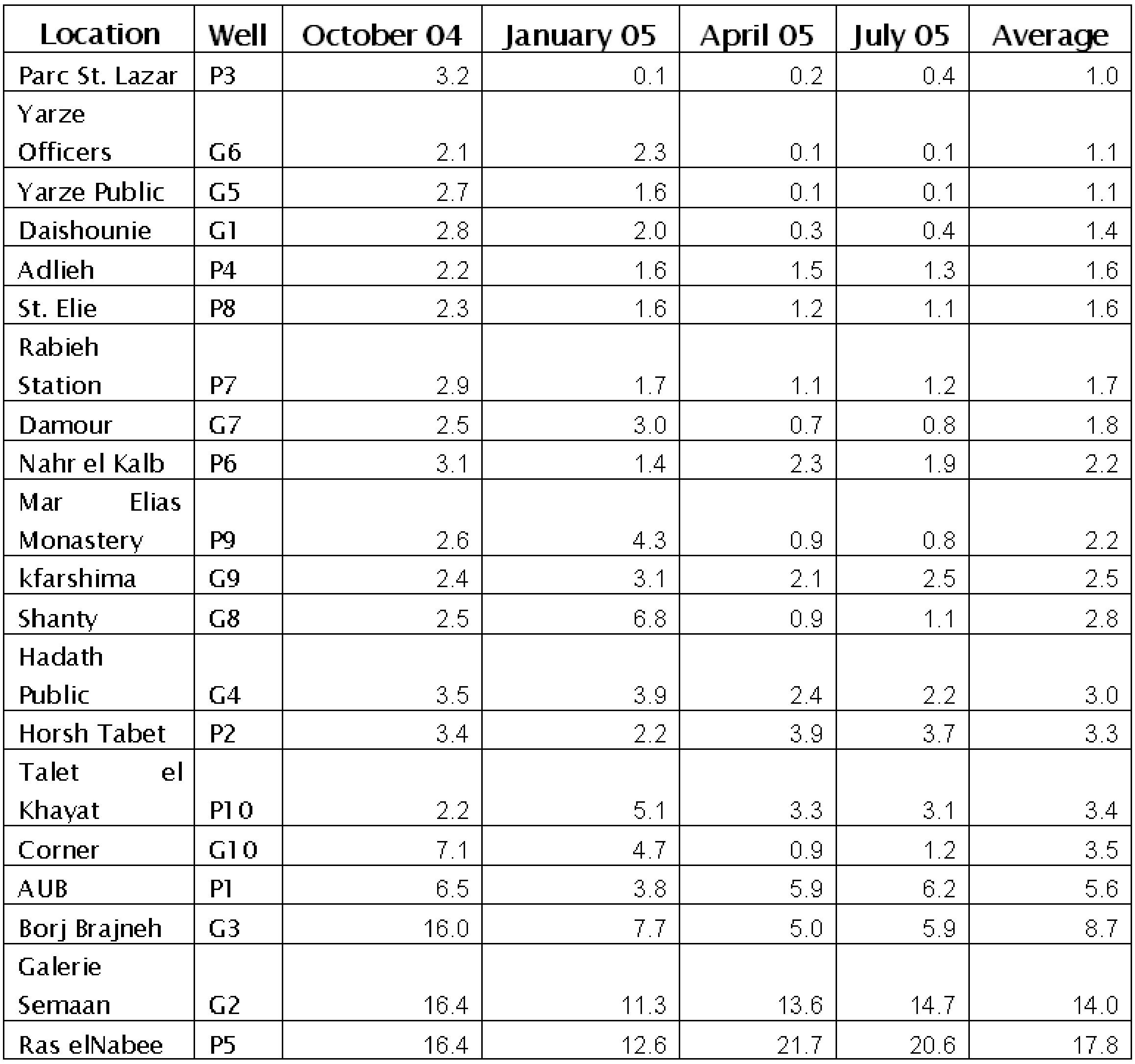


Figure 6.8: rCa to rMg Variation in Greater Beirut Wells

5. Gallery Semaan (G2),
6. Horsh Tabet (P2),

Of the aforementioned wells with the lowest calcium to magnesium ratio are expectedly G2, P1 and P5, as attested by the elevated chloride and TDS values discussed in the previous sections clearly indicative of seawater intrusion. However, P2, P6 and G4 have not particularly exhibited elevated signs of salinity or TDS throughout the duration of the study, hence, sources other than seawater may be contributing magnesium to the water abstracted from these wells which is inadvertently lowering the rCa/rMg ratio.

Table 6.5: NCH/CH Index Ratio of Greater Beirut Wells



Location	Well	October 04	January 05	April 05	July 05	Average
Parc St. Lazar	P3	3.2	0.1	0.2	0.4	1.0
Yarze Officers	G6	2.1	2.3	0.1	0.1	1.1
Yarze Public	G5	2.7	1.6	0.1	0.1	1.1
Daishounie	G1	2.8	2.0	0.3	0.4	1.4
Adlieh	P4	2.2	1.6	1.5	1.3	1.6
St. Elie	P8	2.3	1.6	1.2	1.1	1.6
Rabieh Station	P7	2.9	1.7	1.1	1.2	1.7
Damour	G7	2.5	3.0	0.7	0.8	1.8
Nahr el Kalb	P6	3.1	1.4	2.3	1.9	2.2
Mar Elias Monastery	P9	2.6	4.3	0.9	0.8	2.2
kfarshima	G9	2.4	3.1	2.1	2.5	2.5
Shanty	G8	2.5	6.8	0.9	1.1	2.8
Hadath Public	G4	3.5	3.9	2.4	2.2	3.0
Horsh Tabet	P2	3.4	2.2	3.9	3.7	3.3
Talet el Khayat	P10	2.2	5.1	3.3	3.1	3.4
Corner	G10	7.1	4.7	0.9	1.2	3.5
AUB	P1	6.5	3.8	5.9	6.2	5.6
Borj Brajneh	G3	16.0	7.7	5.0	5.9	8.7
Galerie Semaan	G2	16.4	11.3	13.6	14.7	14.0
Ras elNabee	P5	16.4	12.6	21.7	20.6	17.8

Non-Carbonate/Carbonate Hardness Index Ratio

The groundwater in the study area is expected to be rich in carbonate hardness (calcium carbonates and bicarbonates) and poor in non carbonate hardness (chlorides and sulfates of magnesium and calcium) unless it is affected by seawater intrusion, then the chemistry would be different.

So a coastal well that is overabstracting groundwater is expected to progressively become richer in non carbonate hardness as opposed to carbonte hardness due to seawater intrusion, and this is summarized in Table 6.5.

Hence the index ratio of non carbonate hardness to carbonate hardness will sharply rise as over pumping continues. The composition of the seawater along the coastline of Beirut has typically a non carbonate to carbonate hardness of about 50 (measured in mg/L).

The Non Carbonate to Carbonate Hardness (expressed in mg/L as CaCO3) index ratio is also expected to fluctuate between the wet and dry seasons as the water becomes more concentrated with non carbonate hardness during the dry period as evidenced in Figure 6.9.

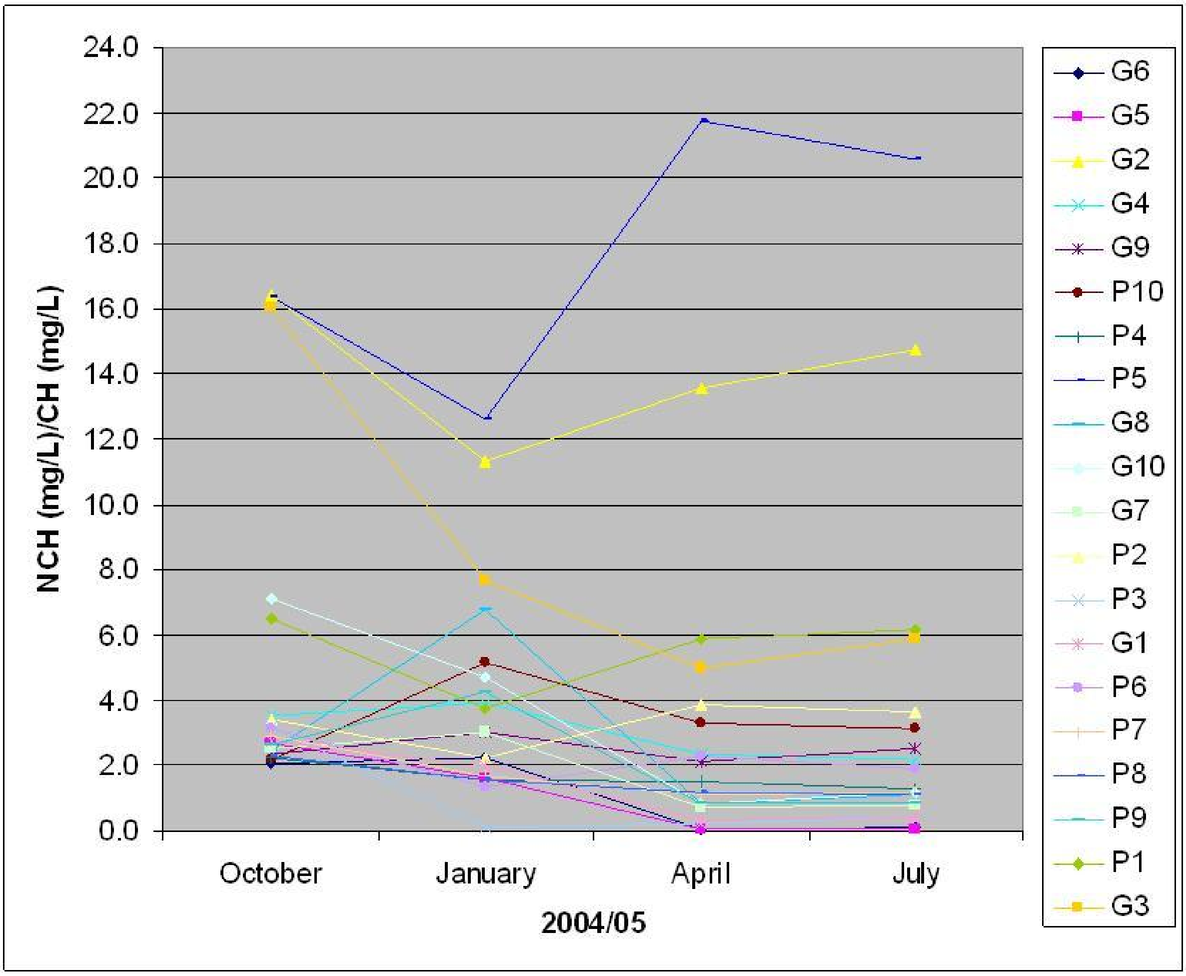


Figure 6.9: Non Carbonate Hardnessto Carbonate Hardness Variations in Greater Beirut Wells

Looking back at Table 6.5 and Figure 6.9, it is clear that the wells with the highest non carbonate to carbonate hardness, indicating potential seawater with freshwater mixing, are wells P5, G2, G3, P1, and P10 in decreasing order. However, well P5 seems to have a considerable influx of magnesium salts which would only indicate a marine origin. This observation is also attested by the fact that the annual average rCa/rMg ratio for said well was in the range of 1.8 and the TDS in the high range of 1,420 mg/L.

Table 6.6: rNa/rCl Index Ratio of Greater Beirut Wells

Location	Well	October 04	January 05	April 05	July 05	Average
Talet el Khayat	P10	1.99	0.76	0.02	0.05	0.71
Ras el Nabee	P5	0.28	0.45	0.62	1.42	0.69
Horsh Tabet	P2	0.19	1.42	0.30	0.64	0.64
Parc St. Lazar	P3	0.03	0.94	0.62	1.34	0.73
Kfarshima	G9	0.25	0.05	0.13	0.29	0.18
Galerie Semaan	G2	0.12	0.19	0.17	0.31	0.20
Hadath Public	G4	0.20	0.03	0.29	0.49	0.25
AUB	P1	0.30	0.77	0.04	0.07	0.30
Corner	G10	0.11	0.06	0.36	0.72	0.31
Yarze Officers	G6	0.25	0.25	0.25	0.51	0.32
Damour	G7	0.32	0.07	0.31	0.58	0.32
Adlieh	P4	0.33	0.37	0.24	0.46	0.35
Yarze Public	G5	0.30	0.71	0.25	0.51	0.44
Nahr el Kalb	P6	0.42	0.43	0.19	0.72	0.44
Mar Elias Monastery	P9	0.36	0.30	0.35	0.77	0.45
Daishounie	G1	0.36	0.58	0.30	0.77	0.50
Rabieh Station	P7	0.17	0.56	0.40	1.01	0.53
Borj Brajneh	G3	0.32	0.81	0.34	0.79	0.56
Shanty	G8	0.11	0.07	0.67	1.47	0.58
St. Elie	P8	0.25	0.71	1.60	3.68	1.56

Sodium/Chloride Index Ratio

Sodium to chloride ratios of seawater/ freshwater mixing are usually lower than the marine values (¡0.86 molar ratio). Thus low Na/Cl ratios combined with other geochemical parameters can be further evidence of the arrival of seawater even at relatively low chloride concentrations (Majdalani, 1997) during the early stages of salinization as is summarized in Table 6.6 and Figure 6.10.

The low Na/Cl ratio of seawater intrusion is distinguishable from the high (> 1) Na/Cl ratios typical of anthropogenic sources such as domestic waste water (Bear, 1999).

From Table 6.6, the wells with the most indicative rNa/rCl index ratio for seawater intrusion, are Kfarshima (G9), Gallery Semaan (G2), Hadath Public (G4), and AUB (P1) in decreasing order. Again the G2 and P1 wells closely conform to the results of elevated TDS and chloride values as expected. However, the G9 well has not exhibited noticeable high concentrations of

TDS or chloride which would do not conform with such an elevated reading for the Na/Cl index ratio. Looking closely at the readings of this ratio for G9, it is noticed that the value for January 2005 is quite low compared to the previous and subsequent readings. This could be attributed to many reasons, anthropogenic being most plausible.

The G4 (Hadath) well on the other hand, with a relatively high Na/Cl ratio has however exhibited a Ca/Mg ratio consistent with seawater mixing. Furthermore, chloride concentrations of 500 mg/L were recorded for said well during the month of December 2005, coupled with TDS values exceeding 1,000 mg/L classifying G4 as slightly to moderately saline. Possibly early signs of seawater encroachement.

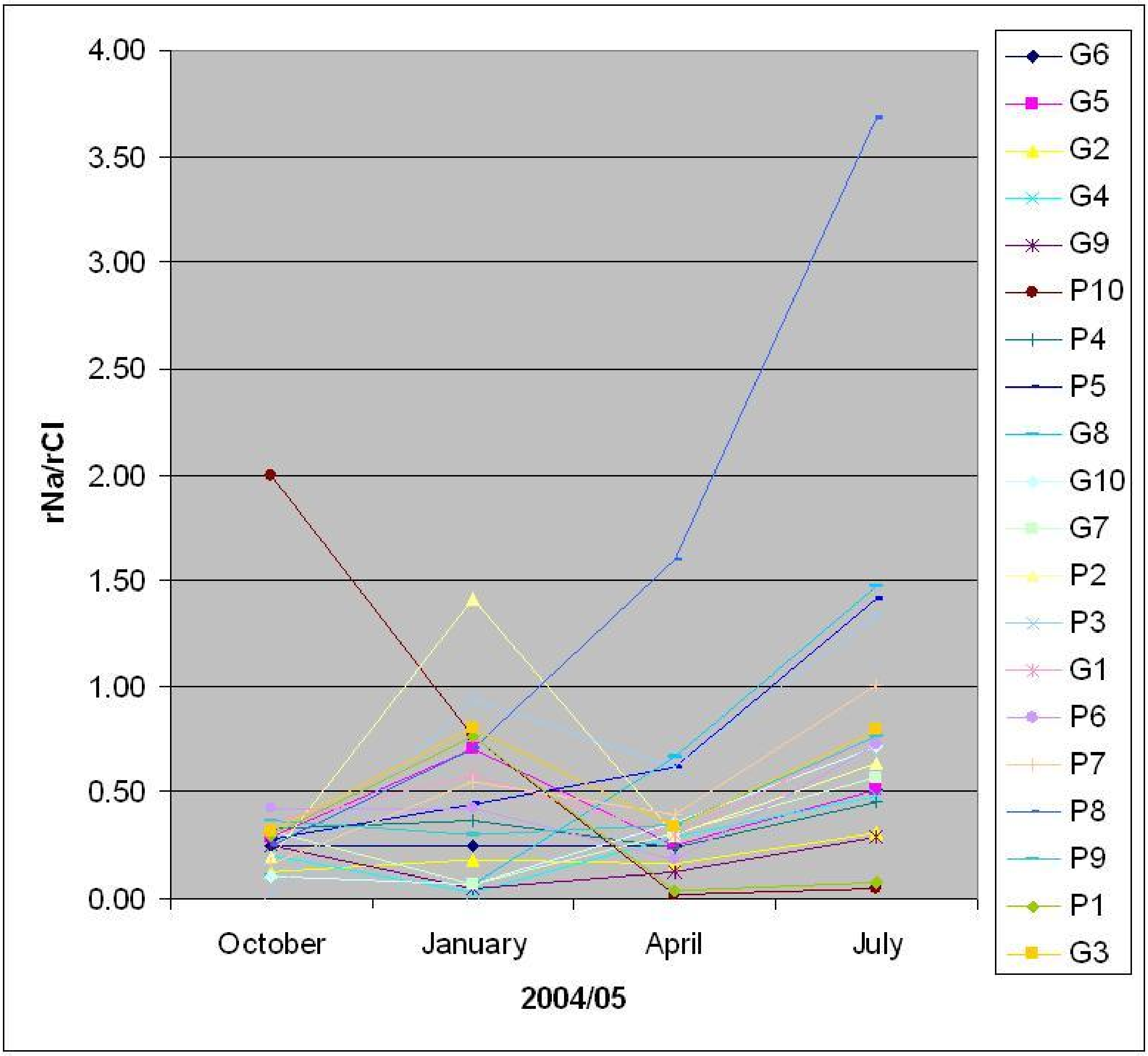
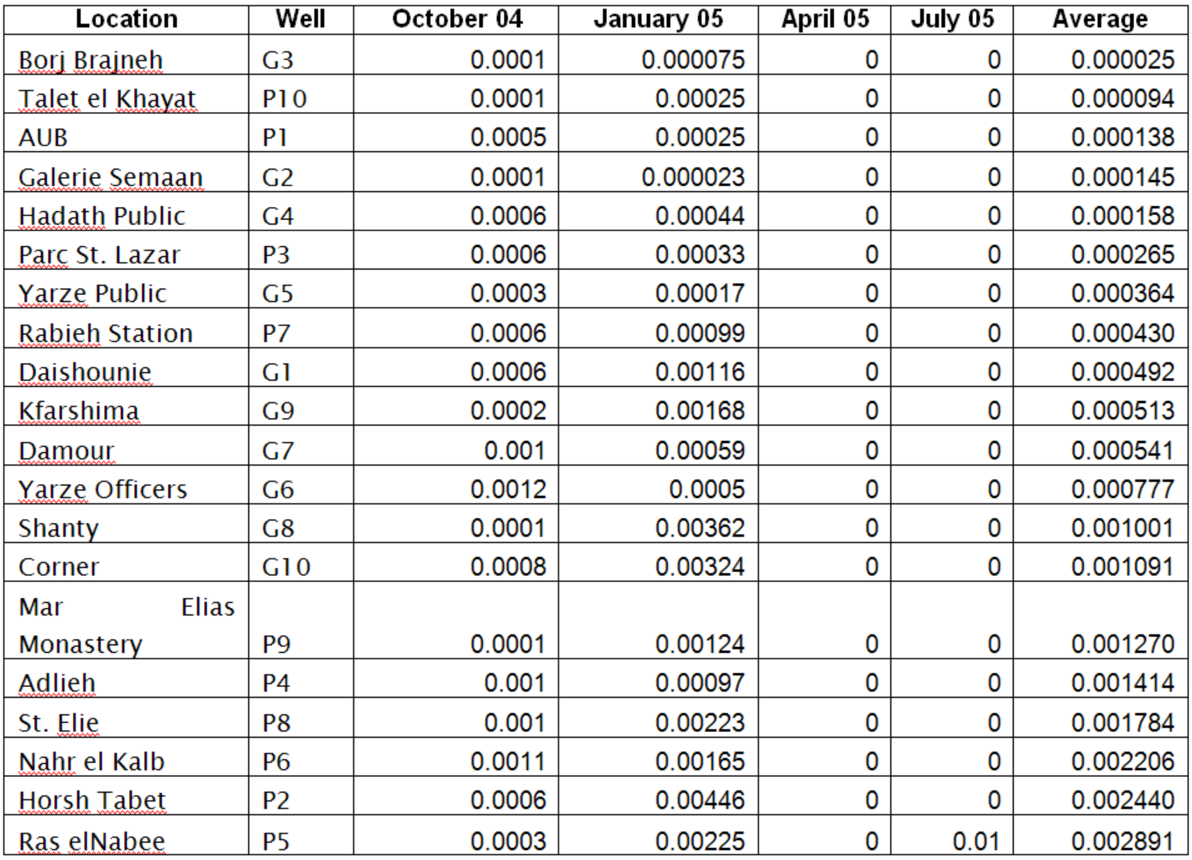


Figure 6.10: rNa to rCl Index Variations in Greater Beirut Wells

Table 6.7: rBr/rCl Index Ratio of Greater Beirut Wells



Location	Well	October 04	January 05	April 05	July 05	Average
Borj Brajneh	G3	0.0001	0.000075	0	0	0.000025
Talet el Khayat	P10	0.0001	0.00025	0	0	0.000094
AUB	P1	0.0005	0.00025	0	0	0.000138
Galerie Semaan	G2	0.0001	0.000023	0	0	0.000145
Hadath Public	G4	0.0006	0.00044	0	0	0.000158
Parc St. Lazar	P3	0.0006	0.00033	0	0	0.000265
Yarze Public	G5	0.0003	0.00017	0	0	0.000364
Rabieh Station	P7	0.0006	0.00099	0	0	0.000430
Daishounie	G1	0.0006	0.00116	0	0	0.000492
Kfarshima	G9	0.0002	0.00168	0	0	0.000513
Damour	G7	0.001	0.00059	0	0	0.000541
Yarze Officers	G6	0.0012	0.0005	0	0	0.000777
Shanty	G8	0.0001	0.00362	0	0	0.001001
Corner	G10	0.0008	0.00324	0	0	0.001091
Mar Elias Monastery	P9	0.0001	0.00124	0	0	0.001270
Adlieh	P4	0.001	0.00097	0	0	0.001414
St. Elie	P8	0.001	0.00223	0	0	0.001784
Nahr el Kalb	P6	0.0011	0.00165	0	0	0.002206
Horsh Tabet	P2	0.0006	0.00446	0	0	0.002440
Ras elNabee	P5	0.0003	0.00225	0	0.01	0.002891

Bromide/Chloride Index Ratio

The Br/Cl ratio can be used as a reliable tracer as both Cl and Br usually behave conservatively (they do not react with the aquifer) as explained in the FAO report on seawater intrusion in the aquifers of Beirut by (Majdalani, 1997), 1997. Seawater, specifically the Lebanese coast, has a Br/Cl ratio of approximately 0.0015. Anthropogenic sources like sewage effluents have a lower Br/Cl ratio of 0.00125. See Figure 6.11 and Table 6.7 for a summary of the results. Bear et al, has relied heavily on this index ratio to shed more light on the evident increase in this ratio (0.0015 for the coastal aquifers of Palestine) as a sign of the arrival of seawater intrusion.

The wells with the lowest annual average rBr/rCl ratio, indicative of seawater intrusion, are the following:

- Burj el Barajne (G3)
- Talet el Khayat (P10)

- AUB (P1)
- Gallery Semaan (G2)
- Hadath (G4)

These results conform closely when compared to values of salinity, TDS, and the index ratios discussed in the previous sections indicating only one thing clearly: seawater intrusion. Again the Hadath well (G4) has shown signs of seawater intrusion as attested by the Na/Cl and Ca/Mg ratios even though chloride values were not noticeably high (in the range of 500 mg/L). Again, possibly due to the recent arrival of seawater.

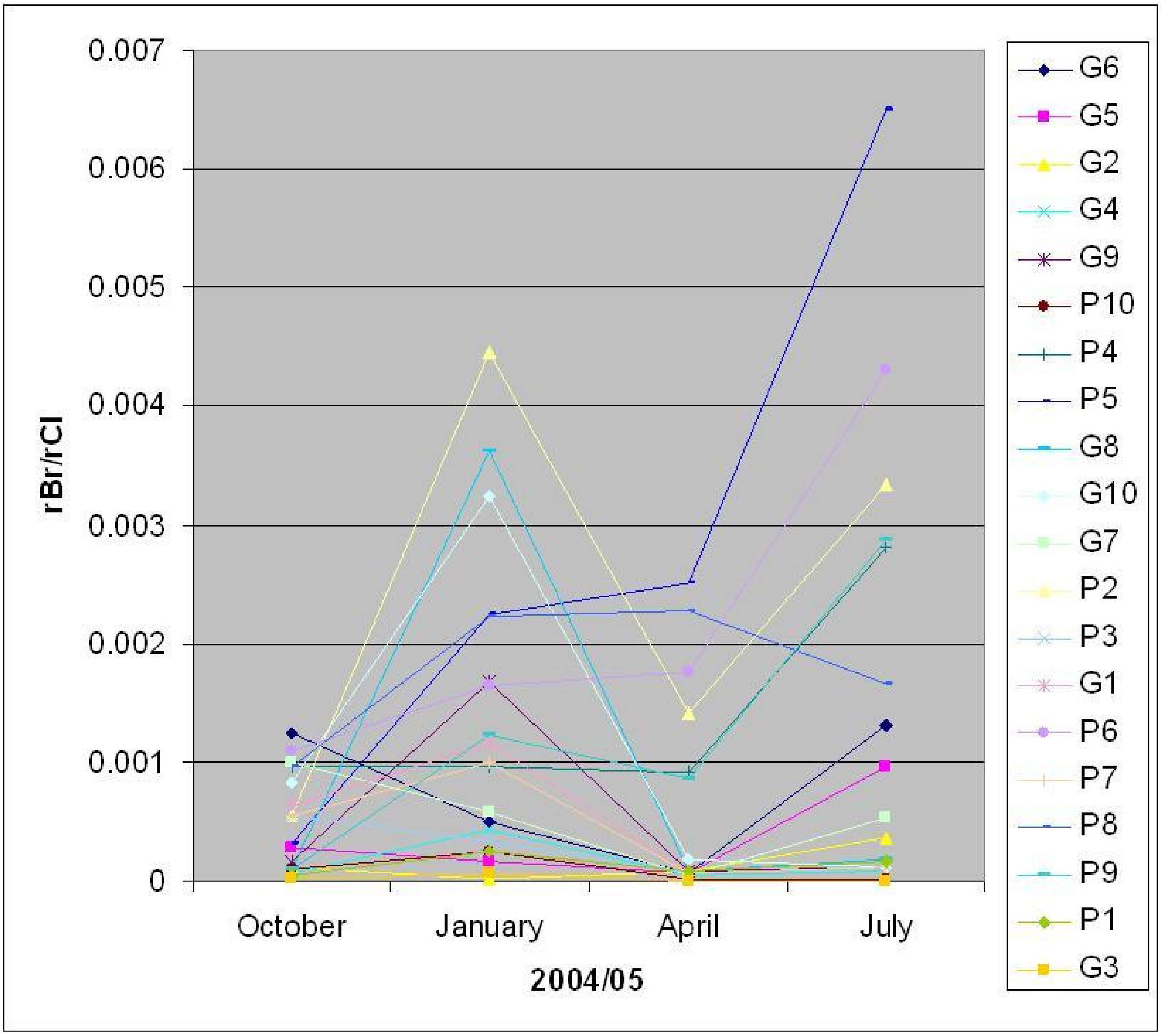


Figure 6.11: rBr to rCl Index Variations in Greater Beirut Wells

Chloride/Total Alkalinity Index Ratio

A fairly reliable index of groundwater contamination due to seawater intrusion and used by many authors is the chloride to alkalinity ratio (Todd, 1980). Although contaminants other than seawater can change the value of this ratio, they are considered rather insignificant in comparison to water drawn from wells subjected to seawater intrusion.

Normally, total alkalinity in natural waters usually implies the presence of carbonates and bicarbonates. Their comparative abundance in water depends on the actual pH value. Field measured pH values are summarized in Appendix E for the sampled wells during every month of the study period. As such, all values ranged between 7 and 8.3 which would indicate that the sampled waters are dominantly bicarbonate rich as opposed to carbonate. Hence, the total alkalinity measurements would result mainly from bicarbonate. This would especially figure in the calculations done for the Piper diagrams.

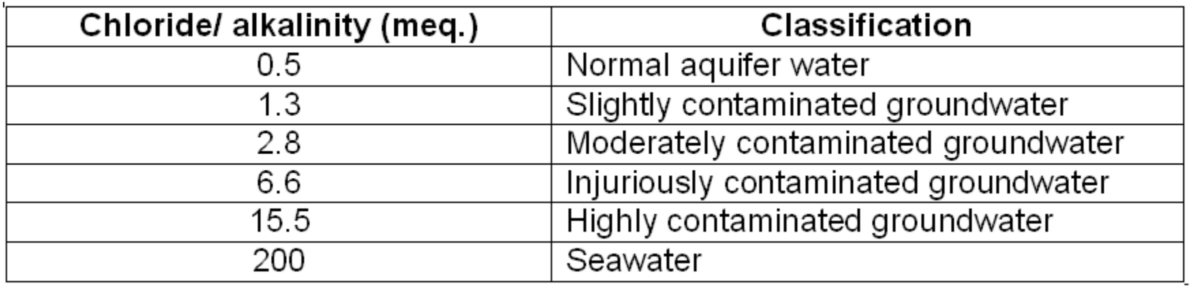
It is apparent that the wells which indicate high concentrations of salinity, show a close correlation to the elevated index ratio of chloride to alkalinity. The water from wells that have high chloride concentrations as well as an aforementioned high index ratio (in the range of two and above) is further evidence that the wells in question are plagued by seawater intrusion as is summarized in Table 7.1 and Figure 6.12.

Several MSc theses from the American University of Beirut (AUB) were carried out during the early seventies and eighties on the quality of groundwater in Beirut, most notably, (Peltekian, 1980). Both authors used the mentioned index ratio to shed light on groundwater contamination due to seawater intrusion. Basit's wells that were severely affected by salinity indicated high values in the range of 1.1, whereas Peltekian's sampled wells ten years later would indicate even higher values in the range of 1.95. Both sources also noted that the ratio would generally decline as the wells were located further away from the coastline.

The high values of the chloride to alkalinity ratio in the monitored wells show a close correlation with the elevated measured concentrations of chloride. Hence this ratio is used as supporting evidence to show that high concentrations of chloride ions in the monitored wells are due to seawater intrusion. Namely these wells include Borj Barajne (G3), Galerie Semaan (G2), Talet el Khayat (P10), AUB (P1), and Ras el Nabeh (P5) in decreasing order of seawater/ freshwater mixing.

In comparing the results of Table 6.9 with the classification system of Table 6.8, it becomes

Table 6.8: Classification of rCl/ rAlkalinity Ratio in Groundwater (Todd, 1980)



Chloride/ alkalinity (meq.)	Classification
0.5	Normal aquifer water
1.3	Slightly contaminated groundwater
2.8	Moderately contaminated groundwater
6.6	Injuriously contaminated groundwater
15.5	Highly contaminated groundwater
200	Seawater

evident that the monitored wells of Burj El Barajne, Gallery Semaan, and Talet el Khayat are injuriously contaminated with seawater intrusion, followed to a lesser extent by AUB and Ras el Nabaa wells.

The Hadath well (G4) does not particularly rank high (see Figure 6.11) on the Cl/alkalinity table when it comes to indicating seawater contamination, in contrast to the previous indexes such as Ca/Mg and Na/Cl and Cl/Alkalinity and an average TDS of about 1400.

In Figure 6.12, the Cl/alkalinity ratio is plotted against the relative distances of the wells from the coastline, since the ratio is expected to drop for wells located further away from the coast, the ones which do not conform are potentially due to contamination by seawater intrusion.

6.3 Groundwater Types

No hydrochemical investigation such as this, would be complete without a graphical representation of the cationic and anionic species on one template that would categorize the water chemistry in question at a quick glance. To that end, the Trilinear or Piper diagrams discussed in this section shows the typical chemical characteristics of the sampled wells on a seasonal basis, during 2004 and 2005, incorporating the following ionic species:

- Sodium
- Calcium
- Magnesium
- Potassium

Table 6.9: Summary of rCl/ rAlkalinity Index Ratio in the Study Area

Location	Well	Cl/ alkalinity (October 2004)	Cl/ alkalinity (January 2005)	Cl/ alkalinity (April 2005)	Cl/ alkalinity (July 2005)	Average Annual Cl/ alkalinity
Yarze Public	G5	0.5	0.4	1.2	0.6	0.6
Kfarshima	G9	0.5	0.5	0.9	0.7	0.6
Parc St. Lazar	P3	0.5	0.8	0.7	0.4	0.6
Yarze Officers	G6	0.5	0.8	1.2	0.6	0.7
Daishounie	G1	0.6	1.1	0.8	0.4	0.7
Horsh Tabet	P2	0.5	0.4	1.7	0.8	0.8
Nahr el Kalb	P6	0.3	0.7	1.5	0.7	0.8
Rabieh Station	P7	0.6	0.6	1.6	0.8	0.9
St. Elie	P8	0.6	0.9	0.9	1.3	0.9
Choueifat Shanty	G8	0.8	1.9	0.9	0.4	1.0
Damour	G7	1.5	1.0	1.1	0.5	1.0
Hadath Public	G4	1.1	0.8	1.7	0.8	1.1
Mar Elias Monastery	P9	0.8	1.1	2.0	0.7	1.1
Adlieh	P4	0.7	0.4	2.5	1.2	1.2
Choueifat Corner	G10	1.3	2.1	1.7	0.6	1.4
Ras elNabee	P5	**4.0**	**0.6**	**2.5**	**1.1**	**2.0**
AUB	P1	**3.8**	**2.0**	**2.1**	**2.0**	**2.4**
Talet el Khayat	P10	**0.9**	**7.4**	**10.9**	**5.5**	**6.1**
Galerie Semaan	G2	**8.2**	**6.6**	**7.8**	**2.7**	**6.3**
Borj Brajneh	G3	**12.4**	**8.8**	**8.6**	**4.7**	**8.6**

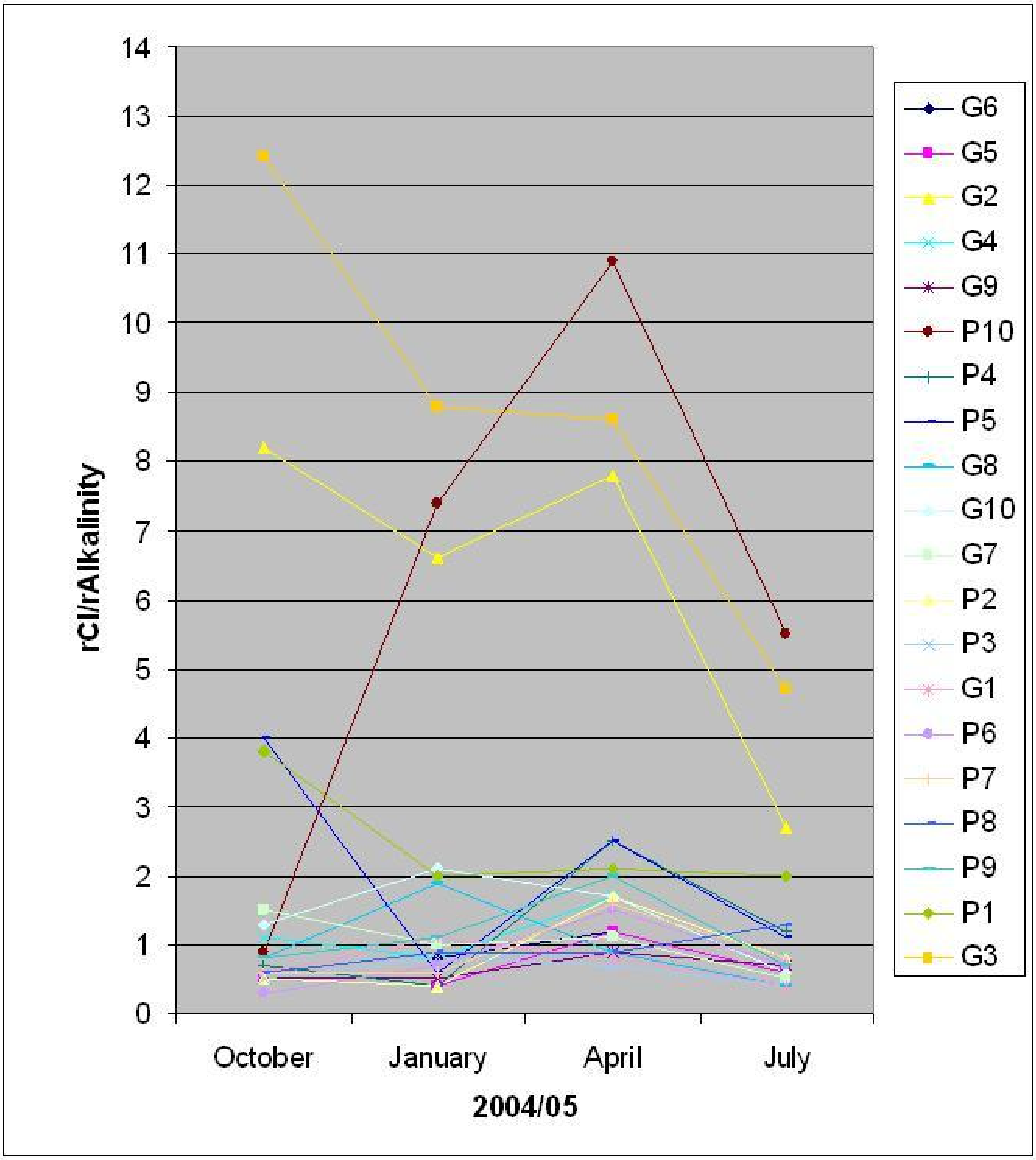


Figure 6.12: rCl to rAlkalinity Index Variations in Greater Beirut Wells

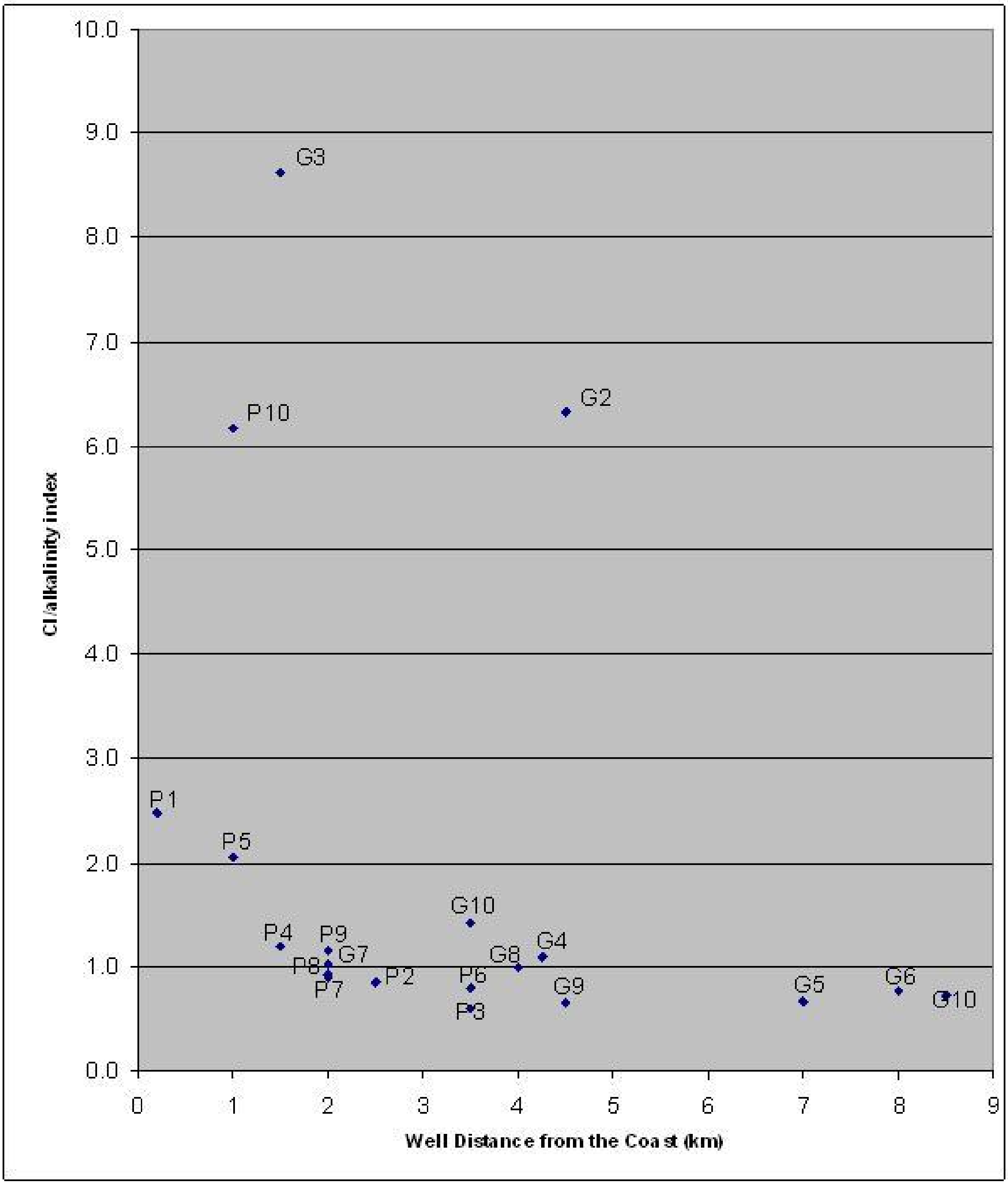


Figure 6.13: rCl to rAlkalinity Index Ratio Variation from the Coastline

- Alkalinity
- Chloride
- Sulfate
- Total Dissolved Solids

The Piper "Trilinear" diagram software used in this study plots the major ions (here in %) in two base triangles, then the data points in the two triangles are projected onto an overlying diamond shaped polygon. This plot reveals useful properties and relationships for large sample groups. The main purpose of the Piper diagram is to show clustering of data points to indicate samples that have similar chemical compositions.

This diagram reserves equal areas for all possible kinds of water and is convenient for the representation of widely divergent water types (Todd, 1980) as is the case in this study summarized in Figure 6.16.

The effects of cation exchange become particularly evident when the analyses are plotted on a Piper diagram. For example, the average compositions of fresh water and seawater would fall somewhere in the middle of the top diamond between the two extreme compositions (Appelo and Postma, 2005).

On one hand, the fresh water composition would plot on the left corner of the top diamond, while seawater would plot on the right hand corner of the diamond. Hence seawater intrusion would exhibit compositions between the two corners. In the case of Figure 7.1, the analyses not only indicate a mixing of freshwater with seawater, but additionally, the data plots in the upper corner of the diamond shape, which also indicates that the compositions are shifting away from calcium and magnesium bicarbonates rich water, typical of limestone aquifers, to a composition richer in calcium and magnesium chlorides and sulfates, which is progressively more saline in nature.

Hence, the compositions indicate a freshwater-seawater interface which is still very dynamic and far from reaching saturation in terms becoming dominant in sodium, potassium, chlorides and sulfates, typical of the major ions of seawater.

The remaining three Piper diagrams are found in Appendix B. They total four in number, reflecting the compositions of groundwater during October 2004, January, April and July of 2005. Please note that the symbols in the diamond shape of the Piper diagram represent the different wells clustered together prohobiting proper numbering.

It is apparent from these diagrams, that the groundwater has only slightly altered in composition from October 2004 to July 2005, indicating that the seawater and freshwater interface is advancing slowly but steadily with the passing of time.

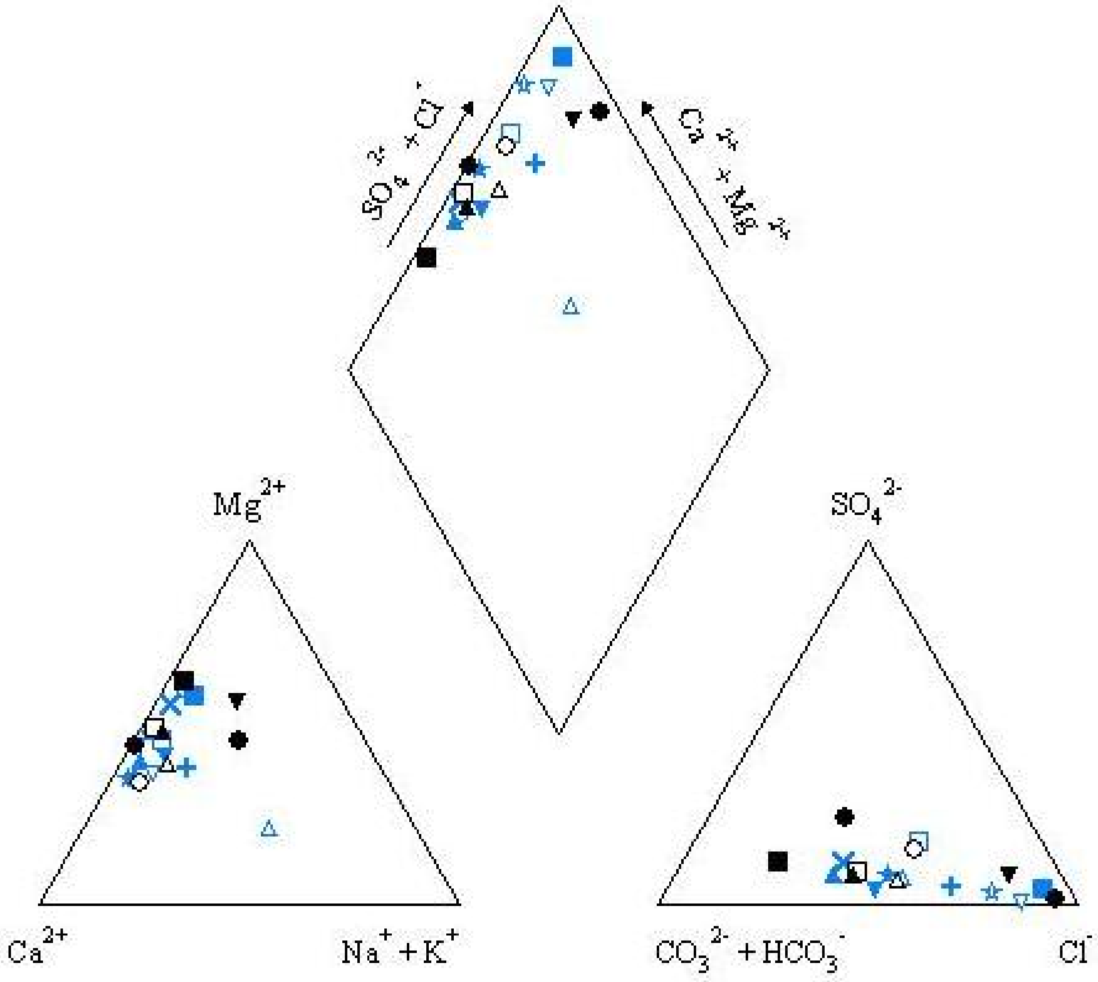


Figure 6.14: Greater Beirut Groundwater Chemistry (October 2004)

7 Conclusions

Before diving into the final conclusions of this study, it is pertinent, to elaborate, that Greater Beirut metropolitan is effectively divided into three municipalities, and as such, the three seawater intrusion affected coastal zones can be compared and contrasted. This division will coincide with the limits of the constituent three municipalities as depicted in Figure 7.1 for practicality reasons. They are:

- El Metn Municipality (north of Beirut)
- Beirut Municipality (Beirut proper)
- Baabda Municipality (south of Beirut)

Throughout this section, reference will be made in terms of severity of groundwater degradation, in each of the three aforementioned Beirut municipalities. It is noteworthy to mention that the seawater intrusion phenomenon has affected the coastal strips of the three municipalities differently in each case. The extent of this intrusion has affected the southern coastal strip of the Baabda Municipality the most, followed by Beirut in second place, and El Metn the least.

7.1 Baabda Municipality

The municipality with the highest groundwater chloride concentrations coincides with areas of the highest known population densities in Greater Beirut, as is the case in the southern suburbs of Beirut (Baabda municipality), adjacent to the international airport, an area locally known as the Dahia.

This observation may be explained by the fact that no less than half the population of Beirut's estimated 1.5 million is purported to reside in these suburbs alone. Such conditions would lead to a relatively high population density and inadvertently stressing the already limited domestic water supplied by the Beirut Water Authority.

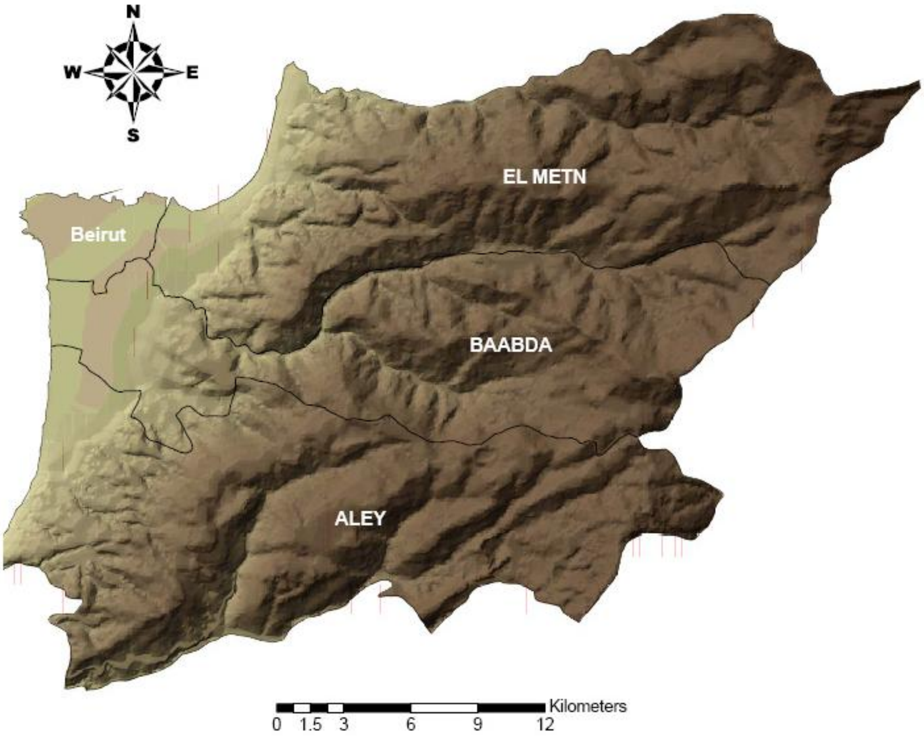
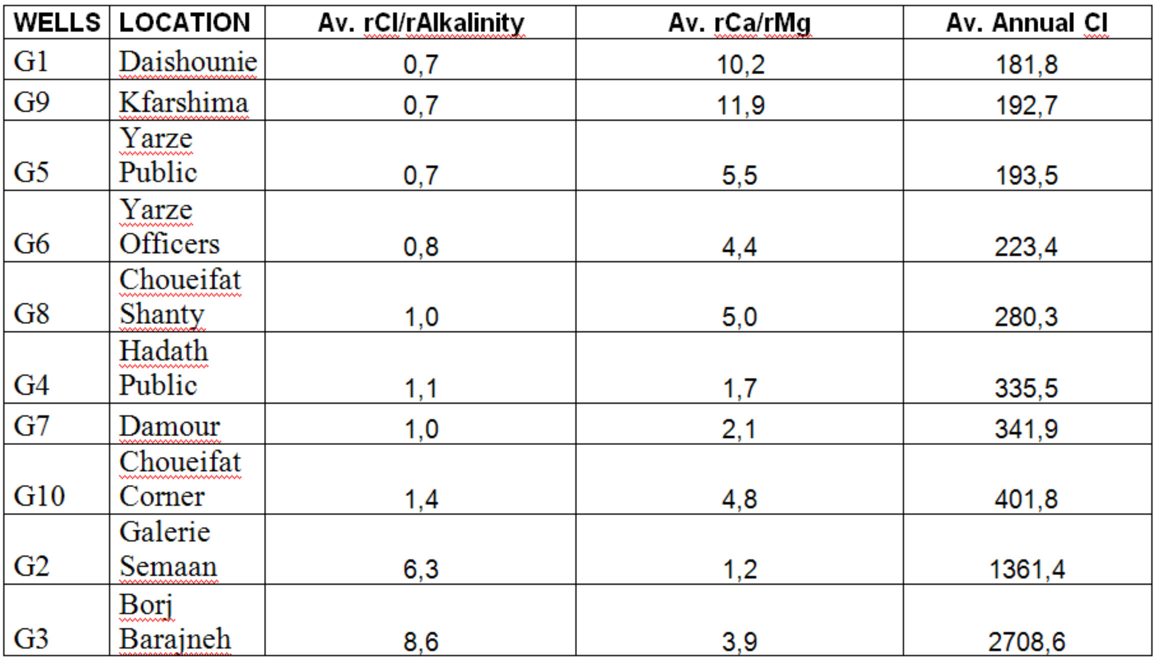


Figure 7.1: Municipalities of Greater Beirut

Table 7.1: Summary of Data for the Baabda Wells



WELLS	LOCATION	Av. rCl/rAlkalinity	Av. rCa/rMg	Av. Annual Cl
G1	Daishounie	0,7	10,2	181,8
G9	Kfarshima	0,7	11,9	192,7
G5	Yarze Public	0,7	5,5	193,5
G6	Yarze Officers	0,8	4,4	223,4
G8	Choueifat Shanty	1,0	5,0	280,3
G4	Hadath Public	1,1	1,7	335,5
G7	Damour	1,0	2,1	341,9
G10	Choueifat Corner	1,4	4,8	401,8
G2	Galerie Semaan	6,3	1,2	1361,4
G3	Borj Barajneh	8,6	3,9	2708,6

Hence, the inevitable outcome means that the locals of Dahia are causing the rampant over-abstraction of the coastal aquifers, namely the Quaternary (Q) and Cenomanian (C4) both being adjacent to the coast. Furthermore, the well with the highest continual chloride readings throughout the duration of this study. was the Burj El Barajne (G3) well, constructed by the Ministry of Energy and Water, in order to supply the locals with domestic water on a regular basis.

However, wells G4, G5 and G9 are also tapping the same aquifer as G2, but they rarely have monthly chloride concentrations exceeding 400 mg/L. The explanation for this appearance could very well lie in the distance of these wells from the coastline, see Table 7.1 for a summary of the results.

The Cenomanian aquifer in said area has a general dip running east to west with recharge coming from the foot of the mountains just a few kilometers to the east. Since G4, G5 and G9 are located at altitudes of 82, 192 and 63 meters respectively above mean sea level (AMSL), this would indicate that they are up-gradient of the groundwater flow with respect to G2 which only lies at about 20m AMSL. The implication of this would be that since G2 is at a lower relief than the others, it would more likely be susceptible to seawater intrusion coming from the northern coastline. But this requires further examination which is beyond the scope of this research.

The other important aquifer in the area is the Quaternary formation, which extends along the coastline and hence is in direct contact with seawater. See the geological cross section number 2, in Appendix A.

Wells G8 and G10 in the vicinity of G3 are also beginning to exhibit elevated signs of chloride concentrations exceeding 800 mg/L during some months. Furthermore, a subsequent survey of the Dahia area during October 2006, again yielded very high chloride readings in some private wells, most notably O1 and O3 of 1,320 and 2,600 mg/L respectively.

All of the aforementioned wells show TDS values in the range of 1,000 mg/L and above, which would classify them as being slightly saline except for the G3 well which would be categorized as moderately saline.

Furthermore, it is noteworthy to mention that wells G8 and G10 are only rarely operated which would account for the lower chloride and TDS readings when compared to G3 which is operated on a more or less daily basis.

7.2 Beirut Municipality

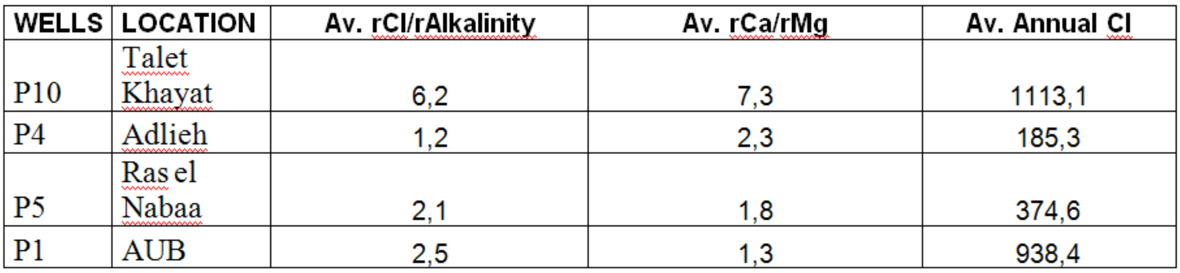
Beirut Municipality has less residents than those found in Baabda, hence less abstraction of groundwater is expected. Furthermore, the network for domestic water supply is purported to be in a better condition (Rammal, 2005).

Elevated concentrations of chloride (see Table 7.2), were observed in wells P1 and P10 being coastal wells, that means that the aquifers they are tapping (namely the Quaternary and Cenomanian) are in direct contact with western coastal waters conducive to seawater intrusion. The results indicated that the intrusion was confined to the coastal Quaternary and Cenomanian aquifers from the west, and that chloride contamination decreased noticeably beginning at only 800 m from said coastline.

The northern coastline of Beirut does not appear to exhibit any elevated chloride values in well waters. An important factor appears to be that the campus of the American University of Beirut (about 1 km^2) is acting as a buffer between the sea and the wells located further inland, since it is an area with practically little to no groundwater abstraction.

As for well P5 on the other hand, average chloride and TDS concentrations are in the range of 375 and 1,423 mg/L respectively. Such values are not very indicative of seawater intrusion, and

Table 7.2: Summary of Data for the Beirut Wells



WELLS	LOCATION	Av. rCl/rAlkalinity	Av. rCa/rMg	Av. Annual Cl
P10	Talet Khayat	6,2	7,3	1113,1
P4	Adlieh	1,2	2,3	185,3
P5	Ras el Nabaa	2,1	1,8	374,6
P1	AUB	2,5	1,3	938,4

may not be very suitable for human consumption.

7.3 Metn Municipality

As for the northern suburbs of Beirut, extending from Beirut River to the Kalb River in the north, wells P6, P7, P8, and P9, have begun to show early signs of seawater intrusion, as seen in Table 7.3.

Most of the wells monitored in this area exhibit salinities in the range of about 500 mg/L. These findings are also supported by an MSc thesis on groundwater pollution which was conducted by (Derkevorkian, 2002). Said study indicated that the coastal Quaternary and Cenomanian formations were affected by some saline water wells, apparent by chloride measurements reaching 500 mg/L in some wells. These formations only extended about a kilometer from the coast.

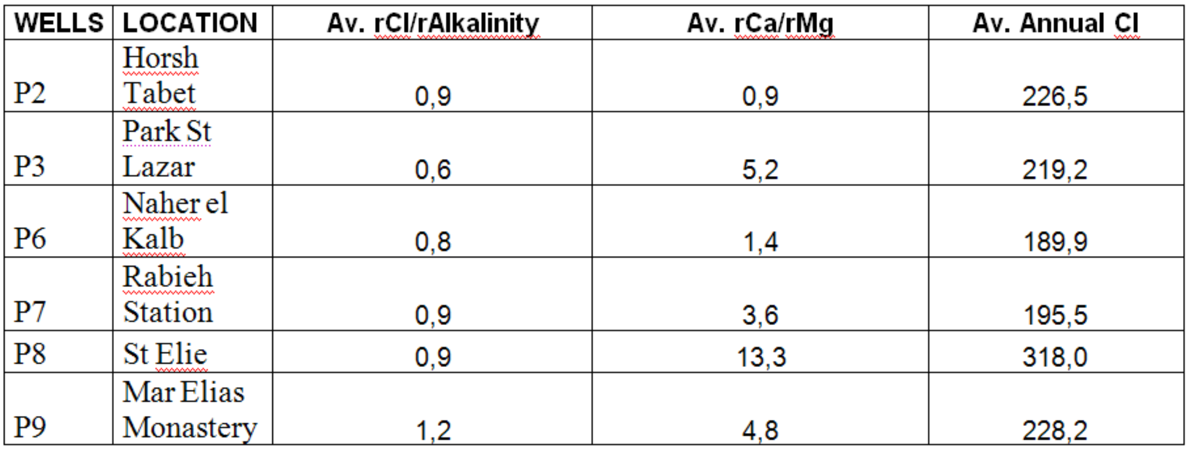
On a different note though, well (G2) is the only one to have exhibited such high levels of chloride concentrations throughout the year on par with the Borj Barajne well (G3), even though it is situated inland and in an area of relatively low population density.

Said well (G2) exhibits elevated chloride values that can very well be attributed to the fact that it lies along a north-south running bedding plane Cenomanian (C4), which intersects the coastline along Naher Beirut (Beirut River), refer to Figure 2.3.

Such a bedding plane could likely be conducive to seawater intrusion into said area and become a source of excessive salinity for these aquifers, but this would require further field examination which may be undertaken through subsequent studies.

Furthermore, Beirut River would have normally acted as an impediment to seawater intrusion as a natural source of groundwater recharge in the area, had it not been entirely lined with

Table 7.3: Summary of Data for the Metn Wells

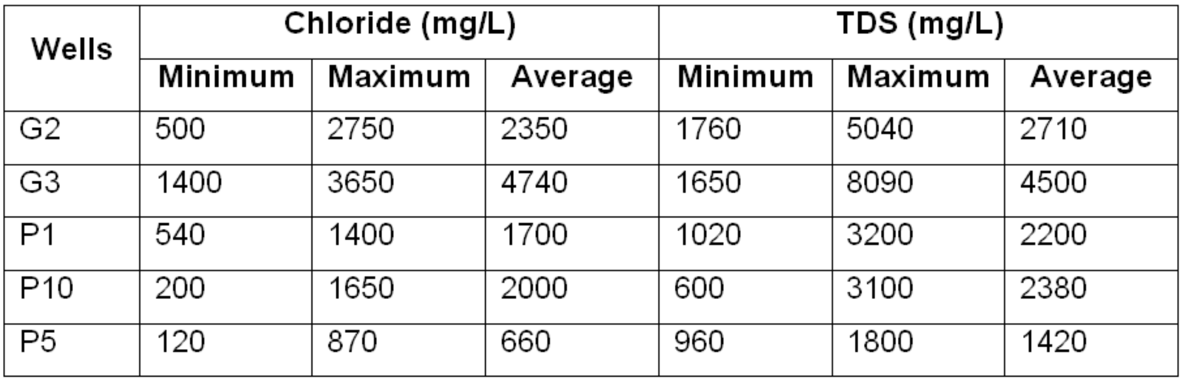


WELLS	LOCATION	Av. rCl/rAlkalinity	Av. rCa/rMg	Av. Annual Cl
P2	Horsh Tabet	0,9	0,9	226,5
P3	Park St Lazar	0,6	5,2	219,2
P6	Naher el Kalb	0,8	1,4	189,9
P7	Rabieh Station	0,9	3,6	195,5
P8	St Elie	0,9	13,3	318,0
P9	Mar Elias Monastery	1,2	4,8	228,2

concrete several kilometers from the coastline in recent years.

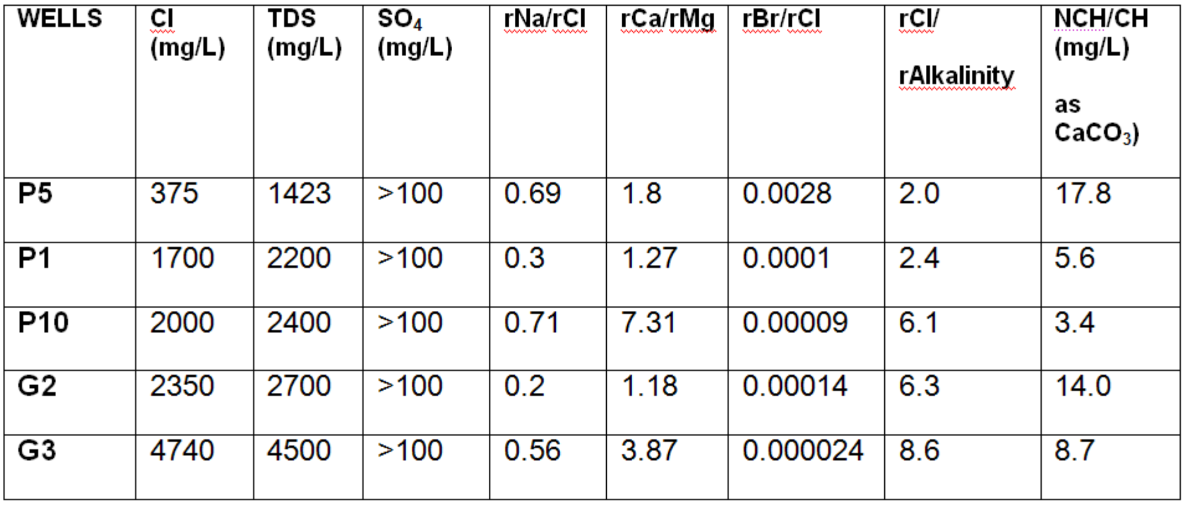
To conclude the discussion on this section, would not be complete without a comparison of the most saline water wells of Greater Beirut combined into Tables 7.4 and 7.5.

Table 7.4: Wells Most Affected by Seawater intrusion in Greater Beirut



Wells	Chloride (mg/L)			TDS (mg/L)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
G2	500	2750	2350	1760	5040	2710
G3	1400	3650	4740	1650	8090	4500
P1	540	1400	1700	1020	3200	2200
P10	200	1650	2000	600	3100	2380
P5	120	870	660	960	1800	1420

Table 7.5: Comparative List of Average Water Indexes for the Most Contaminated Wells in Greater Beirut

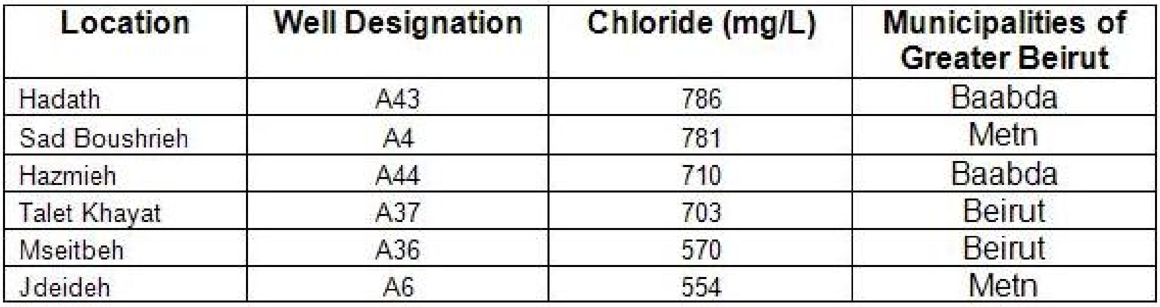


WELLS	Cl (mg/L)	TDS (mg/L)	SO_4 (mg/L)	rNa/rCl	rCa/rMg	rBr/rCl	rCl/ rAlkalinity	NCH/CH (mg/L) as $CaCO_3$)
P5	375	1423	>100	0.69	1.8	0.0028	2.0	17.8
P1	1700	2200	>100	0.3	1.27	0.0001	2.4	5.6
P10	2000	2400	>100	0.71	7.31	0.00009	6.1	3.4
G2	2350	2700	>100	0.2	1.18	0.00014	6.3	14.0
G3	4740	4500	>100	0.56	3.87	0.000024	8.6	8.7

7.4 Sampling 2006

Additional wells were sampled on August 2006, offering a glimpse into the groundwater conditions nearly a year after the completion of the initial field work. The 44 sampled wells corroborate the findings of the initial survey in terms of the zones most affected by the seawater intrusion in Greater Beirut.

Table 7.6: Chloride Values of Wells Sampled inAugust 2006



Location	Well Designation	Chloride (mg/L)	Municipalities of Greater Beirut
Hadath	A43	786	Baabda
Sad Boushrieh	A4	781	Metn
Hazmieh	A44	710	Baabda
Talet Khayat	A37	703	Beirut
Mseitbeh	A36	570	Beirut
Jdeideh	A6	554	Metn

Again, we find that the southern suburbs of Greater Beirut, or Baabda Municipality, is most affected by seawater intrusion. Second in place is Ras Beirut, or Beirut Municipality, which is dominated by the Quaternary and the Cenomanian aquifers, both of which intersect the coastline in the west, leading to localized seawater intrusion.

Lastly, the zone least affected by seawater intrusion is the northern suburbs of Greater Beirut or the Metn Municipality, were most of the August 2006 surveyed wells were located. The geology in this area is unique in the sense that even though the Quaternay and Cenomanian aquifers are adjacent to the coastline, thus susceptible to intrusion, the underlying marly formations of the Albian (C_3), lying close to the coast and steeply dipping, acts as an aquiclude barrier to the ingress of seawater to the underlying aquifers located further inland.

The suburbs of Beirut towards the south, or Baabda Municipality, could not be well covered during the August 2006 survey, because of the devastation to the infrastructure which targeted Dahia during the conflict with Israel in the Summer of 2006.

As seen in Table 8.1, the wells with the highest chloride concentrations of more than 500 mg/L are dominantly in the municipality of Baabda, followed by those of Beirut Municipality. Some wells with more than 500 mg/L of chloride concentrations are found in the Metn Municipality, like wells A4 and A6, that would require constant monitoring in the future.

Well A6 adjacent to A4, are both located along the Beirut River, which as already mentioned, is believed to be a conduit for seawater intrusion attested by the Gallery Semaan (G2) well, monitored during the initial field survey of 2004/05. As for wells A29, A9 and A8 in the Metn Municipality, the chloride concentration ranges between 250 and 500 mg/L, and they are tapping into the coastal Quaternary formation which points to signs of increasing seawater intrusion. Further inland, the chloride concentrations dropped to below 100 mg/L for wells tapping the Cretaceous C3, C2b and C2a formations. This drop in chloride concentrations is supported by the fact that marly C3 formation, is generally considered an aquiclude thus preventing the ingress of any seawater.

Finally, it can be concluded, that the seawater/freshwater interface is heading inland from a south-westerly to a north-easterly direction with the highest concentrations in the Baabda Municipality or Dahia area. The northern coast of Beirut, or Beirut Municipality is relatively less affected than Baabda, while the Metn Municipality remains the least affected by the phenomena of seawater intrusion.

8 Recommendations

Local groundwater is generally less expensive than imported water, primarily because of the development and transmission costs of the imported water. As is often the case, the economic benefit of controlling seawater intrusion appears to be significantly greater than the costs of constructing and operating the artificial recharge and seawater intrusion barrier systems after it has occured. The pros and cons of the following measures are elaborated

8.1 Engineering Techniques

The Ministry of Energy and Water has been re-injecting about 700,000 m3 per year, of treated domestic water into a well in the Gallery Semaan district of Beirut in hope of recharging the aquifer considerably enough to lower the salt concentration prior to abstraction and distribution. This project has been active since 2004, but needs to be expanded to cover Greater Beirut.

Another project in the pipeline is the construction of a dam on the Bisri river some 35 km south of Beirut (Rammal, 2005). This project is supposed to meet the water needs of Greater Beirut by damming the Bisri river thus creating an artificial lake with a capacity of nearly 120 MCM per year. In the initial phase, water will be conveyed to Greater Beirut at a rate of 375,000 m3 per day. During the second and final phases, water will be conveyed to Greater Beirut at a rate of 500,000 m^3 to 750,000 m^3 per day respectively.

With this project about to launch in the coming years, the total water needs of Greater Beirut could very well be met, thus encouraging the population to abandon groundwater abstraction altogether. Only then could the effects of seawater intrusion begin to be reversed. Nevertheless, the following recommendations below represent some potential methods for tackling seawater intrusion. Some areas may necessitate the use of one or more of the following measures:

- Modified pumping rates: lowering or even turning the coastal well pumps off every now and then, can mitigate the problem of salinity in the well.

- Well relocation: in some specific cases, relocating wells further inland to where the water table is high could alleviate the problem of seawater intrusion. However, this method could also induce the intrusion of seawater in some cases if the execution is ill prepared.

- Artificial recharge: coastal aquifers can be artificially recharged by increasing infiltration of surface waters into designated coastal wells.

- Injection barriers: a hydraulic barrier can be created by injecting fresh water to form a narrow zone in which the freshwater gradient is towards the sea as depicted in Figure 8.1 and Table 8.1. This prevents intrusion of seawater into unaffected portions of the aquifer system. However, this measure is very expensive and complicated and is not feasible at the present time.

- Treatment of saline water: this could include reverse osmosis treatment to desalination plants using groundwater. Desalination is currently quite expensive and would cost two to four times more than is being currently charged for domestically supplied water.

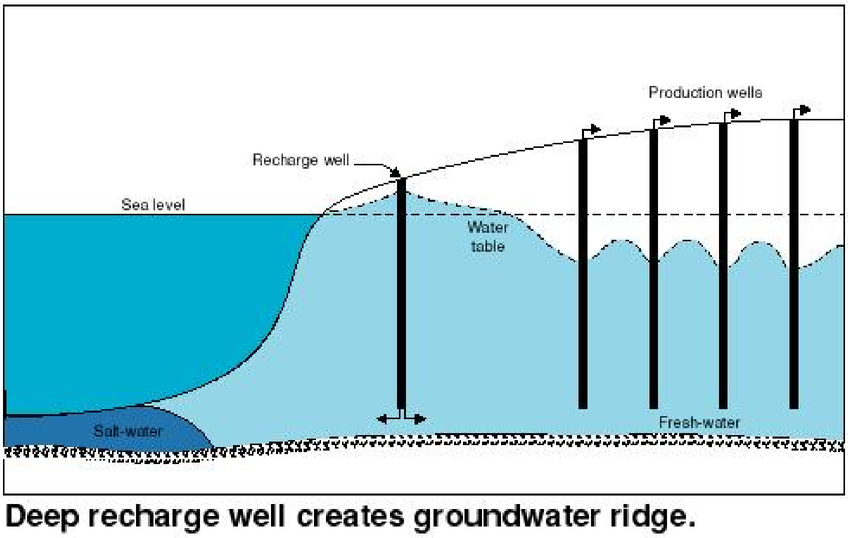
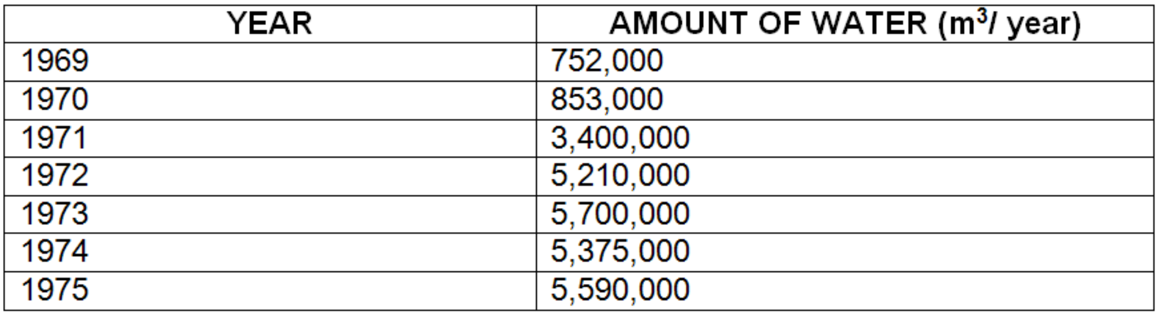


Figure 8.1: Salt-Water Interface Control, not to scale (USGS, cicular 1262, 2004)

Table 8.1: Ministry of Energy and Water Recharge Project



YEAR	AMOUNT OF WATER (m^3/ year)
1969	752,000
1970	853,000
1971	3,400,000
1972	5,210,000
1973	5,700,000
1974	5,375,000
1975	5,590,000

8.1.1 Artificial Recharge

The main purpose of artificial aquifer recharge technology is to store excess fresh water for later use, while decreasing the salinity concentrations of the coastal aquifers. There are many artificial recharge techniques in use today, including infiltration basins, water traps, surface runoff drainage wells, and septic-tank-effluent disposal wells to name a few.

Recharge or injection wells are used to directly recharge fresh surface waters into coastal aquifers. Recharge wells are a suitable only in areas where an impervious layer or “aquiclude” exists between the surface of the soil and the aquifer to be recharged. Under ideal conditions a recharge well will accept water as readily as it will yield or provide water through subsequent well pumping.

The Ministry of Energy and Water first practiced artificial recharge between 1968 and 1975, the year the civil war in Lebanon began. This was carried out by injecting surface water from the Beirut River, through the Daishounieh Canal into the Cenomanian (C4)-Quaternary (Q) aquifer. Data indicates that the recharge met with favorable results, especially in mitigating seawater intrusion in said aquifers. The following table includes data of the initial trials of surface water injected up to 1975:

The recharge of the aquifers raised the piezometric levels and improved the water quality by decreasing water hardness. The extent of recovery of the recharged water was 94% for volumes up to 400,000 m^3. This percentage could decrease with increased volumes, because the rise of the piezometric levels tend to increase the natural discharge of the aquifer and thus result in the partial waste of the recharged water by dissipation to the sea (Peltekian, 1980).

In 2004, the Ministry of Energy and Water again injected successfully from the same source at

Daishounie and into the Gallery Semaan well a quantity of about 700,000 m^3 (Rammal, 2005). These efforts however need to be continuous and monitored for any adjustments.

8.1.2 Advantages of Artificial Recharge

Artificial recharge has several potential advantages:

- The use of saline aquifers for storage of surface water and removal of contaminants by natural cleaning processes may occur as this surface water infiltrates down through the various geological formations.
- Groundwater recharge stores excess water during the wet season for later use during the dry season, when demand is at its highest.
- Recharge could significantly increase the long term sustainable yield of an aquifer.
- In river watersheds, control of surface water runoff to provide aquifer recharge reduces sedimentation problems.

8.1.3 Disadvantages of Artificial Recharge

- There is always a potential for contamination of the groundwater aquifer from injected surface water runoff, which often is not pre-treated prior to injection.
- Unless significant volumes of surface water can be injected into an aquifer, groundwater recharge may not be economically feasible in small scale operations.
- The hydrogeology of an aquifer should be fully investigated and understood before any recharge project is implemented. In karstic terrain, such as found in Lebanon, dye tracer studies can assist in acquiring this knowledge.

8.2 Regulatory (Legislative) Techniques

The single most important element for controlling water abstraction (beyond the licensed rate) is by imposing a fee on the pumped water. Progressive charges impose a self-control mechanism on the user and ensures that wasteful consumption is avoided. Penalties must be imposed for over-abstraction.

The Ministry of Energy and Water holds the responsibility for setting regulations and ensuring implementation of groundwater supply equitably. Regulations to control, restrict or even to stop groundwater abstractions, should be implemented immediately to combat seawater intrusion not just in Beirut, but along the entire Lebanese coastline.

A system for registering and licensing new and existing wells must be established before imposing restrictions on the abstraction of groundwater. Decree 14438 of 2 May 1970, regulates groundwater exploration and use by exempting the drilling of wells on private property from acquiring permits as long as well depth does not exceed 100 m and daily abstraction is limited to less than 150 m3. Hence wells can be drilled anywhere without approval from authorities.

Once a system for permitting and registering of wells is established in Lebanon, licenses can be issued for specific abstraction rates. Licenses should only be issued for operation of wells that have meters installed in order to measure the amount of water pumped. The licenses should specify the maximum amount of water that can be abstracted and only be valid for a fixed period of time, after which a re-evaluation should be carried out to determine whether the license should be renewed, modified, or in some cases even revoked.

Such a decision depends on the overall picture of the inventory of the existing wells and abstraction rates, and a master plan in which all available water resources are allocated to or reserved for the various users, also taking into account the water quality requirements for different user categories such as domestic, industrial or agricultural.

Regulation must also be issued warranting the closing of wells. This should be the case for wells where salinity has reached a threshold level and/or continued abstraction poses a threat to the freshwater supply (in other wells) in the vicinity. The municipalities, in cooperation with the regional water authorities, should be given authority to conduct assessment and implement this regulation.

8.3 Management Recommendations

The Ministry of Energy and Water (MoEW) is the main authority responsible for the management of water resources, including the coastal aquifers. The MoEW should therefore set the pace for developing solutions to mitigate the problem of seawater intrusion. Together with the Ministry of Environment and local water authorities, the MoEW should develop a strategy for the sustainable exploitation of groundwater from coastal aquifers.

The strategy for sustainable exploitation of groundwater should lay out a long-term plan that provides direction for government authorities and private institutions to work towards a common goal rather than invest in patches of independent plans that serve no end and only lead to further exacerbation of the problem of seawater intrusion. Regarding seawater intrusion, the strategy should stipulate development of a program for management of the coastal aquifers, with the following specific objectives of halting seawater intrusion.

- Demand management: essentially lowering the demand for water to reduce pumping stress on the aquifer. Managing demand includes reducing losses in the network, improving irrigation techniques (which is not the case for Beirut), devising methods for reusing non-potable water (grey water), regulating groundwater abstraction, use, discharge and implementing proper pricing schemes for all the aforementioned mehtods.
- Educate, inform and train government administrators as well as stakeholders: essentially building human capacities to a level of sufficient knowledge to enable them to recognize the severity of the problem and act accordingly.

8.4 Scientific Monitoring and Assessment

The process of seawater intrusion is normally very fast, while the phase of recovery through freshwater can be considered complete only after the transit of a volume of water many times higher than the volume of aquifer pores is accomplished. Moreover, the reversal of the flow does not bring back the chemical quality of the aquifer water to the original conditions. After a short time during which there is the complete displacement of salt and brackish waters, an almost complete recovery of the aquifer may be reached in 15 years. This is due to both the very low cation exchange capacity (CEC) and the high recharge rate, typical of karst aquifers, which result in a relative fast replacement of the water reserve (Hamdy, 2001).

The key therefore, to controlling the potential problem of seawater intrusion is to maintain the proper balance between water being abstracted from the aquifer and the amount of water recharging it. A constant monitoring on a seasonal basis for the salt-water interface is absolutely imperative in determining proper control measures in Lebanon. A network of monitoring wells along the entire Lebanese coast can be maintained with as little as a total of 100 wells measuring piezometeric levels, and sampling for about seven water parameters which include; magnesium, potassium, sodium, sulfate, alkalinity, chloride, and TDS at the very least. This monitoring program should be the first step in addressing the pressing issue of seawater intrusion in Lebanon and can be undertaken if the following ministries concert their efforts, namely the Ministry of Energy and Water, and the Ministry of Environment.

This monitoring program is a crucial first step in determining the potential control measures that can be considered. The monitoring program will provide a clear picture of the extent of damage and delineate the progress of the zone of mixing. The following guidelines should be implemented during monitoring:

1. Measure following parameters: water level, water abstraction, temperature, electric conductivity, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, K^+, TDS and pH on a monthly basis.

2. Monitor freshwater levels in unexploited wells or piezometers penetrating the aquifer, also on a monthly basis. Only once the monitoring program is up and running can policy makers proceed with considering appropriate control measures, which can broadly be divided into engineering, regulatory, or management measures.

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A Geological Cross Sections

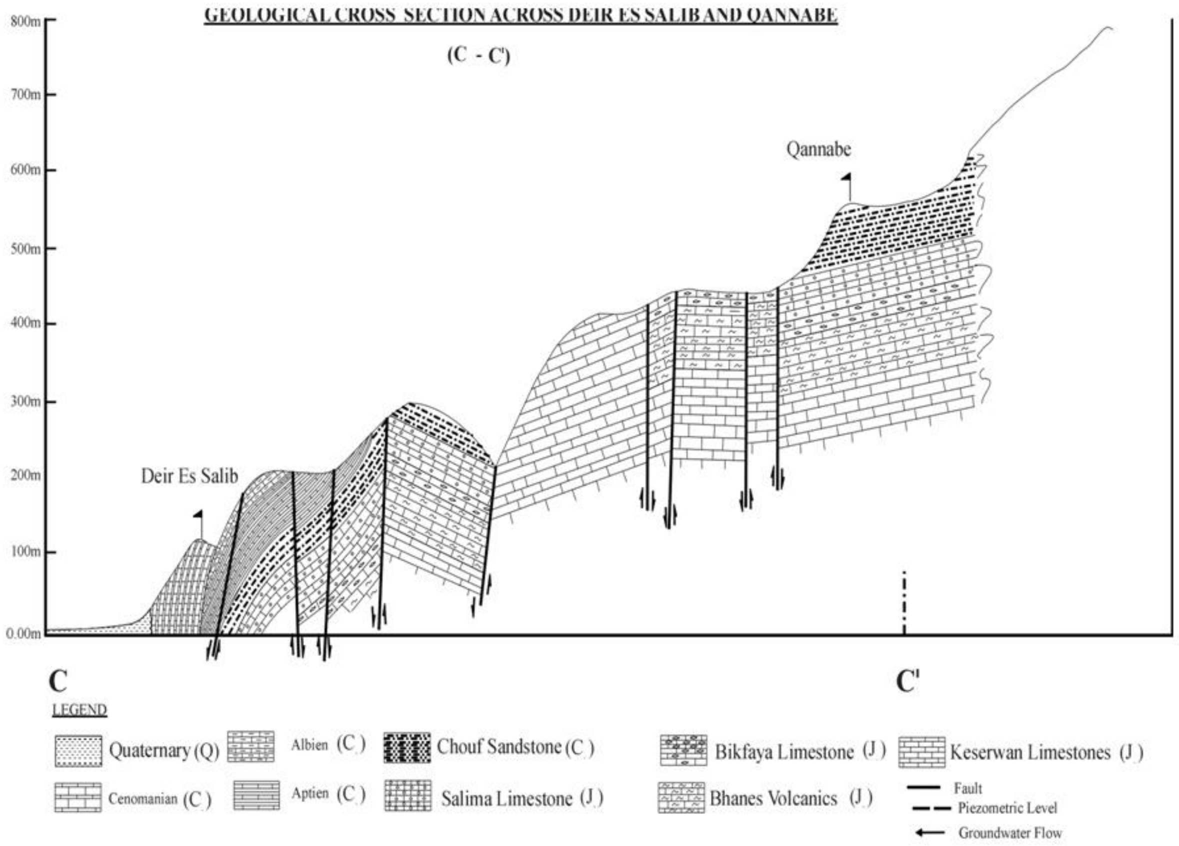


Figure A.1: Geological Cross Section 1: Deir Es Salib and Qannabe

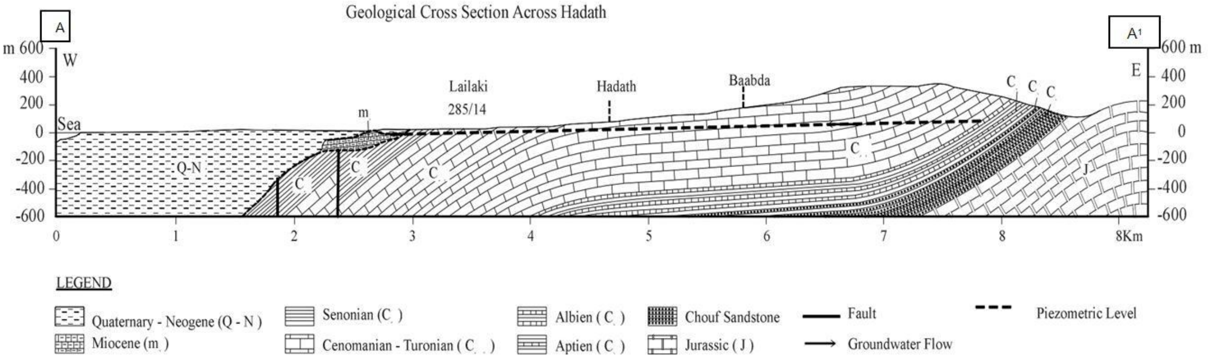


Figure A.2: Geological Cross Section 2: Hadath

B Piper Diagrams

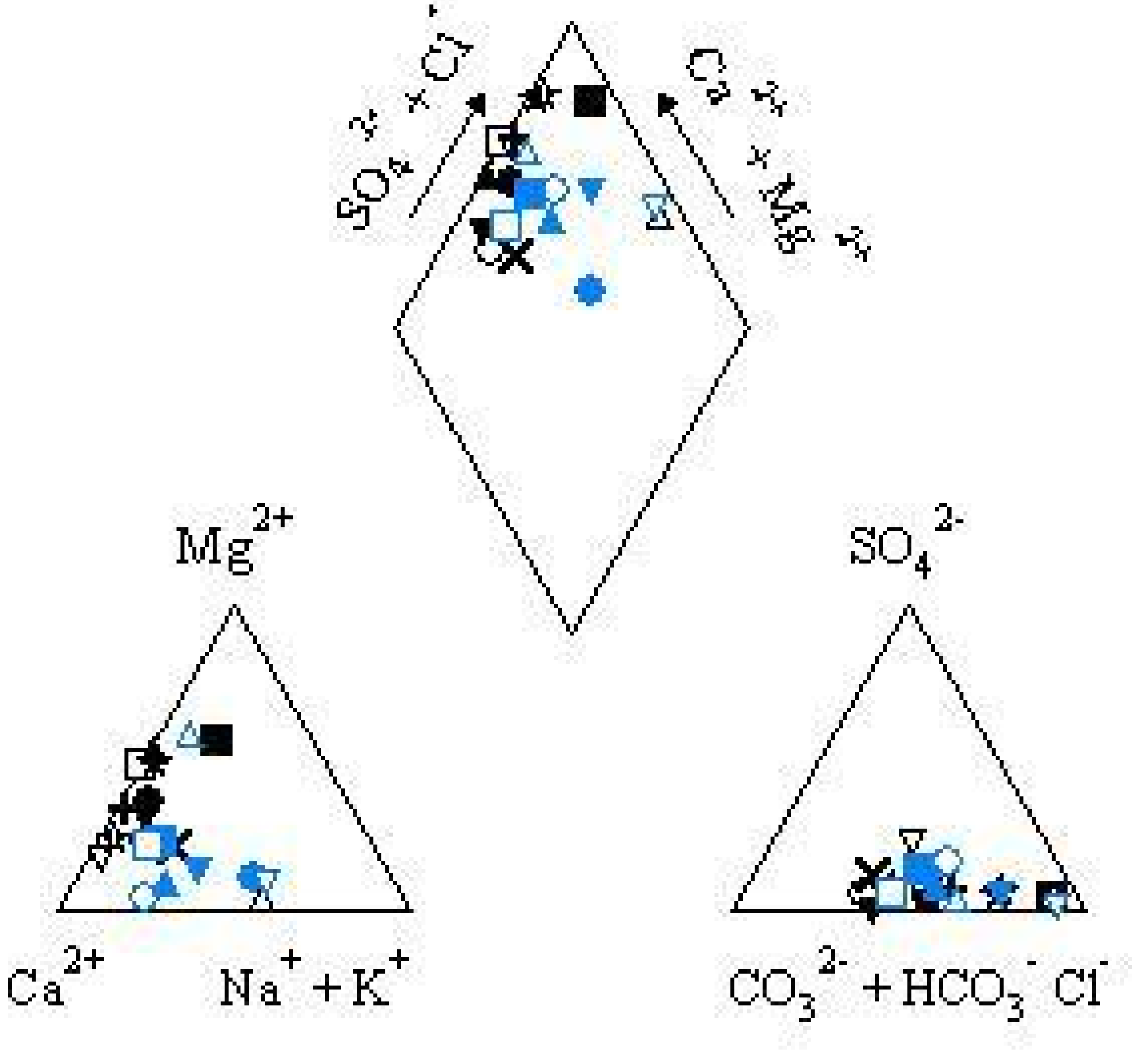


Figure B.1: Piper Diagram 1: Greater Beirut Groundwater Chemistry, January 2005

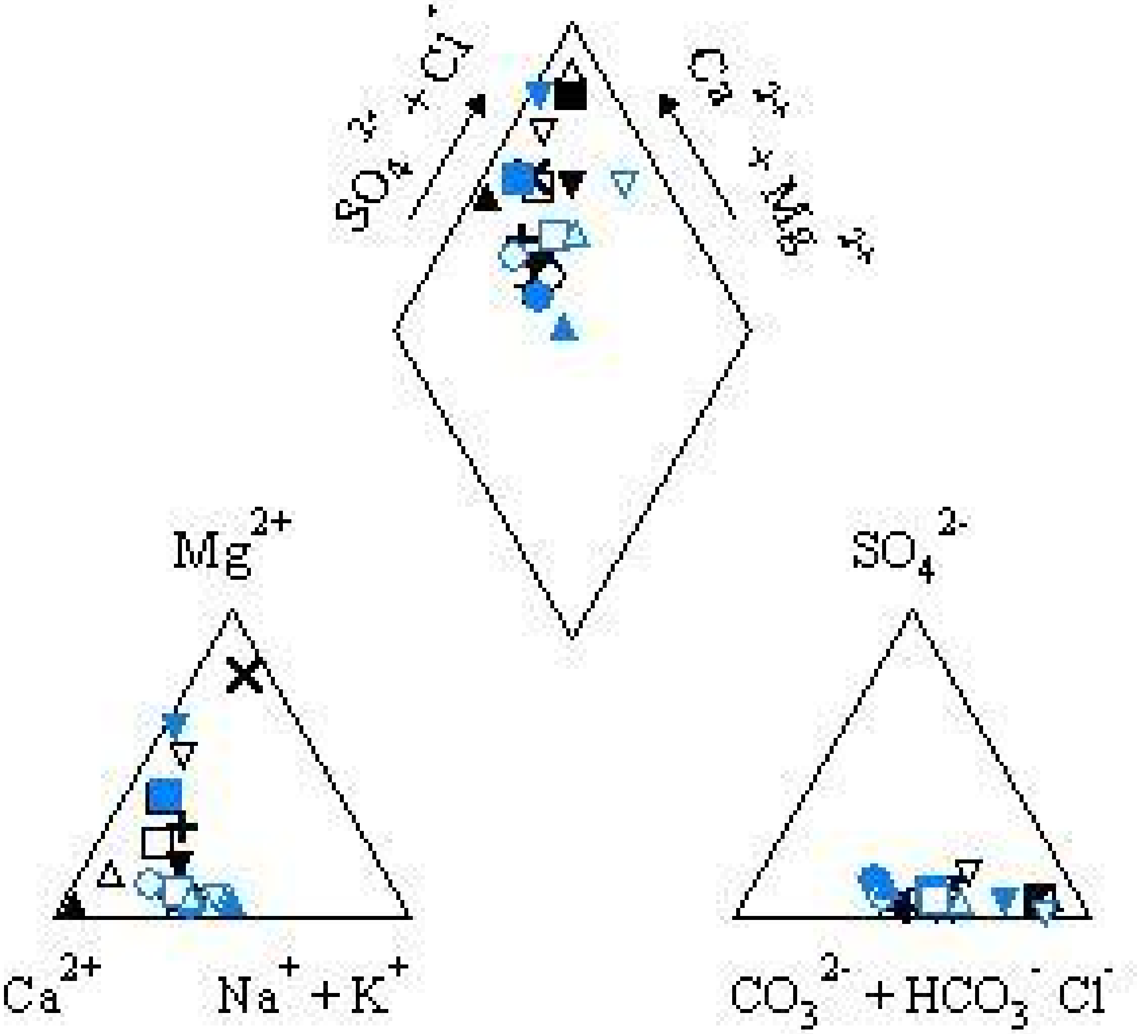


Figure B.2: Piper Diagram 2: Greater Beirut Groundwater Chemistry, April 2005

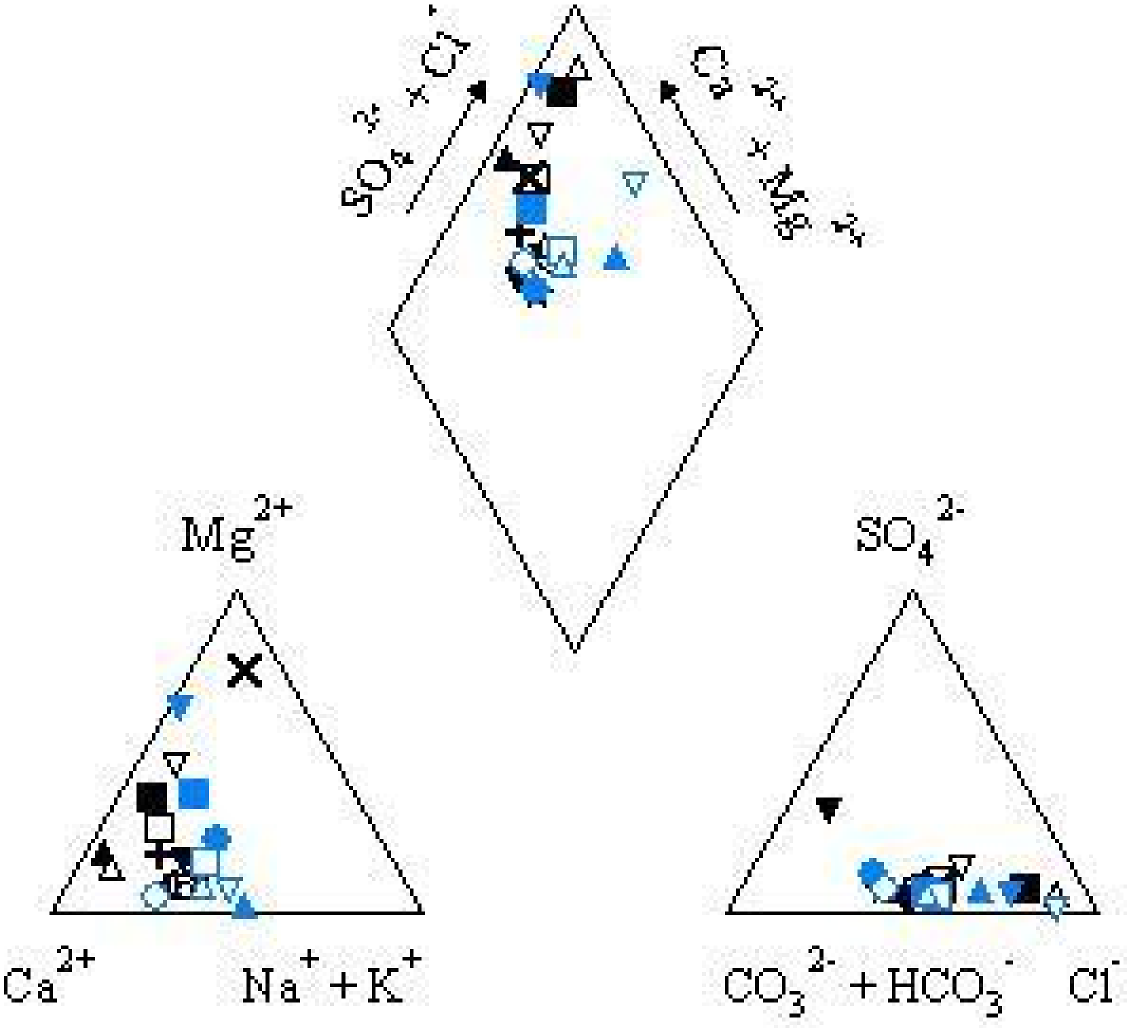


Figure B.3: Piper Diagram 3: Greater Beirut Groundwater Chemistry, July 2005

C Groundwater Chloride Maps

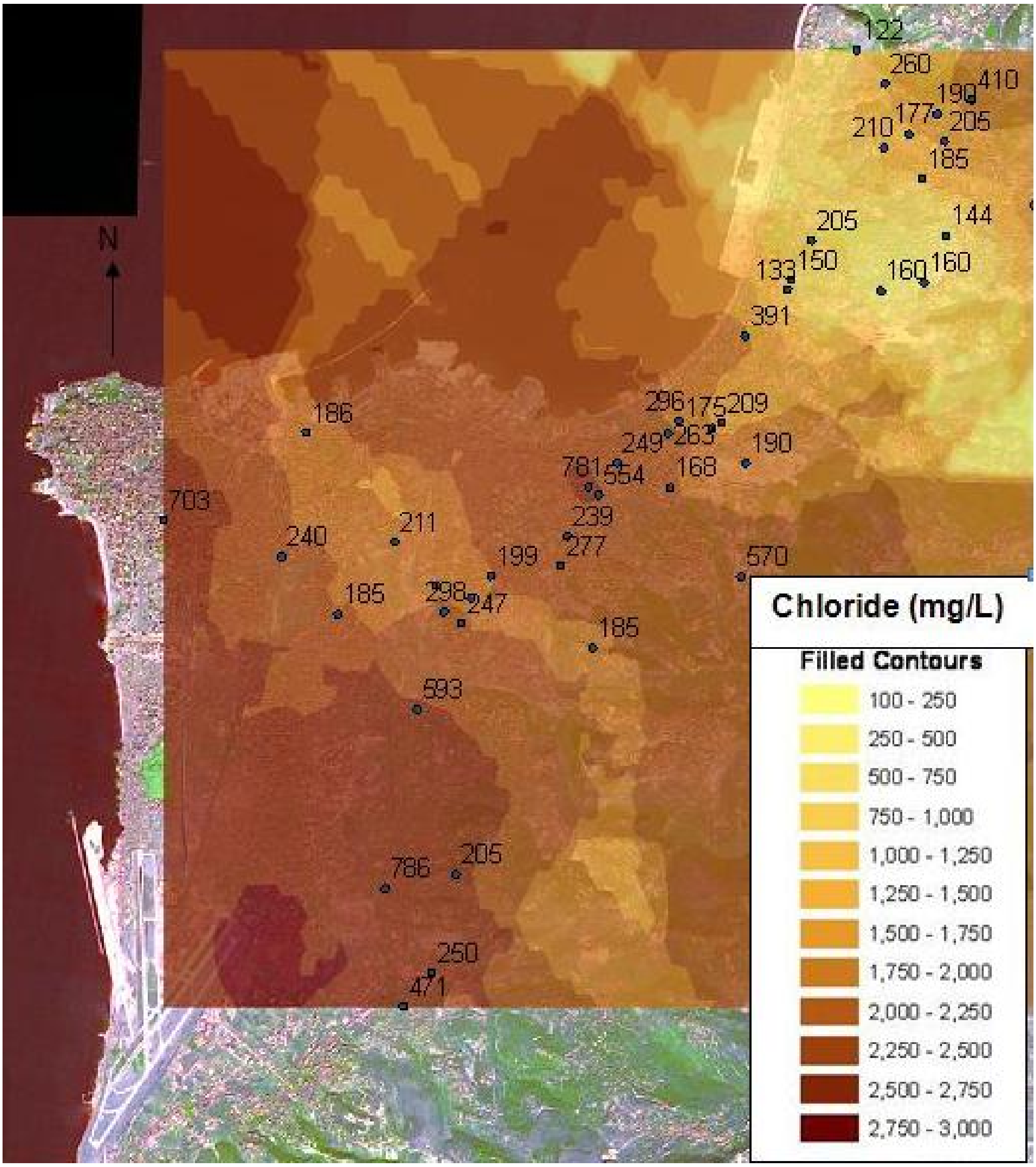


Figure C.1: Groundwater Chloride (mg/L): August 2006

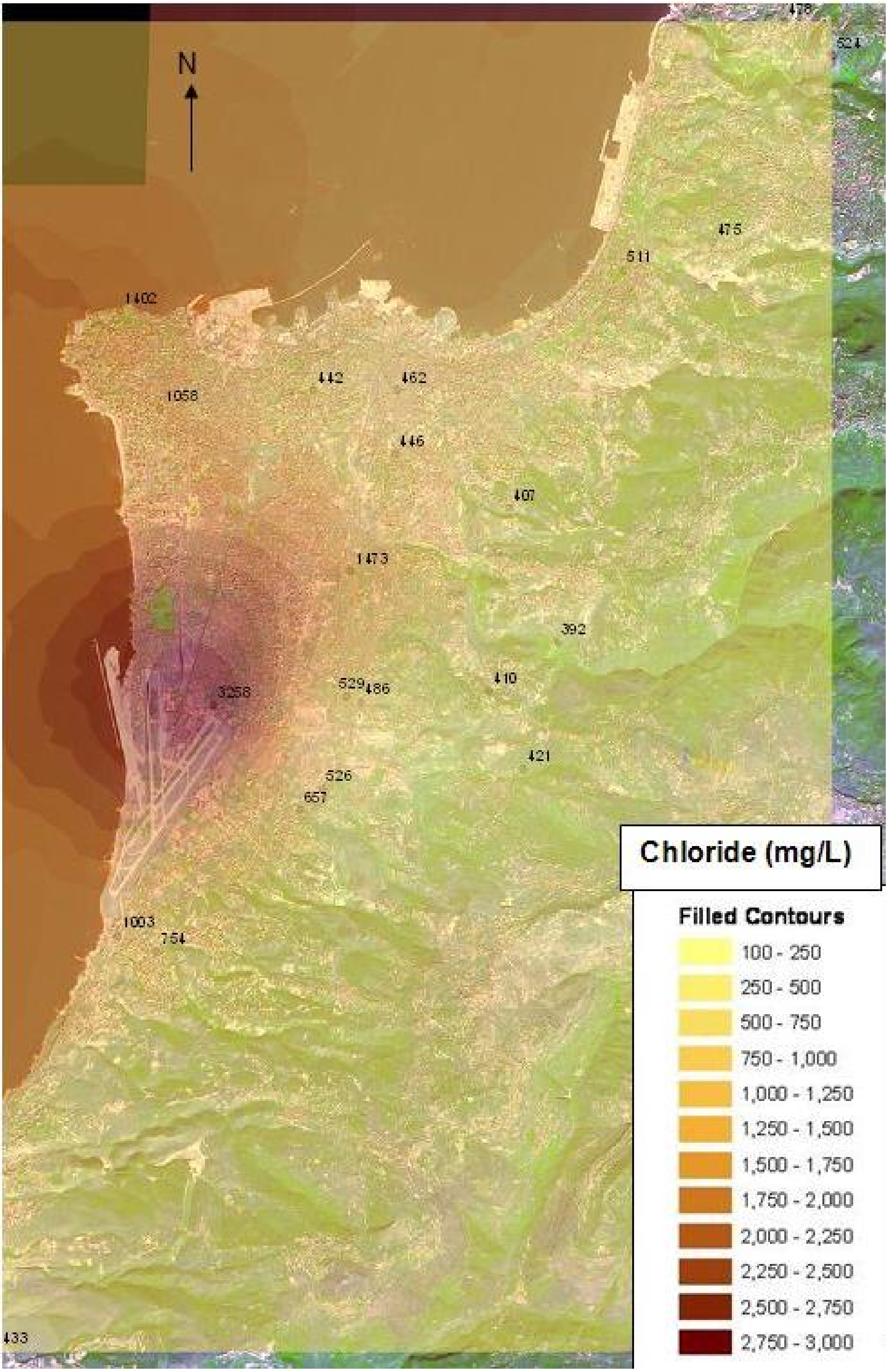


Figure C.2: Groundwater Chloride (mg/L): December 2005

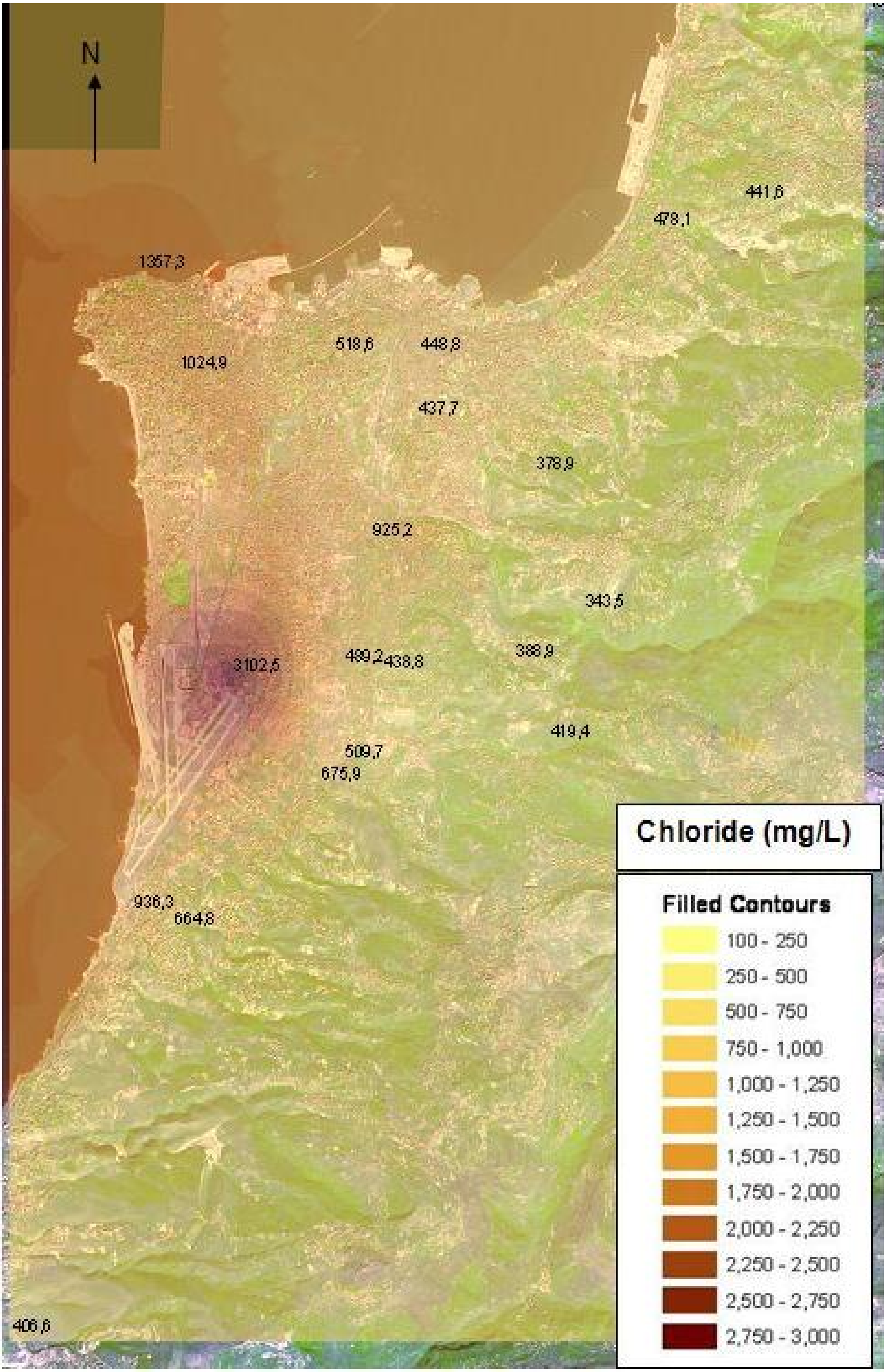


Figure C.3: Groundwater Chloride (mg/L): November 2005

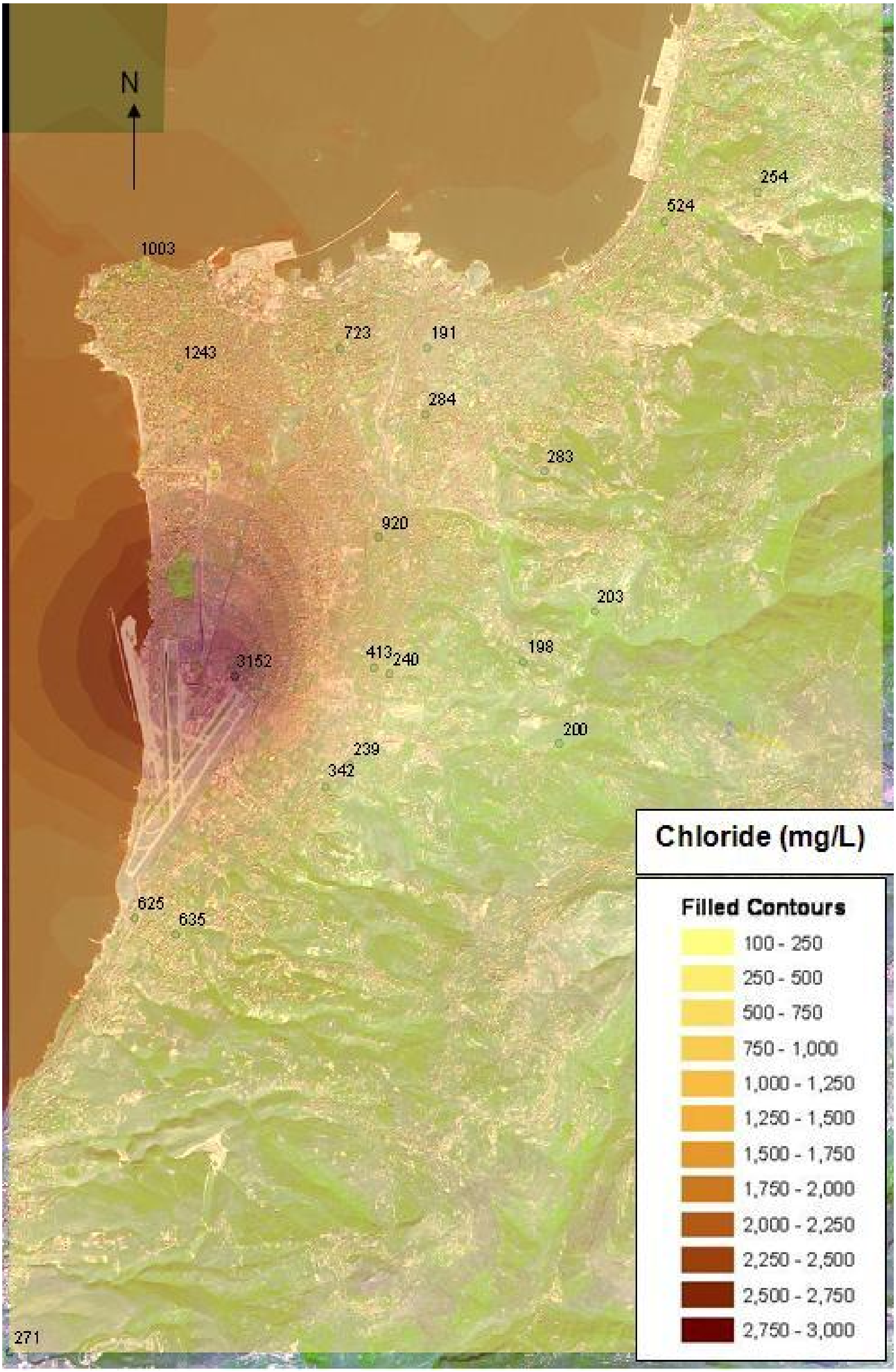


Figure C.4: Groundwater Chloride (mg/L): October 2005

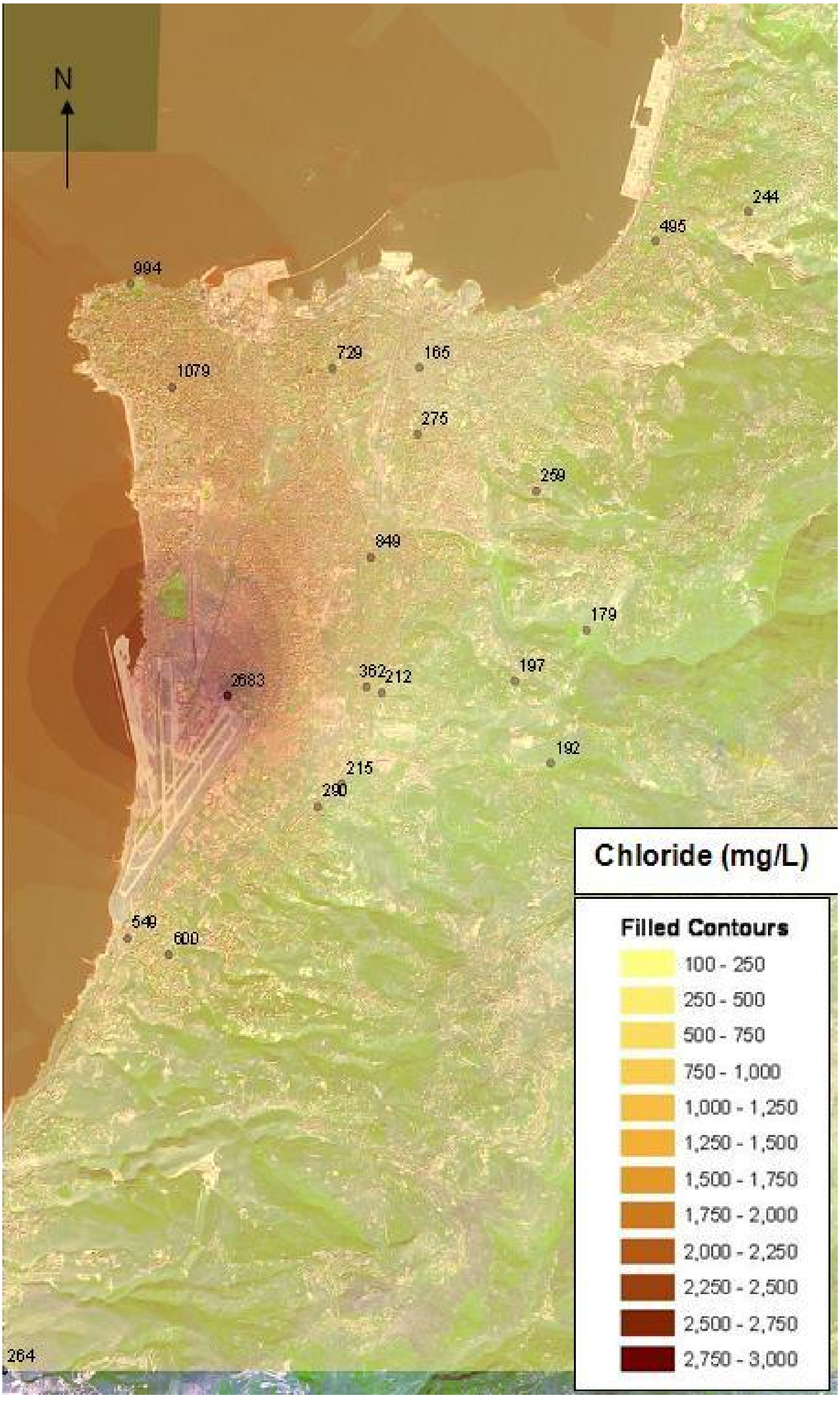


Figure C.5: Groundwater Chloride (mg/L): September 2005

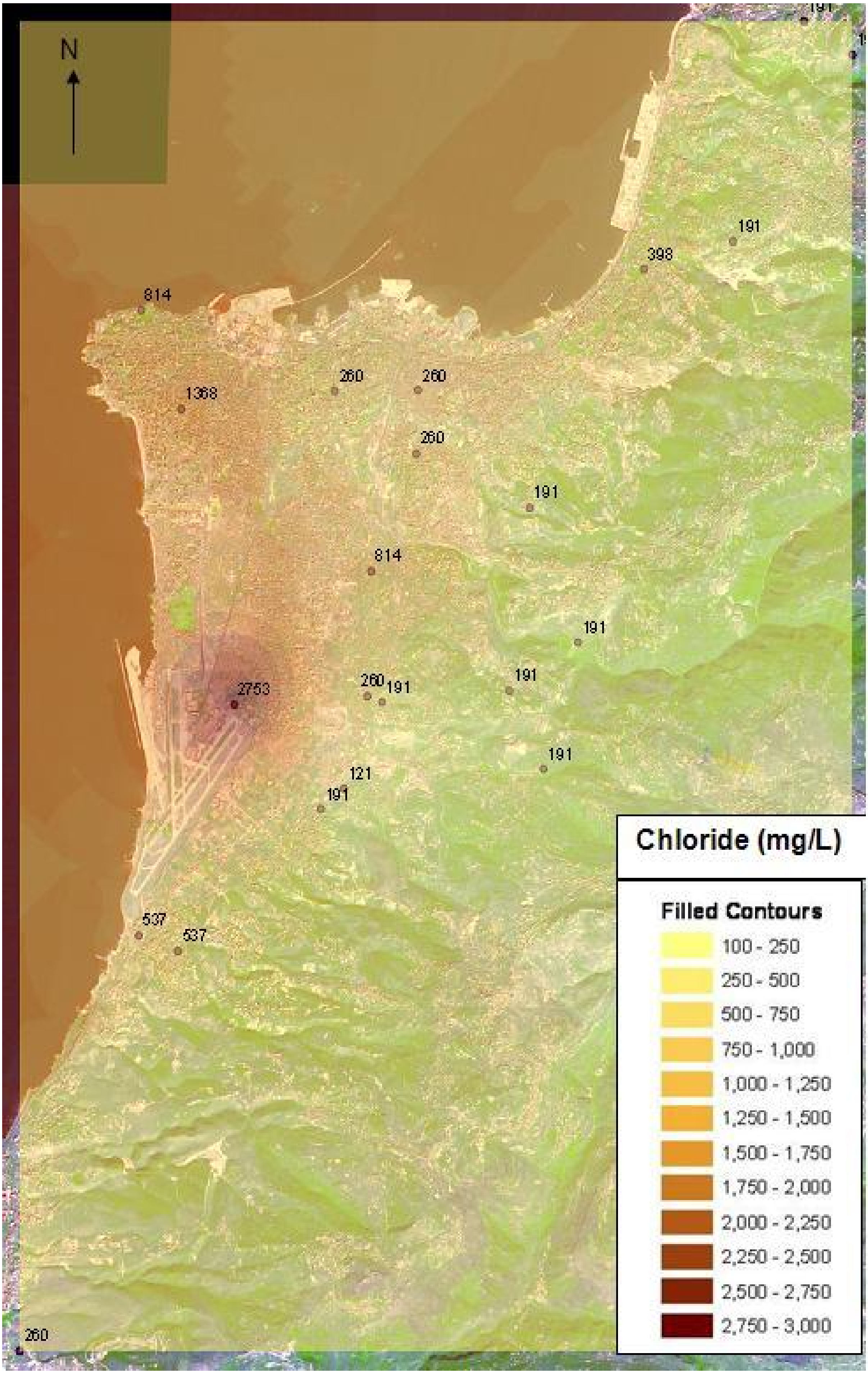


Figure C.6: Groundwater Chloride (mg/L): August 2005

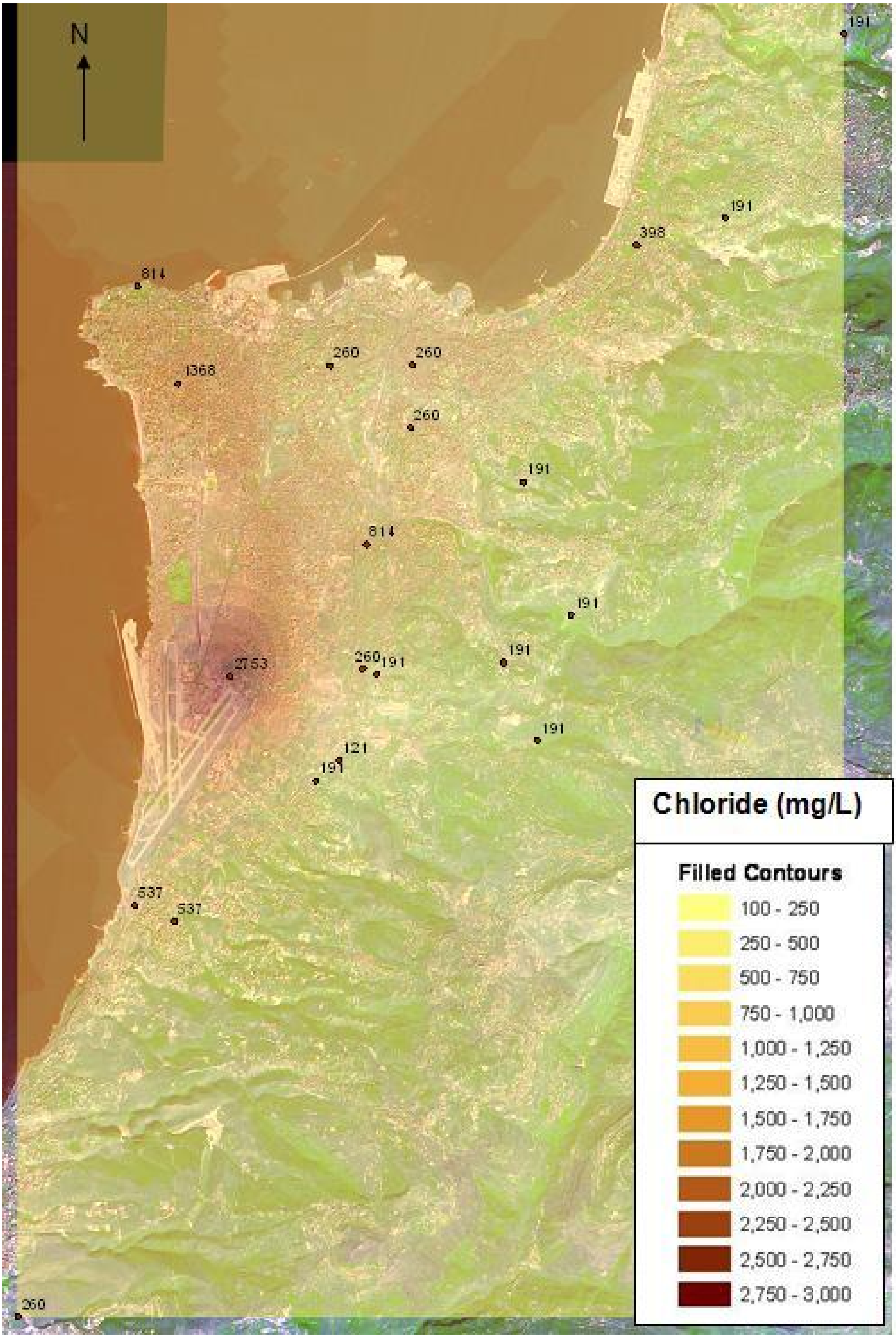


Figure C.7: Groundwater Chloride (mg/L): July 2005

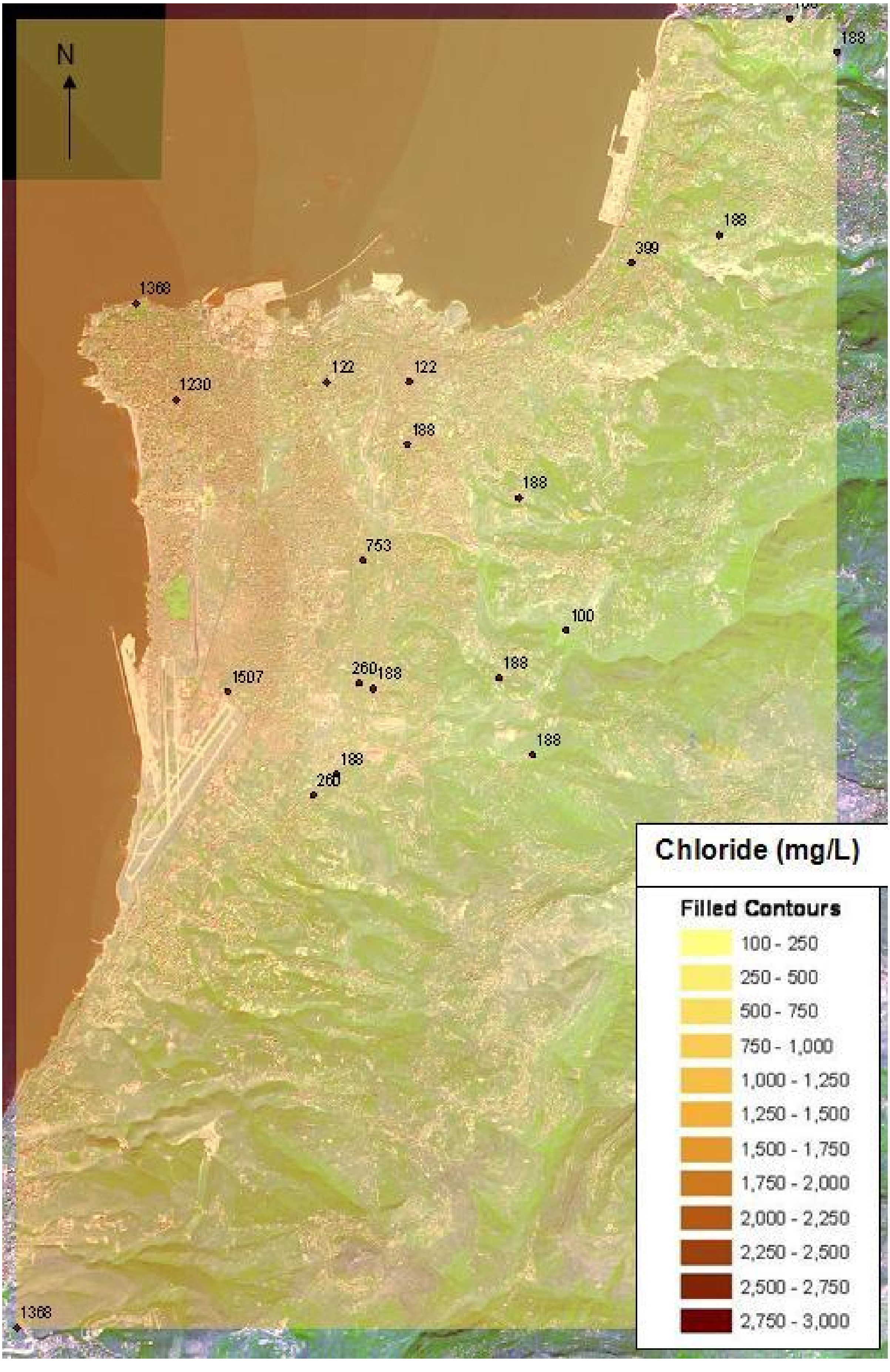


Figure C.8: Groundwater Chloride (mg/L): June 2005

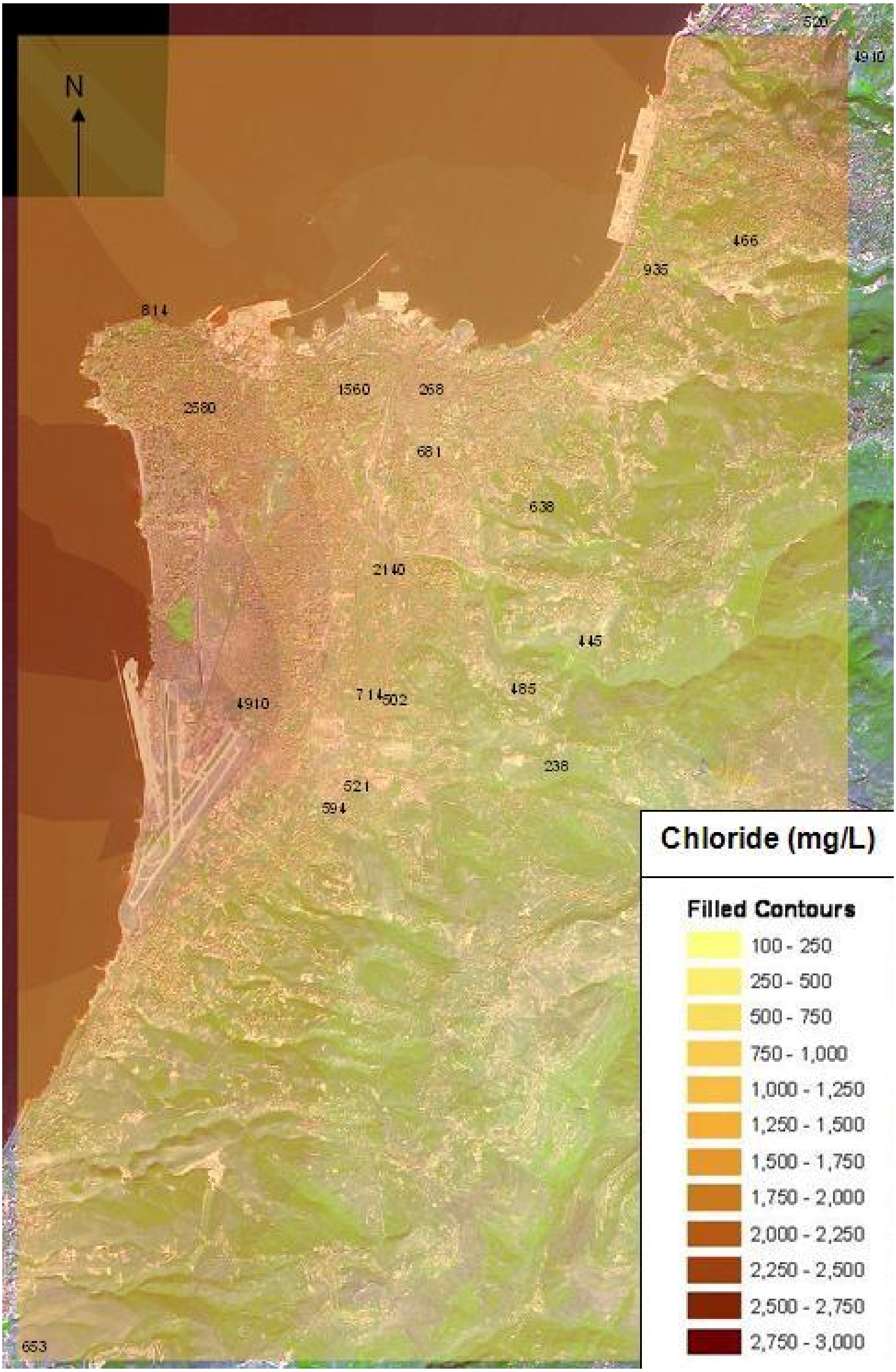


Figure C.9: Groundwater Chloride (mg/L): May 2005

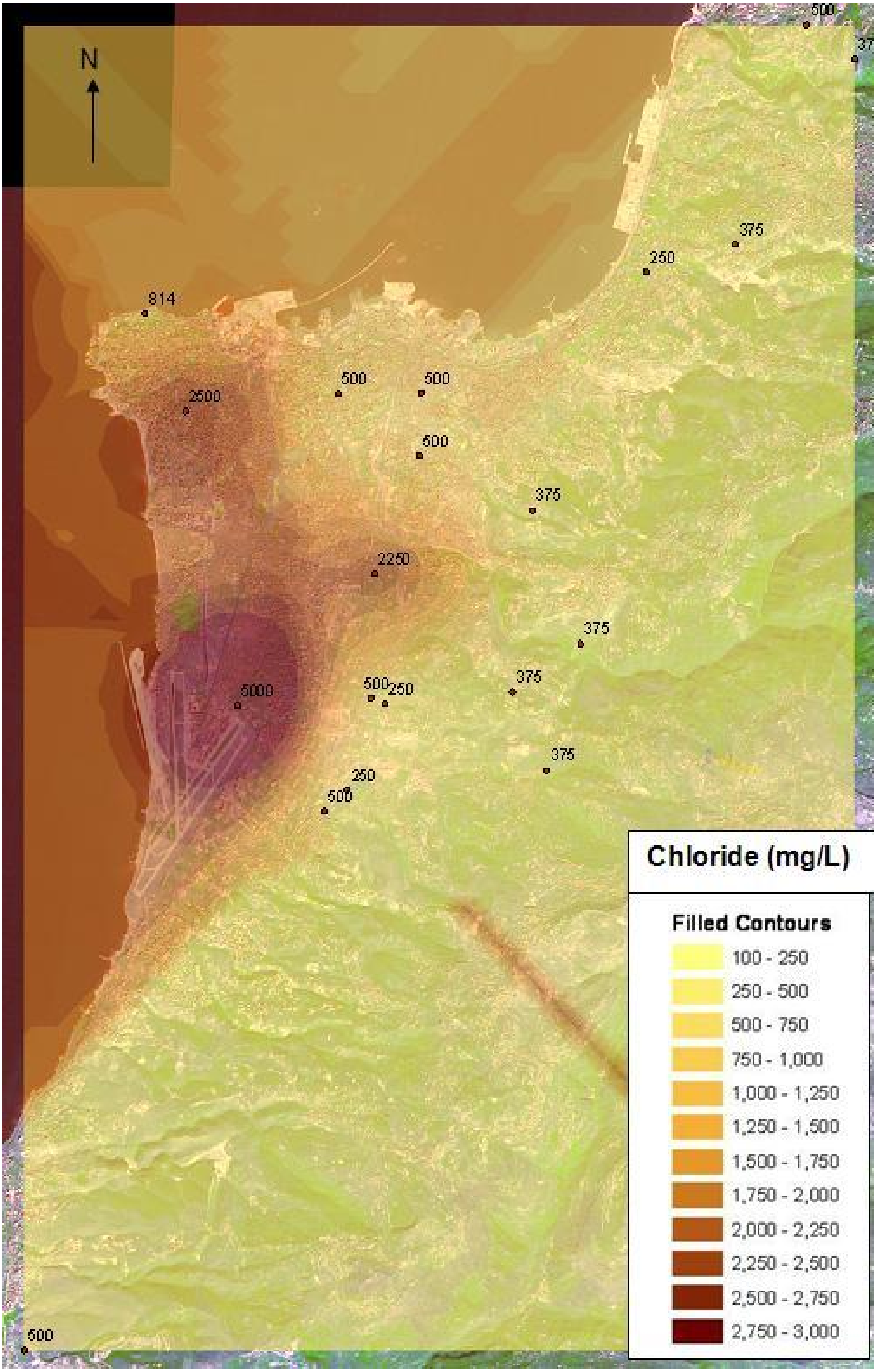


Figure C.10: Groundwater Chloride (mg/L): April 2005

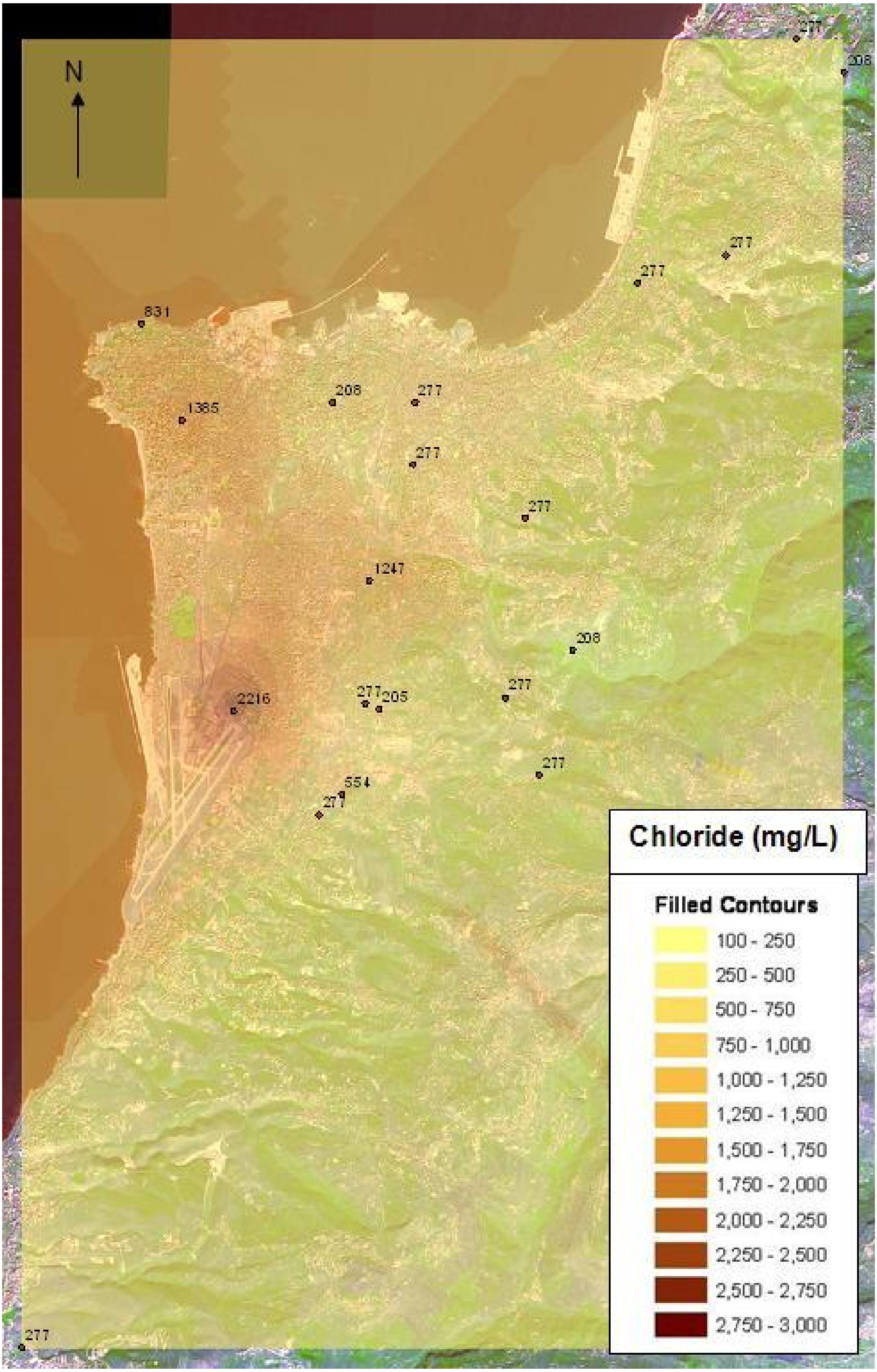


Figure C.11: Groundwater Chloride (mg/L): March 2005

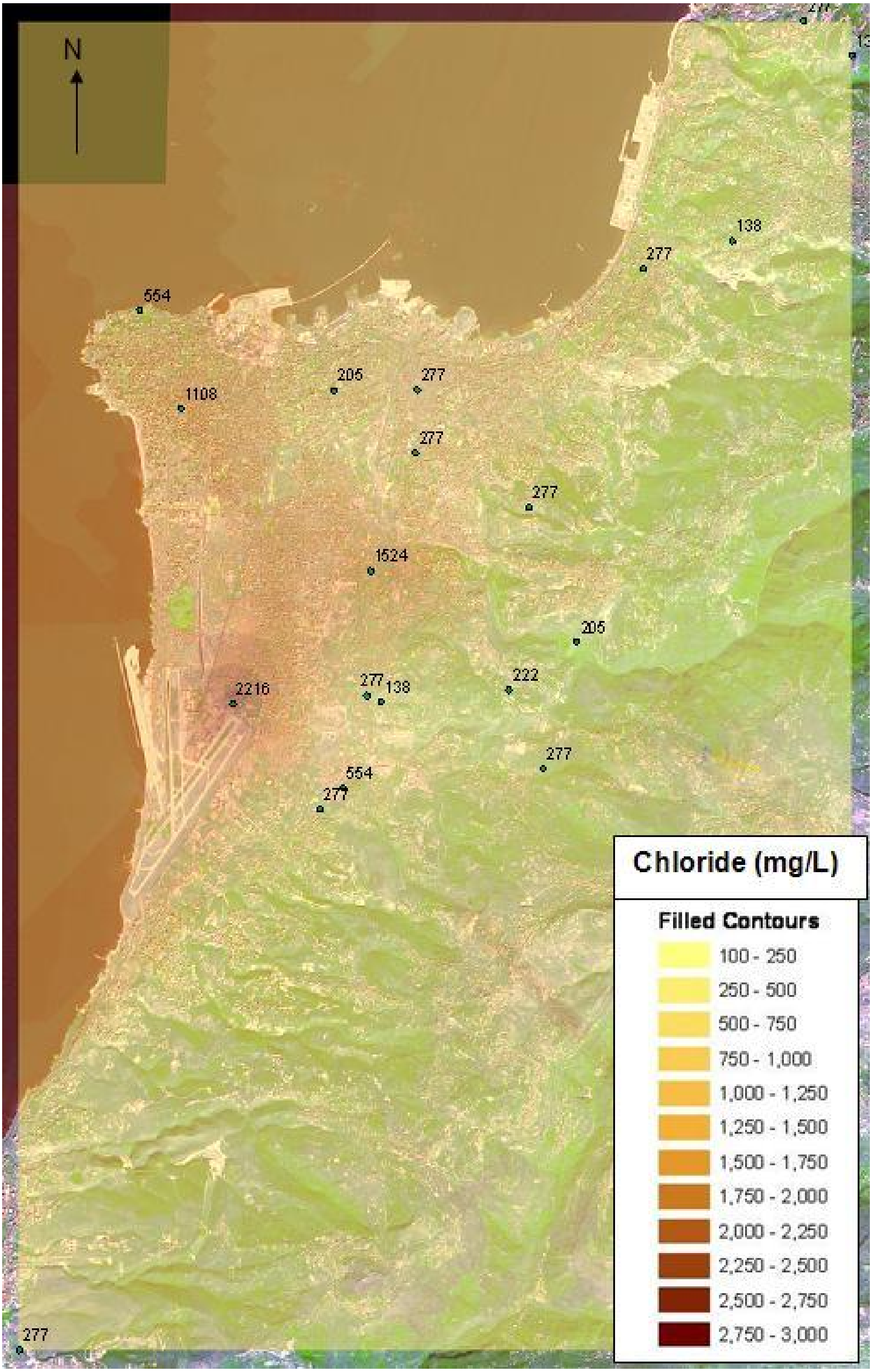


Figure C.12: Groundwater Chloride (mg/L): February 2005

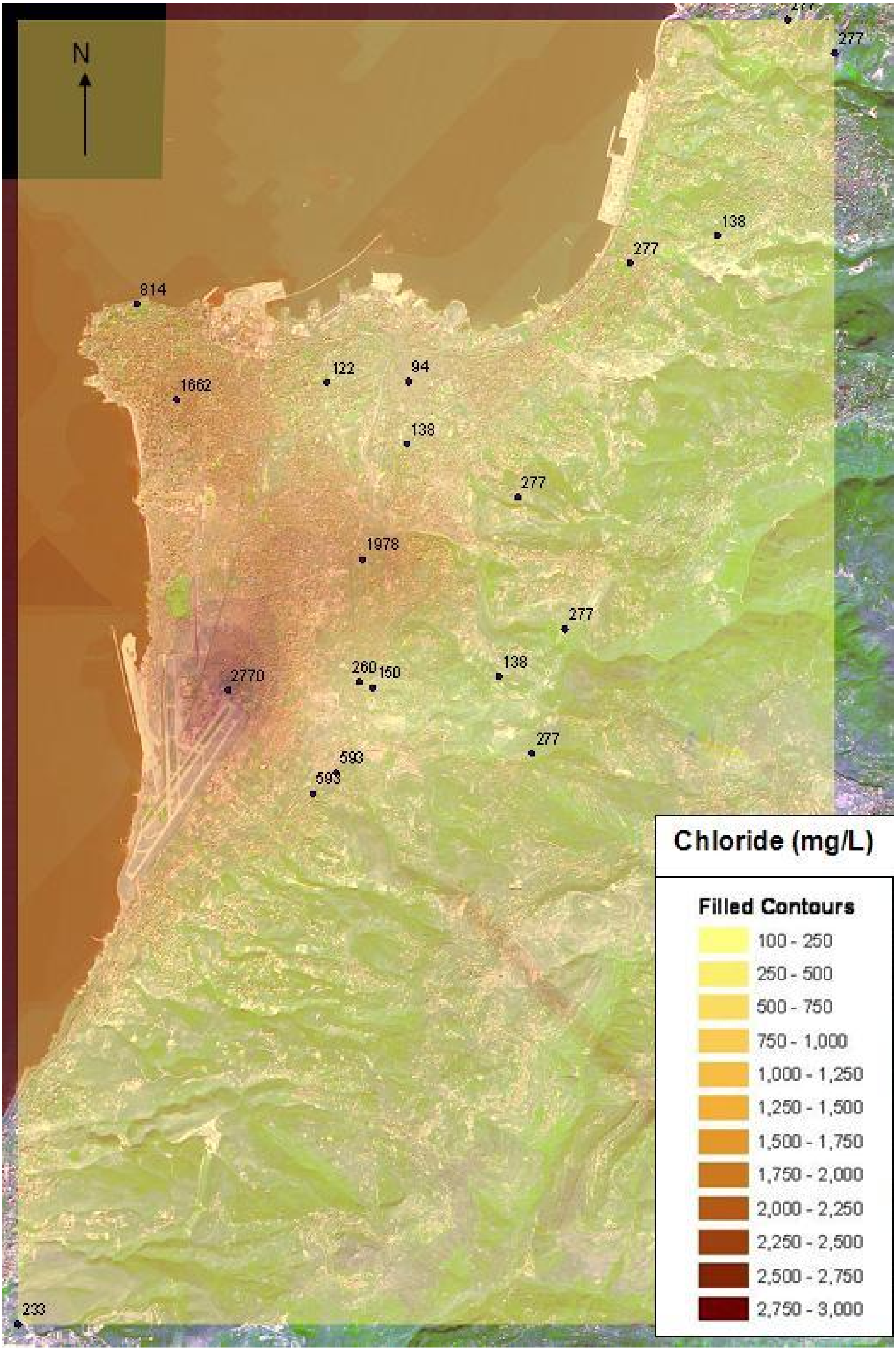


Figure C.13: Groundwater Chloride (mg/L): January 2005

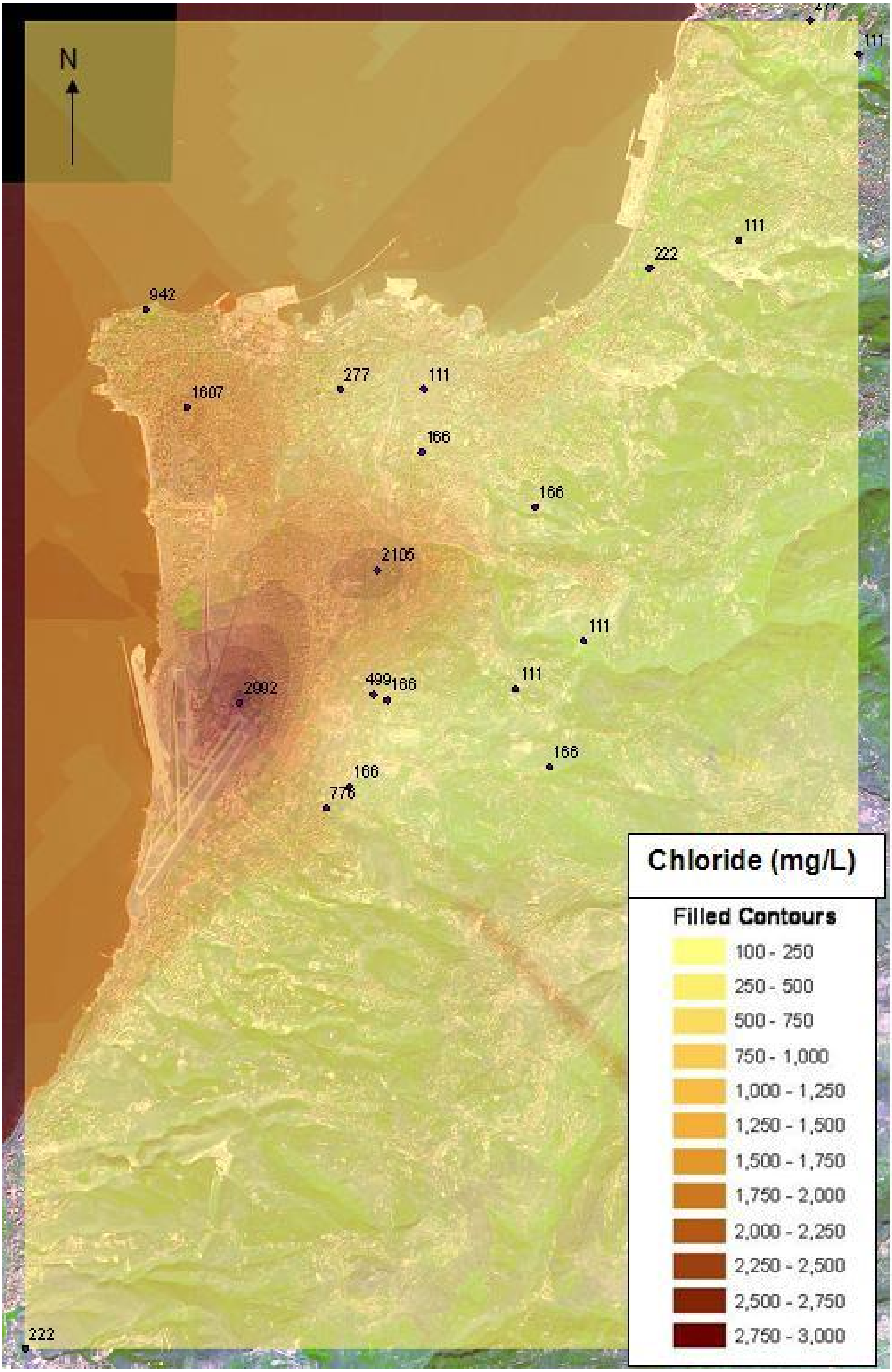


Figure C.14: Groundwater Chloride (mg/L): December 2004

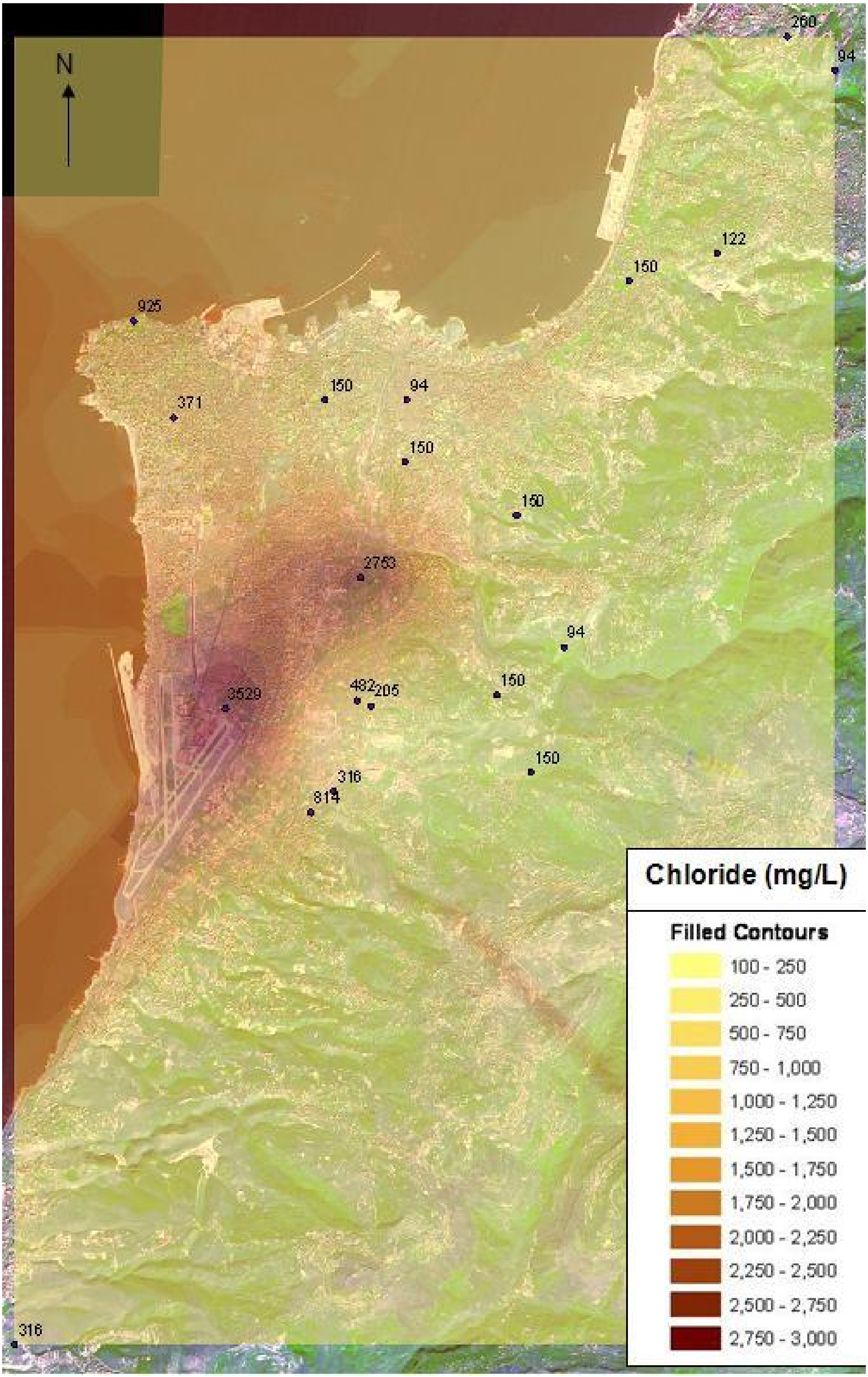


Figure C.15: Groundwater Chloride (mg/L): November 2004

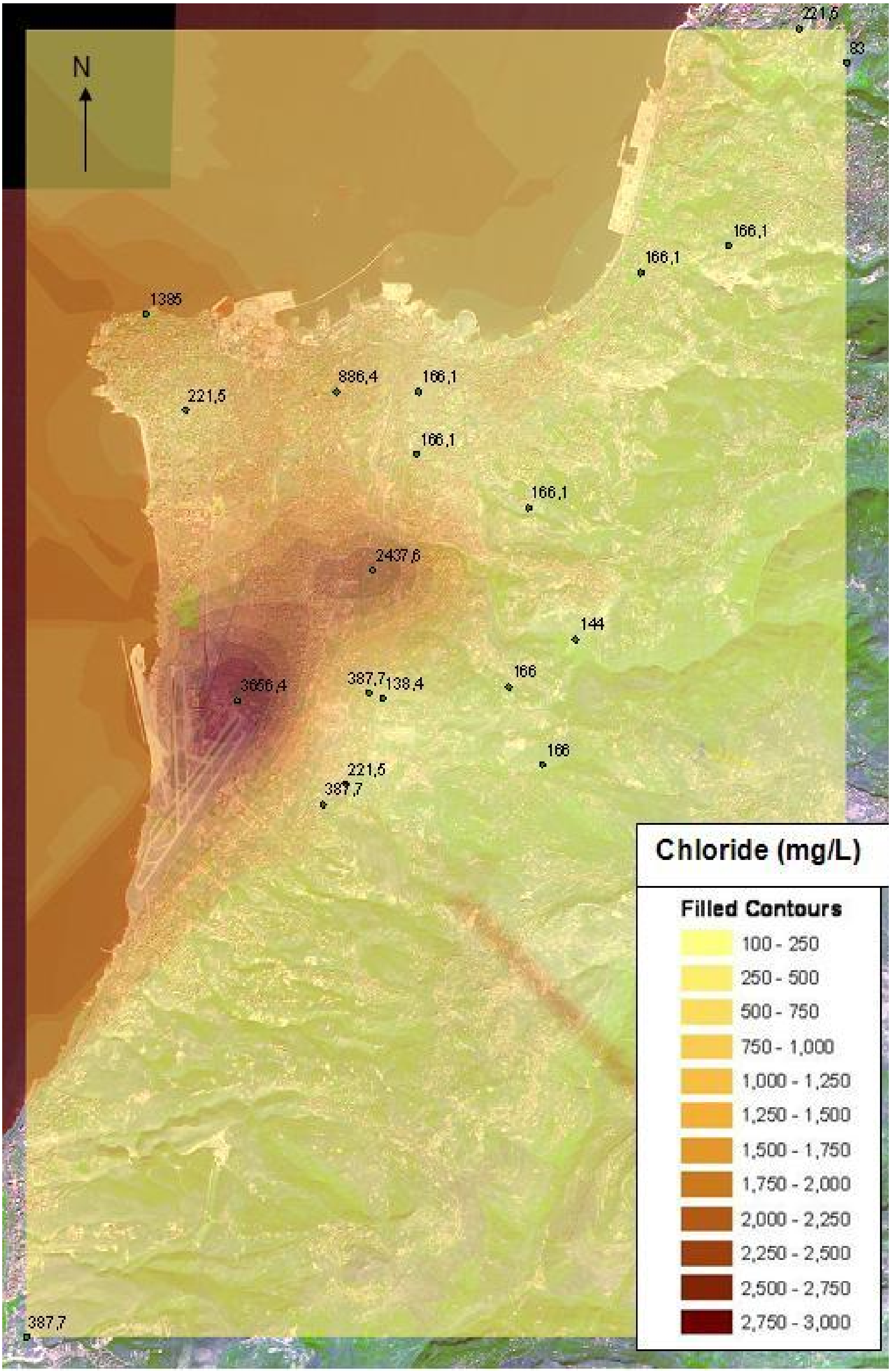
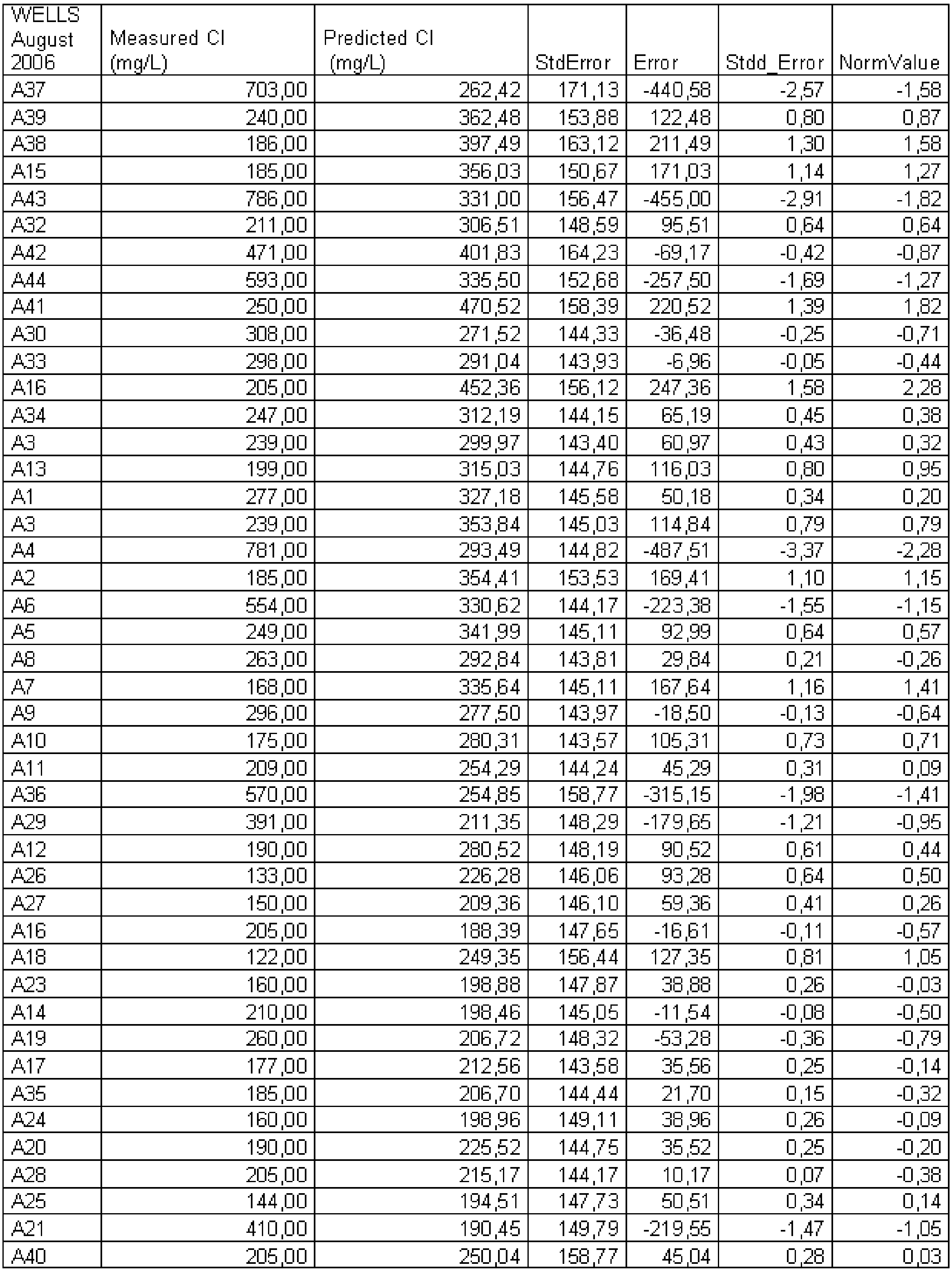


Figure C.16: Groundwater Chloride (mg/L): October 2004

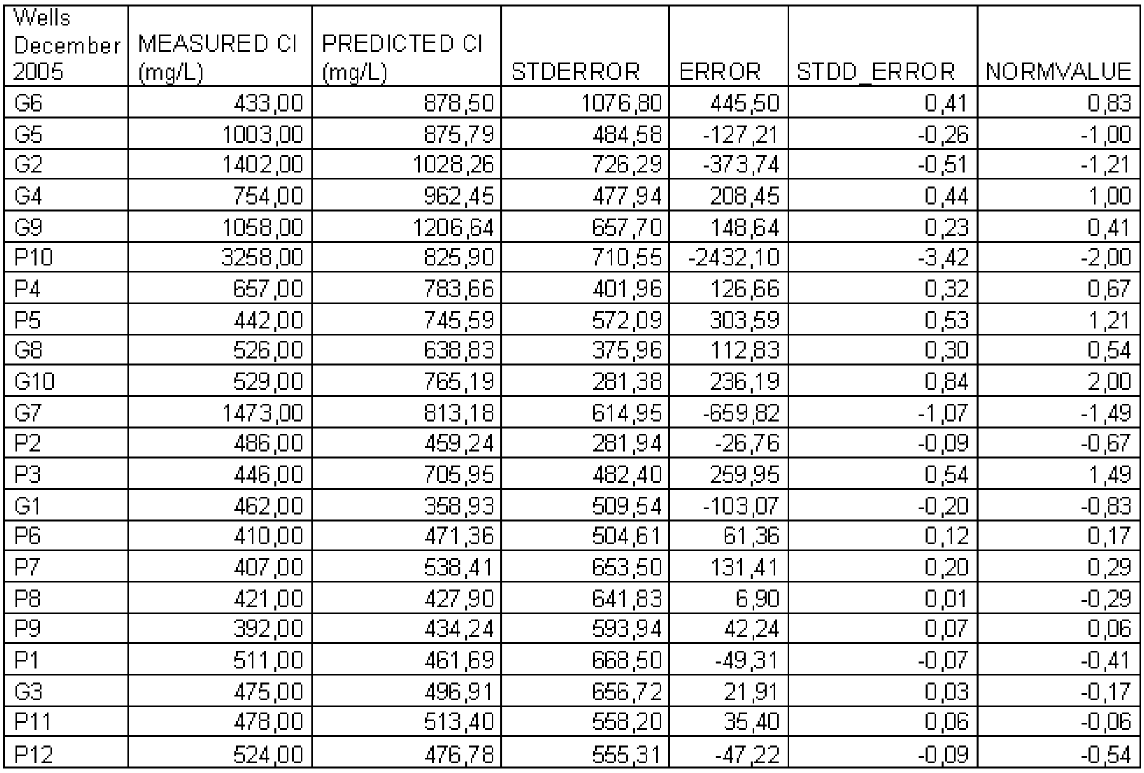
D Groundwater Chloride Tables

Table D.1: Differences between Measured and Predicted Values for Chloride (August 2006)



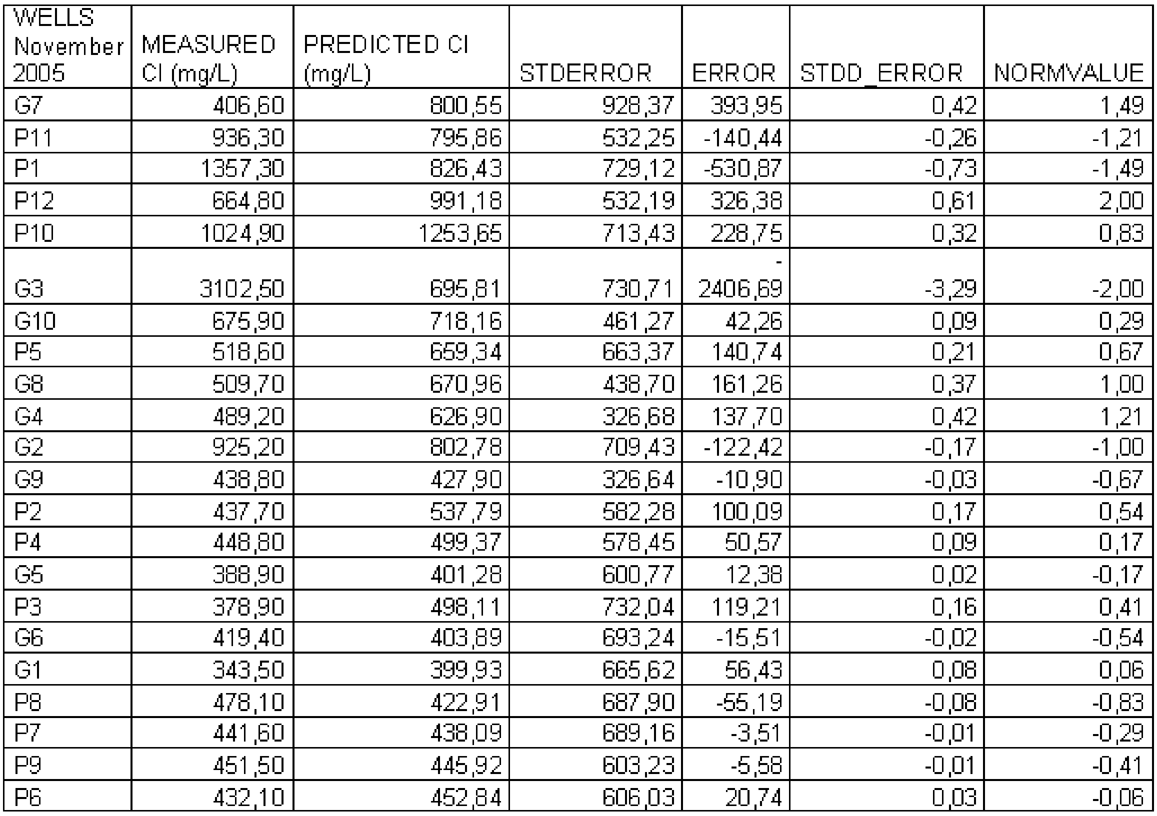
WELLS August 2006	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
A37	703,00	262,42	171,13	-440,58	-2,57	-1,58
A39	240,00	362,48	153,88	122,48	0,80	0,87
A38	186,00	397,49	163,12	211,49	1,30	1,58
A15	185,00	356,03	150,67	171,03	1,14	1,27
A43	786,00	331,00	156,47	-455,00	-2,91	-1,82
A32	211,00	306,51	148,59	95,51	0,64	0,64
A42	471,00	401,83	164,23	-69,17	-0,42	-0,87
A44	593,00	335,50	152,68	-257,50	-1,69	-1,27
A41	250,00	470,52	158,39	220,52	1,39	1,82
A30	308,00	271,52	144,33	-36,48	-0,25	-0,71
A33	298,00	291,04	143,93	-6,96	-0,05	-0,44
A16	205,00	452,36	156,12	247,36	1,58	2,28
A34	247,00	312,19	144,15	65,19	0,45	0,38
A3	239,00	299,97	143,40	60,97	0,43	0,32
A13	199,00	315,03	144,76	116,03	0,80	0,95
A1	277,00	327,18	145,58	50,18	0,34	0,20
A3	239,00	353,84	145,03	114,84	0,79	0,79
A4	781,00	293,49	144,82	-487,51	-3,37	-2,28
A2	185,00	354,41	153,53	169,41	1,10	1,15
A6	554,00	330,62	144,17	-223,38	-1,55	-1,15
A5	249,00	341,99	145,11	92,99	0,64	0,57
A8	263,00	292,84	143,81	29,84	0,21	-0,26
A7	168,00	335,64	145,11	167,64	1,16	1,41
A9	296,00	277,50	143,97	-18,50	-0,13	-0,64
A10	175,00	280,31	143,57	105,31	0,73	0,71
A11	209,00	254,29	144,24	45,29	0,31	0,09
A36	570,00	254,85	158,77	-315,15	-1,98	-1,41
A29	391,00	211,35	148,29	-179,65	-1,21	-0,95
A12	190,00	280,52	148,19	90,52	0,61	0,44
A26	133,00	226,28	146,06	93,28	0,64	0,50
A27	150,00	209,36	146,10	59,36	0,41	0,26
A16	205,00	188,39	147,65	-16,61	-0,11	-0,57
A18	122,00	249,35	156,44	127,35	0,81	1,05
A23	160,00	198,88	147,87	38,88	0,26	-0,03
A14	210,00	198,46	145,05	-11,54	-0,08	-0,50
A19	260,00	206,72	148,32	-53,28	-0,36	-0,79
A17	177,00	212,56	143,58	35,56	0,25	-0,14
A35	185,00	206,70	144,44	21,70	0,15	-0,32
A24	160,00	198,96	149,11	38,96	0,26	-0,09
A20	190,00	225,52	144,75	35,52	0,25	-0,20
A28	205,00	215,17	144,17	10,17	0,07	-0,38
A25	144,00	194,51	147,73	50,51	0,34	0,14
A21	410,00	190,45	149,79	-219,55	-1,47	-1,05
A40	205,00	250,04	158,77	45,04	0,28	0,03

Table D.2: Differences between Measured and Predicted Values for Chloride (December 2005)



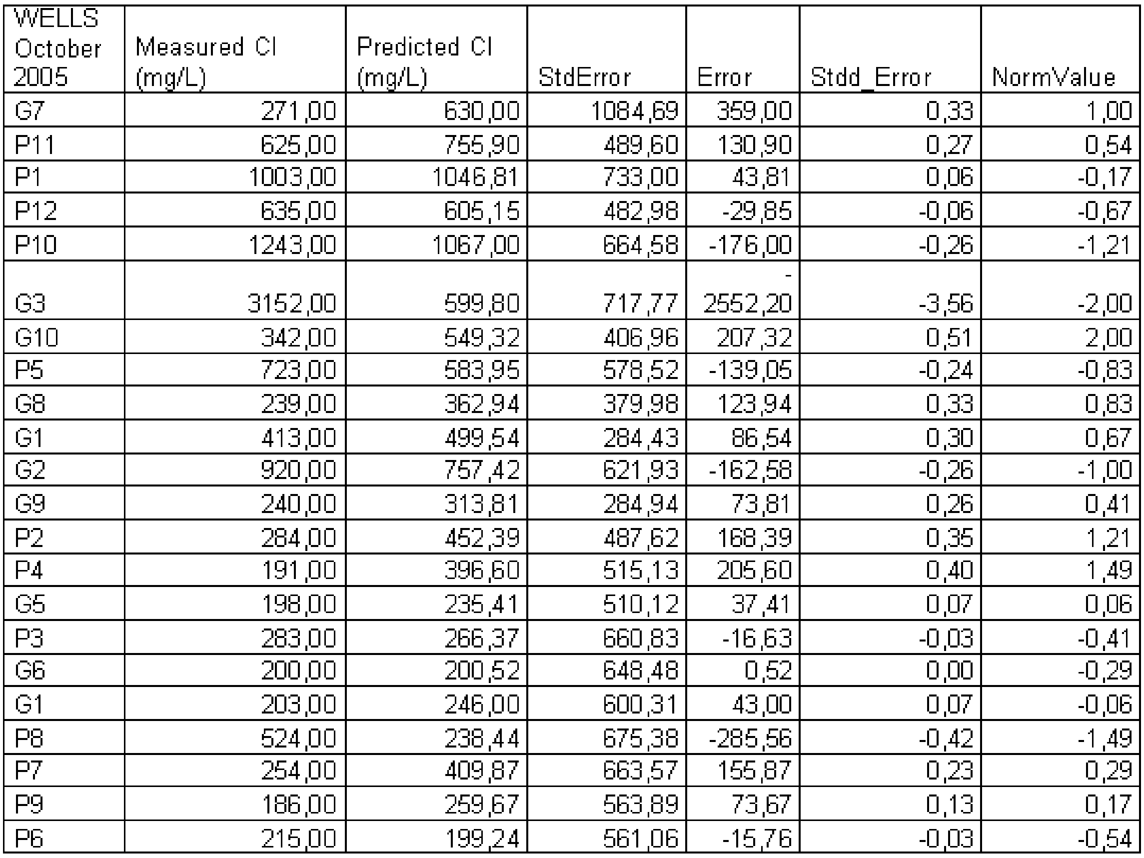
Wells December 2005	MEASURED Cl (mg/L)	PREDICTED Cl (mg/L)	STDERROR	ERROR	STDD_ERROR	NORMVALUE
G6	433,00	878,50	1076,80	445,50	0,41	0,83
G5	1003,00	875,79	484,58	-127,21	-0,26	-1,00
G2	1402,00	1028,26	726,29	-373,74	-0,51	-1,21
G4	754,00	962,45	477,94	208,45	0,44	1,00
G9	1058,00	1206,64	657,70	148,64	0,23	0,41
P10	3258,00	825,90	710,55	-2432,10	-3,42	-2,00
P4	657,00	783,66	401,96	126,66	0,32	0,67
P5	442,00	745,59	572,09	303,59	0,53	1,21
G8	526,00	638,83	375,96	112,83	0,30	0,54
G10	529,00	765,19	281,38	236,19	0,84	2,00
G7	1473,00	813,18	614,95	-659,82	-1,07	-1,49
P2	486,00	459,24	281,94	-26,76	-0,09	-0,67
P3	446,00	705,95	482,40	259,95	0,54	1,49
G1	462,00	358,93	509,54	-103,07	-0,20	-0,83
P6	410,00	471,36	504,61	61,36	0,12	0,17
P7	407,00	538,41	653,50	131,41	0,20	0,29
P8	421,00	427,90	641,83	6,90	0,01	-0,29
P9	392,00	434,24	593,94	42,24	0,07	0,06
P1	511,00	461,69	668,50	-49,31	-0,07	-0,41
G3	475,00	496,91	656,72	21,91	0,03	-0,17
P11	478,00	513,40	558,20	35,40	0,06	-0,06
P12	524,00	476,78	555,31	-47,22	-0,09	-0,54

Table D.3: Differences between Measured and Predicted Values for Chloride (November 2005)



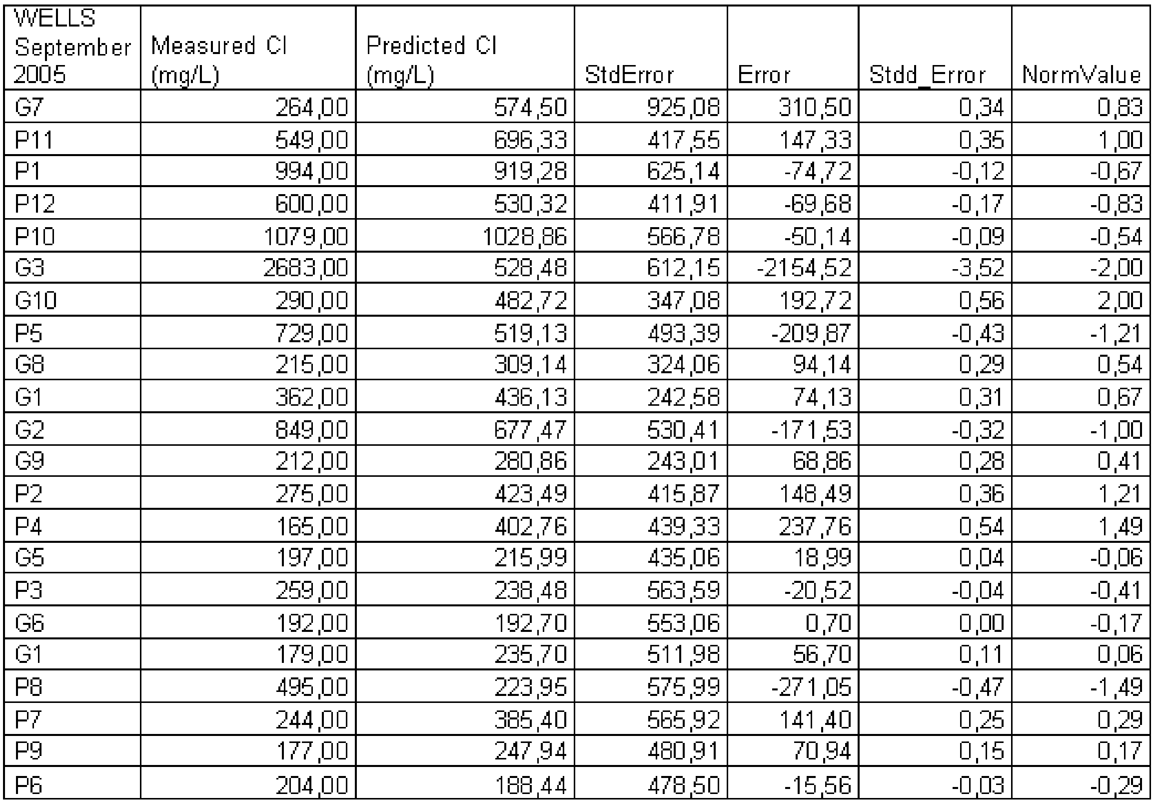
WELLS November 2005	MEASURED Cl (mg/L)	PREDICTED Cl (mg/L)	STDERROR	ERROR	STDD_ERROR	NORMVALUE
G7	406,60	800,55	928,37	393,95	0,42	1,49
P11	936,30	795,86	532,25	-140,44	-0,26	-1,21
P1	1357,30	826,43	729,12	-530,87	-0,73	-1,49
P12	664,80	991,18	532,19	326,38	0,61	2,00
P10	1024,90	1253,65	713,43	228,75	0,32	0,83
G3	3102,50	695,81	730,71	-2406,69	-3,29	-2,00
G10	675,90	718,16	461,27	42,26	0,09	0,29
P5	518,60	659,34	663,37	140,74	0,21	0,67
G8	509,70	670,96	438,70	161,26	0,37	1,00
G4	489,20	626,90	326,68	137,70	0,42	1,21
G2	925,20	802,78	709,43	-122,42	-0,17	-1,00
G9	438,80	427,90	326,64	-10,90	-0,03	-0,67
P2	437,70	537,79	582,28	100,09	0,17	0,54
P4	448,80	499,37	578,45	50,57	0,09	0,17
G5	388,90	401,28	600,77	12,38	0,02	-0,17
P3	378,90	498,11	732,04	119,21	0,16	0,41
G6	419,40	403,89	693,24	-15,51	-0,02	-0,54
G1	343,50	399,93	665,62	56,43	0,08	0,06
P8	478,10	422,91	687,90	-55,19	-0,08	-0,83
P7	441,60	438,09	689,16	-3,51	-0,01	-0,29
P9	451,50	445,92	603,23	-5,58	-0,01	-0,41
P6	432,10	452,84	606,03	20,74	0,03	-0,06

Table D.4: Differences between Measured and Predicted Values for Chloride (October 2005)



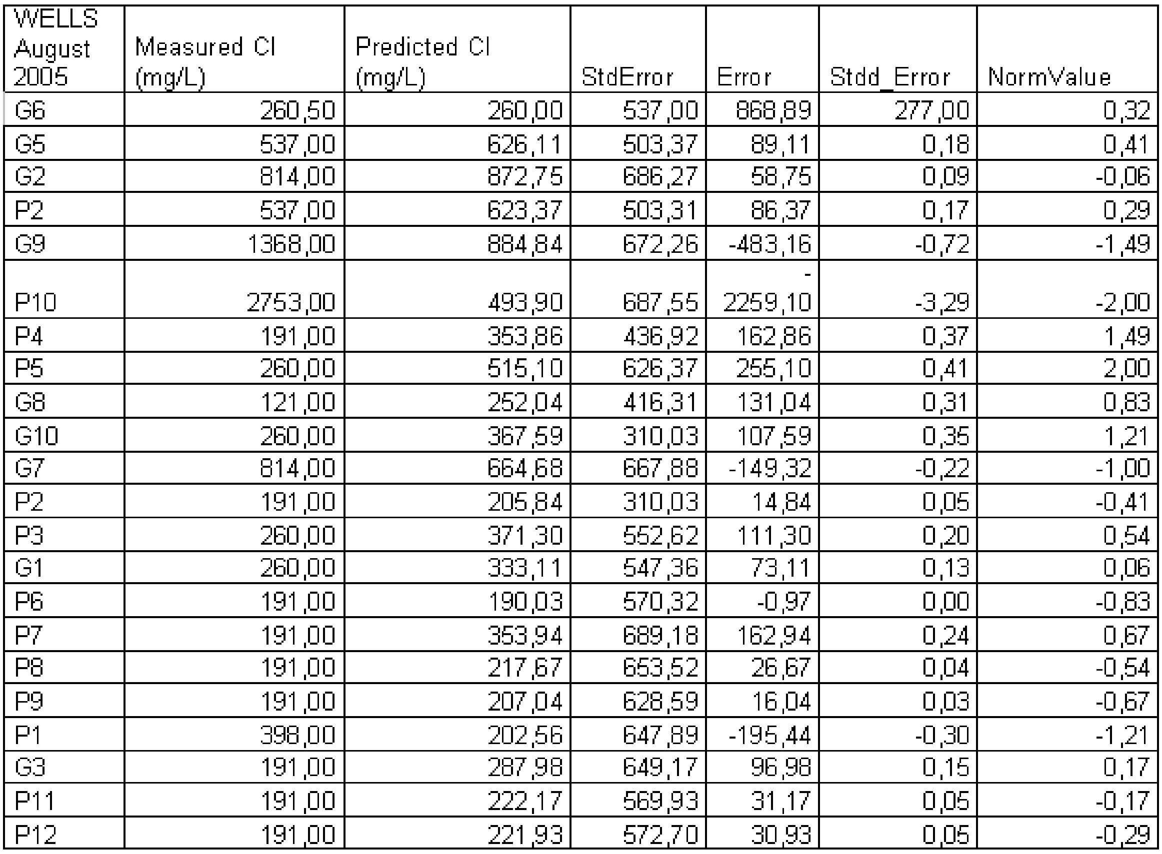
WELLS October 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	271,00	630,00	1084,69	359,00	0,33	1,00
P11	625,00	755,90	489,60	130,90	0,27	0,54
P1	1003,00	1046,81	733,00	43,81	0,06	-0,17
P12	635,00	605,15	482,98	-29,85	-0,06	-0,67
P10	1243,00	1067,00	664,58	-176,00	-0,26	-1,21
G3	3152,00	599,80	717,77	-2552,20	-3,56	-2,00
G10	342,00	549,32	406,96	207,32	0,51	2,00
P5	723,00	583,95	578,52	-139,05	-0,24	-0,83
G8	239,00	362,94	379,98	123,94	0,33	0,83
G1	413,00	499,54	284,43	86,54	0,30	0,67
G2	920,00	757,42	621,93	-162,58	-0,26	-1,00
G9	240,00	313,81	284,94	73,81	0,26	0,41
P2	284,00	452,39	487,62	168,39	0,35	1,21
P4	191,00	396,60	515,13	205,60	0,40	1,49
G5	198,00	235,41	510,12	37,41	0,07	0,06
P3	283,00	266,37	660,83	-16,63	-0,03	-0,41
G6	200,00	200,52	648,48	0,52	0,00	-0,29
G1	203,00	246,00	600,31	43,00	0,07	-0,06
P8	524,00	238,44	675,38	-285,56	-0,42	-1,49
P7	254,00	409,87	663,57	155,87	0,23	0,29
P9	186,00	259,67	563,89	73,67	0,13	0,17
P6	215,00	199,24	561,06	-15,76	-0,03	-0,54

Table D.5: Differences between Measured and Predicted Values for Chloride (September 2005)



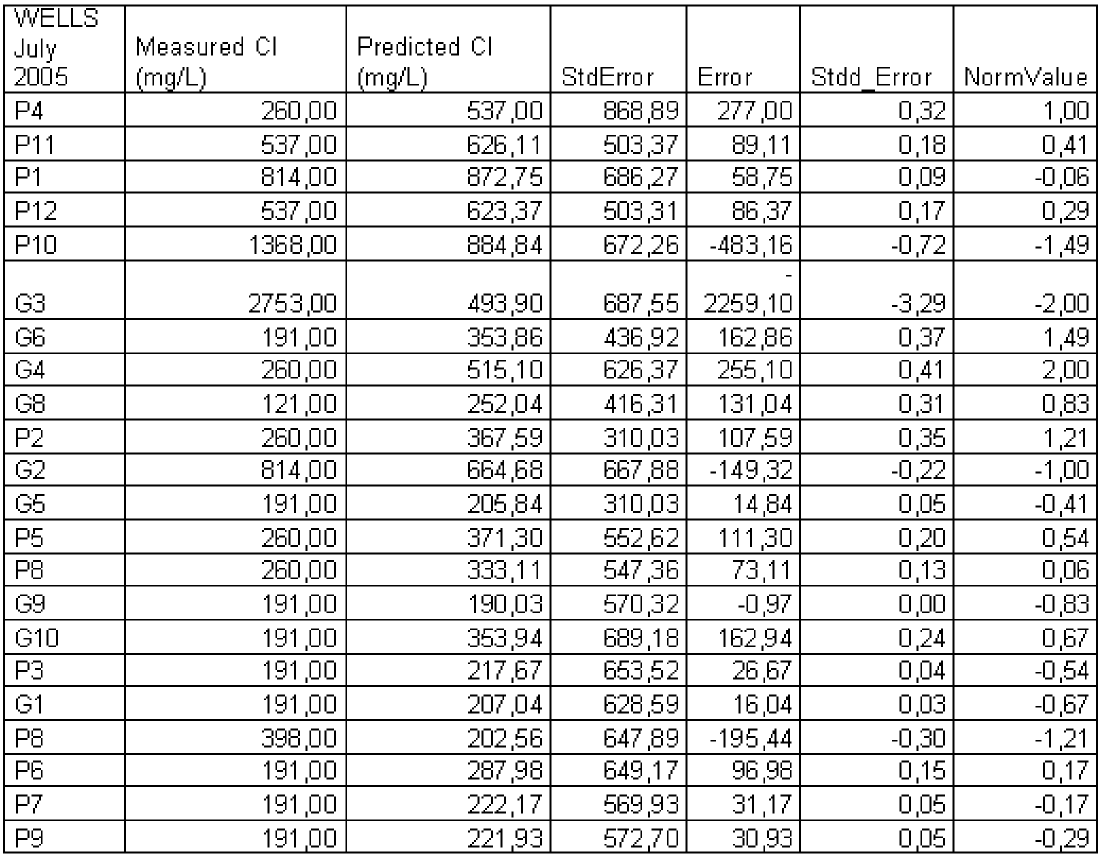
WELLS September 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	264,00	574,50	925,08	310,50	0,34	0,83
P11	549,00	696,33	417,55	147,33	0,35	1,00
P1	994,00	919,28	625,14	-74,72	-0,12	-0,67
P12	600,00	530,32	411,91	-69,68	-0,17	-0,83
P10	1079,00	1028,86	566,78	-50,14	-0,09	-0,54
G3	2683,00	528,48	612,15	-2154,52	-3,52	-2,00
G10	290,00	482,72	347,08	192,72	0,56	2,00
P5	729,00	519,13	493,39	-209,87	-0,43	-1,21
G8	215,00	309,14	324,06	94,14	0,29	0,54
G1	362,00	436,13	242,58	74,13	0,31	0,67
G2	849,00	677,47	530,41	-171,53	-0,32	-1,00
G9	212,00	280,86	243,01	68,86	0,28	0,41
P2	275,00	423,49	415,87	148,49	0,36	1,21
P4	165,00	402,76	439,33	237,76	0,54	1,49
G5	197,00	215,99	435,06	18,99	0,04	-0,06
P3	259,00	238,48	563,59	-20,52	-0,04	-0,41
G6	192,00	192,70	553,06	0,70	0,00	-0,17
G1	179,00	235,70	511,98	56,70	0,11	0,06
P8	495,00	223,95	575,99	-271,05	-0,47	-1,49
P7	244,00	385,40	565,92	141,40	0,25	0,29
P9	177,00	247,94	480,91	70,94	0,15	0,17
P6	204,00	188,44	478,50	-15,56	-0,03	-0,29

Table D.6: Differences between Measured and Predicted Values for Chloride (August 2005)



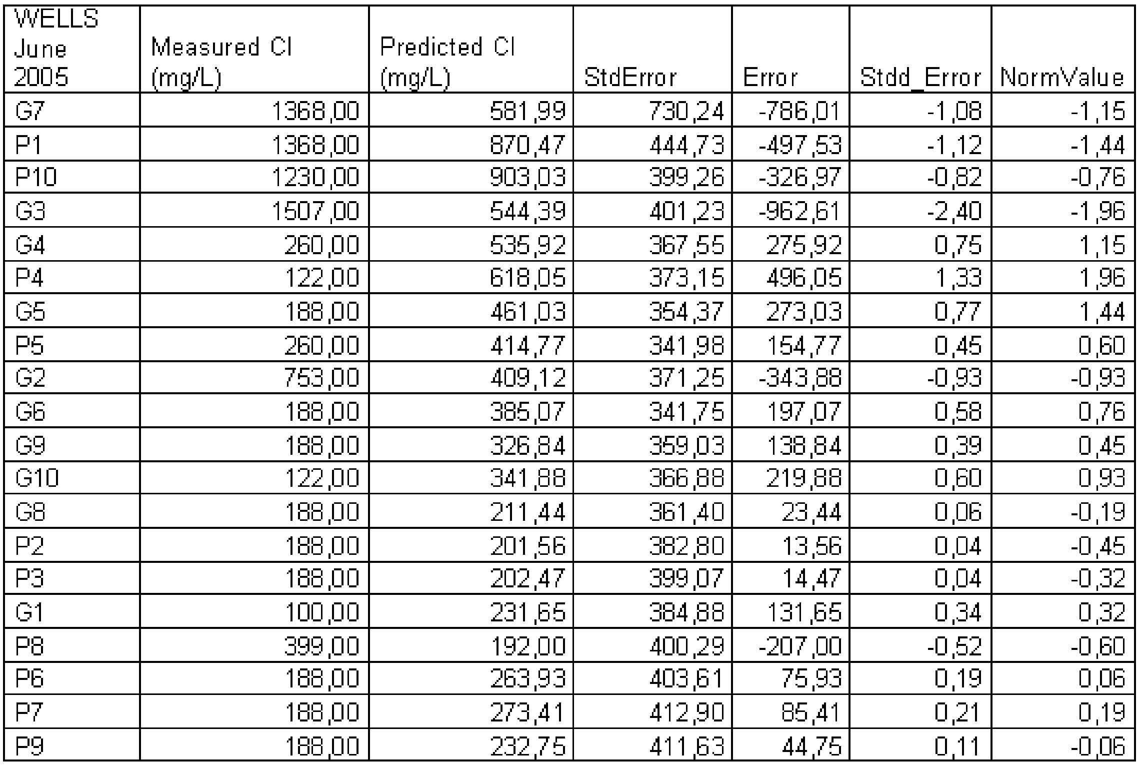
WELLS August 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G6	260,50	260,00	537,00	868,89	277,00	0,32
G5	537,00	626,11	503,37	89,11	0,18	0,41
G2	814,00	872,75	686,27	58,75	0,09	-0,06
P2	537,00	623,37	503,31	86,37	0,17	0,29
G9	1368,00	884,84	672,26	-483,16	-0,72	-1,49
P10	2753,00	493,90	687,55	-2259,10	-3,29	-2,00
P4	191,00	353,86	436,92	162,86	0,37	1,49
P5	260,00	515,10	626,37	255,10	0,41	2,00
G8	121,00	252,04	416,31	131,04	0,31	0,83
G10	260,00	367,59	310,03	107,59	0,35	1,21
G7	814,00	664,68	667,88	-149,32	-0,22	-1,00
P2	191,00	205,84	310,03	14,84	0,05	-0,41
P3	260,00	371,30	552,62	111,30	0,20	0,54
G1	260,00	333,11	547,36	73,11	0,13	0,06
P6	191,00	190,03	570,32	-0,97	0,00	-0,83
P7	191,00	353,94	689,18	162,94	0,24	0,67
P8	191,00	217,67	653,52	26,67	0,04	-0,54
P9	191,00	207,04	628,59	16,04	0,03	-0,67
P1	398,00	202,56	647,89	-195,44	-0,30	-1,21
G3	191,00	287,98	649,17	96,98	0,15	0,17
P11	191,00	222,17	569,93	31,17	0,05	-0,17
P12	191,00	221,93	572,70	30,93	0,05	-0,29

Table D.7: Differences between Measured and Predicted Values for Chloride (July 2005)



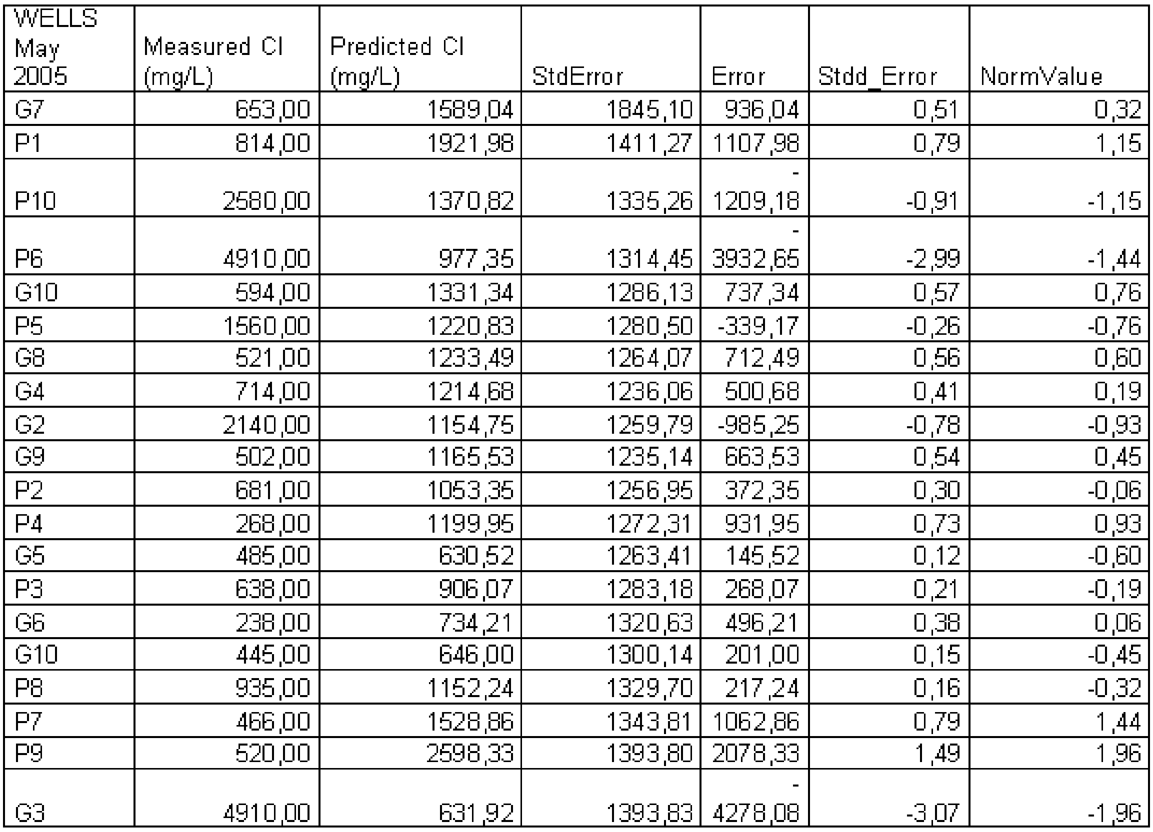
WELLS July 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
P4	260,00	537,00	868,89	277,00	0,32	1,00
P11	537,00	626,11	503,37	89,11	0,18	0,41
P1	814,00	872,75	686,27	58,75	0,09	-0,06
P12	537,00	623,37	503,31	86,37	0,17	0,29
P10	1368,00	884,84	672,26	-483,16	-0,72	-1,49
G3	2753,00	493,90	687,55	-2259,10	-3,29	-2,00
G6	191,00	353,86	436,92	162,86	0,37	1,49
G4	260,00	515,10	626,37	255,10	0,41	2,00
G8	121,00	252,04	416,31	131,04	0,31	0,83
P2	260,00	367,59	310,03	107,59	0,35	1,21
G2	814,00	664,68	667,88	-149,32	-0,22	-1,00
G5	191,00	205,84	310,03	14,84	0,05	-0,41
P5	260,00	371,30	552,62	111,30	0,20	0,54
P8	260,00	333,11	547,36	73,11	0,13	0,06
G9	191,00	190,03	570,32	-0,97	0,00	-0,83
G10	191,00	353,94	689,18	162,94	0,24	0,67
P3	191,00	217,67	653,52	26,67	0,04	-0,54
G1	191,00	207,04	628,59	16,04	0,03	-0,67
P8	398,00	202,56	647,89	-195,44	-0,30	-1,21
P6	191,00	287,98	649,17	96,98	0,15	0,17
P7	191,00	222,17	569,93	31,17	0,05	-0,17
P9	191,00	221,93	572,70	30,93	0,05	-0,29

Table D.8: Differences between Measured and Predicted Values for Chloride (June 2005)



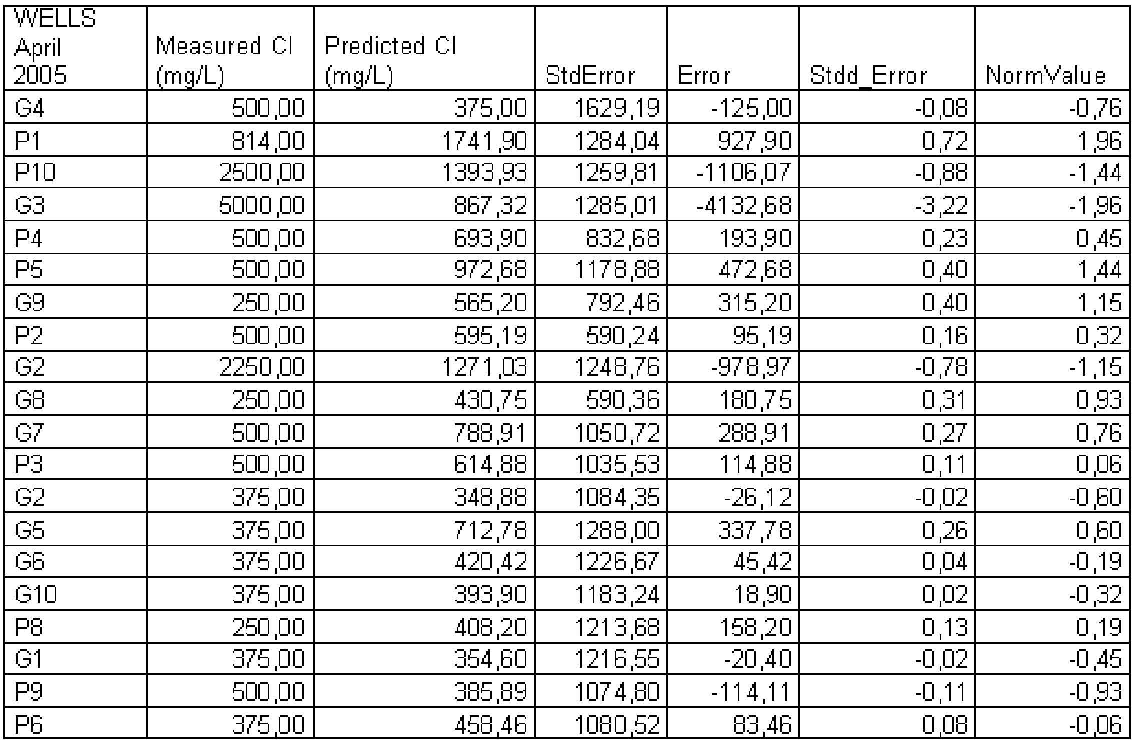
WELLS June 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	1368,00	581,99	730,24	-786,01	-1,08	-1,15
P1	1368,00	870,47	444,73	-497,53	-1,12	-1,44
P10	1230,00	903,03	399,26	-326,97	-0,82	-0,76
G3	1507,00	544,39	401,23	-962,61	-2,40	-1,96
G4	260,00	535,92	367,55	275,92	0,75	1,15
P4	122,00	618,05	373,15	496,05	1,33	1,96
G5	188,00	461,03	354,37	273,03	0,77	1,44
P5	260,00	414,77	341,98	154,77	0,45	0,60
G2	753,00	409,12	371,25	-343,88	-0,93	-0,93
G6	188,00	385,07	341,75	197,07	0,58	0,76
G9	188,00	326,84	359,03	138,84	0,39	0,45
G10	122,00	341,88	366,88	219,88	0,60	0,93
G8	188,00	211,44	361,40	23,44	0,06	-0,19
P2	188,00	201,56	382,80	13,56	0,04	-0,45
P3	188,00	202,47	399,07	14,47	0,04	-0,32
G1	100,00	231,65	384,88	131,65	0,34	0,32
P8	399,00	192,00	400,29	-207,00	-0,52	-0,60
P6	188,00	263,93	403,61	75,93	0,19	0,06
P7	188,00	273,41	412,90	85,41	0,21	0,19
P9	188,00	232,75	411,63	44,75	0,11	-0,06

Table D.9: Differences between Measured and Predicted Values for Chloride (May 2005)



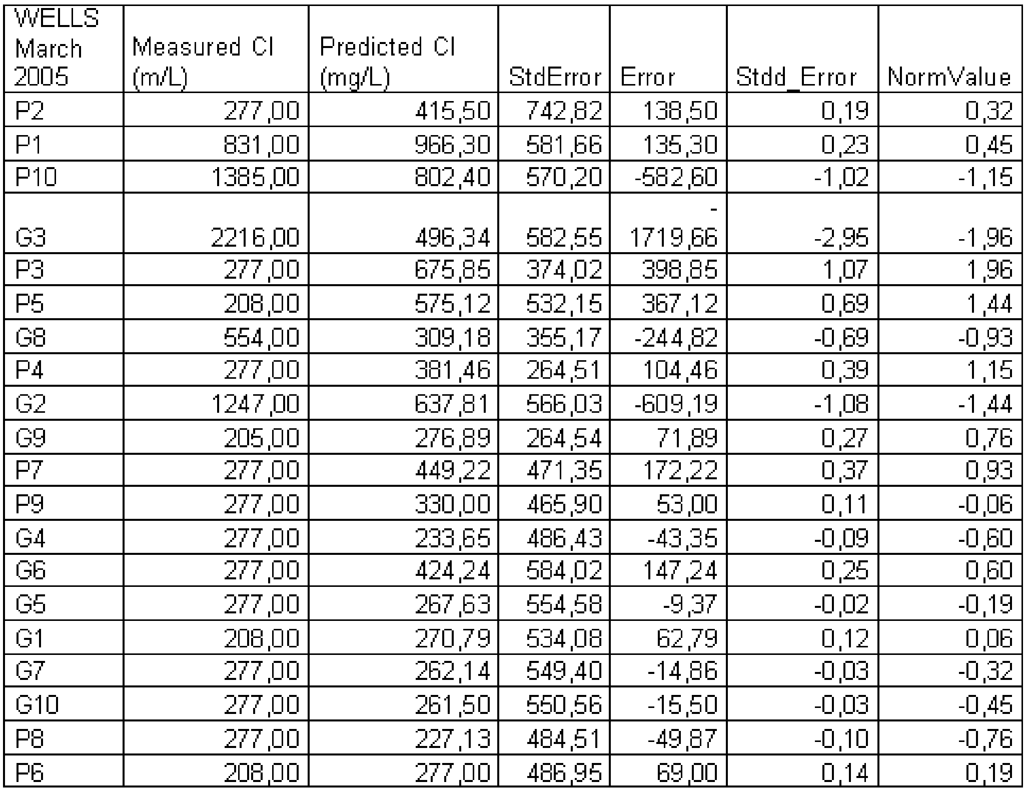
WELLS May 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	653,00	1589,04	1845,10	936,04	0,51	0,32
P1	814,00	1921,98	1411,27	1107,98	0,79	1,15
P10	2580,00	1370,82	1335,26	-1209,18	-0,91	-1,15
P6	4910,00	977,35	1314,45	-3932,65	-2,99	-1,44
G10	594,00	1331,34	1286,13	737,34	0,57	0,76
P5	1560,00	1220,83	1280,50	-339,17	-0,26	-0,76
G8	521,00	1233,49	1264,07	712,49	0,56	0,60
G4	714,00	1214,68	1236,06	500,68	0,41	0,19
G2	2140,00	1154,75	1259,79	-985,25	-0,78	-0,93
G9	502,00	1165,53	1235,14	663,53	0,54	0,45
P2	681,00	1053,35	1256,95	372,35	0,30	-0,06
P4	268,00	1199,95	1272,31	931,95	0,73	0,93
G5	485,00	630,52	1263,41	145,52	0,12	-0,60
P3	638,00	906,07	1283,18	268,07	0,21	-0,19
G6	238,00	734,21	1320,63	496,21	0,38	0,06
G10	445,00	646,00	1300,14	201,00	0,15	-0,45
P8	935,00	1152,24	1329,70	217,24	0,16	-0,32
P7	466,00	1528,86	1343,81	1062,86	0,79	1,44
P9	520,00	2598,33	1393,80	2078,33	1,49	1,96
G3	4910,00	631,92	1393,83	-4278,08	-3,07	-1,96

Table D.10: Differences between Measured and Predicted Values for Chloride (April 2005)



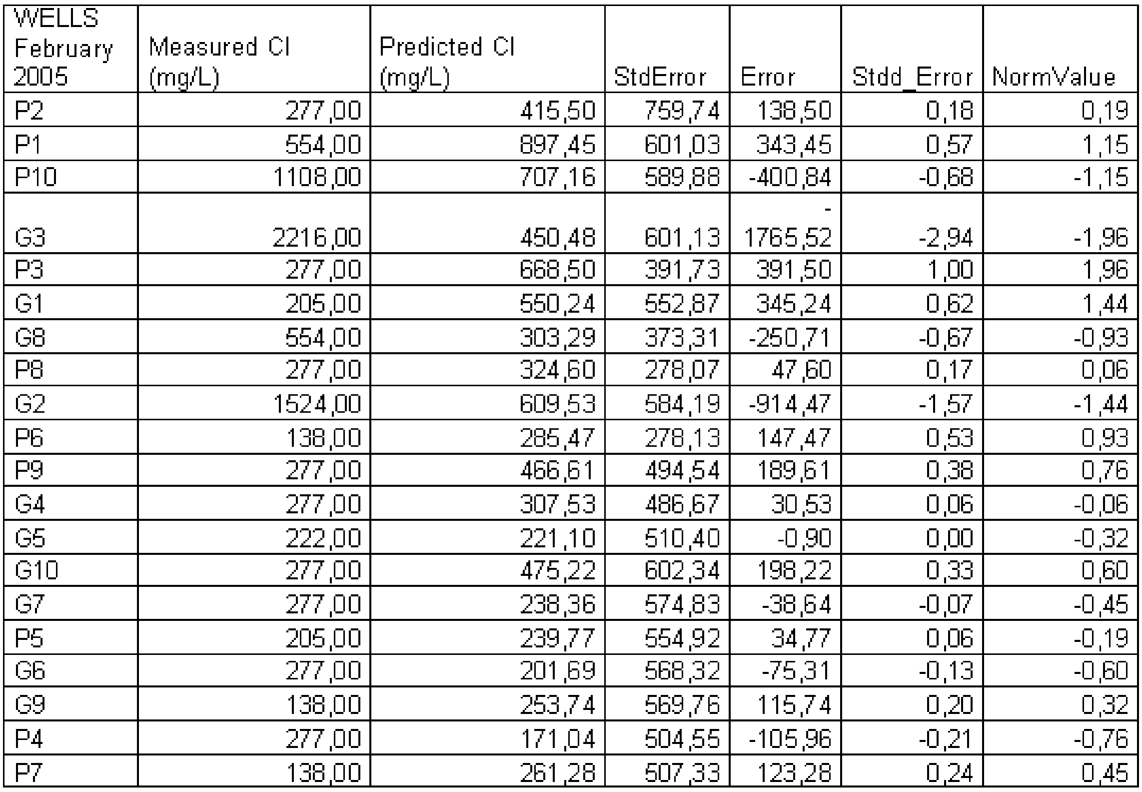
WELLS April 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G4	500,00	375,00	1629,19	-125,00	-0,08	-0,76
P1	814,00	1741,90	1284,04	927,90	0,72	1,96
P10	2500,00	1393,93	1259,81	-1106,07	-0,88	-1,44
G3	5000,00	867,32	1285,01	-4132,68	-3,22	-1,96
P4	500,00	693,90	832,68	193,90	0,23	0,45
P5	500,00	972,68	1178,88	472,68	0,40	1,44
G9	250,00	565,20	792,46	315,20	0,40	1,15
P2	500,00	595,19	590,24	95,19	0,16	0,32
G2	2250,00	1271,03	1248,76	-978,97	-0,78	-1,15
G8	250,00	430,75	590,36	180,75	0,31	0,93
G7	500,00	788,91	1050,72	288,91	0,27	0,76
P3	500,00	614,88	1035,53	114,88	0,11	0,06
G2	375,00	348,88	1084,35	-26,12	-0,02	-0,60
G5	375,00	712,78	1288,00	337,78	0,26	0,60
G6	375,00	420,42	1226,67	45,42	0,04	-0,19
G10	375,00	393,90	1183,24	18,90	0,02	-0,32
P8	250,00	408,20	1213,68	158,20	0,13	0,19
G1	375,00	354,60	1216,55	-20,40	-0,02	-0,45
P9	500,00	385,89	1074,80	-114,11	-0,11	-0,93
P6	375,00	458,46	1080,52	83,46	0,08	-0,06

Table D.11: Differences between Measured and Predicted Values for Chloride (March 2005)



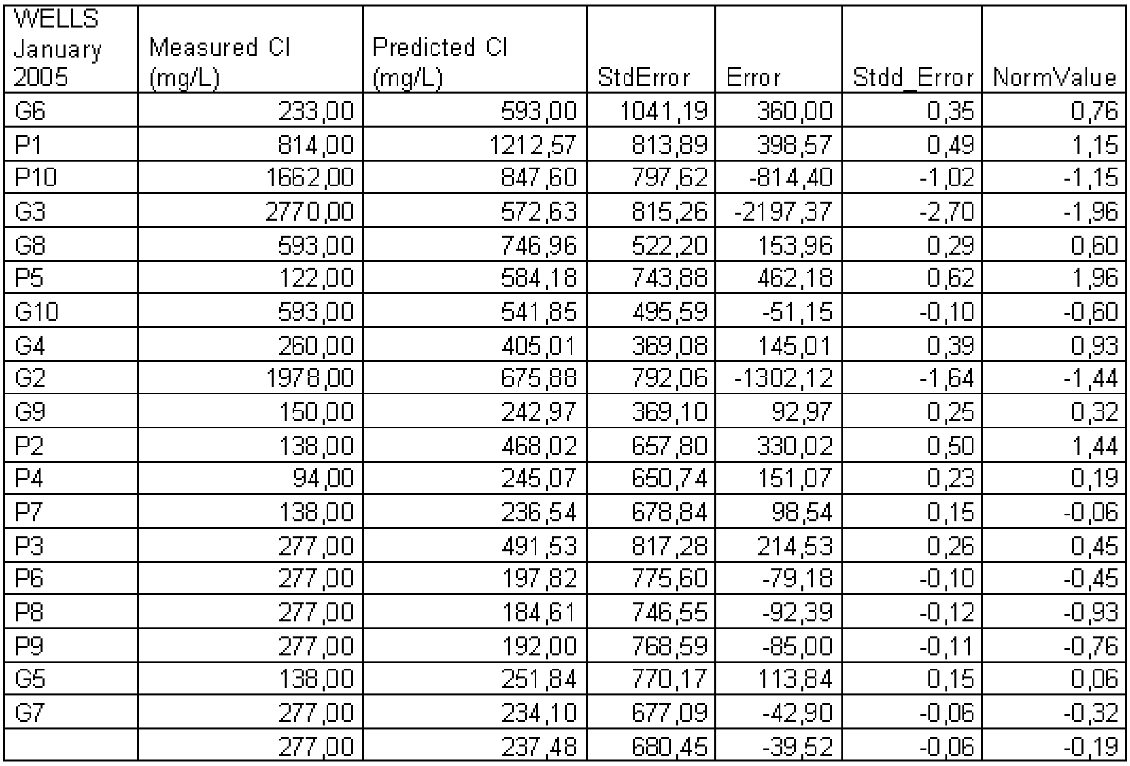
WELLS March 2005	Measured Cl (m/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
P2	277,00	415,50	742,82	138,50	0,19	0,32
P1	831,00	966,30	581,66	135,30	0,23	0,45
P10	1385,00	802,40	570,20	-582,60	-1,02	-1,15
G3	2216,00	496,34	582,55	-1719,66	-2,95	-1,96
P3	277,00	675,85	374,02	398,85	1,07	1,96
P5	208,00	575,12	532,15	367,12	0,69	1,44
G8	554,00	309,18	355,17	-244,82	-0,69	-0,93
P4	277,00	381,46	264,51	104,46	0,39	1,15
G2	1247,00	637,81	566,03	-609,19	-1,08	-1,44
G9	205,00	276,89	264,54	71,89	0,27	0,76
P7	277,00	449,22	471,35	172,22	0,37	0,93
P9	277,00	330,00	465,90	53,00	0,11	-0,06
G4	277,00	233,65	486,43	-43,35	-0,09	-0,60
G6	277,00	424,24	584,02	147,24	0,25	0,60
G5	277,00	267,63	554,58	-9,37	-0,02	-0,19
G1	208,00	270,79	534,08	62,79	0,12	0,06
G7	277,00	262,14	549,40	-14,86	-0,03	-0,32
G10	277,00	261,50	550,56	-15,50	-0,03	-0,45
P8	277,00	227,13	484,51	-49,87	-0,10	-0,76
P6	208,00	277,00	486,95	69,00	0,14	0,19

Table D.12: Differences between Measured and Predicted Values for Chloride (February 2005)



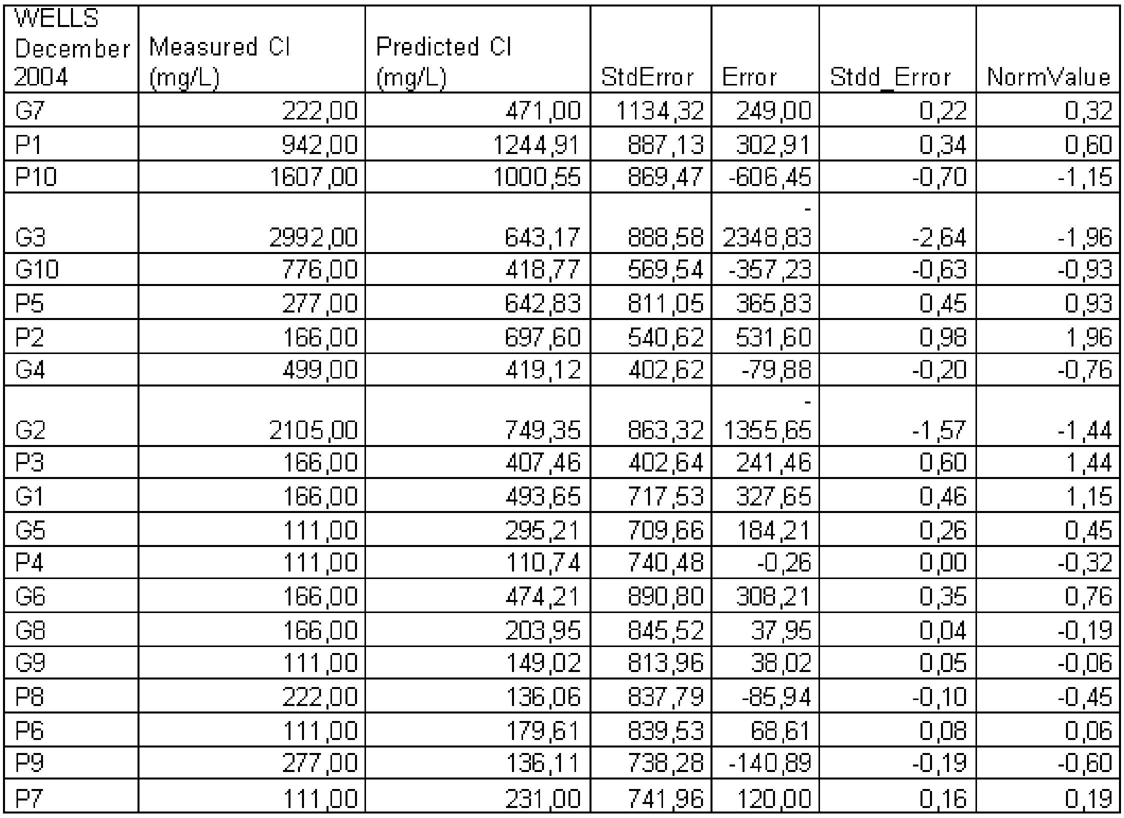
WELLS February 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
P2	277,00	415,50	759,74	138,50	0,18	0,19
P1	554,00	897,45	601,03	343,45	0,57	1,15
P10	1108,00	707,16	589,88	-400,84	-0,68	-1,15
G3	2216,00	450,48	601,13	-1765,52	-2,94	-1,96
P3	277,00	668,50	391,73	391,50	1,00	1,96
G1	205,00	550,24	552,87	345,24	0,62	1,44
G8	554,00	303,29	373,31	-250,71	-0,67	-0,93
P8	277,00	324,60	278,07	47,60	0,17	0,06
G2	1524,00	609,53	584,19	-914,47	-1,57	-1,44
P6	138,00	285,47	278,13	147,47	0,53	0,93
P9	277,00	466,61	494,54	189,61	0,38	0,76
G4	277,00	307,53	486,67	30,53	0,06	-0,06
G5	222,00	221,10	510,40	-0,90	0,00	-0,32
G10	277,00	475,22	602,34	198,22	0,33	0,60
G7	277,00	238,36	574,83	-38,64	-0,07	-0,45
P5	205,00	239,77	554,92	34,77	0,06	-0,19
G6	277,00	201,69	568,32	-75,31	-0,13	-0,60
G9	138,00	253,74	569,76	115,74	0,20	0,32
P4	277,00	171,04	504,55	-105,96	-0,21	-0,76
P7	138,00	261,28	507,33	123,28	0,24	0,45

Table D.13: Differences between Measured and Predicted Values for Chloride (January 2005)



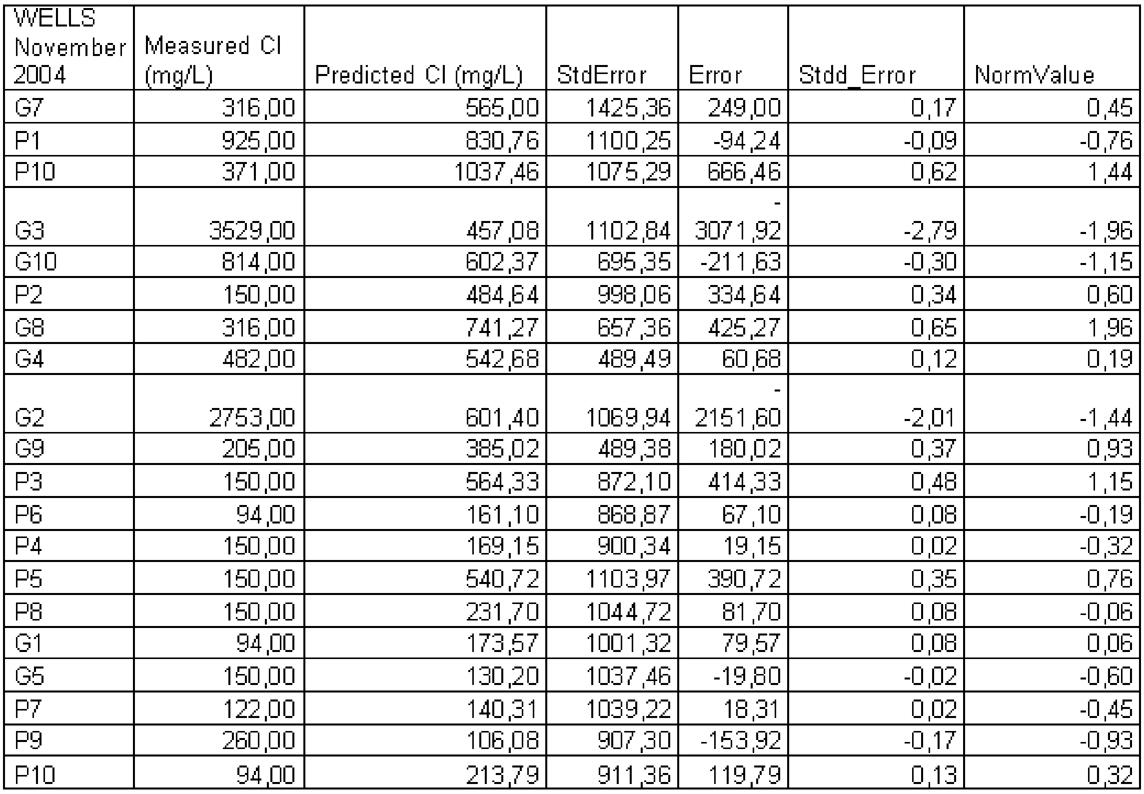
WELLS January 2005	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G6	233,00	593,00	1041,19	360,00	0,35	0,76
P1	814,00	1212,57	813,89	398,57	0,49	1,15
P10	1662,00	847,60	797,62	-814,40	-1,02	-1,15
G3	2770,00	572,63	815,26	-2197,37	-2,70	-1,96
G8	593,00	746,96	522,20	153,96	0,29	0,60
P5	122,00	584,18	743,88	462,18	0,62	1,96
G10	593,00	541,85	495,59	-51,15	-0,10	-0,60
G4	260,00	405,01	369,08	145,01	0,39	0,93
G2	1978,00	675,88	792,06	-1302,12	-1,64	-1,44
G9	150,00	242,97	369,10	92,97	0,25	0,32
P2	138,00	468,02	657,80	330,02	0,50	1,44
P4	94,00	245,07	650,74	151,07	0,23	0,19
P7	138,00	236,54	678,84	98,54	0,15	-0,06
P3	277,00	491,53	817,28	214,53	0,26	0,45
P6	277,00	197,82	775,60	-79,18	-0,10	-0,45
P8	277,00	184,61	746,55	-92,39	-0,12	-0,93
P9	277,00	192,00	768,59	-85,00	-0,11	-0,76
G5	138,00	251,84	770,17	113,84	0,15	0,06
G7	277,00	234,10	677,09	-42,90	-0,06	-0,32
	277,00	237,48	680,45	-39,52	-0,06	-0,19

Table D.14: Differences between Measured and Predicted Values for Chloride (December 2004)



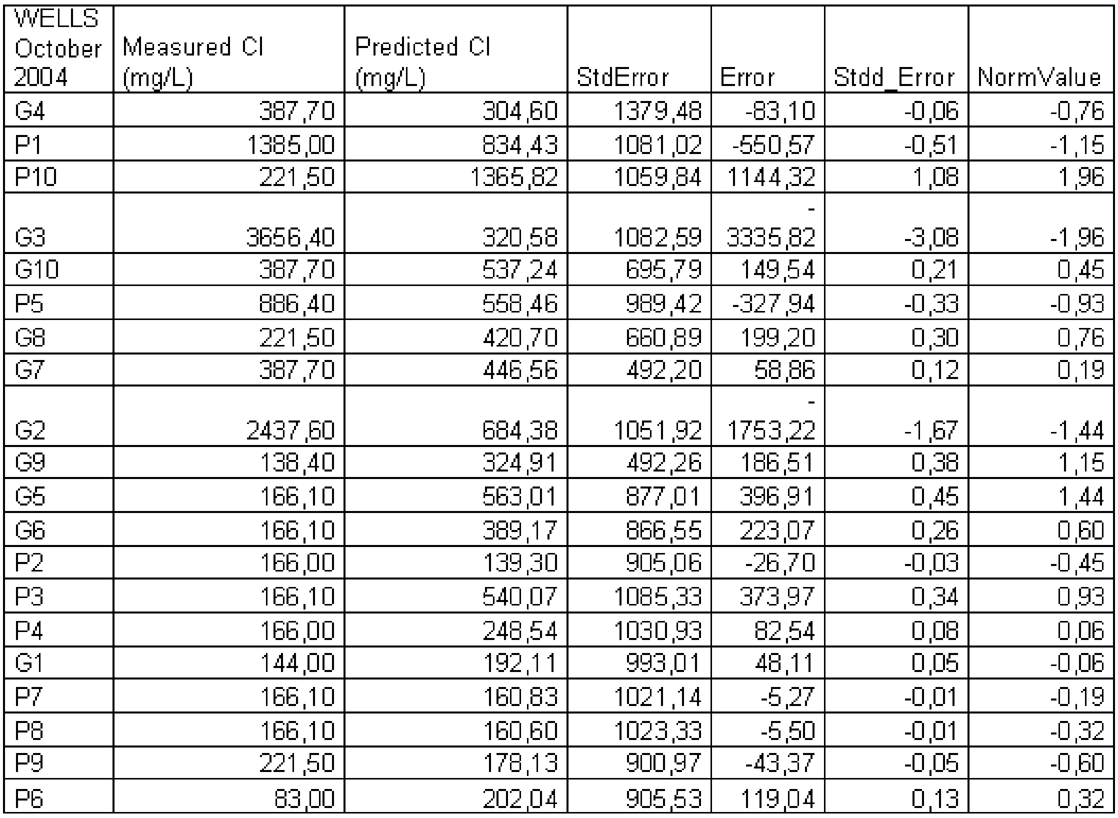
WELLS December 2004	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	222,00	471,00	1134,32	249,00	0,22	0,32
P1	942,00	1244,91	887,13	302,91	0,34	0,60
P10	1607,00	1000,55	869,47	-606,45	-0,70	-1,15
G3	2992,00	643,17	888,58	-2348,83	-2,64	-1,96
G10	776,00	418,77	569,54	-357,23	-0,63	-0,93
P5	277,00	642,83	811,05	365,83	0,45	0,93
P2	166,00	697,60	540,62	531,60	0,98	1,96
G4	499,00	419,12	402,62	-79,88	-0,20	-0,76
G2	2105,00	749,35	863,32	-1355,65	-1,57	-1,44
P3	166,00	407,46	402,64	241,46	0,60	1,44
G1	166,00	493,65	717,53	327,65	0,46	1,15
G5	111,00	295,21	709,66	184,21	0,26	0,45
P4	111,00	110,74	740,48	-0,26	0,00	-0,32
G6	166,00	474,21	890,80	308,21	0,35	0,76
G8	166,00	203,95	845,52	37,95	0,04	-0,19
G9	111,00	149,02	813,96	38,02	0,05	-0,06
P8	222,00	136,06	837,79	-85,94	-0,10	-0,45
P6	111,00	179,61	839,53	68,61	0,08	0,06
P9	277,00	136,11	738,28	-140,89	-0,19	-0,60
P7	111,00	231,00	741,96	120,00	0,16	0,19

Table D.15: Differences between Measured and Predicted Values for Chloride (November 2004)



WELLS November 2004	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G7	316,00	565,00	1425,36	249,00	0,17	0,45
P1	925,00	830,76	1100,25	-94,24	-0,09	-0,76
P10	371,00	1037,46	1075,29	666,46	0,62	1,44
G3	3529,00	457,08	1102,84	-3071,92	-2,79	-1,96
G10	814,00	602,37	695,35	-211,63	-0,30	-1,15
P2	150,00	484,64	998,06	334,64	0,34	0,60
G8	316,00	741,27	657,36	425,27	0,65	1,96
G4	482,00	542,68	489,49	60,68	0,12	0,19
G2	2753,00	601,40	1069,94	-2151,60	-2,01	-1,44
G9	205,00	385,02	489,38	180,02	0,37	0,93
P3	150,00	564,33	872,10	414,33	0,48	1,15
P6	94,00	161,10	868,87	67,10	0,08	-0,19
P4	150,00	169,15	900,34	19,15	0,02	-0,32
P5	150,00	540,72	1103,97	390,72	0,35	0,76
P8	150,00	231,70	1044,72	81,70	0,08	-0,06
G1	94,00	173,57	1001,32	79,57	0,08	0,06
G5	150,00	130,20	1037,46	-19,80	-0,02	-0,60
P7	122,00	140,31	1039,22	18,31	0,02	-0,45
P9	260,00	106,08	907,30	-153,92	-0,17	-0,93
P10	94,00	213,79	911,36	119,79	0,13	0,32

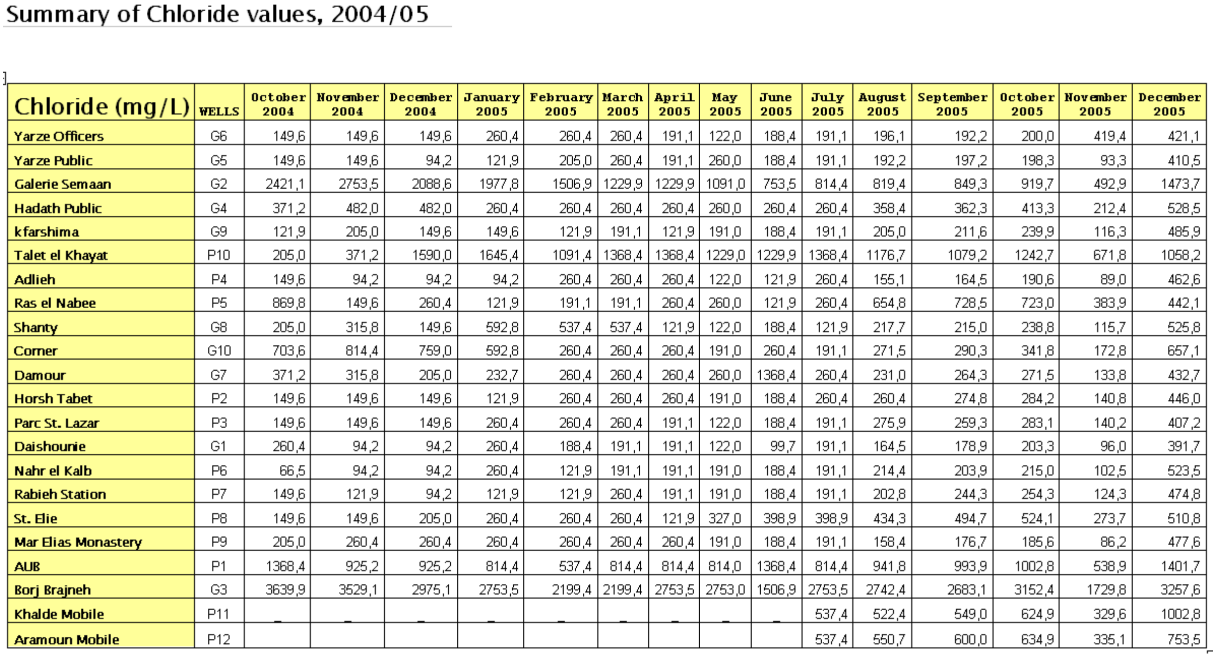
Table D.16: Differences between Measured and Predicted Values for Chloride (October 2004)



WELLS October 2004	Measured Cl (mg/L)	Predicted Cl (mg/L)	StdError	Error	Stdd_Error	NormValue
G4	387,70	304,60	1379,48	-83,10	-0,06	-0,76
P1	1385,00	834,43	1081,02	-550,57	-0,51	-1,15
P10	221,50	1365,82	1059,84	1144,32	1,08	1,96
G3	3656,40	320,58	1082,59	-3335,82	-3,08	-1,96
G10	387,70	537,24	695,79	149,54	0,21	0,45
P5	886,40	558,46	989,42	-327,94	-0,33	-0,93
G8	221,50	420,70	660,89	199,20	0,30	0,76
G7	387,70	446,56	492,20	58,86	0,12	0,19
G2	2437,60	684,38	1051,92	-1753,22	-1,67	-1,44
G9	138,40	324,91	492,26	186,51	0,38	1,15
G5	166,10	563,01	877,01	396,91	0,45	1,44
G6	166,10	389,17	866,55	223,07	0,26	0,60
P2	166,00	139,30	905,06	-26,70	-0,03	-0,45
P3	166,10	540,07	1085,33	373,97	0,34	0,93
P4	166,00	248,54	1030,93	82,54	0,08	0,06
G1	144,00	192,11	993,01	48,11	0,05	-0,06
P7	166,10	160,83	1021,14	-5,27	-0,01	-0,19
P8	166,10	160,60	1023,33	-5,50	-0,01	-0,32
P9	221,50	178,13	900,97	-43,37	-0,05	-0,60
P6	83,00	202,04	905,53	119,04	0,13	0,32

E Summary of Sampled Values

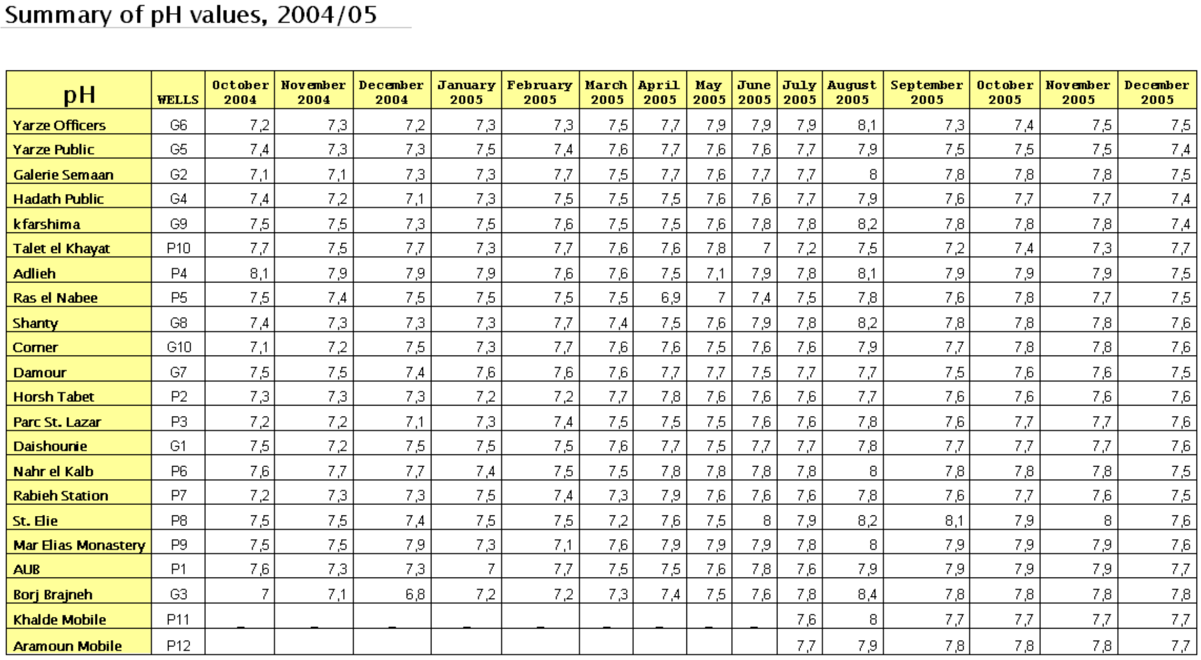
Table E.1: Summary of Chloride Values, 2004/05



Summary of Chloride values, 2004/05

Chloride (mg/L)	WELLS	October 2004	November 2004	December 2004	January 2005	February 2005	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005
Yarze Officers	G6	149,6	149,6	149,6	260,4	260,4	260,4	191,1	122,0	188,4	191,1	196,1	192,2	200,0	419,4	421,1
Yarze Public	G5	149,6	149,6	94,2	121,9	205,0	260,4	191,1	260,0	188,4	191,1	192,2	197,2	198,3	93,3	410,5
Galerie Semaan	G2	2421,1	2753,5	2088,6	1977,8	1506,9	1229,9	1229,9	1091,0	753,5	814,4	819,4	849,3	919,7	492,9	1473,7
Hadath Public	G4	371,2	482,0	482,0	260,4	260,4	260,4	260,4	260,0	260,4	260,4	358,4	362,3	413,3	212,4	528,5
kfarshima	G9	121,9	205,0	149,6	149,6	121,9	191,1	121,9	191,0	188,4	191,1	205,0	211,6	239,9	116,3	485,9
Talet el Khayat	P10	205,0	371,2	1590,0	1645,4	1091,4	1368,4	1368,4	1229,0	1229,9	1368,4	1176,7	1079,2	1242,7	671,8	1058,2
Adlieh	P4	149,6	94,2	94,2	94,2	260,4	260,4	260,4	122,0	121,9	260,4	155,1	164,5	190,6	89,0	462,6
Ras el Nabee	P5	869,8	149,6	260,4	121,9	191,1	191,1	260,4	260,0	121,9	260,4	654,8	728,5	723,0	383,9	442,1
Shanty	G8	205,0	315,8	149,6	592,8	537,4	537,4	121,9	122,0	188,4	121,9	217,7	215,0	238,8	115,7	525,8
Corner	G10	703,6	814,4	759,0	592,8	260,4	260,4	260,4	191,0	260,4	191,1	271,5	290,3	341,8	172,8	657,1
Damour	G7	371,2	315,8	205,0	232,7	260,4	260,4	260,4	260,0	1368,4	260,4	231,0	264,3	271,5	133,8	432,7
Horsh Tabet	P2	149,6	149,6	149,6	121,9	260,4	260,4	260,4	191,0	188,4	260,4	260,4	274,8	284,2	140,8	446,0
Parc St. Lazar	P3	149,6	149,6	149,6	260,4	260,4	260,4	191,1	122,0	188,4	191,1	275,9	259,3	283,1	140,2	407,2
Daishounie	G1	260,4	94,2	94,2	260,4	188,4	191,1	191,1	122,0	99,7	191,1	164,5	178,9	203,3	96,0	391,7
Nahr el Kalb	P6	66,5	94,2	94,2	260,4	121,9	191,1	191,1	191,0	188,4	191,1	214,4	203,9	215,0	102,5	523,5
Rabieh Station	P7	149,6	121,9	94,2	121,9	121,9	260,4	191,1	191,0	188,4	191,1	202,8	244,3	254,3	124,3	474,8
St. Elie	P8	149,6	149,6	205,0	260,4	260,4	260,4	121,9	327,0	398,9	398,9	434,3	494,7	524,1	273,7	510,8
Mar Elias Monastery	P9	205,0	260,4	260,4	260,4	260,4	260,4	260,4	191,0	188,4	191,1	158,4	176,7	185,6	86,2	477,6
AUB	P1	1368,4	925,2	925,2	814,4	537,4	814,4	814,4	814,0	1368,4	814,4	941,8	993,9	1002,8	538,9	1401,7
Borj Brajneh	G3	3639,9	3529,1	2975,1	2753,5	2199,4	2199,4	2753,5	2753,0	1506,9	2753,5	2742,4	2683,1	3152,4	1729,8	3257,6
Khalde Mobile	P11	_	_	_	_	_	_	_	_	_	537,4	522,4	549,0	624,9	329,6	1002,8
Aramoun Mobile	P12										537,4	550,7	600,0	634,9	335,1	753,5

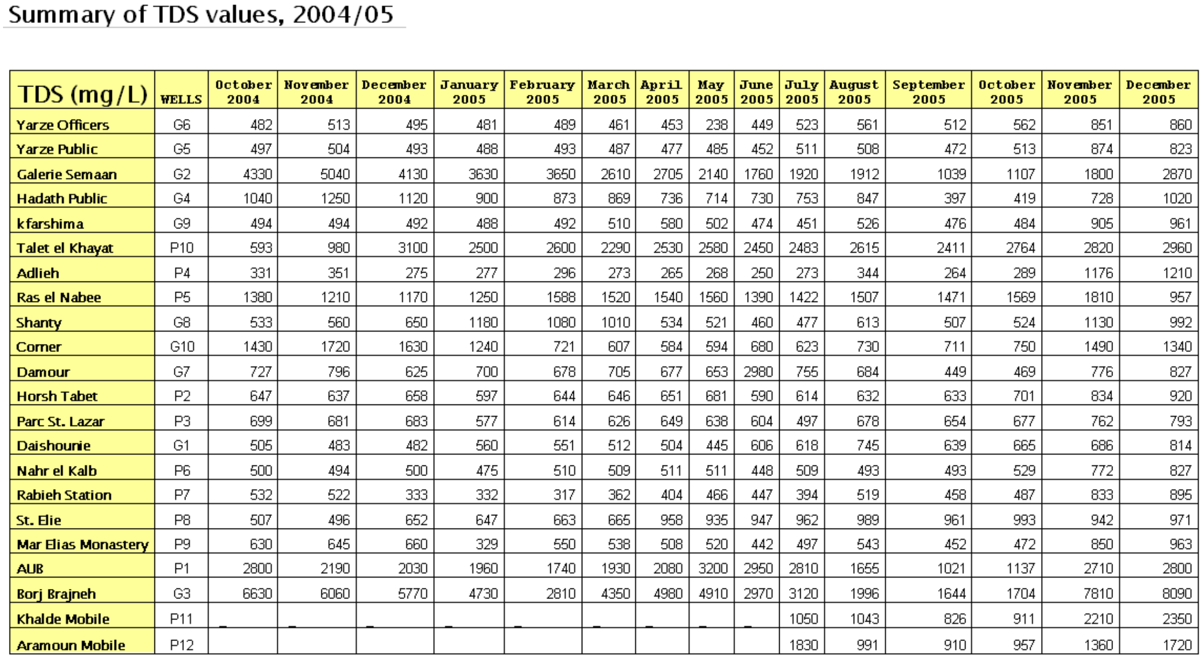
Table E.2: Summary of pH Values, 2004/05



Summary of pH values, 2004/05

pH	WELLS	October 2004	November 2004	December 2004	January 2005	February 2005	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005
Yarze Officers	G6	7,2	7,3	7,2	7,3	7,3	7,5	7,7	7,9	7,9	7,9	8,1	7,3	7,4	7,5	7,5
Yarze Public	G5	7,4	7,3	7,3	7,5	7,4	7,6	7,7	7,6	7,6	7,7	7,9	7,5	7,5	7,5	7,4
Galerie Semaan	G2	7,1	7,1	7,3	7,3	7,7	7,5	7,7	7,6	7,7	7,7	8	7,8	7,8	7,8	7,5
Hadath Public	G4	7,4	7,2	7,1	7,3	7,5	7,5	7,5	7,6	7,6	7,7	7,9	7,6	7,7	7,7	7,4
kfarshima	G9	7,5	7,5	7,3	7,5	7,6	7,5	7,5	7,6	7,8	7,8	8,2	7,8	7,8	7,8	7,4
Talet el Khayat	P10	7,7	7,5	7,7	7,3	7,7	7,6	7,6	7,8	7	7,2	7,5	7,2	7,4	7,3	7,7
Adlieh	P4	8,1	7,9	7,9	7,9	7,6	7,6	7,5	7,1	7,9	7,8	8,1	7,9	7,9	7,9	7,5
Ras el Nabee	P5	7,5	7,4	7,5	7,5	7,5	7,5	6,9	7	7,4	7,5	7,8	7,6	7,8	7,7	7,5
Shanty	G8	7,4	7,3	7,3	7,3	7,7	7,4	7,5	7,6	7,9	7,8	8,2	7,8	7,8	7,8	7,6
Corner	G10	7,1	7,2	7,5	7,3	7,7	7,6	7,6	7,5	7,6	7,6	7,9	7,7	7,8	7,8	7,6
Damour	G7	7,5	7,5	7,4	7,6	7,6	7,6	7,7	7,7	7,5	7,7	7,7	7,5	7,6	7,6	7,5
Horsh Tabet	P2	7,3	7,3	7,3	7,2	7,2	7,7	7,8	7,6	7,6	7,6	7,7	7,6	7,6	7,6	7,6
Parc St. Lazar	P3	7,2	7,2	7,1	7,3	7,4	7,5	7,5	7,5	7,6	7,6	7,8	7,6	7,7	7,7	7,6
Daishounie	G1	7,5	7,2	7,5	7,5	7,5	7,6	7,7	7,5	7,7	7,7	7,8	7,7	7,7	7,7	7,6
Nahr el Kalb	P6	7,6	7,7	7,7	7,4	7,5	7,5	7,8	7,8	7,8	7,8	8	7,8	7,8	7,8	7,5
Rabieh Station	P7	7,2	7,3	7,3	7,5	7,4	7,3	7,9	7,6	7,6	7,6	7,8	7,6	7,7	7,6	7,5
St. Elie	P8	7,5	7,5	7,4	7,5	7,5	7,2	7,6	7,5	8	7,9	8,2	8,1	7,9	8	7,6
Mar Elias Monastery	P9	7,5	7,5	7,9	7,3	7,1	7,6	7,9	7,9	7,9	7,8	8	7,9	7,9	7,9	7,6
AUB	P1	7,6	7,3	7,3	7	7,7	7,5	7,5	7,6	7,8	7,6	7,9	7,9	7,9	7,9	7,7
Borj Brajneh	G3	7	7,1	6,8	7,2	7,2	7,3	7,4	7,5	7,6	7,8	8,4	7,8	7,8	7,8	7,8
Khalde Mobile	P11	_	_	_	_	_	_	_	_	_	7,6	8	7,7	7,7	7,7	7,7
Aramoun Mobile	P12										7,7	7,9	7,8	7,8	7,8	7,7

Table E.3: Summary of TDS Values, 2004/05

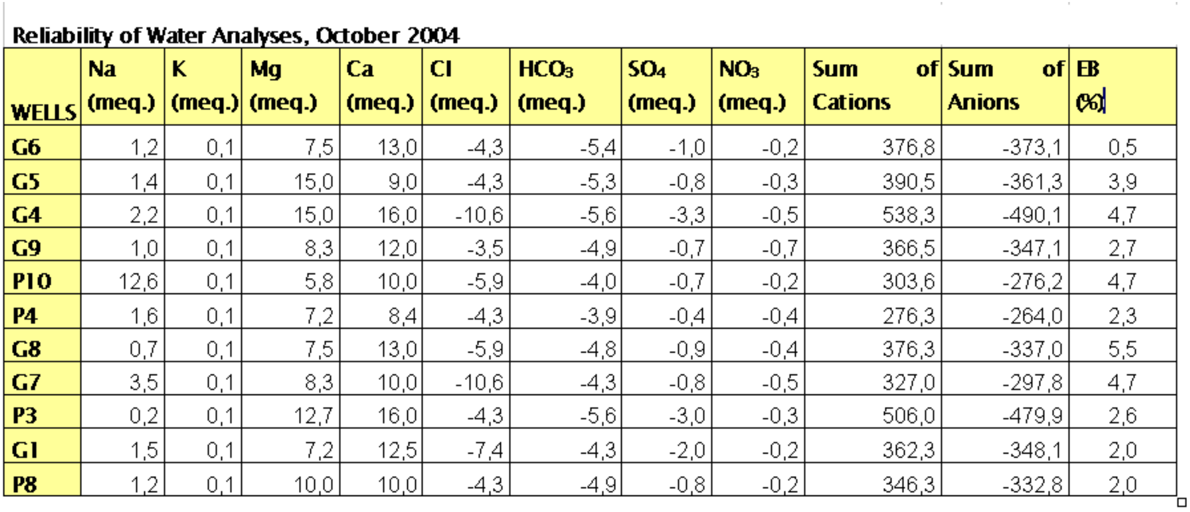


Summary of TDS values, 2004/05

TDS (mg/L)	WELLS	October 2004	November 2004	December 2004	January 2005	February 2005	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005
Yarze Officers	G6	482	513	495	481	489	461	453	238	449	523	561	512	562	851	860
Yarze Public	G5	497	504	493	488	493	487	477	485	452	511	508	472	513	874	823
Galerie Semaan	G2	4330	5040	4130	3630	3650	2610	2705	2140	1760	1920	1912	1039	1107	1800	2870
Hadath Public	G4	1040	1250	1120	900	873	869	736	714	730	753	847	397	419	728	1020
kfarshima	G9	494	494	492	488	492	510	580	502	474	451	526	476	484	905	961
Talet el Khayat	P10	593	980	3100	2500	2600	2290	2530	2580	2450	2483	2615	2411	2764	2820	2960
Adlieh	P4	331	351	275	277	296	273	265	268	250	273	344	264	289	1176	1210
Ras el Nabee	P5	1380	1210	1170	1250	1588	1520	1540	1560	1390	1422	1507	1471	1569	1810	957
Shanty	G8	533	560	650	1180	1080	1010	534	521	460	477	613	507	524	1130	992
Corner	G10	1430	1720	1630	1240	721	607	584	594	680	623	730	711	750	1490	1340
Damour	G7	727	796	625	700	678	705	677	653	2980	755	684	449	469	776	827
Horsh Tabet	P2	647	637	658	597	644	646	651	681	590	614	632	633	701	834	920
Parc St. Lazar	P3	699	681	683	577	614	626	649	638	604	497	678	654	677	762	793
Daishounie	G1	505	483	482	560	551	512	504	445	606	618	745	639	665	686	814
Nahr el Kalb	P6	500	494	500	475	510	509	511	511	448	509	493	493	529	772	827
Rabieh Station	P7	532	522	333	332	317	362	404	466	447	394	519	458	487	833	895
St. Elie	P8	507	496	652	647	663	665	958	935	947	962	989	961	993	942	971
Mar Elias Monastery	P9	630	645	660	329	550	538	508	520	442	497	543	452	472	850	963
AUB	P1	2800	2190	2030	1960	1740	1930	2080	3200	2950	2810	1655	1021	1137	2710	2800
Borj Brajneh	G3	6630	6060	5770	4730	2810	4350	4980	4910	2970	3120	1996	1644	1704	7810	8090
Khalde Mobile	P11	_	_	_	_	_	_	_	_	_	1050	1043	826	911	2210	2350
Aramoun Mobile	P12										1830	991	910	957	1360	1720

F Reliability of Water Analyses

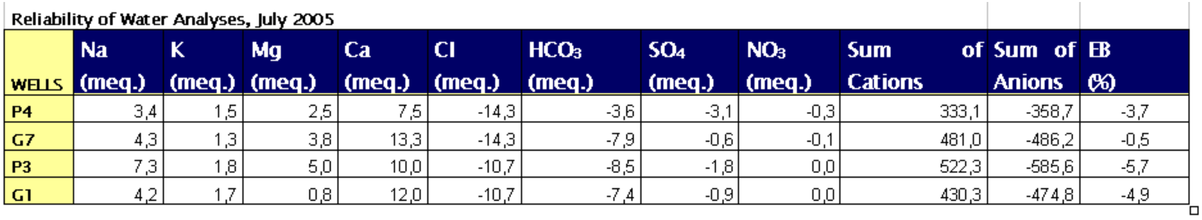
Table F.1: Reliability of Water Analyses, October 2004



Reliability of Water Analyses, October 2004

WELLS	Na (meq.)	K (meq.)	Mg (meq.)	Ca (meq.)	Cl (meq.)	HCO_3 (meq.)	SO_4 (meq.)	NO_3 (meq.)	Sum of Cations	Sum of Anions	EB (%)
G6	1,2	0,1	7,5	13,0	-4,3	-5,4	-1,0	-0,2	376,8	-373,1	0,5
G5	1,4	0,1	15,0	9,0	-4,3	-5,3	-0,8	-0,3	390,5	-361,3	3,9
G4	2,2	0,1	15,0	16,0	-10,6	-5,6	-3,3	-0,5	538,3	-490,1	4,7
G9	1,0	0,1	8,3	12,0	-3,5	-4,9	-0,7	-0,7	366,5	-347,1	2,7
P10	12,6	0,1	5,8	10,0	-5,9	-4,0	-0,7	-0,2	303,6	-276,2	4,7
P4	1,6	0,1	7,2	8,4	-4,3	-3,9	-0,4	-0,4	276,3	-264,0	2,3
G8	0,7	0,1	7,5	13,0	-5,9	-4,8	-0,9	-0,4	376,3	-337,0	5,5
G7	3,5	0,1	8,3	10,0	-10,6	-4,3	-0,8	-0,5	327,0	-297,8	4,7
P3	0,2	0,1	12,7	16,0	-4,3	-5,6	-3,0	-0,3	506,0	-479,9	2,6
G1	1,5	0,1	7,2	12,5	-7,4	-4,3	-2,0	-0,2	362,3	-348,1	2,0
P8	1,2	0,1	10,0	10,0	-4,3	-4,9	-0,8	-0,2	346,3	-332,8	2,0

Table F.2: Reliability of Water Analyses, July 2005



Reliability of Water Analyses, July 2005

WELLS	Na (meq.)	K (meq.)	Mg (meq.)	Ca (meq.)	Cl (meq.)	HCO_3 (meq.)	SO_4 (meq.)	NO_3 (meq.)	Sum of Cations	Sum of Anions	EB (%)
P4	3,4	1,5	2,5	7,5	-14,3	-3,6	-3,1	-0,3	333,1	-358,7	-3,7
G7	4,3	1,3	3,8	13,3	-14,3	-7,9	-0,6	-0,1	481,0	-486,2	-0,5
P3	7,3	1,8	5,0	10,0	-10,7	-8,5	-1,8	0,0	522,3	-585,6	-5,7
G1	4,2	1,7	0,8	12,0	-10,7	-7,4	-0,9	0,0	430,3	-474,8	-4,9

Curriculum vitae

28. September 1968	Born in Beirut, Lebanon
1980 - 1986	St. Mary's Orthodox College Beirut, Lebanon
1986 - 1990	B.Sc. Geology, American University of Beirut, Lebanon
1990 - 1994	M.Sc. Geology, American University of Beirut, Lebanon