Exploitation of submarine springs in Lebanon: assessment of potential

G. Ayoub, R. Khoury, J. Ghannam, A. Acra and B. Hamdar

ABSTRACT

The extreme shortage of public water supplies in most countries of the Middle East has steadily commanded a great political importance. Regional disputes over the riparian rights relevant to the transboundary surface and groundwater resources are imminent. Therefore, it is opportune to plan for feasible, affordable, and sustainable measures such as conservation, wastewater reclamation, artificial recharge, and particularly utilization of deep groundwater and submarine springs. Chekka Bay, in the north of Lebanon, is well known for its freshwater springs. A general objective of the study was set at evaluating the feasibility of exploiting the submarine springs in the Chekka Bay taking into consideration the technical, economic, social and environmental aspects of such a project. The study has been subdivided into three parts, namely hydrogeological, marine and socio-economic. Off-shore exploitation of the submarine springs could face implementation problems as it is technically difficult, financially expensive, and yields a qualitatively unacceptable water. A more suitable alternative would be to tap the submarine springs inland through wells of differing depths. The financial feasibility of the latter alternative has been confirmed through a cost-benefit analysis.

Key words | Chekka Bay, exploitation, feasibility, submarine springs, water source

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INTRODUCTION

The extreme shortage of public water supplies in most countries of the Middle East has steadily commanded a great political importance. Regional disputes over the riparian rights relevant to the transboundary surface and groundwater resources are imminent (Lonegran & Brooks 1994). Although it has been presumed by some that Lebanon enjoys an abundance of water with excess to share with neighboring countries, available reports have indicated that Lebanon cannot afford to share any portion of its national water resources (Acra & Inglessis 1978; Fawaz 1992). The country may actually be facing an acute water shortage in the early years of the new millennium (El Fadel & Zeinati 2000). Therefore, it is opportune to plan for feasible, affordable, and sustainable measures such as conservation, wastewater reclamation, artificial aquifer recharge, and particularly utilization of submarine springs.

While off-shore freshwater springs and seeps have captured the interest of scientists and engineers since the days of the Romans, studies on the magnitude and effects of the discharges of groundwaters into the sea have been very limited. Submarine springs are well known to occur off the coast of Florida, Mexico's Yucatan Peninsula, around the Pacific rim including Chile, Hawaii, and Australia; and in the Mediterranean Sea off Spain, France, Italy, Greece, Israel, Libya, Syria, and Lebanon. Chekka Bay, in the north of Lebanon (Figure 1), is well known for its freshwater springs. One of the 17 reported freshwater submarine springs in the bay is alleged to be the largest in the Mediterranean Sea (Todd 1967) with a peak flow of 50 m^3/s. This flow is comparable to about 6 to 7 times the flow of the largest river in Lebanon, the Litani River (Figure 1), during the low-flow period.

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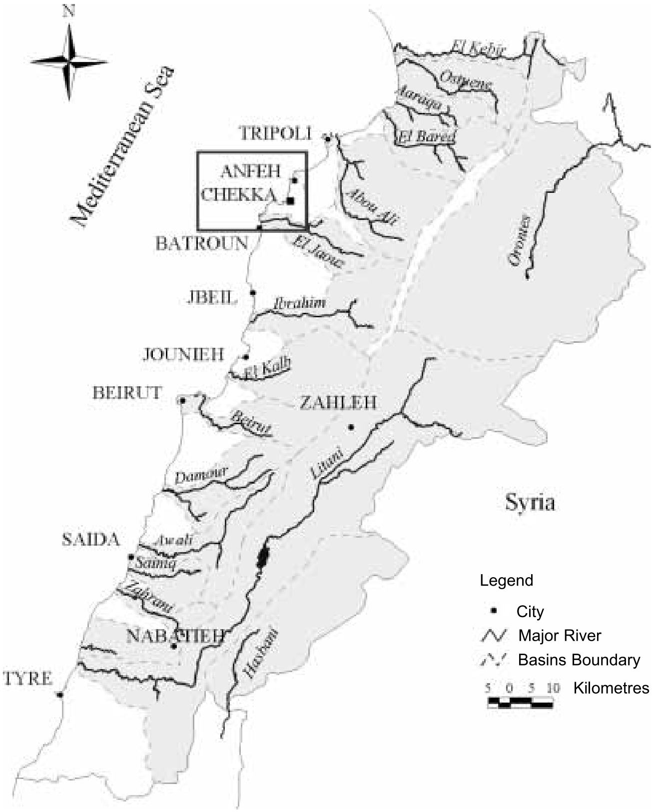

Figure 1 | Location of Chekka in Lebanon.

Realizing the importance of such a water resource and its potential impact on the local area, country, and possibly the region, a study was undertaken to evaluate the feasibility of exploiting the submarine springs in the Chekka Bay, taking into consideration the technical, economic, social and environmental aspects of the project. The study aimed at delineating the terrestrial catchment area that feeds the Chekka submarine springs, and establishing a water budget for the local area of concern. In addition, it aimed at identifying the geographic location of the major submarine springs, quantifying their discharges where possible, assessing their physico-chemical and biological characteristics, and evaluating alternatives for the exploitation of the submarine springs while assessing associated economic aspects and environmental impacts. To meet these objectives, the study was divided into three parts: hydrogeological, marine, and socio-economic.

PREVIOUS RESEARCH

Among the earliest observations on the submarine springs off the coast of Lebanon were those reported by Gruvel (1930), and later by Dubertret (1955). The latter noted that the most important submarine springs occur off the coasts of Tyre in the south and Chekka in the north. A diving program in search of the submarine springs along the coast of Lebanon was launched in 1963 as part of the ‘Projet d’Etude des Eaux Souterraines du Liban’ with the collaboration of the United Nations (UNDP 1970). Using infrared imagery, Hakim (1974, 1976) studied the location of coastal and submarine springs along the shores of Lebanon. The submarine springs in the Chekka Bay were studied by Kareh (1966, 1967), Moullard *et al.* (1967), and Todd (1967). The latter has claimed to have measured the discharge of one of the largest submarine springs in the Chekka Bay during the month of March, and reported a discharge of 50 m^3/s, representing the peak flow of the spring at the end of the rainy season. The method employed to measure the discharge was not specified in his report.

A more recent investigation employed thermal infra red (TIR) technology to locate the submarine springs that are characterized by a lower temperature than that of the ambient seawater as well as other discharges such as wastewater (NCRS 1997).

METHODOLOGY

The methods adopted in conducting the hydrogeological, marine, and socio-economic parts of the study are discussed below.

Hydrogeological work

The objectives of the hydrogeological investigation included the delineation of the catchment area, identification of the water-bearing formations, and explanation of the processes, tectonics, and sedimentation leading to the generation of the submarine springs. To achieve these objectives, the following field activities were conducted:

1. Preliminary field assessment of the catchment area feeding the submarine springs.
2. Field verification, using the spot check technique, of existing geological maps covering an area of about 400 km^2. The mapping was performed by the hydrogeological research team at a scale of 1:20,000.
3. Special attention was paid to the structural control of the delineated catchment area. The faults were traced and measured. The Sannine-Maameltein Formation (C_4–C_5) was also assessed in detail since it forms the geological strata that relate to the submarine springs. Several inland springs that issue from this formation (e.g. the Rachaine springs) were also surveyed.

Some of the techniques used during the desk and field surveys are described below:

1. Aerial photographs at a scale of 1:25,000 were used for preliminary mapping of the catchment area and checking the possible occurrence of lineaments along the existing fault traces.
2. Detailed aerial photographs (scale of 1:10,000) for the neighboring inland area were also utilized to detect any lineament relating to the presence of faults that may be linked to the line of the submarine springs of Chekka.
3. Topographic maps (scales of 1:20,000 and 1:50,000) prepared by the Lebanese army were used as base maps for various field activities.
4. Geological maps (Dubertret 1955) were assessed, in addition to some unpublished maps and theses.

The geological mapping was founded on lithostratigraphy that employs a nomenclature partially adopted from Walley (1997). Minor changes in the nomenclature of the Upper Cretaceous formations were introduced. Bedding, joints, and faults were measured and plotted on the geological maps.

Marine work

The marine part of the study had three major objectives: (a) identifying the geographic location of the major submarine springs; (b) measuring their discharge; and (c) assessing the physico-chemical and biological quality of the waters of the springs. Local fishermen were consulted about the location of the major springs in the area. Besides offering relatively precise locations for the springs, they also indicated the springs that have intermittent (seasonal) flow and those that have permanent flow. The position of each of the detected springs was determined by using the Global Positioning System (GPS). The instrument used (MARCH II, supplied by Geneq, Montreal, Quebec, Canada) has an accuracy of about 50 m which was considered to be satisfactory for the purposes of the study. The flow meter (Argonaut SL) adopted for measuring the discharge was supplied by SonTek, San Diego, California, and was satisfactorily checked for accuracy in a laboratory set-up prior to its deployment in the field. This meter uses the Doppler shift principle. A portable computer was used to configure the flow meter, and to retrieve data stored in the internal memory of the meter. The placement of the meter across the opening of the springs was accomplished by professional divers.

The water quality was characterized both in the field and in the laboratory. A field analyzer, Aquacheck, (supplied by Alpkem Corporation, College Station, Texas), was used to measure pH, conductivity, dissolved oxygen and temperature of both the freshwater and the seawater. Its probe was placed as deep as possible into the entrance of the springs to avoid taking measurements in the region where seawater and freshwater intermingle. A portable sampling system (Reel E-Z) supplied by Instrumentation Northwest Inc., Redmond, Washington, connected to a Redi-Flo 2 pump supplied by Grundfos, Clovis, California, was used to retrieve the desired water samples. The samples were collected, bottled, stored at a low temperature (4°C), and transported to the laboratory. Table 1 summarizes the tests performed and the analytical methods used.

The seawater samples were also collected and analyzed for comparative purposes. The tests performed to assess the chemical quality of the fresh- and seawater were chloride, calcium, magnesium, sulfate, nitrate, sodium and potassium; fecal and total coliform tests were also performed to assess the bacteriological quality of the water. All tests were conducted at the Environmental

Table 1 | Instruments and methods used for water analysis

Analyte	Type of analysis	Reference method
Nitrates	Colorimetric	4500-NO_3^- E Cadmium reduction method
Ca Hardness	Titrimetric	3500-Ca D EDTA titrimetric method
Total Hardness	Titrimetric	2340 C EDTA titrimetric method
Chlorides	Titrimetric	4500-Cl^- B Argentometric method
Sulfates	Colorimetric	4500-SO_4^{2-} E Turbidimetric method
Sodium	Photometric	3500-Na D
Potassium	Photometric	3500-K D
Fecal coliforms	Membrane filtration	9222D
Total coliforms	Membrane filtration	9222B

Engineering Research Center (EERC) at AUB and in accordance with *Standard Methods for the Examination of Water and Wastewater* (1995).

Socio-economic work

The objective of the fieldwork related to this part of the study was to collect the necessary information that could serve as a basis for an environmental and socio-economic study linked to the possible exploitation of the submarine springs in the Chekka Bay. The study area covered the towns of Chekka and Anfeh (Figure 1). The town of Chekka is situated in the Batroun caza, mohafaza of north Lebanon at an altitude of 60 m. It is about 86 km to the north of the capital Beirut, and 17 km to the south of the second largest city, Tripoli. A 1994 estimate of the population of Chekka was about 12,500, which had increased to about 14,400 by the year 2000. Anfeh had an estimated population of 8,200 in 1994, and a projected population of about 9,370 for the year 2000 (Khatib & Alami 1994).

The main existing sources of income in Chekka and Anfeh are industry, fishing, and free business. Agriculture is limited and is primarily practised to satisfy home consumption needs. The industrial sector operating in Chekka consists mainly of cement and calcareous factories (four factories forming 57% of the total industries). The others include a sugar-refining factory, two paper-bag factories for cement packaging, and a fish-canning factory. The existing water sources in the area include nine artesian wells and three springs. The most important of the wells are the Al-Jaradeh wells referred to as Chekka, Anfeh and Fea'a wells. The total current discharge from these wells is about 3,000 m^3/day, and it may be considerably increased in the event that the networks are rehabilitated.

A field survey was conducted in the study area to solicit information from the local fishermen, households, and industries. A fisherman-specific questionnaire was formulated with the objective of collecting information on the present fish population, fish productivity, fish market prices, fishing techniques, and opinions as to the potential impact of the project on the existing fish population, distribution, and the fishing industry in general. A total of 45 responses was considered to be representative of the study area, covering about 20% of the target group. Interviews with a specialist at the Ministry of Agriculture were also held to collect further information concerning the impact of the project on the fish environment. At the industrial level, the survey targeted all the industries in the area. The questions addressed in the survey were mainly related to water sources and usage. One of the objectives of the household survey in Chekka and Anfeh was to acquire a rough estimate of the current water consumption and/or deficiency in the area based on different usages. A limited sample, intended to be indicative of the current situation in the area and by no means to be statistically significant, was chosen. Two main types of houses typical of the area were targeted, namely three apartments and five individual houses with gardens.

RESULTS AND DISCUSSION

Hydrogeological results

The submarine springs are located offshore from the towns of Chekka and Anfeh. Kareh (1966) delineated 17 springs in the area with various discharges.

The catchment area (the area directly receiving precipitation) that is contributing to the springs is estimated at approximately 600 km^2. In the event that the river basins bounding the area are included within the catchment area, then the total area would increase to about 900 km^2. The catchment area is bounded to the north by the Abou Ali River, to the south by El Jaouz River, and to the east by the topographic divide of the western mountain range (Figure 1). Accessibility is easy due to the extensive road network in the area.

The large catchment area covers various geomorphological features. High mountain ranges with significant snow infiltration outcrop to the east with the highest peak at 3,088 m (Qornet el Saouda). Coastal plains containing dolines and alluvial sinkholes, in addition to the karstic terrain with direct sinkholes related to the submarine springs are also present. El Jaouz and Abou Ali rivers also contribute water to the C_4 aquifer through sinkholes associated with the rivers. The origin and mode of formation of the sinkholes are still undefined, and are thought to be related to the tectonics and the earthquakes that hit the area in the past.

The submarine springs and their catchment area represent a typical karst system. It is a mature system as indicated by the conduit type flow of the springs and their high seasonal fluctuations. Other karst features include sinkholes, especially within the C_4 formation, which act as fast passageways of infiltrating water to the groundwater system. Alluvial sinkholes present in the vicinity of the coastal plain are directly related to the submarine springs. These sinkholes act as springs during the high water level seasons and as sinkholes during the dry seasons, exactly similar to the behavior of the submarine springs.

The average precipitation or the effective uniform depth (EUD) was calculated using two methods. The first method consisted simply of calculating the average precipitation recorded by the rainfall stations located within the catchment area, and resulted in an estimated EUD value of 971 mm/year. The second method consisted of plotting isohyetal contours using the precipitation data from stations within and outside the area. The catchment area was calculated by using a grid system. The EUD obtained using this method is 1,115 mm/year. The difference between the methods is in the order of only 12%. The EUD of 1,115 mm/year was adopted on the basis of several annotations.

The stratigraphic sequence within the 600 km^2 area is quite complex and diverse, starting from the oldest exposed formation, the Jurassic formation (J_4), to the most recent alluvial shoreline deposits. The stratigraphic column identified is typical for north Lebanon and was studied by several investigators (Moullard *et al.* 1967; Walley 1997). Table 2 summarizes each stratigraphic unit with a description of major hydrogeological characteristics. Figures 2 and 3 show a geological map and a cross-section of the study area, respectively, that were prepared during the study.

The general bedding attitude was found to be towards the west, and no obvious structural control was observed relating inland structures to the submarine springs. Eventually, two major types of recharge were identified in the area: (1) direct recharge into the C_4–C_5 aquifer, and (2) surface recharge from rivers into the C_4–C_5 aquifer.

Marine work results

Identification of the springs

Six permanent springs and six intermittent springs were identified and located on a map (Figure 4). Table 3 indicates the coordinates of the springs in the X-Y system. Except for the intermittent spring S12 only the permanent springs were investigated, since during the flow measurement period the intermittent springs did not show any discharge.

Since spring (S12) is believed to be the largest spring in the area and possibly one of the largest in the Mediterranean basin (Hakim 1976), in the absence of flow data it was deemed necessary to investigate some of its physical characteristics. Visual inspection by professional divers has shown the discharge outlet of the spring to be

Table 2 | Summary of stratigraphic units with indication of major hydrogeological features

Stratigraphic unit	Major features
Kesrouane Formation (J_4)	• Oldest exposed rocks in the region.
	• Mainly composed of vertical jointing that helps water to percolate.
	• Joints, fractures, karstification, dolomitization with some marly intercalations control the quantity and quality of the water circulating within this formation.
	• The general dip of this formation is toward the west; that is toward the sea where most of the water will go as deep recharge.
	• The Kesrouane Formation is an excellent aquifer forming the first water tower of Lebanon.
Bhannes Formation (J_5)	• Characterized by two different types of rocks that transform it into an impervious layer defined as an aquiclude.
Chouf Sandstone Formation (C_1)	• Average thickness ranging between 100–150 m.
	• Has the hydrogeological characteristics of a semi-aquifer.
	• Formation of a perched water table that might discharge at the outcrop in the form of a spring or seepage zone.
Abeih Formation (C_{2a})	• Average thickness of 130 m.
	• Has the characteristics of an aquiclude.
	• Acts as a confinement for Chouf Sandstone semi-aquifer.
Hammana Formation (C_3)	• Average thickness ranging between 115–150 m.
	• The varying lithology of the formation makes it a perfect seal or aquifer.
	• Forms the lower barrier of the second water tower of Lebanon, the Sannine Formation (C_4) which is the major outcropping formation along with the Miocene and Chekka Formation (C_6) in the catchment area.
Sannine Formation (C_4) and Maameltein Formation (C_5)	• Both formations do not present major lithological differences.
	• Combined formation forms a 900 m thick unit.
	• Last unit that was deposited across the country since later units are restricted to the flanks of the mountain ranges.
	• There is a high degree of fracturing and karstification in the Sannine Formation.
	• The Sannine-Maameltein Formations cover 45% of the catchment area and are thought to be the main aquifer for the submarine springs.
	• The Sannine-Maameltein succession has a pothole aspect and is characterized by the presence of sinkholes, such as the Bziza sinkhole. The Bziza sinkhole was tested by tracers, which showed that the sinkhole discharges in the sea near Chekka.

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Table 2 | Continued

Stratigraphic unit	Major features
Chekka Marl (C_6)	• Its thickness may reach up to 500 m in Chekka.
	• It is believed that the formation (C_6) is acting as a confining layer or aquiclude to the C_4–C_5 aquifer. No springs issue from this formation.
Miocene Formation (M)	• This formation is variable in thickness.
	• It is possible that the Miocene formation contributes to the water discharging from the submarine springs if it is considered that the Miocene outcrops in the sea beneath the quaternary deposits at the coast.
Quaternary Formation (Q)	• It is the most recent formation consisting of alluvial deposits, beach deposits, and sand.

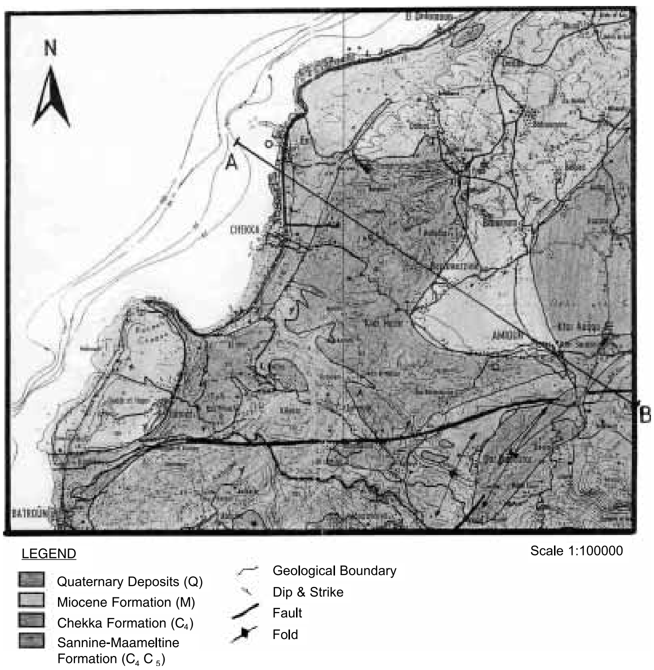

Figure 2 | Geological map of the catchment area.

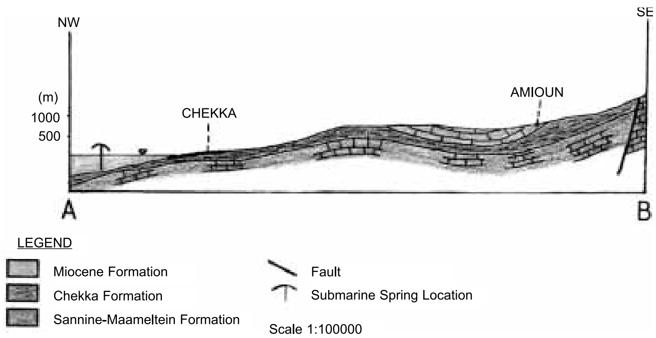

Figure 3 | Geological cross-section.

located at a water depth of about 80 m and with an estimated opening of about 10 m diameter. The opening flares up to form a larger opening of an estimated average diameter of 35 m at the seabed with a measured depth of 62 m. In the absence of any detectable flow from the remaining intermittent springs, it was not possible to locate the other springs by the divers. On the other hand, the permanent springs were easily located as their slicks were visible on the water surface (Figure 5).

Spring (S2) is the largest of the permanent springs. It consists of three discharge openings located at a water depth of about 20 m. These are denominated by I, II and III for reference purposes. Opening I has an irregular shape of a length of 120 cm (north-south direction) and a variable width. The maximum width at its centre is 50 cm. It discharges water continuously from the quasi-totality of its opening. Opening II, having the most irregular shape, is approximately 130 cm long (east-west direction) and has a maximum width of 60 cm. Several objects lying along its rim partially obstruct its opening, leading to a reduced discharge area. Opening III has a trapezoidal shape, with

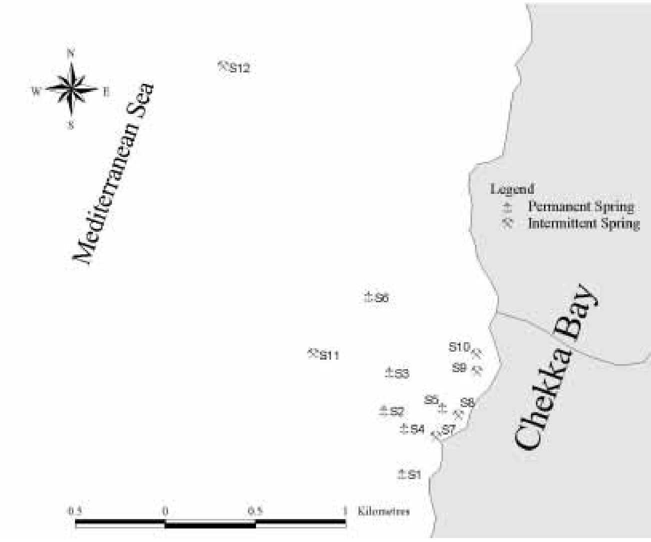

Figure 4 | Location of submarine springs in Chekka Bay.

Table 3 | Coordinates of the located springs in the Chekka Bay (km)

Spring	Type	X-coordinate	Y-coordinate
S1	Permanent	150.2	265.9
S2	Permanent	150.1	266.3
S3	Permanent	150.1	266.5
S4	Permanent	150.2	266.2
S5	Permanent	150.4	266.3
S6	Permanent	150.0	266.9
S7	Intermittent	150.5	266.1
S8	Intermittent	150.6	266.3
S9	Intermittent	150.6	266.5
S10	Intermittent	150.6	266.6
S11	Intermittent	149.7	266.6
S12	Intermittent	149.2	268.2

bases of about 80 cm and 35 cm, and a height of about 120 cm (east-west direction). With the opening clear from any obstruction, such a configuration was ideal for flow measurement using the available current meter.

The remaining five springs (S1, S3, S4, S5 and S6) were characterized by weaker flows from undefined openings and discharge through fractures in the soil. Spring (S4) appears to have the largest yield area with a discharge diameter of around 7 m. It is situated at a water depth of 11.5 m. Springs (S1), (S3), (S5) and (S6) have smaller discharge areas and are located at depths of 10.5, 16, 10.5 and 14 m, respectively. In addition to the X-Y coordinates indicated in Table 3, GPS records for the location of springs (S2), (S5) and (S12) are shown in Table 4. Since the springs are relatively close to each other, except for (S12), and the GPS has a limited accuracy (about 50 m), only the position of these representative springs was recorded.

Spring (S5) represents the springs closest to the coast (S1, S4 and S5), while (S2) represents those farther away (S2, S3 and S6), and (S12) is the farthest spring from the coast. It is to be noted that these readings are simply an indication of the approximate location of the slick of each of these springs on the sea surface.

Figure 5 | Submarine spring slick in the Chekka Bay.

Discharge of the springs

One of the main objectives of this fieldwork was to measure the flow of spring (S12). However, due to the excessive depth of the opening of the spring, and its dimensions, excessive time and effort was necessary to

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Table 4 | GPS records of selected submarine springs

Spring	Latitude	Longitude
S2	34°20′15.20″N	35°43′22.94″E
S5	34°20′6.68″N	35°43′29.31″E
S12	34°20′54.17″N	35°42′45.54″E

survey the area, install a system to set the flow meter, and then to take the measurements. Moreover, at such depths the divers could not make more than a single dive per day, and only for a short duration. The survey included an exploratory first dive in which the divers observed the absence of any flow from the spring, which was followed by a second and third dive directed at carrying out confirmatory flow measurements. All measurements taken across the outlet had negative values, indicating that the flow had reversed in direction. This phenomenon has been reported to occur at large cavities in the sea whenever these are not discharging (Ford & Williams 1989). Spring (S12) flows during a limited number of months, ranging from 3 to 6 months according to information supplied by local fishermen. They reported that the slick of the spring was still observable about a fortnight before the measurements were taken. This seems to indicate that the flow stops abruptly rather than gradually. Based on these observations, work on spring (S12) was discontinued and attention was directed at collecting flow and water quality data from the smaller permanent springs. It was decided to focus on spring (S2) mainly because of its significant flow and defined discharge openings. After a preliminary analysis of the flow in the three openings forming the spring, the flow meter was set to measure the discharge at opening III on 3 different days and for approximately 6 hours each day. The velocity measurements are shown in Figure 6.

The measured resultant velocities in each of the figures reflect the combination of the vertical and horizontal velocities. The results indicated a fairly constant velocity with an average of about 25 cm/s. Interestingly, a peak flow of about twice the average flow was detected in each of the recorded periods. Three

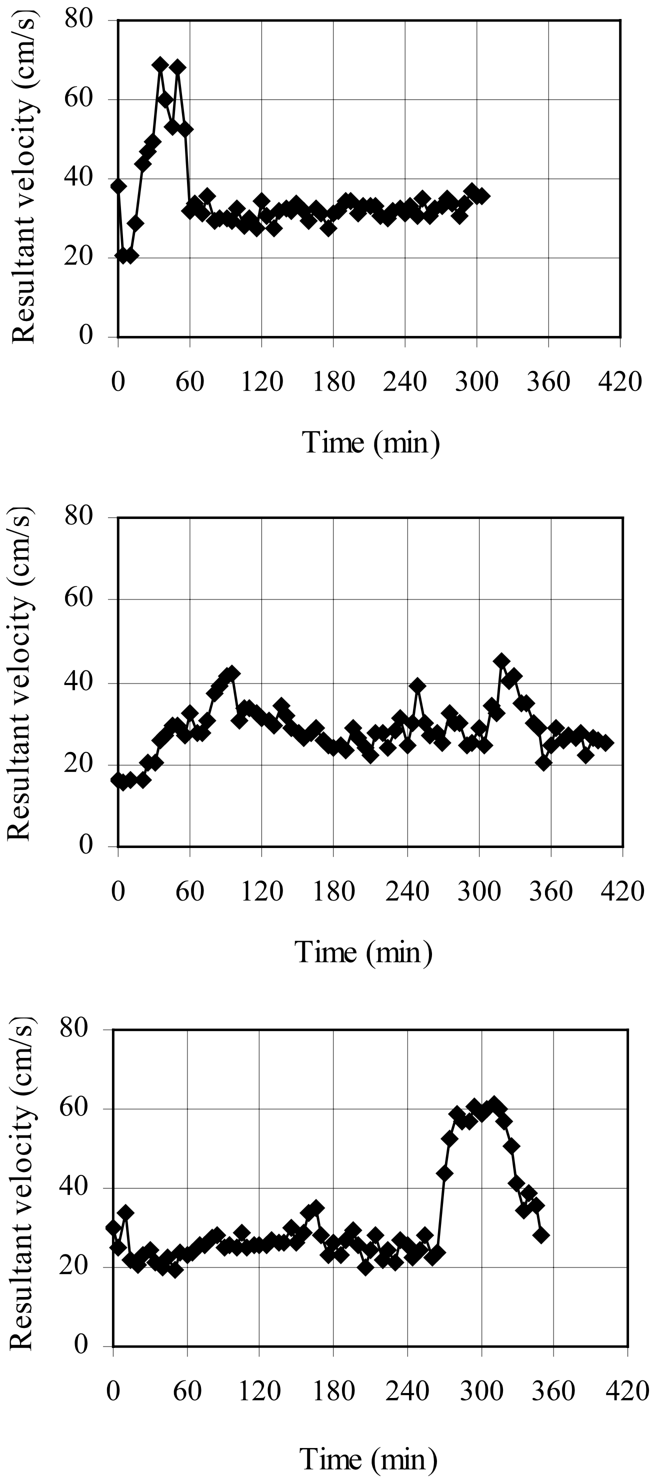

Figure 6 | Resultant velocities measured at the outlet of cavity III (spring S2) on three different days during the month of June.

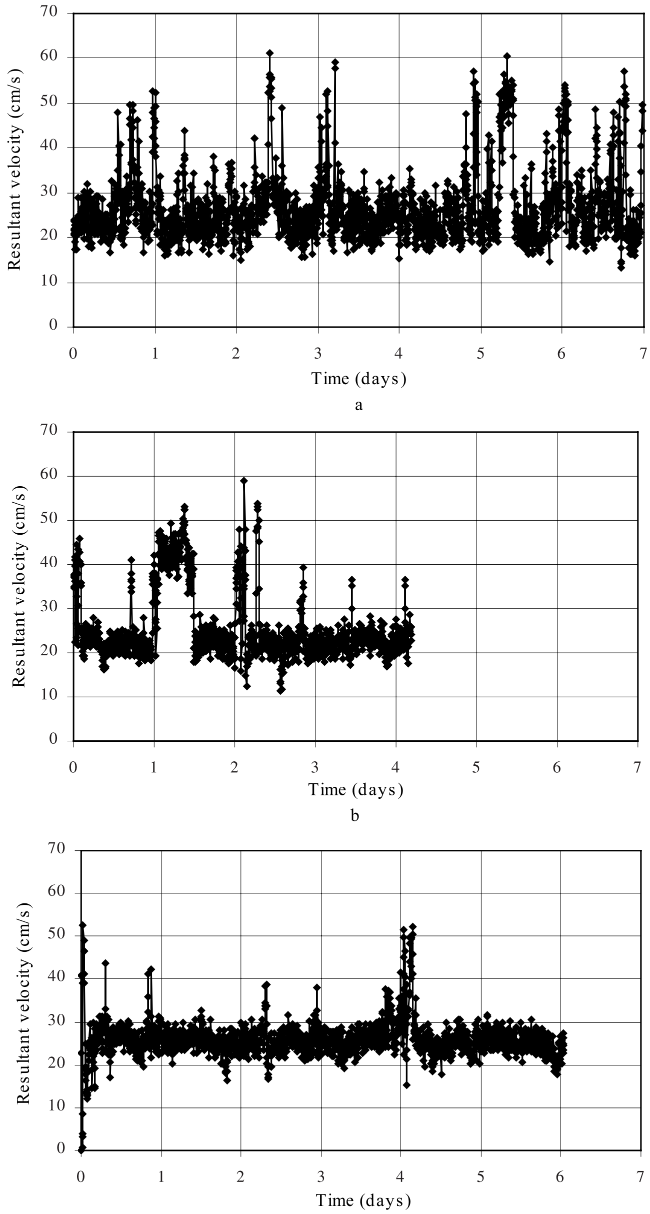

Figure 7 | Resultant velocities measured at the outlet of cavity III (spring S2) in three different months: (a) July; (b) August; (c) September.

one-week continuous flow measurements were then performed during the months of July, August, and September in order to determine whether any periodicity in the occurrence of these peaks exists and to verify if the flow decreases during the summer. The data obtained are presented in Figure 7.

The flow velocities did not show any significant variation during the summer period and the flow was relatively uniform and continuous. No periodicity was observed in the occurrence of peaks, and these were not considered to significantly affect the overall discharge behavior of the spring.

As a tentative estimate of the total flow discharged by the springs, it can be first assumed that from May to November (dry season), the 6 permanent springs are the only active ones. Spring (S2) has an average flow velocity of 25 cm/s and a total area of nearly 1.6 m^2, yielding a flow of about 0.4 m^3/s. It may be assumed that since the remaining five springs have relatively weak flows, as noted from field observations, the total flow from the permanent springs during the summer may not exceed 1 m^3/s (2.59 Mm^3/month). At the onset of the rainy season (December–April), while intermittent springs begin to discharge fresh water, permanent springs observe an increase in their flows by a factor of nearly 10, similar to subterranean springs and rivers (Ghannam 1999). As such, flow attributed to permanent springs could be as high as 10 m^3/s during the winter (25.9 Mm^3/month). Spring (S12) has an estimated peak flow of 50 m^3/s, probably from February to April. The remaining intermittent springs (10 as reported by Kareh 1967) may have a flow of about 15 m^3/s (38.85 Mm^3/month). According to the above assumptions, the total annual discharge may reach an amount as high as 730 Mm^3.

Water quality

Qualitative analyses of the water from the springs as well as from wells located onshore were performed. In the former, two testing procedures were used: direct field analysis and laboratory chemical analysis on collected samples. Laboratory tests were also conducted on samples collected from the onshore wells.

Table 5 presents the results obtained using the field water analyzer. The data summarize the results collected during the study period. Freshwater discharged from the springs was consistently colder, with a lower pH, a higher dissolved oxygen content, and approximately half the electrical conductivity as compared to seawater.

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Table 5 | Average values for certain parameters measured for seawater and freshwater using field water analyzer

Type of water	Number of readings	Temperature (°C)	pH	Dissolved oxygen (ppm)	Conductivity (mS/cm)
Seawater	12	25.2	8.17	6.5	64.4
Freshwater	20	18.8	7.5	8.3	29

Table 6 | Chemical analysis of water samples collected from spring (S2) and the sea and tested in the laboratory[a]

Analyte	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Seawater
Chlorides	11,500	12,900	12,350	13,350	12,350	26,400
Calcium	280	300	260	270	260	490
Magnesium	670	645	655	660	650	1,465
Sulfates	920	1,210	1,010	1,080	1,010	2,320
Nitrates	2.0	2.2	2.3	1.8	1.8	1.8
Sodium	7,900	7,290	7,780	8,750	8,750	16,000
Potassium	170	160	165	185	185	435

[a]All units in mg/l.

Table 6 shows the chemical analysis obtained for 5 samples of water collected from spring (S2) using a sampling pump. A seawater sample was also collected and analyzed for purposes of comparison.

Figure 8 provides a graphical comparison between seawater and submarine spring water for selected parameters.

The significant amounts of chlorides, magnesium, sulfates, and sodium indicate that the water discharged by the spring is mixed with seawater. The ratio between seawater concentration and spring water concentration for the measured ions is somewhat uniform (about 2.2), indicating that mixing of seawater and spring water is occurring prior to discharge into the sea. The concentration of such ions in typical mineral water seldom exceeds 10 mg/l. Other investigators had also encountered large amounts of chlorides in samples collected from the springs (Kareh 1966). One reason lies in the difficulty of retrieving clean samples from the sea. Kareh (1966) also collected samples during winter and found that chloride concentrations decreased dramatically. This may be attributed to the dilution induced by the higher flows of the submarine springs during that season. Table 7 shows the results obtained for water samples collected from the wells with depths ranging from 25 m to 30 m.

The concentrations of chlorides, sulfates, sodium, and magnesium were found to be much lower in the samples taken from the wells than in the samples collected from the springs. Except for well (1), the water in the wells is not contaminated with seawater. The fact that seawater contamination appeared to exist in well (1) indicates the imminent risk of further seawater intrusion if spring water exploitation is performed without control. In addition,

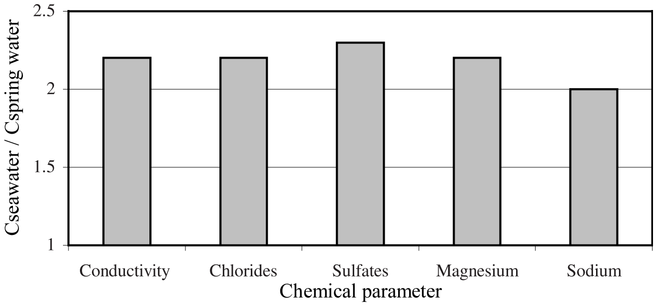

Figure 8 | Ratios of the concentrations of certain parameters in seawater to those in spring water.

Table 8 | Bacteriological analysis of spring water[a]

Type of coliform	Sample 1	Sample 2	Sample 3	Control (seawater)
Fecal	3	4	7	2
Total	9	4	10	2

[a]Units are in cfu/100 ml.

Table 7 | Water quality from the tested onshore wells[a]

Analyte	Well 1	Well 2	Well 3
pH	7.38	7.32	6.65
Conductivity	3.44	1.24	1.19
Chlorides	800	260	185
Magnesium	110	52	35
Sulfates	50	8.1	9.9
Nitrates	13.4	15	45.5
Sodium	3200	680	430
Potassium	170	23	6.5

[a]All units in mg/l, except for pH (unitless) and conductivity (ms/cm).

extremely low concentrations of heavy metals were detected in the three samples.

Table 8 shows the results from the microbiological tests performed on three samples collected from the submarine spring. The limited number of counts observed is not sufficient to confirm bacteriological contamination, as the source of contamination could have been due to sampling procedures. Coliforms were also detected in the control seawater sample taken 2 km from the coast.

Socio-economic results

Fishermen survey

If any negative impact is to occur as a consequence of the exploitation of the freshwater submarine springs in the Chekka Bay, such an impact will mostly affect the marine environment and subsequently the fishing industry. In order to evaluate the extent of this impact, special attention was awarded to the survey pertaining to the fishermen in the area. The results of the questionnaires and the interviews conducted with 45 fishermen (representing 20% of the population practising the profession in the Chekka area) are summarized as follows:

1. The fishing profession is practised by a wide range of age groups (those interviewed range between 25 and 68 years).
2. Of the sample group, 82% are married, and more than 70% have family sizes of 4–6 members.
3. Of the total number of fishermen, 89% practise fishing on a full-time basis, while the remaining 11% practise the profession on a part-time basis.
4. A correlation was found between the fishermen practising on a full-time or part-time basis and their educational level, whereby those practising on a full-time basis represent those with an intermediate education level or lower, while those practising on a part-time basis are those with higher education levels.
5. In general, fishermen were not responsive when asked about their average monthly incomes, however, it is estimated that an average monthly income per fisherman is in the range of 350 US $.

Types of fish and sale value

There are eight most common types of fish that inhabit the Chekka and Anfeh waters over the different seasons. Six additional types are present in the area, but these are of lower importance and less frequently found.

On average, the sale value per kilogram for the different types of fish was found to range between 2 US $ for the cheapest and 30 US $ for the more expensive ones. However, the lack of governmental support and the competition created by imported fish, typically sold at lower prices, place fishermen in a difficult situation.

Exploitation impact on fish population

About 85% of the fishermen interviewed believe that the exploitation of the springs will have a minimal impact, if any, on the fish population. The justifiable reason is that only one kind of fish (Mugil) inhabits the vicinities of the submarine springs, and this species is of minor importance as it is not commonly found. In any case, it may adapt to the increased salinity of the ambient water. This opinion was negated by the specialist interviewed at the Ministry of Agriculture who declared that the exploitation of the spring water will lead to detrimental impacts on the fish population in the Chekka bay.

Industrial and household surveys

The results of the survey on the industrial sector indicate that all the factories in the area have their own private wells, and therefore do not face any water shortage problems. In the case of the cement factories, the bulk of the water is used for cooling purposes and the effluent is not recycled. The water is not used in the production process. In the case of the fish-canning factory, water is used in the cleaning, canning, and steaming processes. The daily water demand is between 50 and 70 m^3/day. Water forms a major part of the production process in the sugar factory, and the water demand is estimated at one ton per ton of sugar produced. Water is also a primary element in paper production. The daily water demand for the paper factories is at least 5 m^3 per factory.

In terms of water quality, most of the industries concerned are treating their water to meet drinking water standards, particularly by decreasing the salinity levels encountered. According to the survey, the cost of the operation and maintenance of the wells and the pumps is reasonable and affordable. No other problems are encountered in the quality of the water from these wells.

At the household level, the responses on the questions addressed were limited. The responses indicate that a shortage in domestic water supply occurs mostly during the summer due to cuts in the power supply rather than a water shortage. This deficiency in water is normally overcome by the purchase of water handled by tankers. The current purchase price reported was 10 US $ for 4,000 litres (or 2.5 US $ per cubic metre). The rate paid by the subscribers to the Chekka water authority varies between 80 and 100 US $ annually, which is equivalent to about 45 to 55 cents per cubic metre, based on a supply of 500 litres per day. Some of the people interviewed doubted the purity of the water supplied, and thus have resorted to the purchase of bottled water at an average cost of $5.3 per box of 12 1.5-litre bottles. However, only a limited number of families resorted to this practice because of the expense involved.

Cost benefit analysis

Major assumptions of the analysis

The cost-benefit analysis (CBA) theory was adopted in the economic feasibility study. The analysis was applied to two scenarios for the exploitation of the submarine springs, by inland and offshore drilling. This requires a description of two alternative designs followed by an evaluation of the expected costs (i.e. investment costs, operation and maintenance, etc.) and benefits (i.e. water value, etc.).

The physical location (distance from the shore and depth of outlet) of the springs and the salinity of the spring water as determined by the marine studies have shown that offshore exploitation of the submarine springs is technically and financially unbeneficial. For this purpose the offshore exploitation scenario was discarded, and so the economic evaluation was restricted to onshore exploitation. In this context, indirect costs and benefits of the project were considered, including the contribution of the new sources of water to the potential local or national deficit and the impact of an increase in salinity on fish populations.

Table 9 | Cost (US$) of onshore exploitation

	Depth (m)		
Cost	**50**	**100**	**150**
Capital cost ($)	7,500	15,000	26,250
Operation cost ($/m^3)	0.1	0.12	0.16
Maintenance cost ($/m^3)	0.05	0.05	0.1

The CBA included a net present value (NPV) and benefit-cost ratio (B/C) analysis. The analysis was conducted for three flow levels with a minimum flow (F_1) equal to 150 m^3/d, an average flow (F_2) equal to 225 m^3/d, and a maximum flow (F_3) equal to 300 m^3/d. In addition, three levels of depth were considered in the exploitation of the springs: $D_1 = 50$ m, $D_2 = 100$ m, and $D_3 = 150$ m. A 10% annual depreciation cost was adopted. An interest rate of 6%, being the current rate considered locally for public projects, was applied. However, two additional interest rates of 8 and 10% were considered in the calculations of NPV and B/C to test the feasibility of the project at higher interest rates. Capital, operational, and maintenance costs were considered to be a function of the depth and the water flow (Table 9), while benefits are a function of water flow. Note that water transmission costs were not included in the analysis, and therefore profits of the project are somewhat overestimated.

However, in case water is also distributed to other regions of the country, which would considerably increase transmission costs, these should be incorporated in the economic analysis of the project. As for the price of water, three scenarios were considered: namely 0.3, 0.4, and 0.5 US $/m^3.

Results of the economic analysis

The option of inland exploitation of the submarine springs was found to be economically feasible for all tested scenarios except for (D_3) at flow rates (F_1) and (F_2). Therefore, the project is financially viable at costs of 0.40 and 0.50 US $/m^3 and partly viable at the low cost of 0.30 US $/m^3. Obviously, as the price of water increases, more benefits are generated. Table 10 shows the different B/C values for the considered water prices, well depths, water flows, and discount rates. The table also indicates the minimum and maximum B/C obtained.

The minimum value (0.81) corresponds to the most critical condition, whereby water is sold at the lowest price, the well depth is highest, water flow is lowest, and discount rate is highest. The maximum value (3.19) corresponds to the most favorable scenario. Finally, it has also been verified that the project is economically feasible at the most critical condition (deepest well, highest flow, and maximum interest rate) at a very competitive water price of 0.30 US $/m^3.

Estimated flow versus recharge area

Based on the geological map and the catchment areas of the three rivers draining the Chekka region, the submarine springs are recharged through the following potential sources:

1. Infiltrated water through the outcrop of the C_4–C_5 formation.
2. Percolated water from the surface water rivers crossing the C_4–C_5 exposure.
3. Groundwater leakage from remote aquifers (Jurassic) to the C_4–C_5 formation through fault systems.

The last possibility necessitates extensive field investigation in order to accept or deny the premise of interconnectivity of aquifers. Furthermore, the quantification of the actual groundwater leakage is difficult to determine. On the other hand, careful gauging of the rivers, before and after the crossing of the C_4–C_5 formation, is mandatory in order to determine the amount of river runoff lost to recharge in the aquifer. Because this gauging is not available, the only possible method is to estimate the percolation rate over the length of river stretches running over the C_4–C_5 outcrop. The total length of the rivers crossing the C_4–C_5 formation in the region of Chekka is approximately 11 km. Assuming that the rivers' average width is 10 m, and assuming a percolation rate of 0.5 m/day (this rate is conservative for a karstic terrain especially

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Table 10 | B/C for different water prices, well depths, water flows and discount rates

	P=0.3 US $			P=0.4 US $			P=0.5 US $		
	6%	8%	10%	6%	8%	10%	6%	8%	10%
$D_1 = 50$									
$F_1 = 150$	1.70	1.68	1.65	2.26	2.23	2.21	2.83	2.79	2.76
$F_2 = 225$	1.79	1.77	1.76	2.38	2.36	2.34	2.98	2.95	2.93
$F_3 = 300$	1.92	1.90	1.89	2.55	2.54	2.52	**3.19**	3.17	3.15
$D_2 = 100$									
$F_1 = 150$	1.34	1.32	1.29	1.79	1.75	1.72	2.24	2.19	2.15
$F_2 = 225$	1.46	1.44	1.42	1.94	1.92	1.89	2.43	2.40	2.36
$F_3 = 300$	1.64	1.62	1.60	2.18	2.16	2.13	2.73	2.70	2.66
$D_3 = 150$									
$F_1 = 150$	0.85	0.83	**0.81**	1.13	1.11	1.08	1.41	1.38	1.35
$F_2 = 225$	0.93	0.92	0.90	1.24	1.22	1.20	1.55	1.53	1.50
$F_3 = 300$	1.06	1.05	1.03	1.41	1.39	1.37	1.77	1.74	1.72

if huge water losses through sinkholes are excluded) over a period of 6 months, then the total annual recharge from the river flow is approximately 20 Mm^3/year. This value should be confirmed through further investigations.

Previous works have suggested a total discharge of 60 m^3/s for the submarine springs and a recharge area of 200 km^2. The C_4–C_5 formation is not limited to the Chekka region, but extends from Jounieh, in the south, to Becharri, in the north, to cover a total area of about 2,100 km^2. Therefore, it is difficult to delineate the area of the C_4–C_5 formation that is contributing to the recharge of the submarine springs. The average annual precipitation (over the rivers' catchment areas) is equal to 1,115 mm/year. In view of the absence of records for evapotranspiration and run-off, estimates of 50% and 20%, respectively, can be adopted for first-hand calculations. As such, a rate of 335 mm/year could be assumed for the amount of infiltration recharge over the C_4–C_5 formation. Accordingly, if the whole Cenomanian-Turonian aquifer, extending from near Jounieh to Becharri, is contributing to the recharge of the submarine springs, then an annual recharge of 700 Mm^3 could be anticipated in these springs. It is certain that the whole of this area is not participating in the recharge of submarine springs, and consequently the total discharge of the springs should be less than the estimated value of 730 Mm^3/year. If, on the other hand, the recharge area delineated by the total catchment area defined by the river basins bounding the area, estimated at 900 km^2 for all formations (which is not the case as the C_4–C_5 area is only 200 km^2) is considered, then the annual recharge will amount to about 300 Mm^3. Accordingly, the annual recharge should fall between 300 and 700 Mm^3.

It is to be noted further that the reported estimated peak discharge of 50 m^3/s from the major intermittent spring is an exaggerated figure as this spring would by itself discharge between 215 and 430 Mm^3/year, based on an average flow of 27.5 m^3/s (average of 5 m^3/s at minimum flow and 50 m^3/s at peak flow) over a period of 3 to 6 months. The contradictory figures shown above confirm the current uncertainty regarding the reported discharge quantities of the Chekka submarine springs. It is man datory that further investigation be undertaken in order to establish reliable discharge values.

Mode of exploitation

The distance from the shoreline and the depth below the mean sea level are two major factors that control the method of exploitation of the submarine springs. One additional factor to be considered is the mode of discharge of the springs (conduit or fractured). This factor influences the velocity of water discharge and the aerial extent of the plume. The current study has revealed the occurrence of freshwater plumes at a distance from the shoreline ranging between 500 and 1,500 m. The locations of the plumes do not accurately represent the location of the points of discharge of the submarine springs at the sea bottom, because of the three-dimensional setting of the freshwater cone within the seawater. However, these large distances indicate that the submarine springs are discharging at relatively far distances from the seashore. Moreover, the studies have demonstrated that not all springs are occurring at shallow depths below the mean sea level. In fact, one important spring is located at a depth of about 85 m while most of the springs are discharging at depths ranging between 20 and 85 m. In addition, the water quality tests at the outlets of the submarine springs have indicated substantial mixing between the freshwater and the seawater which renders it unfit for use unless treated. All these factors render the offshore exploitation of the submarine springs technically difficult, qualitatively contaminated, and financially expensive. A more suitable alternative would be to tap the submarine springs inland through wells of variable depths ranging from 50 to 150 m. However, such form of exploitation has to be controlled to avoid seawater intrusion, which the study has shown to have already occurred in certain areas. This mode of exploitation can be achieved at a relatively low cost, using local skills and technology.

Impact assessment

In the short term, no major impacts have been anticipated. However, in the longer term, two impacts have been considered, namely a change in marine ecosystem leading to loss of certain marine species, and seawater intrusion due to over-exploitation of fresh water leading to contamination of the latter.

As mentioned earlier, the survey conducted concerning the first issue resulted in two contradictory opinions from fishermen and the Ministry of Agriculture. Two facts are mentioned here to attempt to find a preliminary scientific answer to this issue.

1. Only 6 of the 17 springs in the Chekka Bay are permanent, and the remaining springs flow during limited months of the year; therefore there is a natural cycle in the bay where salinity would eventually increase and decrease depending on the number of springs discharging. In addition, the major spring only flows during 2 or 3 months of the year, and should not contribute significantly to the overall decrease in salinity in the seawater surrounding it, except during that limited period of the year.
2. Actual field measurements of electrical conductivity taken during the marine study showed that salinity above the cavities of the springs is very close to that of the surrounding seawater, and decreases significantly only when readings are taken from inside the spring cavities (prior to the complete mixing of waters); this means that freshwater is rapidly mixing with seawater without really significantly affecting the seawater salinity, except perhaps in localized plumes.

Based on these facts, it appears that minimal impact on the marine ecosystem will occur due to potential freshwater exploitation, and no mitigation measures are necessary.

When questioned about the quality of the groundwater in the Chekka area, local residents appeared to agree on the following:

1. Wells are present in almost every house in the region, and exploitation of such wells is totally uncontrolled.

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2. The region can be subdivided into two sub-regions: one where no seawater intrusion has been detected, and another where seawater intrusion has been detected; the boundary between these two areas is almost in the center of the bay and extends inside the Chekka area.

From these facts it can be concluded that the geology of the area is propitious to seawater intrusion if freshwater pumping is not controlled. It is therefore strongly believed that any unmanaged water exploitation in the region would lead to deterioration of the water quality. A maximum pumping rate has to be set in case the submarine springs of Chekka Bay are exploited. The value of this rate is to be calculated based on available data coupled with mathematical modeling to simulate the behavior of the seawater-freshwater interface with varying pumping rates. In conclusion, it appears that the exploitation of the submarine springs will cause minor negative impacts on the surrounding environment, provided adequate measures are taken, particularly in terms of setting appropriate freshwater pumping rates from the feeding aquifer. On the other hand, the socio-economic benefits of the project are promising based on the following facts:

1. According to local water authorities, current sources of water may not be able to meet the growing demand with the increase in population; water deficiency is already perceived at the household level, particularly during the summer, when residents need to opt for alternative sources of water such as mobile water tankers and bottled water.
2. Industries in the area have a moderate water consumption, and although they operate private wells, they would benefit from the additional water provided by the project, particularly if the government imposes regulations and controls on private well usage in the future, therefore limiting water availability from private sources.
3. The economic feasibility of inland exploitation was demonstrated in the socio-economic analysis for several well depths, flows, and interest rates.
4. The presence of good water sources may promote and enhance agriculture in the area and attract industries that are water intensive, thus improving the standards of living of the population in the area.
5. Major cities like Tripoli and Beirut, where water scarcity is becoming frequent, could benefit from the exploitation of submarine springs in Chekka. Water would be stored and sent to locations requiring extra supplies.

CONCLUSIONS AND RECOMMENDATIONS

The current investigation has determined the framework within which the submarine springs occur and discharge their waters in the sea. Furthermore, it has shown the feasibility of onshore exploitation of the springs under different operation scenarios. This study also contributed in narrowing down the possibilities of the potential yield of the springs to a more realistic and factual discharge range. However, it is anticipated that further investigations are necessary along six major tracks:

1. Determination of the real annual discharge of the submarine springs through a monthly compilation of discharge velocity measurements of the different springs.
2. Measurement of precipitation and snow melting data to be correlated with springs' discharge.
3. Delineation of the recharge area through multiple dye-tracing experiments in the field. Dye could be injected into the sinkholes and shafts or through existing water wells in the area.
4. Determination of a maximum safe pumping rate in case of onshore water exploitation to avoid seawater contamination in the aquifer.
5. Determination of the actual impact, if any, of the exploitation of the submarine springs on the fish population through further environmental assessment.
6. Study of the feasibility of exploiting large-scale seasonal discharges through storage and transport to more remote areas of the country, including evaluation of the impact of such a venture on the area and region.

These exercises could assist in the delineation of the groundwater divides, in the determination of the type and velocity of groundwater flow, and in setting limits for the exploitation of the water. It will also establish the feasibility of exploiting such a source to meet water needs that could occur elsewhere in the country.

ACKNOWLEDGEMENTS

This study was conducted with the aid of a grant from the International Development Research Center, Ottawa, Canada.

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First received 20 July 2000; accepted in revised form 28 August 2001