AMERICAN UNIVERSITY OF BEIRUT

GROUNDWATER-BASED WATER PROVISION OF GREATER BEIRUT AREA: POLICY OPPORTUNITIES AND CHALLENGES

by

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AN ABSTRACT OF THE THESIS OF

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Water shortage in Lebanon is perceived as a reality to tackle with engineering solutions, while the major problem is a matter of management, along a futile regulatory framework. Accordingly, this research aims at delving in the potential alternative of a groundwater-based supply in the Greater Beirut Area, in contrast to national strategies promoting dams and other white elephant alternatives. This thesis focuses on a study area comprising of the governorates of Beirut and Mount Lebanon including the districts of Aaley, Baabda, Beirut, Chouf, Jbeil, Keserwan and Metn and on a served area being the Greater Beirut Area. The thesis uses qualitative and quantitative methods to verify whether the proposed alternative is feasible. Data was collected or derived from available literature; interviews along with a Geographic Information System platform to support the study. Based on the analysis of existing wells, springs and water demand in the study area, existing groundwater resources are able to cover the needs of the Greater Beirut Area. Results showed that the water demand ranges between 89.7 and 224.3 MCM in 2020 and decreases to between 85.2 and 213.1 MCM in 2035 for a demand ranging between 100 and 250 L/day/capita. In contrast, the Greater Beirut Water Supply Augmentation Project bets on a population growth and an increase in water demand between 2010 and 2035 to showcase the need for large infrastructure projects and to promote proposed dams.

Keywords: Groundwater, Water Resources, Water Demand, Dams, Wells, Spring Discharge Rate, Reservoir-Induced Seismicity.

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LIST OF ABBREVIATIONS

AUB	American University of Beirut
BGR	German Federal Institute for Geosciences and Natural Resources
BOD	Biochemical Oxygen Demand
CDR	Council for Development and Reconstruction
COD	Chemical Oxygen Demand
DGUP	Directorate General of Urban Planning
DSP	Dam Safety Panel
EIA	Environmental Impact Assessment
ESIA	Environmental and Social Impact Assessment
ESP	Environmental and Social Panel
FAO	Food and Agriculture Organization
GBA	Greater Beirut Area
GBWSAP	Greater Beirut Water Supply Augmentation Project
GDP	Gross Domestic Product
GIS	Geographic Information System
IAPCA	Institute of Archaeology and Polish Centre for Archaeology
Km	Kilometer
Km^2	Squared Kilometer
Km^3	Cubic Kilometer
L	Liter
L/day	Liters per Day
L/day/capita	Liters per Day per Capita
LMP	Local Management Plan
M	Meter
M^2	Squared Meter
M^3	Cubic Meter
M^3/day	Cubic Meter per Day

M^3/hour	Cubic Meter per Hour
M^3/second	Cubic Meter per Second
MCM	Million Cubic Meters
MoA	Ministry of Agriculture
MoE	Ministry of Environment
MoEW	Ministry of Energy and Water
MW	Megawatt
NKP	Nitrogen, Phosphorus and Potassium
NPMPLT	National Physical Master Plan of the Lebanese Territory
NWSS	National Water Sector Strategy
RIS	Reservoir-Induced Seismicity
SGMA	Sustainable Groundwater Management Act
TWCC	The World Coordinate Converter
UN	United Nations
UN-DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
UTM	Universal Transverse Mercator
WHO	World Health Organization
WTP	Water Treatment Plant
WWAP	World Water Assessment Program

CHAPTER 1

INTRODUCTION

During the French Mandate, Lebanon was named the Water Tower or the "Chateau D'Eau" of the Levant. Policy-makers in the water sector have often claimed that there is urgent need for rapid intervention and action through large engineering solutions, notably the construction of dams. Groundwater has always been the main source of provision but was never given priority by the Lebanese water reforms as an alternative and sustainable source of water. Groundwater governance in itself has been a missing piece in the national water governance and water public policy puzzle.

To date, hundreds of millions of dollars have been spent and mainly lent by international donors to Lebanese government to undertake studies and strategies which all concluded that dams are the primary solution for water supply shortages in Lebanon. A major example is the Lebanese government-led Greater Beirut Water Supply Augmentation Project (GBWSAP) to increase the volume of water available to the Greater Beirut Area (GBA). The Project is financed by the World Bank, the Islamic Development Bank and the Government of Lebanon. As part of the project, the Bisri Dam on the Bisri River designed to store 125 Million Cubic Meters (MCM) of water and supply the GBA (World Bank, 2013). Saroj Kumar Jha, World Bank Regional Director for the Middle East, stressed on the importance of the Bisri Dam project in resolving severe and chronic water shortages (World Bank, 2017). The

Council for Development and Reconstruction (CDR) also stated that the project is an "economically efficient" solution to the severe shortages in public supply of water in the GBA. In addition to the Bisri Dam, the Jannah Dam on the Nahr Ibrahim River was also designed to store 38 MCM of water to supply the areas of Byblos, Beirut and its suburbs (BMLWE, 2014). Aside from their expected social and environmental impacts and their financial burden, dams may not be a suitable option because of their financial and socio-environmental costs, as well as Lebanon's geological nature and seismicity (Nemer, 2019). Lebanon is known for its tectonic setting and seismic potential of its active faults. Also Lebanon's major geological formation is made of karst limestone considered as highly pervious, thus not suitable for water retention in dams, especially when feasibility studies are lacking substantial investigations.

This research aims at delving in the potential alternative of a groundwater-based supply in the GBA, in contrast to national strategies promoting dams and other alternatives. This thesis attempts to answer the following: Would a Groundwater-based water supply in the Greater Beirut and Mount Lebanon Area be a potential sustainable alternative to dams? Both qualitative and quantitative methods are used to verify whether the proposed alternative is feasible. Data was collected or derived from available literature; interviews along with a Geographic Information System (GIS) platform are employed to support the study.

This thesis focuses on an area comprising of a study area and a served area (Figure 1). The study area (outlined in black) covers the governorates of Beirut and Mount Lebanon and covers the 7 districts of Aaley, Baabda, Beirut, Chouf, Jbeil, Keserwan and Metn and is studied for water supply purposes. The GBA (outlined in red) is the served area to be supplied by study area based on its demographic characteristics and water demand.

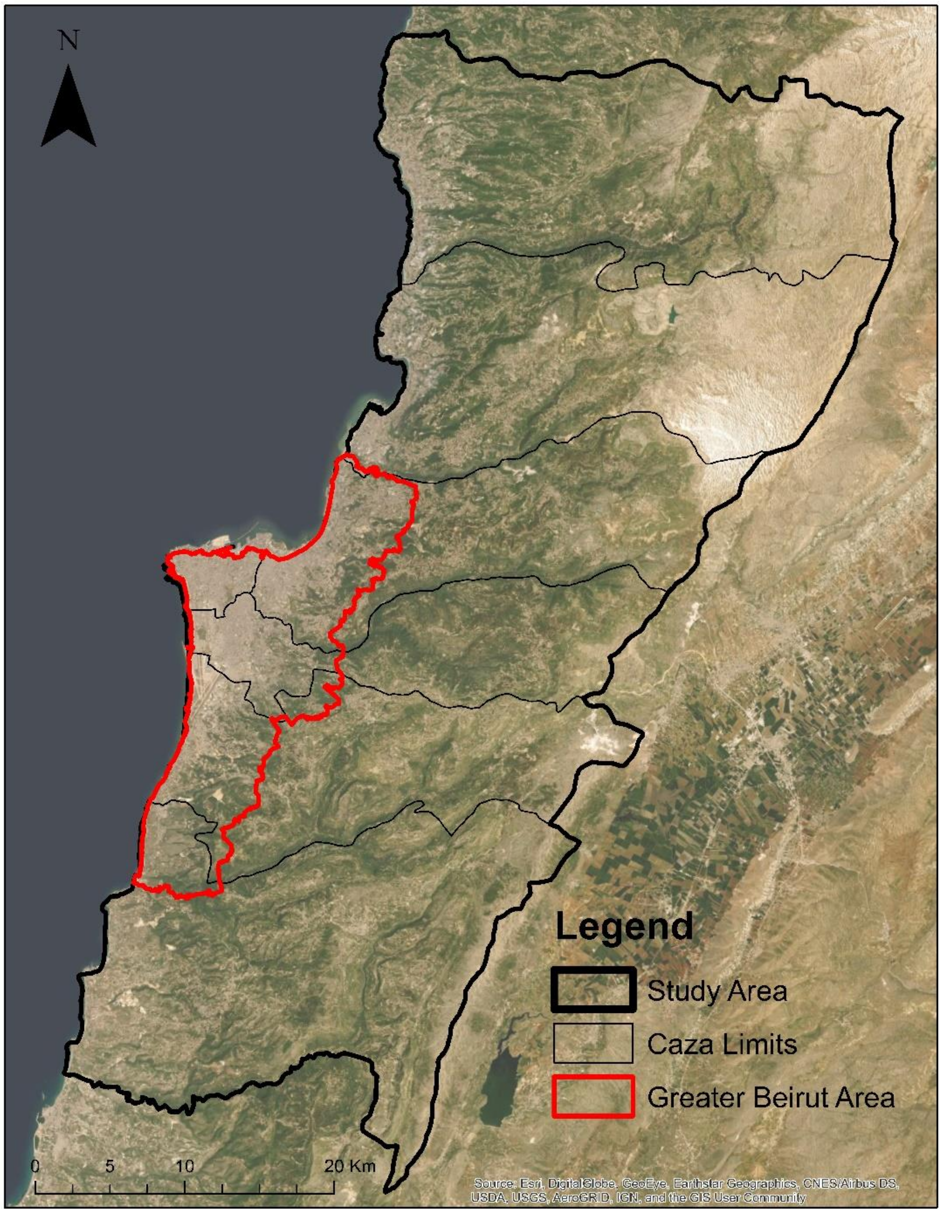

Figure 1 Study Area and Served Area
(Basemap Source: ESRI, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

The following thesis is divided into five (7) main chapters. The first chapter introduced the herein thesis. The second chapter presents the methodology and the different methods used. The third chapter highlights the concepts of groundwater governance and management, and presents groundwater policies around the world. The chapter also pinpoints the environmental and social impacts of dams globally and nationally, and gives an overview of proposed dams in Lebanon, and presents the trend of dam decommissioning in many countries. The fouth chapter provides an overview of the groundwater resources and provisions in Lebanon, and of the legal framework of Lebanese groundwater, in addition to a presentation of groundwater recharge factors and potential sources of groundwater pollution in the country. The fifth chapter provides a detailed assessment of groundwater resources and infrastructure in the GBA in addition to water demand calculations. The sixth chapter presents the main findings of this research and provides recommendations to be taken into considerations by policy and decision makers. Finally, the seventh chapter concludes the herein thesis with a summary of the results and recommendations and with suggestions of future research subjects.

CHAPTER 2

METHODOLOGY

The thesis aims at assessing groundwater resources in the Greater Beirut and Mount Lebanon area. The area is subject to several official studies stressing on the importance of dams to maintain a sustainable water supply for residents. This thesis investigates the possibility of relying on existing groundwater resources in the area using both qualitative and quantitative methods.

From a qualitative sense, a review of the available literature, studies and research related to water resources management were conducted. A conceptual framework was built to serve as a road to pursue the investigation consistent with the objectives of this thesis using a mix of the variables from the literature review. National laws, regulations and policies were also examined to evaluate the groundwater-related ones. Policies regarding groundwater management in Lebanon were assessed in the aim of evaluating the effectiveness of the current framework in achieving sustainable management of the resource. Thus, relevant policy papers, laws and decrees were analyzed. In addition, a review of groundwater management guidelines and lessons learned from other countries also helped in understanding groundwater vulnerability, quality, quantity and decision-making around the world.

On the other hand, the Bisri and Jannah dams are taken as examples of dams in Lebanon. Their project description was reviewed and complemented with quantitative data for assessment. Moreover, interviews were conducted with public officials from administrations involved in the water sector as key informants who could help build a reasonable understanding and shed light on the topic at hand. All these qualitative methods helped point out the current challenges in the water sector in Lebanon and provide useful approaches to overcome them.

From a quantitative approach, data on existing public and private wells and abstraction rates in the study area were collected from the Ministry of Energy and Water (MoEW). Available maps or ones found in literature were also used to identify and locate different aspects related to groundwater management in Lebanon: patterns of urbanization, land use and land cover, existing wells, as well as geological, hydrogeological and seismic patterns. The methodology is supported by the use of a Geographic Information System software, ArcGIS 10.5. Data on existing public and private wells in the study area were collected from the MoEW after having submitted a letter asking the General Director of the MoEW to provide the data on existing private and public wells in the governorates of Beirut and Mount Lebanon for academic purposes. The ministry only provided the number of private wells in Mount Lebanon and Beirut. As for public wells, data was provided in numerical format and included, location of public wells, their stereographic coordinates, their depth in meters and their abstraction rates in cubic meters per hour if available and operational status (in service, not yet in service or out of service). Stereographic coordinates were converted to Universal Transverse Mercator (UTM) using The World Coordinate Converter (TWCC). Once coordinates were converted to UTM, data was transferred to ArcGIS. On the other hand, both personal GIS shapefiles and maps available in literature were used in this study. Shapefiles including but not limited to Lebanese administrative limits, population, rainfall, geology, seismicity and land use were compiled and handled on ArcGIS to generate relevant and useful data. Official population data was found in the 2004 National Physical Master Plan of the Lebanese Territory (NPMPLT) report (CDR, 2004) out of which population percentages were estimated for each district and cadastral unit and applied to the United Nations' Department of Economic and Social Affairs (UN-DESA) population estimates and projections (UN-DESA, 2019).

Consequently, both qualitative and quantitative data were collected and merged together for extensive evidence-based analysis, in the purpose of examining the proposed alternative of this thesis: relying on groundwater resources, and reconsidering policies, to supply the GBA with domestic water. This alternative comes without depleting the resources or preventing other Lebanese regions from having their share of groundwater.

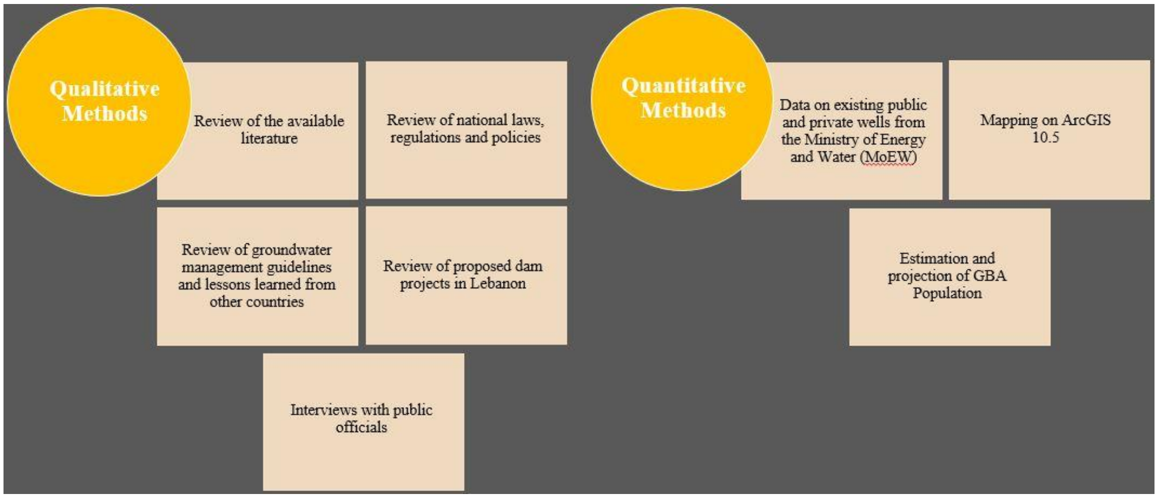

Figure 2 Methodology flowchart

CHAPTER 3

LITERATURE REVIEW

3.1 Groundwater: Governance, Management and Policy Making

Groundwater is water stored in and moving through geologic formations called aquifers. Aquifers are layers of highly permeable rocks/material with relatively high porosity that can store and transmit large quantities of ground water (Doummar, 2014). The depth of the groundwater is highly variable and can range from very shallow to very deep. Usually, water tables are shallow near permanent surface water bodies. Also, the elevation of the water table varies seasonally and from a year to another, as it is affected by rainfall, snowfall and groundwater recharge rates.

Groundwater is a major source of domestic, potable, agricultural and industrial water supply worldwide. To date, 50 percent of the world's drinking water supply and 43 percent of the global irrigation water is provided from Groundwater (FAO, 2010). Over 2.5 billion people from around the world depend exclusively on Groundwater resources to satisfy their basic daily water needs (UNESCO, 2012), and the volume of Groundwater abstractions is increasing between 1 and 3 percent annually (Margat and van der Gun 2013; Wada et al. 2013). According to the European Economic Commission, groundwater is the main source of domestic and drinking water in the majority of European countries. In Budapest, Copenhagen, Hamburg, Munich, Rome and Vienna, water supply is almost completely provided from groundwater. In some countries of the world like Bulgaria, Hungary and Russia, there is strict water legislation according to which fresh groundwater shall only be used as a domestic and drinking water supply. It is only possible to use groundwater for industrial or irrigation purposes in areas with considerable groundwater reserves with a special permit issued by nature-protecting institutions. In a large number of countries, groundwater is the foundation on which agriculture, urban development, rural jobs, and safe drinking water supply systems have been built, making it a major contributor to Gross Domestic Product (GDP). Groundwater irrigation contributes an estimated US$ 10-12 billion per year to the Asian economy excluding earnings from groundwater sales for irrigation which increases the estimate to US$ 25–30 billion (Shah et al., 2003). In 2004, the total annual value of the groundwater draft for different sectors in the United States of America (USA) was valued at US$ 20.9 billion. In 2013, Australia's estimated annual economic value of the groundwater draft was US$ 3.85 billion.

Extensive exploitation of groundwater tables implies impacts on geology, hydrogeology, biodiversity, water quality as well as on communities. In terms of geology, the drilling of wells requires excavation which has various impacts associated with geologic conditions and disturbs the existing geology due to removal of existing material and disposal of new material. Also, there are possibilities of soil erosion as a result of overexploitation of groundwater resources (McCully, 2001). As groundwater extraction increases, subsurface hydraulic pressure decreases and land subsidence increases, due to aquifers compression and compaction of clays and silts.

Land subsidence and soil erosion can damage infrastructure. In terms of hydrogeology, groundwater sustains subterranean ecosystems in karst or alluvial aquifers. Overexploitation of aquifers first affect groundwater levels by decreasing them. Excessive pumping can lower groundwater tables and cause wells to no longer reach groundwater. Also, as groundwater and surface water are connected, depleted aquifers affect springs by reducing or even stopping spring discharges. They also reduce the base flow of rivers and streams, making them shallower and narrower, and sometimes triggering seasonal drought to permanent streams (McCully, 2001). As for biodiversity, as both water quantity and quality decline, fish and wildlife living in and around affected water bodies are affected as well. The drop of water quantity and degradation of water quality in a river or stream affects animals that depend on it to drink, as well as fish populations living in it. The environment for fish and other aquatic species can also be altered as the stream level drops. On the other hand, plants at the interface between land and a river or stream that grew because of the close proximity of the water table to the land surface may also be affected by the drop of water levels. In terms of water quality, excessive withdrawals and depletion of groundwater tables imply severe water quality issues. On the first hand, depleted coastal aquifers experiment saltwater intrusion from the sea, making groundwater unusable for drinking given its deteriorated quality and high salinity. On the other hand, the more aquifers are exploited, the more they are vulnerable to pollutants and contaminants (e.g. domestic and industrial wastewater, leachate from waste dumps, pesticides and fertilizers…) and infiltrating through the soil strata. Polluted groundwater is less visible than polluted surface water, but it is far more difficult to treat and clean than in rivers and lakes.

All the above impacts have severe socio-economic implications due to a reduction in both water quality and quantity which in turn reflect on human health and livelihoods. In terms of health, declining groundwater quality exposes users to a set of diseases. On the other hand, as groundwater tables decline, more energy is needed to reach deeper levels which can be expensive. Also, declining groundwater quality results in declining agricultural yield, especially with the expensive treatment and purification cost of contaminated water. Accordingly, groundwater resources are important to remain under control of involved authorities and parties whereby the latter are responsible for estimating aquifer capacity, quantifying available resources and monitoring abstractions.

3.1.1 Groundwater: Governance or Management?

The notion of "groundwater governance" emerged after the articulation of hierarchical organizations of the state driven by authority and power with those of the private sector driven by market competition, as well as those of civil society characterized by citizens' voluntary action, reciprocity, and solidarity (Castro, 2007). Hence, governance came as a response to Market and State Failure, transcending the forms of traditional state hierarchies and market systems (Hirst 1994, Held 1995, Amine 1997, Castro 2007). However, the term was not given a particular definition. In 1991, the World Bank defined "governance" as the "exercise of political authority and the use of institutional resources to manage society's problems and affairs". For some, water governance is an administrative and technical tool to achieve certain targets in different contexts, such as enforcing a particular water policy. For others, water governance is a debate of different project alternatives for societal development and the definition of the objectives and processes to be pursued by society, through a process of substantive democratic participation. For Saunier and Meganck (2009), governance is how and the extent to which individuals and institutions, public and private, team up to manage their common affairs. A policymaking definition would be the political, organizational, and administrative processes through which citizens and other stakeholders can share their interests, contribute to decision making and mediate their differences. In brief, "governance" emerged in recent decades as an attempt to reconcile the market and state divides and a shift from "government towards governance" and the rise of non-governmental actors. Groundwater governance can be defined as the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision making between and among different stakeholders and scales (Varady et al. 2013). According to Bakker (2010), Governance Failure occurs when decision-making fails to conciliate between citizens and their political rights, between institutional practices and culture, between discourse and outcomes. Some tangible examples of Governance Failure would be top-down decisions, the inability of poor households to speak out, elite-focused decisions… In turn, Jessop (2003) also acknowledges governance failure claiming that addressing failure requires new forms of requisite variety, requisite reflexivity, and romantic public irony as three tools to produce conditions for continuing efforts towards effective governance and learn from previous failures. Requisite variety supposes that radical neo-liberalist regimes prioritize market solutions and fail to provide essential supporting mechanisms. Requisite reflexivity highlights the need for appropriate levels of reflexivity and supervision in governance practices. As for romantic public irony, Jessop (2003) claims it is the hardest governance condition and defines it as an experimental approach that uses collective intelligence to prevent scepticism, opportunism, and revolution and that requires overcoming the "democratic deficit in policy-making and the recognition of lay expertise" as important features of the governance process. Accordingly, addressing groundwater governance failure not only necessitates expertise and supervision, but requires respecting citizen democratic rights throughout the decision and policy making process.

On the other hand, although "groundwater management" was not a common concept in the 20st century, the practice in itself is not new. Traditionally, countries or states used to intervene to manage the use of groundwater resources. Good examples illustrating water management approaches are the cases of India and China, two different countries with two different political regimes. In the 1950s, both countries were facing population growth, were self-sufficient in food and had a massive agriculture-based economy relying on groundwater irrigation (Siebert et al. 2010). Reliance on groundwater has led to the depletion of groundwater tables in some parts of both countries. As an attempt to reverse the status-quo in India, local communities in the State of Gujarat started capturing rainwater for groundwater recharge in the absence of proper governmental action. This practice began spreading gradually throughout the country through a movement of agents of change, until the government finally recognized the movement, resulting in a coexistence of formal groundwater legislation in line with informal rules set by the movement, establishing a typical public-private partnership. In China, the approach was more centralized whereby a governmental agent was paid by villagers' taxes to plan irrigation patterns and set prices in groundwater markets in each village (Shah, 2000). Nowadays, the institutional setting of the water sector in any country comprises the government, the private sector, and sometimes non-governmental organizations. A noticeable feature of groundwater today is that its exploitation is to a large extent in the hands of the private sector such as irrigation farmers, water supply companies or domestic well-owners (Varady et al. 2013). With growing emphasis on equitable, sustainable and efficient management of resources over the last years, many countries have recognized the implications of the game of power relations and the efficiency of bottom-up decision-making in the water sector. A vertical integration of actions and responsibilities among all stakeholders has been seen as a more efficient configuration. Providing stakeholders with information and integrating them in the management of resources and in the decision-making process are essential strategies to create incentives for compliance.

In Australia, considerable attention is drawn on groundwater. In Tasmania, an island state of Australia's south coast, Groundwater Areas are appointed by an order of the Minister as areas where groundwater resources are intensively extracted and where a license is required to ensure equitable and sustainable management of the water resource. A license is also required in areas covered by a local or regional Water Management Plan (The Department of Primary Industries, Parks, Water and Environment, 2017). In Victoria, a state in south-eastern Australia, Local Management Plan (LMP) Guidelines were developed to provide local authorities and local water corporations with a "framework for development, approval, implementation, reporting and review of an LMP" (Department of Environment, Land, Water and Planning - Victoria State Government, 2014). In the USA, due to aquifer overexploitation, most states have recognized the lack of resource allocation rules. States like Colorado, Kansas, Nebraska, New Mexico, and Texas, among others, all have legislation allowing for the designation and regulation of critical area (Kaiser & Skillern, 2001). Most recently in California, local management of groundwater resources has gotten greater support as a bottom-up governance approach. After a long period of mismanagement, the state adopted a new approach to develop new groundwater governance systems far from political tensions. The Sustainable Groundwater Management Act (SGMA) was developed, inviting local entities and agencies to plan and regulate the access to groundwater resources that account for between one third (in wet years) and two thirds (in dry years) of the state's water use (Downing, 2018).

Accordingly, groundwater management is key to ensure protection and sustainable use of groundwater resources. Many countries or regions around the world have been giving special attention to groundwater through thorough investigation, strict legislation and management plans to protect groundwater resources from overexploitation and contamination, California being one of the latest examples. California is one of the few regions where five major climate types occur at a time, including the Mediterranean and Desert climates (Kauffman, 2003). Precipitation in California varies across the state with and ranges between 127 mm and 2540 mm annually (U.S. Department of the Interior, 2005). In terms of groundwater resources, groundwater exploitation has largely been unregulated and 21 basins are considered critically overexploited (Chappelle et al. 2017). On the other hand, Lebanon is known for its typical Mediterranean climate and for the major reliance on groundwater and poor groundwater management. In view of that, California and Lebanon are characterized by similar climate patterns and by overexploited aquifers, hence management plans proposed in California's SGMA can be taken as reference for proper management and protection of Lebanese groundwater resources. The SGMA provides local agencies with a groundwater management framework and aims at (California Department of Water Resources, 2015):

- Providing a tailored approach to planning taking into account regional differences;
- Protecting water rights;
- Establishing minimum standards for sustainable groundwater management;
- Improving consistency between land use and groundwater planning;
- Providing technical assistance;

- Creating a mechanism for intervention if local agencies are not properly managing groundwater resources.

According to the California Farm Bureau Federation, the SGMA suggests Groundwater Sustainability Plans which will describe the state of existing basins, develop a water budget, set groundwater management standards and objectives, identify actions and projects to meet those standards and objectives, and establish a monitoring program to measure success. The SGMA also grants authority to Groundwater Sustainability Agency authorities which will be responsible of regulating pumping, measuring and reporting groundwater use, charging fees and enforcing the Groundwater Sustainability Plans by managing both supply and demand (California Farm Bureau Federation, 2019). The mentioned measures and plans are not really tailored specifically for California. They can be taken as a reference to build on towards proper groundwater management in other contexts, including Lebanon.

3.1.2 Conceptualizing Groundwater Policies

Governments have often responded to challenges related to groundwater management by issuing water permits, in the purpose of keeping annual water abstractions at a rate equal to, or less than, a given safe yield of a given aquifer (Mukherji and Shah, 2005). However, it has been proven that such solutions tend to be demanding in terms of surveillance and, in most cases, have not induced a significant reduction in the rate of overexploitation given that groundwater abstractions often occur outside of the legal framework imposed by the state. Also, common policies to control illegal abstractions is inviting owners of unlicensed well for official registration. One would expect that such policies would help the government control the number and prevent the expansion of illegal wells. However, such policies would worsen the situation and would encourage well owners to break the rule, deepen their wells or dig new ones until the government announces the open registration of unlicensed wells (Nabavi, 2018).

Many countries had legal reforms taking place to adapt laws and regulations with modern groundwater views and functions. Legislative frameworks vary around the world but in general define groundwater ownership schemes and user rights. The degree of government control over groundwater resources also varies. For example, in the Netherlands, groundwater abstraction laws are very strict in contrast with the USA where constraints to private abstraction are relatively low in many states of the country (de Chaisemartin M. et al., 2017). Nevertheless, groundwater governance is not limited to policy making. Other forms of groundwater governance have recently emerged. The emergence of new terms, new commitments and new research topics evolving around groundwater came also as an attempt towards groundwater governance. For instance, the term “sustainable yield” adopted in Australia is defined as the amount of water that can be extracted from an aquifer for consumptive use, while leaving enough water to maintain the integrity of the resource and water dependent values, namely environmental, social and cultural values (Braimbridge M., 2010). Similar terminologies are also adopted in India and other African countries as well. Innovative forms of groundwater management have emerged worldwide through a variety of instruments (Theesfeld 2010) including technical, managerial, regulatory and economic instruments. Molle and Closas (2017) have developed a conceptual framework synthetizing the challenges that decision-makers and policy-makers face related to groundwater water governance, and each one of these challenges can be addressed by adopting key groundwater policy objectives and tools:

- Challenge one - Controlling the expansion of wells addressed through:
    - Community rules such as licensing wells, prohibition zones, ban new wells, sanctioned deepening…;
    - Reverting to rainfed agriculture
- Challenge two - Controlling abstractions and existing wells addressed through:
    - Collective rules such as impose extraction quotas, restrict crop types, water pricing…;
    - Reverting to micro-irrigation
- Challenge three - Managing groundwater-based water supply addressed through:
    - Deepening/cleaning wells;
    - Water harvesting and artificial recharge;
    - Reverting to surface water or treated/desalinated water.

According to Hoogesteger and Wester (2015), understanding the dynamics of both formal and informal groundwater access mechanisms is key for a regulated and efficient groundwater governance. The authors studied legal and illegal access to groundwater through a three-layered conceptual framework:

- The first layer examines the ability of technologies, humans and other productive material resources to shape access to groundwater resources;
- The second layer examines how the interaction between the political economy of groundwater-dependent commodity chains and related policies can contribute to prevailing water use patterns by identifying:
    - Impact of plural laws on access, whether formal or informal;
    - How commodity chains and associated profit margins determine who gets to extract groundwater, where and what for;
    - How policies, laws and customs defining who can legally access groundwater, how and why.
- The third layer examines the role of discourses in mediating groundwater access and accumulation.

Today, while many have already legal frameworks addressing groundwater in particular, a lot of countries still did not develop water policies directly related to groundwater. The absence of clear regulations and legal texts providing guidance and controlling the access to and exploitation of groundwater resources is indicative of poor water resource management schemes. The poor water resource management in a lot of countries around the world explains why those countries are not able to quantify their water resources, including groundwater, and why they tend to look for water supply alternatives and infrastructure they don’t really need such as dams and other costly alternatives.

3.2 Environmental, Social and Technical Drawbacks of Dams: National vs. Global Trends

Dams are barriers built across rivers or streams to confine water and use it for human purposes (e.g. water storage for irrigation, domestic water supply, reservoir fisheries, hydropower generation, flood control, recreation…), forming vast lakes or reservoirs over large areas of land. The below section describes the environmental, social and technical problems associated with dams, highlights examples from Lebanon with emphasis on the dams of Bisri and Janneh, and ends with examples of dam failures around the world to show the growing trend of dam decommissioning in the developed countries and reliance on conjunctive alternative sources of water, while developing countries still use the “national interest” argument to promote dam projects (McCully, 2001).

3.2.1 Potential Environmental and Social Impacts of Dams

Environmental and social impacts of dams can sometimes be predicted and sometimes not. Some manifest directly or in the short run, while some others might manifest in the long run. Dams differ in terms of structural and operational patterns: size, height, area of reservoir, area submerged, hydropower generation capacity, storage capacity… which explains why impacts are not exactly the same for all dams. Streams and rivers also differ in terms of flow patterns and species, and lands differ in terms of geology, biodiversity, land use and land cover. Accordingly, environmental and social impacts of dams cannot really be generalized. In the coming section, potential environmental and social impacts of dams are described, and linked to dams in Lebanon with emphasis on two controversial dams: the dams of Janneh and Bisri (Figure 3).

The Janneh Dam is to be built across the Nahr Ibrahim river. It is located 37 km away from Beirut between the villages of Qartaba and Hdaine to the north east and of Lassa and Saraaita to the south east. The reservoir is designed with a catchment area of some 242 km^2, extends for 3.2 km upstream from the dam with a storage capacity of 37 MCM. The main objective of the Janneh dam is to provide drinking water for the region extending to an elevation of 900 m in Jbail Caza, the regions extending on the coast of Kesrouane and Ftouh to an elevation of 300 m and the suburbs of Northern Beirut between Dbaye and Borj Hammoud. The Janneh dam is also intended to provide irrigation water to the areas located on the coastal plain of Tabarja to Jbail and Amchit and to the regions of Qartaba, Aaqoura, Lassa and Afqa, and their surroundings (GICOME, 2015).

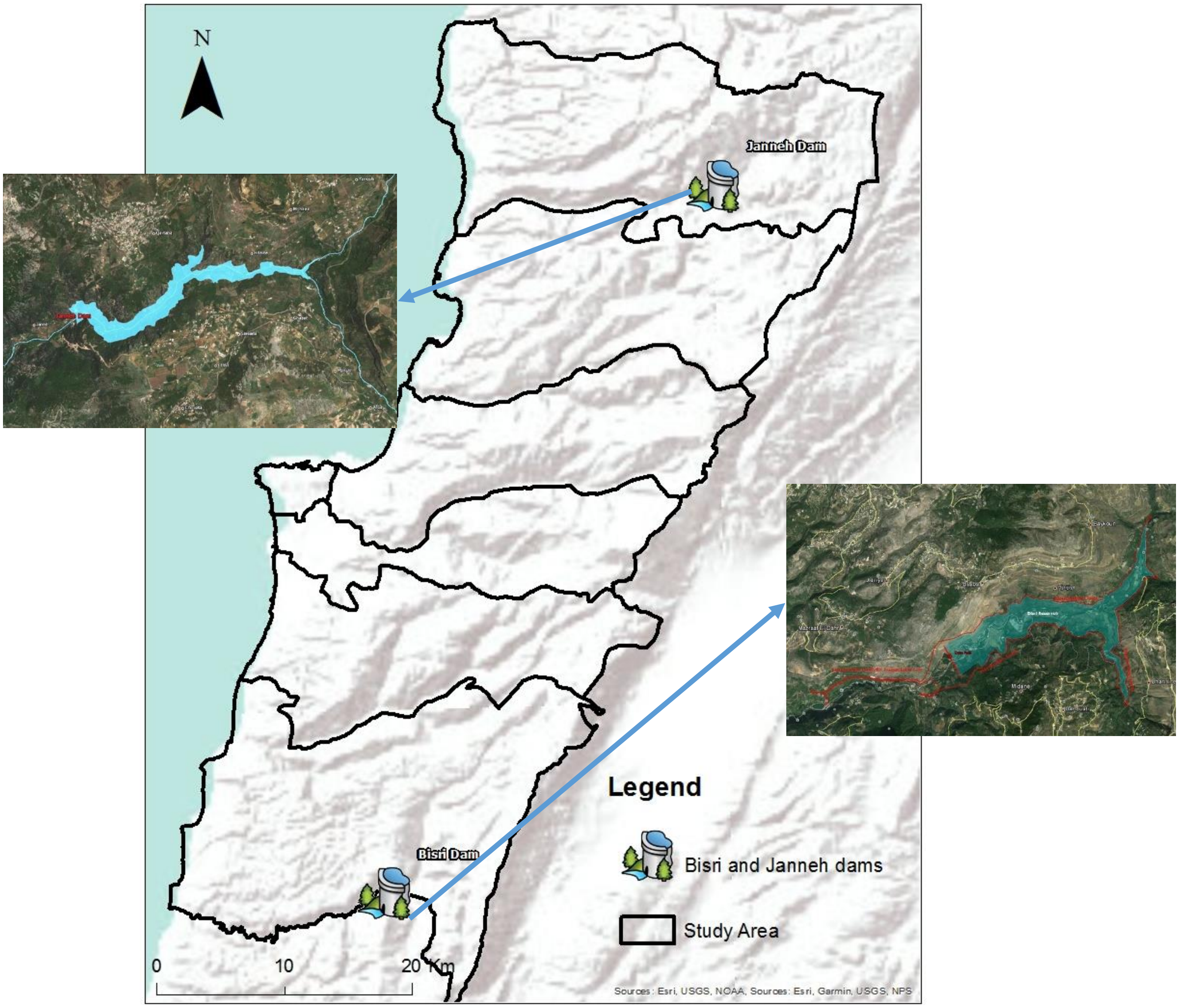

Figure 3 Location of Bisri and Janneh dams
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

On the other hand, as part of the World Bank's GBWSAP in Lebanon, the Bisri Dam is to be located across the Awali River, between the Cazas of Jezzine and Chouf with a storage capacity of 125 MCM per year. The main objective of the dam is to provide Beirut and Mount Lebanon with drinking water. The dam site passes through more than 20 villages with a total length of 6 km. The World Bank claims that over 1.6 million residents in the GBA will benefit from the dam, 32% of which live on less than 4$ per day (World Bank, 2014).

3.2.2 Geology, Hydrogeology and Seismicity

Geology, hydrogeology and seismicity are three separate fields, but are very much intertwined when it comes to large dam infrastructure. In terms of geology, the construction of dams requires blasting, excavation and quarrying which has various impacts associated with geologic conditions and bring about heavy topographical modifications. These activities can possibly result in consequent landslides or rock falls and in disturbing the existing geology due to removal of existing material and disposal of new material (Petley, 2013). An example of reservoir-induced landslides is the Vajont Dam that was built in 1959 using the latest technical expertise but without proper review of geological reports and implementation of soil conservation requirements. In 1960, small landslides were already observed. In 1963, 260 MCM of rock broke off and fell into the reservoir of the Vajont Dam, producing a wave of at least 50 MCM of water, destroying villages located in the valley and killing almost 2,000 people (Hardenberg, 2011).

In terms of hydrogeology, dams are associated with downstream sediment deprivation whereby they trap sediments in the reservoir, stopping the natural flow of sediments, which makes the downstream channel deeper and narrower over time. Since the completion of the Sidi Salem dam on the Medjerda river in 1981, a progressive narrowing and deepening of the downstream channel has been observed

(Zahar el al., 2008). Riverbed deepening lowers groundwater tables along a river or stream and drop the water level in adjoining wells. Also, the loss of sediments involves shrinking deltas and coastlines which are formed and maintained by the accumulation of river sediments over the years and which are constantly exposed to erosion due to the natural motion of waves. In some areas, coastal cliff erosion is also a potential impact of sediment deprivation. For examples, some beaches of the northern littoral of San Diego were more than 300 m wide in 1922 and used to protect cliffs from wave erosion. They have now disappeared and have led to damaging cliff erosions (McCully, 1996). Sedimentation is also a major factor of technical failure of a dam. In Himalayan rivers, the flow of large quantities of sediments from weak rocks and extreme reliefs has been a serious challenge in the establishment of hydropower dams. By stopping the natural flow of water, a dam also stops the natural movement of sediments which accumulate to fill the bottom of the reservoir and get stuck in and clog the turbines resulting in eroded or cracked turbine blades. The efficiency of a dam is subsequently reduced and repair can be very costly to repair if no proper maintenance was ensured (Thapa et al., 2004).

Regarding seismicity, the weight of large dams is a potential stimulator of seismic activity and can trigger earthquakes, especially if located on active or unstable fault lines. This is known as reservoir-induced seismicity (RIS). Typically, when the level of water in a reservoir increases, pressure exerted on the earth increases, and when the level of water in the reservoir decreases, the pressure decreases. This fluctuation of pressure can disturb the balance between tectonic plates and faults under the dam, potentially stimulating them. Another stimulus is potentially the water per se. When the pressure increases, water is forced into the ground and fills and expands cracks and fissures and even creates new ones, causing greater instability below ground. And as water infiltrates deeper, it lubricated rock plates causing them to slip. Globally, hundreds of cases of earthquakes were believed to be triggered by reservoirs (Gupta, 2002), one of which is the 7.9-magnitude Sichuan earthquake in May 2008 which killed around 80,000 people and was linked to the construction of the Zipingpu dam. The largest accepted reservoir-induced earthquake to date being the 6.5-magnitude earthquake which occurred at Koyna dam in India in 1967. Dam reservoirs are believed to have induced five out of the nine earthquakes on the Indian peninsula in the 1980s (McCully, 1996).

In Lebanon, the Janneh dam site lies over the Kesrouane Formation (J4), a highly fractured and karstic formation. The planning of the dam lacks hydrogeological investigation as the dam site is located in a groundwater infiltration zone in the uppermost J4 aquifer and will probably fail to reach its storage capacity due to expected leakage losses into the underlying J4 aquifer (GITEC & German Federal Institute for Geosciences and Natural Resources (BGR), 2011; MARGANE, 2012). Also, several faults cut the dam site. The Nahr Ibrahim basin, around the dam site, is deformed by different systems of West - East and North East - South West faults including a major fault (Eeast-West) that passes parallel to Nahr Ibrahim river and diverges into several branches having both normal and strike-slip types of movement, both being in the order of hundreds of meters. This fault is responsible for the dolomitization of the lower part of the Jurassic strata. There is also another fault trending approximately North East- South West crosscut West of the Qartaba village. The normal displacement along this fault reaches up to 500 m, it is make a horst on the western side known as Qartaba horst (GICOME, 2015).

As for the Bisri dam, it is located in a geologically complex and tectonically active area, according to Nemer (2019). The author claims that the north-south trending Roum Fault extends for about 35 km from the Hula basin to the Bisri river where it is subdued within inherited geological structures. The Roum Fault is replaced immediately north of the Bisri river by the Chouf Monocline, and the accommodation of the transition from the Fault to the Monocline is provided by the East-West trending Bisri Fault that underlies the fluvial deposits and the river bed of the Bisri river. Nemer states that this interconnection of these geological structures makes of the Bisri river area a geologically complex area that requires special attention and in-depth consideration when it comes to proposing and planning infrastructure projects. The instrumental seismicity of Lebanon (1903-2004) shows a scatter of moderate earthquake epicenters around the Roum Fault with one important event, namely the earthquake of March 16, 1956. The epicenters of this double shock was located in the Bisri river area, and most probably the Roum Fault - Bisri Fault intersection. The biggest earthquake ever recorded dates back to 1837 with a magnitude of 7.1 on the Richter scale. The most recent earthquake on the Roum fault dates back to 1956 with a magnitude of 5.1 on the Richter scale. Moreover, since the Bisri Fault are the Roum fault are interconnected, any induced seismicity on the Bisri Fault would change the delicate stress regimes around the faults including the Roum Fault, which can lead to a stress release on the Roum Fault and to an unpredictable and uncontrollable seismic response. Furthermore, the weight of water in the future Bisri reservoir can have a similar effect on the stress perturbation around the Bisri Fault, which as a consequence can lead to the same effect of stress change around the Roum Fault and subsequently to stress release in the form of seismic activity (Nemer, 2019).

Accordingly, a seismic event can be triggered and provoked by a dam earlier than its natural reoccurrence. RIS is thus a threat and an important consideration to take into account before the construction of a dam in geologically complex and seismically active areas.

Figure 4 Limestone Cliffs surrounding the Bisri Valley

3.2.3 Biodiversity

During the construction phase of dams, biodiversity is disturbed. Trees are cut down, natural habitats are destructed and migratory routes are cut off. The whole ecosystem around the dam site is disrupted. 3129 km^2 of forest were inundated by the Balbina Dam, a 250-megawatt hydroelectric dam and power station built on the Uatuma river in Brazil (Benchimol et al., 2015). In addition, impacts on biodiversity are not restricted to the construction phase. The operation phase of a dam also results in the fragmentation and disruption of ecosystems. Plants and land covers that remained intact during operation around the dam site are also affected since plants living in a dry ecosystem cannot easily adapt in a wet one. Impacts of dams mentioned in previous sections result in loss of biodiversity. By blocking the movement of water and building an obstacle across water streams, populations of species living upstream and downstream are isolated and migration is interrupted. Damming watersheds has led to a considerable reduction in the number of riverine species. More than 200 stocks of pacific salmonids became extinct in the Columbia river in the USA (McAllister et al., 2001). Spawning salmon contributed to 45,150 metric tons of biomass to the aquatic and terrestrial ecosystems prior to dam construction. In 1997, only 3,400 metric tons were contributed following construction of multiple dams (Cederholm et al.,1999).

Going back to the case of Lebanon, the Janneh dam site is located within the protected area of Nahr Ibrahim as per MoE’s Decision 34/1 dated 1997. A forest area of 482,346 m2 is found within the inundation area of the dam. Tree species to be removed are mainly pine, oak, poplar and willow trees. GICOME - Antoine Salamé & Associés Sarl conducted a screening of the project settlement area. The area constitutes a natural habitat to 404 species of plants, 739 species of invertebrates, 6 species of amphibians, 23 species of reptiles, 32 species of mammals and 140 species of birds (Gicome, 2015). 85,890 m2 of annual trees and 9,195 m2 of fruitful trees will also be submerged (Khatib & Alami, 2015). As for the Bisri dam, Al Awali river was classified as a natural site protected by Decision 131 dated 1998 of the Minister of Environment (MoE, 1998) from the Barouk region, passing through the Bisri valley and up to its outlet, with all its tributaries. Still, the dam was financed and studied and is now under construction. Thousands of pine and oak trees will soon be removed; some are a couple of hundred years old and some others are already subject of clandestine timber extraction. The whole ecosystem around the dam site will be disrupted.

Figure 5 Pine trees in the Bisri Valley

3.2.4 Water Quality

Dams capture nutrients naturally carried by rivers. Highly nutrient-enriched waters are favorable environments for algae proliferation and eutrophication. Through photosynthesis, algae consume nutrients and produce considerable amounts of oxygen, and the surface layer of the dam reservoir becomes warm, nutrient-depleted, rich in dissolved oxygen and covered with algae. In addition, algae evapo-transpiration can lower the level of water in a reservoir at a higher rate than natural evaporation of open waters (Kassas, 1980). Moreover, perished algae sink to the bottom of the reservoir, consuming some of the limited amount of oxygen there. As a result, water becomes acidic and the aquatic environment becomes no longer suitable for aquatic organisms and water no longer potable because of bacteria and mosquito proliferation and eutrophication. The detection of plant nutrient (Nitrates NO3− and Phosphates PO43−) in a reservoir is a sign of eutrophication (De Ceballos et al., 1998). Eutrophication and algae proliferation give water a bad smell and taste, block out light for other organisms and clog turbines as well as water intakes in the reservoir. They can also affect a wide variety of water uses such as water supply for drinking water, livestock, irrigation, fisheries and others (Timofti et al., 2011).

In Poland, the Dobczyce dam reservoir serves as a source of drinking water supply for the residents of Krakow and its surroundings. The water quality monitoring over a period of 14 years showed a progressing eutrophication of the reservoir based on 1452 water quality parameters including pH, water saturation with oxygen, total nitrogen, total phosphorus and chlorophyll-a (Neverova-Dziopak and Kowalewski, 2018). Eutrophication is also a source of water-borne diseases due to the proliferation of mosquitoes, insects and other organisms around the stagnant waters of a reservoir.

Rotting vegetation are favorable environments for those organisms that can spread illnesses and diseases and reach consumers and agricultural harvests.

In Lebanon, eutrophication was detected in the Qaraoun lake constructed in 1965. Several studies have been conducted to monitor the water quality of this lake. Agricultural runoff from fertilizers and pesticides are the primary sources of excess nitrogen and phosphorous which are washed into Litani River and eventually deposited in Qaraoun lake (Saad et al., 2005). As a result, the lake was found to be rich in algae and different non-toxic phytoplankton populations during the last few decades (Slim, 1996; Saad et al., 2005). Eutrophication is also observable in the Anan Lake (located in Jezzine district in South Lebanon governorate), whereby the lake is periodically emptied and refilled as a solution to the problem (Figure 6).

Figure 6 Anan lake on June 5, 2019

3.2.5 Socio Economic Impacts

The consequences of dams on humans are as devastating as the ones on the ecosystem. Involuntary resettlement is the most problematic socio-economic impact of dams. McCully estimated that 30 to 60 billion people all over the world were displaced and got their lands and houses flooded by dams till 2001. The construction of the Salto Grande Project forced displacement of more than 20,000 people in Argentina and Uruguay and affected roads, railways and urban and rural infrastructure (Tortajada et al., 2012). In Lebanon, the Janneh dam project required the expropriation of around 320 plots. The expropriated area includes 178,896 m2 of public lands and 1,444,000 m2 of private lands (Khatib & Alami, 2015). As for the Bisri dam, over 950 plots were affected by the dam's expropriation plan, of which 780 were totally expropriated and 180 were partially expropriated (CDR, 2016).

Losses are not limited to lands, as many communities lost their sources of income provided from fisheries, agricultural fields, timber and pasturage lands. Most of the time, the financial compensation of land expropriation payed to landowners is minimal. The case of the Bisri dam manifests explicitly this particular impact whereby a total area of 5.7 million square meters (MSM) of land was expropriated with a financial compensation of 21 to 25$/m2 (Dar Al Handassah, 2014). In addition to land compensation, additional features existing on expropriated lands will be compensated for as follows (Dar Al Handassah, 2014) (Table 1):

Table 1 Compensation value for additional land features

Features	Buildings (Per m^2)	Field Crops (Per m^2)	Large Fruit Trees (Per Tree)	Small Fruit Trees (Per Tree)	Large Forest Trees (Per Tree)	Small Forest Trees (Per Tree)
Lebanese Liras L.L.	95,000	21,500	468,421.05	163,157.89	183,333.33	54,166.66
Us Dollars Usd	63.33	14.33	312.28	108.77	122.22	36.11

The above compensation amounts are undervalued. Each pine tree produced between 7 and 20 kilograms of pine nuts per year. 1 kilogram of pine nuts is worth 150,000 Lebanese liras. However, large pine trees are compensated for no more than 500,000 Lebanese liras. Likewise, olive trees represented a profitable source of revenue within the project area, where over 200,000 olive trees will be removed. The area is also known for producing all sorts of field crops (beans, strawberry, lettuce, bell pepper and others). Over 400 tons of strawberry are produced yearly in the region, and either exported to Turkey or sold to national ice-cream producers (Tahkik, 2019)[1]. According to Engineer Amer Machmouchy (Tahkik, 2019), more than 20 villages used to benefit from the area that generated 150 million US Dollars of revenues per year from agricultural activities.

[1] Review of media reports: Haddad, F. & Abi Nader Hendi C. (2019). Bisri Dam. Tahkik. Season 11, Episode 10, February 6, 2019. MTV Lebanon.

Figure 7 Agricultural Fields in the Bisri Valley

3.2.6 Cultural and Archaeological Features

Another impact of dams is the possible inundation of archaeological and cultural features which reflect the identity and the history of the displaced local community. The Ilisu dam is Turkey is an example of dams with potential impacts on archaeological landmarks, being a controversial project for a variety of political, social, environmental and economic reasons as well. The Ilisu dam project actually violates five policy guidelines of the World Bank on 18 accounts, among which is a violation related to the protection of sites of archaeological and cultural importance. Consequently, the World Bank has declined to fund the dam and the project was suspended until the funds were covered by Turkey's Prime Minister Recep Tayyip Erdoğan.

In the case of Lebanon, both the Janneh and the Bisri dams are located in areas of high archaeological and cultural importance. The Janneh dam site exhibits unique archaeological features. Archaeological findings included historical necropolis, sarcophagus, ancient altars and inscriptions located within the Nahr Ibrahim valley. Archaeological findings also included 30,000 to 300,000-year-old stone tools discovered in explored grottos (GICOME, 2015). As for the Bisri dam, various archaeological and cultural features are found within the dam site. Around 78 other archeological, religious and cultural features are found in the project area. 27 are found within the dam site and the remaining 51 are located in the vicinity of the dam site (Institute of Archaeology and Polish Centre for Archaeology, 2008). The CDR claims that suitable measures were considered to preserve those features in collaboration with the Directorate General of Antiquities and the Maronite Diocese of Saida. Measures are included in the construction cost of the Bisri dam and mainly consist of the relocation of some features such as the Mar Moussa Church, Marj Bisri columns, Marj Bisri Bridge, old houses and other ruins found in the Bisri valley.

Figure 8 Archaeological Features within the Janneh dam site

Figure 9 Archaeological Features in the Bisri valley

Since an Environmental Impact Assessment (EIA) is required before the construction of any large infrastructure project, dam owners and contractors are now forced to adopt mitigation measures to minimize the impact of their projects. Mitigation measures can be confusing as they drive the public into thinking that initial conditions can be restored, as if the dam would no longer have any impacts whatsoever. This is accentuated by the fact that EIAs are elaborated by environmental consultancy firms that tend to sugarcoat impacts of the project at hand for exposure and business purposes. Moreover, mitigation measures can be ineffective and sometimes dangerous. For example, McCully (2001) talks about common mitigation measures that can imply severe effects. He gives the example of how instream flows are proposed as a mitigation measure whereby water is released from the reservoir either in high pressure to flush away accumulated sediments or in moderate pressure to maintain fish populations downstream. The author also talks about selective withdrawals as a way of regulating downstream temperatures whereby water is released from different levels of the reservoir to regulate thermal conditions of water downstream. He finds that both measures are not sufficient to restore the original ecological, hydrological and thermal conditions of a river or stream. To conclude, any intervention in the natural environment is likely to bring about changes and impacts on existing conditions. This does not mean that no intervention and anthropogenic activities should ever take place, but rather that impacts are inevitable and that all possible alternatives shall be investigated and the one with the least impacts shall be selected.

3.2.2 Dams in Lebanon: Oversights and Omissions

Over the years, many dam experiences have explicitly shown the lack of investigation and the need for further studies in Lebanon. The first dam that was built in the country is the Qaraoun dam across the Litani River in 1959, with a storage capacity of 220 MCM/year. The Qaraoun dam has failed to meet its intended capacity and supply because of leakage. It is used to provide water for irrigation and for hydropower generation. It was not until 2007 that the second dam was inaugurated, the Chabrouh dam, with storage capacity of 8 MCM, to cover the water shortage in the Keserwan region. However, about 30% of water stored in the dam are believed to be leaking either through the dam structure itself or through the C4 geological formation (Bou Jaoude et al., 2010). The dam was supposed to cost 40 million dollars, but the amount raised to 100 million dollars due to leakage and the additional cost of cement injections in the karst rocks to stop the leakage of water, in vain (Ghiotti and Riachi, 2013). According to Engineer Ahmad Nizam[2], the cost of the Chabrouh dam went beyond the mentioned amounts and reached 117 million dollars. Similarly, the proposed Boqaata dam is to be located between the J5 (Bhannes Formation - basalt) and J4 (Kesrouan Formation - limestone) geological formations. However, the upper part of the J4 is highly karstified, which explains why the proposed dam was proposed by GITEC and BGR as a managed aquifer recharge dam in 2012 (Raad and Margane, 2013).

[2] Ahmad Nizam to the Army Magazine. Issue Number 4 - January 2016

In 2010, a National Water Sector Strategy (NWSS) was elaborate, with clear emphasis on dams and hill lakes. More than 15 new dam projects were put on the table all over the country. One of the proposed dam projects is the Qaysamani dam. According to the MoEW (2017), the main objective of this project is to address the shortage of potable water and to support the living and economic life of the population of 35 villages in the Metn through 0.8 MCM of water to be stored for use during the summer season to face increasing needs. As per the request of the Hammana municipality, the American University of Beirut (AUB) reviewed studies related to the proposed dam with particular emphasis on potential impacts on the Shagour Hammana spring and on seismic hazards in the area (El Fadel et al., 2014). Based on the review of hydrological, hydrogeological, geological, geotechnical and environmental studies, among others, the authors concluded that the dam was not adequately evaluated in terms of hydrology, hydrogeology, seismicity and environment and social impacts. Reviewed studies were thought to fall short on requirements for a dam project. In addition, many aspects to lack evidence, accuracy and investigation, and so the authors provided comments on the hydrology and hydrogeology assessment, as well as on the environmental impact assessment, whereby they pointed out omissions, inaccuracies and missing pieces of information. On the other hand, the Mseilha dam was also proposed in the NWSS to secure additional water for the domestic and industrial use. The dam is to be located just above the coast, on the downstream part of Nahr El Joz, in the Caza of Batroun, with a storage capacity of 6 MCM/year (MoEW, 2018). It is the very first dam to be built less than 1 kilometer away from the coastline in Lebanon. To date, no EIA was made available to the public and probably was even elaborated to assess and evaluate the environmental impacts of the Mseilha dam.

As for the Janneh dam, the dam location on Nahr Ibrahim was determined by the 1954 American mission to Lebanon. After detailed site investigations, the original location was opposed by the design consultants (Khatib & Alami and Artelia) who claimed that it was exposed to seismic activity, which would undermine the dam's storage capacity. A new location 1,100m upstream was recommended by the consultants and approved by the MoEW. The Janneh dam does not only present environmental and social implications, but the project owner and stakeholders seem to have failed to look after some core requirements. Firstly, the EIA study was assigned to Khatib & Alami, although it is commonly known that the consultant responsible for conducting environmental studies for a particular project should not be also involved in the design. In the EIA report, the cost of environmental degradation was calculated based on a survey conducted and the willingness to pay of the respondents, not based on the actual valuation of environmental damage brought by the construction and operation of the Janneh dam. Secondly, the Directorate General of Urban Planning (DGUP) was not consulted to reduce or prevent future urban development around the dam site. In the absence of tough planning, regulations and restrictions, the dam reservoir will be exposed to different sources pollution associated with urban development, resulting from man-made activities including agricultural and industrial activities (ECODIT, 2015). However, according to a key informant interviewee, the DGUP is currently in the process of zoning the area around the proposed Janneh dam, but this initiative did not start as per the request of the project owner or other stakeholders.

Moving on to the Bisri dam, the World Bank will finance the construction and supervision of the Bisri Dam and the conveyor pipelines to the existing Joun reservoir with their associated access road, as well as two hydropower plants, generating 0.2 megawatt (MW) and 12 MW respectively, and expansion of the Ouardaniyeh water treatment plant (WTP). Today, access to the Bisri dam site is prohibited and construction machinery started taking over the place. The dam will inundate vast areas of lands, forests and agricultural lands and will thus generate severe impacts on the environment, as well as on local community who speaks out about higher risk of seismic hazards and loss of jobs, biodiversity and cultural identify. Two International Panels of Experts were assigned the review and continuous monitoring of all the aspects of the project in its design, construction and operation phases, to ensure due diligence on the technical, social and environmental aspects of the project according to international best practices and as per the policies of the World Bank: the Dam Safety Panel (DSP) which gathers experts in the fields of hydrology, seismology and geology, and the Environmental and Social Panel (ESP) which gathers experts in the fields of environment, sociology, and archeology. Both the DSP and the World Bank reviewed and approved the design and safety plans. However, if enough evidence was provided to prove that the dam can withstand seismic hazards, no scientific evidence was provided to prove that the dam would not actually trigger a seismic event. On the other hand, the ESP is in charge of reviewing the environmental, social and archaeological aspects of the project. One of the key issues to be addressed and reviewed by the ESP is the cost of environmental degradation and ecological offsets. In the final reports of their first and second missions, the ESP expressed the urgent need for an Ecological Offset Plan and mentioned that the latter was under preparation, since most of the loss will be natural habitats in the catchment area (World Bank, 2016; World Bank, 2017). The ESP also claimed that a replanting approach is not enough and that “establishing and maintaining an ecologically similar protected area” should be part of the plan (World Bank, 2017). However, the ESP did not consider nor mention the Awali River, which is already a protected natural site under MoE’s Decision 131 (MoE, 1998). In addition, although both missions were conducted and reported respectively in 2016 and 2017, the panel of experts did not evaluate the cost of environmental degradation, as calculated in the project’s Environmental and Social Impact Assessment (ESIA) in 2014. The cost of environmental degradation usually measures the damage caused by a specific project to several environmental categories: water, air quality, agricultural land, forests, waste, and coastal zone (World Bank, 2010). The cost of environmental degradation of the Bisri dam was estimated at 148,000$ (Dar Al Handassa, 2014). This environmental costs is very negligible and underestimated for such a large dam project. In fact, the cost of environmental degradation of the Bisri dam was estimated based on a study conducted in 2005 which addressed the valuation of Mediterranean forests (Coitoru and Merlo, 2005).

No serious efforts were put towards calculating the actual environmental costs of the Bisri dam project per se, within its own ecological and environmental context. In addition to the environmental and social drawbacks mentioned above, a technical aspect of the Bisri dam is also questionable. The World Bank claims that the Bisri dam reservoir will naturally fill up during the rainy season and that enough water will be stored for the dry season extending over summer and fall. The World Bank also claims that treated water will flow to the GBA entirely by gravity, without pumping, through 25-kilometer underground tunnels (World Bank, 2019). Since pumping stations were not mentioned and supposedly will not be used, no evidence was provided to verify whether or not the water could be conveyed by gravity to destination reservoirs, without the use of pumps and energy. In contradiction with the World Bank's statement, in the final ESIA report elaborated by ELARD, the company pointed out that 9 pumping stations will be established as part of the second phase of the project in order to convey water to 16 different reservoirs in the Greater Beirut and Mount Lebanon area (CDR, 2010). The treatment and distribution chambers are located in coastal areas at a low elevation, and destination reservoirs are located at higher elevations, and as a result the construction of water pumping stations is necessary to ensure adequate distribution of water (Montgomery Watson, 1998).

Table 2 Summary Table of Dams in Lebanon

Dams	Location (District - Governorate)	Storage Capacity (in MCM/year)	Purpose	Weak Points
Qaraoun	Western Beqaa - Beqaa	220	Irrigation water and hydropower	• Failed to meet its capacity • Manifested leakage
Chabrouh	Keserwan – Mount Lebanon	8	Drinking and irrigation water	• Manifested leakage
Qaysamani	Baabda – Mount Lebanon	0.8	Potable water	• Potential impacts on the Shagour Hammana spring • Location in a seismic area • Inadequate investigation and studies (hydrology, hydrogeology, seismicity and environmental and social impacts).
Mseilha	Batroun – North Lebanon	6	Domestic and Industrial Water	• EIA was either not made available to the public, or not elaborated.
Janneh	Keserwan – Mount Lebanon	38	Drinking and Irrigation Water	• Same consultant for design and EIA • Miscalculation of the cost of environmental degradation • DGUP was not consulted to control future urban development around dam site • Location in seismic area.

				• Inundation of vast areas of ecological and archaeological importance. • Inadequate investigation and studies (hydrology, hydrogeology, seismicity and environmental and social impacts). • Possibility of leakage
Bisri	Jezzine – South Lebanon	125	Drinking water and hydropower	• Inundation of vast areas of ecological and archaeological importance. • Location in highly seismic area • Underestimation of the cost of environmental degradation • Inadequate investigation and studies (hydrology, hydrogeology, seismicity and environmental and social impacts). • Possibility of leakage

To sum up, ongoing and completed dams in Lebanon have a lot in common when it comes to manifested and/or foreseen weak points (Table 2). All dam projects lack thorough investigation in terms of hydrology, hydrogeology, geology and social, financial and environmental studies, and very little is done to learn from previous experiences and failures.

3.2.3 Towards Dam Decommissioning around the World

While dam projects are still trendy in the developing world, developed countries have reconsidered their water supply strategies, also as an attempt to restore riverine ecosystems. During the last couple of decades, there has been a growing trend of resisting dam building and finding more suitable alternatives in developed countries. Anti-dam groups have gained more public support and the rate of dam building has considerably decelerated over the years.

According to McCullly (2001), 177 dams were decommissioned in the 1990s in the USA, 29 of which were removed in 1998 alone. Until 2017, around 1,384 dams have already been removed (American Rivers, 2017). Safety, economics and ecological concerns have been the main reasons of dam removal, as removal becomes cheaper and easier than maintenance at some point. The Edwards dam built across the Kennebec river in Maine was the first dam to be removed in the USA after its license expired. As per a 1986 Federal law, the environmental impacts of the dam outweighed the value of the electricity the dam produced. The Federal Energy Regulatory Commission gave the owners two options: either build a fish ladder at a cost of around 9 million US dollars and pay 1 million US dollars to help mitigate the environmental damage induced by the dam, or to remove it. However, owners did not meet the requirements of the first offer; as a result, the Federal Energy Regulatory Commission refused to renew the license and ordered to remove the dam. A year after the dam was removed, migratory fish species returned to the river, that had been eradicated for years. Recently in 2012, Elwha and Glines Canyon dams on the Elwha

River in Washington were also removed for safety and ecological reasons. Around 26,000,000 m^3 of sediments built up behind the dams. A sediment erosion model conducted on the Glines Canyon dam showed that sediment discharge rates would increase, resulting in restored habitats downstream and that fish populations such as Pacific Salmon and Rainbow Trout would return to the river and find their way to sea again (Randle et al., 2012). More recently in 2015, the San Clemente dam across the Carmel River in California was also removed due to a sediment build-up of more than 1,640,000 m^3 out of the 1,758,000 m^3 storage capacity of the dam. Safety concerns related to a nearby fault line and environmental concerns related to the disruption of Rainbow Trout migration and California's red-legged frog habitat (Fact Sheet - San Clemente Dam Removal, 2014).

Dam decommissioning has become more frequent and common around the world. In France, more than 2,300 dams were removed until 2017, making the country the world's frontrunner in removing abandoned and obsolete dams (Dam Removal Europe, 2017). The first dam decommissioning took place in 1996 with the removal of Kernansquillec, Saint-Etienne-du-Vigan and Maisons-Rouges dams due to their substantial impact on species of migratory fishes and to significant silting and rapid sedimentation. In Spain, the Yecla de Yeltes Dam was removed in 2018, since the dam was no longer working and was inducing negative impacts on fish populations, hindering them from reaching spawning grounds. It is thought to be the biggest dam removal project in the European Union (Dam Removal Europe, 2019). Ecologists claim that the dam was responsible for the decline of a freshwater fish species called Sarda and other species like otters and black storks. The removal of the dam resulted in reconnecting 27 kilometers of river and securing migration of fish species. In Japan, the first dam to be removed was the Arase Dam built in the 1950s for hydropower generation, due to certain impacts of the dam, such as noise, vibration and lower catches of ayu fish, one of the most popular Japanese freshwater fish, affecting fishermen’s livelihoods. In Estonia, the Sindi Damm was built in 1975 across the Parnu River, the biggest historical salmon river in the country. The dam obstructed migration routes for salmon and more than 30 other species of fish. Dam removal started in October 2018 and is still underway.

Accordingly, dam decommissioning is gradually emerging as a riverine ecosystem restoration strategy. Over time, dams become obsolete and their environmental and ecological impacts are exacerbated. A dam’s technical failures and/or ageing affect its efficiency and imply economic and safety issues. To avoid this burden, prevention measures can be taken prior to dam construction. Every site has its own characteristics, whether geological, hydrogeological, seismic or ecological. Investigating and understanding these characteristics is a long and expensive process. Most of the times, dams are designed, constructed and operated without the owners, designers and contractors having built enough knowledge of the site’s baseline conditions, resulting in devastating impacts on ecosystems and local communities, as well as major technical failures. Another good prevention measure would be to explore alternative options, before opting for the dam. Priority should be first given to existing resources and infrastructure before deciding on new projects and interventions such as maintaining and improving existing irrigation systems and water distribution networks. Also, regulating and planning existing water supply practices should also be considered such as rainwater harvesting, groundwater withdrawal and graywater and wastewater treatment, among others.

To conclude, while developed countries are now questioning the efficiency and sustainability of dams, the developing world is still planning and adopting dams to solve water shortage problems without conducting sufficient and proper investigation nor exploring more sustainable and affordable alternatives. According to McCully (2001), dams should remain the last option and the last hope to meet a real public water need in the rare cases where no better alternative is feasible and applicable. More sustainable forms of water storage, such as natural ponds and wetlands, improvements in soil moisture and groundwater recharge, could be more sustainable and cost-effective options to explore than dams and other traditional grey infrastructure. Building more reservoirs has become controversial and growingly restricted by environmental, technical and hydrological concerns and factors (WWAP and UN-WATER, 2018). As long as the efficiency and associated benefits of a dam are not guaranteed and proved to outweigh its environmental and social impacts, the dam option is either not the suitable solution, or requires further studies and investigation.

3.3 Groundwater in Greater Beirut Area: Endowments, Challenges and Provisions

3.3.1 Groundwater Resources and Provisions in Lebanon

Lebanon is characterized by a typical Mediterranean climate; winter classically lasts from October to April, with 80 percent of rainfall taking place between November and February. Apart from rainfall, Lebanon has around 40 rivers (of which 17 are more or less perennial) and the 2000 seasonal springs. Numbers become very vague when quantifying public and private wells. Based on numbers presented by the NWSS (2010), 650 public wells and more than 43,000 private wells already existed in 2009 and have helped supply the water establishments throughout the country with drinking and irrigation water. According to UNDP's groundwater assessment study in 2014, only 20,537 private wells were officially registered all over the country until January 2012 based on data from the MoEW, out of which more than 50% are located in the area of Beirut and Mount Lebanon. Accordingly, numbers of wells, in particular private ones, are not clearly and credibly presented. Meanwhile, levels of water consumption are increasing as a result of population growth, industrial and agrarian expansion and uncontrolled groundwater withdrawals.

Based on the re-evaluation of groundwater basins in Lebanon, a total of 44 productive basins and 6 relatively unproductive basins were identified (UNDP, 2014). Most aquifers in Lebanon are karstic, which allows rainwater and snowmelt to be the main sources of natural groundwater recharge and to feed deep groundwater tables. By the end of 1990s, there has been a shift in water use from agricultural to domestic/urban due the population growth in cities, particularly in Beirut. The regulating of public network water supply is particularly critical, where daily water supply drops from 13 hours during the wet season to only 3 hours during the dry season. With an outdated domestic water network, most of it dating back to the 1960s, leakage is estimated to be as high as 50 percent on average, reaching 80 percent in some areas (Riachi, 2014). The deficit between demand and supply for water led to the emergence of new practices to supply domestic water. Almost three-quarter of the Lebanese household budget is allocated to off-network water supply (Riachi, 2014), in the form of water jugs, bottled water and water tanks provided by private suppliers (Riachi, 2016, Ghiotti et.al, 2013). These private water providers have tapped into a lucrative market, taking advantage of the water shortage (Riachi, 2014). According to Riachi (2016), the main growth in irrigation after the war has been due to private initiatives.

Another important common practice and source of water to compensate for water shortage in Lebanon was digging private wells, whether for agricultural or domestic use. In order to fill the gap left by the mismanagement of public institution, farmers and individuals have resorted to drilling private wells. The most recent findings reveal that groundwater irrigated lands reach 78% in South Lebanon followed by 28% in the Bekaa and 25% in North Lebanon (Riachi, 2016, Ghiotti and Riachi, 2013). A recent assessment by the Litani River Authority stated that groundwater levels have decreased by 70 MCM (Amacha, 2014 as cited by Riachi, 2016). This decrease could be attributed to the overexploitation of groundwater in the absence of a proper water supply network and related public policies. In fact, the extraction rate (700 MCM per year) far outweighs the natural recharge rate of aquifers estimated at around 500 MCM per year. Overexploitation is a growing problem, especially in densely populated or agricultural regions in Beirut, Tripoli, South Lebanon and Bekaa and decreasing water tables and seawater intrusion are already manifesting in some aquifers along the Lebanese coast. Various factors have stressed water resources and over reliance on pumping of wells and boreholes has been increasing. This has induced a sever decrease of the water levels in some aquifers, as well as saltwater intrusion in coastal aquifers, resulting in shortages in drinking water supply. Today, the GBA only receives three hours of water supply per day during the dry season. This reality comes in conflict with the view that Lebanon is blessed with relatively more water as compared to neighboring countries.

Several studies have tried to estimate Lebanon's water and groundwater balance per year; however, the findings contain some discrepancies making it hard to derive accurate data. According to Frenken (2009), annual internal renewable water resources are appraised at 4.8 km^3. Annual surface runoff is around 4.1 km^3 and groundwater recharge is 3.2 km^3, of which 2.5 km^3 constitutes the base flow of the rivers. About 1 km^3 of this flow comes from over 2000 springs with an average unit yield of about 10-15 l/s, sustaining a perennial flow for 17 of the total of the major streams in the country. According to Aquastat (2014), Lebanon received 8400 MCM annually from precipitation, from which 4200 to 4500 MCM are lost through evapotranspiration, 820 MCM through outflows to neighboring countries and 880 through infiltration into non exploitable groundwater tables or losses to the sea. Thus, the source states that Lebanon is provided with net potential available resources of 2400 to 2700 MCM per year, of which almost 500 MCM are provided from groundwater. According to UNDP (2014), natural groundwater recharge varies between 4,728 and 7,263 MCM per year and discharge is approximately 2,588 MCM per year. As a result, groundwater balance is estimated to vary from 2,140 MCM in a dry year like 2010-2011) to 4,675 MCM in a wet year like 2011-2012). These estimates do not account for losses to the sea and deep percolation. Also, in the report, authors state that the karstic nature of the main aquifers in Lebanon explains their limited storage capacity.

What is obvious about the numbers stated above is that there is an explicit underestimation of the share of groundwater in the water balance and an inflated estimation of surface water and surface runoff to advocate for large projects that would supposedly help capture water and avoid losses to the sea (Riachi, 2016). As a counter-argument to numbers about underground storage capacity, Bakalowicz et al. (2008) claim that some karst systems in Lebanon show important storage capacity. In their research paper, the authors study four main karst systems in Lebanon: The Anjar–Chamsine karst system (1), the Zarka karst system (2), the Afka system and the Mont Lebanon ridge karst aquifers (3) and the Chekka system and the coastal karst aquifers (4). According to their study, the karst systems have a respective storage capacity of 100 million m^3, 27 billion m^3, 27 million m^3 and 80 million m^3. Ain Al Zarka alone, the spring flowing into the Orontes River, stores 27 billion m^3 with a flow rate of 12.9 m^3/s (Bakalowicz et al., 2007). On the other hand, surface water resources have already witnessed a severe drop over the last 40 years: snow cover and precipitation rates already decreased by 12 to16%, spring flows dropped by 23 to 29% and river flows reached half of their average volumes (Shaban 2009). As for climate prospects, desertification is expected to spread through two-third of the Lebanese territories by 2025 (Ministry of Agriculture (MoA), 2003) and water balance to be reduced by 15% between 2000 and 2020 (Bou Zeid and El Fadel 2002). A study by Doummar et al. in 2018 concluded that temperature is an important parameter that significantly impacts snow cover and the duration of recession period but has little effect on total spring volumes: snow accumulation will decrease but will lead to the flow of surface water into fast preferential pathways, subsequently increasing discharge rates over short periods of times (Doummar et al., 2018).

According to the Assessment of Groundwater Resources of Lebanon (UNDP 2014), natural groundwater recharge forms 53% of the total renewable water resources. The study claims that most of the groundwater basins are not under stress, but rather subject to mismanagement. Accordingly, groundwater is actually a reliable source of water, irrespective of statistics released by dams' promoters, especially under the effect of climate change. Such alternative resources and managing groundwater resources in the case of water excess during the high flow period to increase the storage capacity would be interesting to further investigate.

3.3.2 Legal and Institutional Framework of Lebanese Groundwater

The following section discusses the evolution of the legal and institutional framework in Lebanon. Water laws in Lebanon have evolved and changed with specific political historical moments.

3.3.2.1 Before Independence (before 1945)

The first code to govern water in Lebanon was during the Ottoman Empire. It was based on the Shari'a law. The empire acknowledged that water cannot be owned but it is up to state to manage it. During the Ottoman rule water into two types, the first being the 'mubah' referring to public ownership and the free access of water and the second being the 'mulk' or private ownership represented by canals and wells. Furthermore, the right of irrigation depended on the amount of water and the needs of use. Any riverine landowner had the right to enjoy rivers as long as it did not infringe on others' rights. This was later revised in the mid-19th century, when the Ottoman Empire was then pressured by the Europeans to conduct the necessary reforms in an attempt to regulate their sectors. The 'Medjella' was created in 1877 as the first legal codified text applied in the Levant. It enclosed some decrees regulating the use of water resources such as prohibiting the ownership of groundwater, permitting the use of public water for irrigation/drinking as long as it is not used up, assuring private ownership of wells and rivers if they are within one's property, digging up wells freely as long as they are within the 17m depth and imposing measures to be followed by official authorities and landowners to clear water channels and uphold facilities

(Riachi, 2016). When the French came to colonize Lebanon, they first advocated for stable and transparent property related institutions. In Article 3 of Decree 144 issued in 1925, the French Mandatory authorities recognized acquired rights over water. Decree 320 issued in 1926 stipulated the methods for eliminating acquired rights as well as the conditions for compensating expropriated parties thus the state is the sole actor when it comes to water governance. The decree also exempted the user of a well on private land from having to obtain a permit so long as the outflow did not exceed 100 m3 per day (Ghiotti and Riachi, 2013).

3.3.2.2 After Independence (after 1945)

Following the French Mandate, a trend of privatization overtook water governance of water. In Lebanon in the 1950s-1960s there was the emergence of private irrigation on agricultural land. In the 70s two decrees were issued; decree 3275 which stipulated the establishment of private water companies and decree 4537 which organizes the private water companies. Thus we see the switch of a state led water management (during the Ottoman and French rule) to more private initiatives. Another turning point in the Lebanese water governance was the 1975 civil when the public water network was deteriorating and there was a complete shift towards the private sector and change in perceptions.

In 2000, Law 221 and its amendments (in addition to Laws 228 and 337) were issued, governing the sector until today. Law 221 completely restructured the sector from 21 Water Authorities and over 200 committees and consolidated them under four regional water authorities in addition to the Litani River Authority (Amin et al., 2014). Law 228 enacted a national privatization law, encouraging the participation of the private sector and Law 337 renamed the Ministry of Hydraulic and Electric Resources to the MoEW Resources. Law 221 was proposed as a reform to the old structure of the water sector. The main purpose of this reform was to reduce the water sector fragmentation and to introduce 2 regulators: managerial and financial. However, the Law was not completely implemented. The transfer of function to the four newly created water establishments was confronted with several delays. Furthermore, water establishments were not empowered enough to act with full administrative and financial power (Bassil, 2010). A legal text to organize the four water establishments was not developed; law 4015 which regulates the public establishments in Lebanon has precedence, and therefore cancels law 221. Thus the members of parliament passed a law contradicting a previously enacted law. Doing so could be an illusion attempt of reform to give the impression of work being done to please the public. In 2010, Decision 118 was enacted to organize the procedure to be followed to register wells and/or to acquire a groundwater extraction permit. This text brought on institutional change, as it provides the detailed steps and required documents for the registration process, and externalizes part of the Ministry's responsibilities to three private engineering firms in terms of geological and hydrogeological studies and technical reports. It is important to mention that the registration process is required for wells that need and do not need a permit.

In conclusion, current laws related to groundwater date back to 1926. The Decree 320/1926 allows well owners to dig 150-meter wells or less and pump less than 100,000 L/day without acquiring a permit or a license. The decree eliminated acquired rights over water that were recognized by Decree 144/1925 in its third article. The Decree 320/1926 dates back to the French Mandate. Back then, authorities wanted to encourage agriculture by offering such exemptions. Today, more than 90 years later, this decree still has not been reconsidered or revised. On the contrary, decree 14438/1970 restated projects involving drilling must meet the same permitting requirements for well abstractions, with a valid license for a period from one year up to four years.

On the other hand, the Penal Code (Decree 340/1943) in its 745th Article imposes penalties for illegal activities including unauthorized groundwater exploitation and drilling by imprisonment for up to one year and a fine of 500,000 Lebanese liras, or by one of those sanctions. However, this article of Decree 340/1946 is not enforced. Unlicensed wells are still not sanctioned. Over and above that, the MoEW announces the open registration of unlicensed wells every now and then.

3.3.2.3 Fragmented Management

Within the formal legal and institutional framework, the water sector in Lebanon is attributed to and maneuvered by a myriad of ministries and institutions on the national, regional and local levels.

- MoEW - The Groundwater and Geology Department – The Groundwater Office;
- Regional Water Establishments: South, North, Bekaa and Beirut and Mount Lebanon;
- Litani River Authority;
- Ministry of Environment;
- Ministry of Public Health;
- Ministry of Agriculture;
- Council for Development and Reconstruction;
- Council of the South;
- Municipalities.

Based on an interview conducted with a public official at the Ministry of the Energy and Water, the Groundwater and Geology Department (comprised of the Groundwater Office and the Geology Office) currently has 6 staff members: 3 engineers, 1 topographer, and 1 administrative assistant and 1 doorkeeper. However, as per Decree 6650/1972, the Groundwater Office alone should be composed of 34 staff members (Table 3).

Table 3 Groundwater and Geology Department's structure as per Decree 6650/1972

Responsibility	Number	Responsibility	Number
Head Of Groundwater Office (Engineer Or Geologist)	1	Technician	2
Engineers	8	Trainer Technician	1
Geologists	4	Topographer	1

Trainer	2	Drafter	1
Laboratory Assistant	1	Technical Assistant	12
Administrative Assistant	1	**TOTAL**	**34**

Human resources deficit in public administrations in Lebanon can have several explanations. Riachi claims that the reason behind it is most probably linked to structural adjustment policies, imposed by international donors, whereby employment is freezed under austerity budget measures. He mentions that the use of private companies to fulfill the tasks of the government is a clear violation of public service provision (Riachi, 2016). The deficit in the water sector in Lebanon can also be explained by the strong will to privatization. In fact, understaffed public sectors contribute and incite to privatization. In Lebanon, the deficit in human resources remains to push towards privatization for the benefit of businessmen and company owners who are also politicians and decision makers in the country.

Important actors in terms of capital investment within the water sector and the largest funders of the water sector in Lebanon happen to be foreign development agencies. Provided and administered by the CDR, neoliberal donors such as the World Bank, the European Investment Bank, the Kuwait Fund for Arab Economic Development, the Islamic Development Bank and many others have been involved in funding specific water projects. Additionally, non-governmental and other international organizations are implementing projects related to water governance and management such as organizing awareness campaigns, controlling water consumption, preventing pollution and contamination through proper agricultural practices and even advising government on water policy-making.

All of the above mentioned actors, in addition to the many private companies controlling and providing water in Lebanon, form a crowded and fragmented water sector in the country. This legal pluralism and atomized network, drastically and ambiguously, affect the management of the country's water resources and provision.

3.3.3 Natural Groundwater Recharge Factors

Different factors explain recharge rates variations from a place to another in the study area.

To start with, geological settings are an important factor of natural groundwater recharge. The study area extends over different geological formations. The majority of the study is located on Jurassic (J) or Cretaceous (C) formations as shown in Figure 10 below. The North-East, North-West and South-West are mainly located on Cretaceous formations, while the Jurassic mostly extends from the north to the center and also along the South-Eastern boundary of the study area.

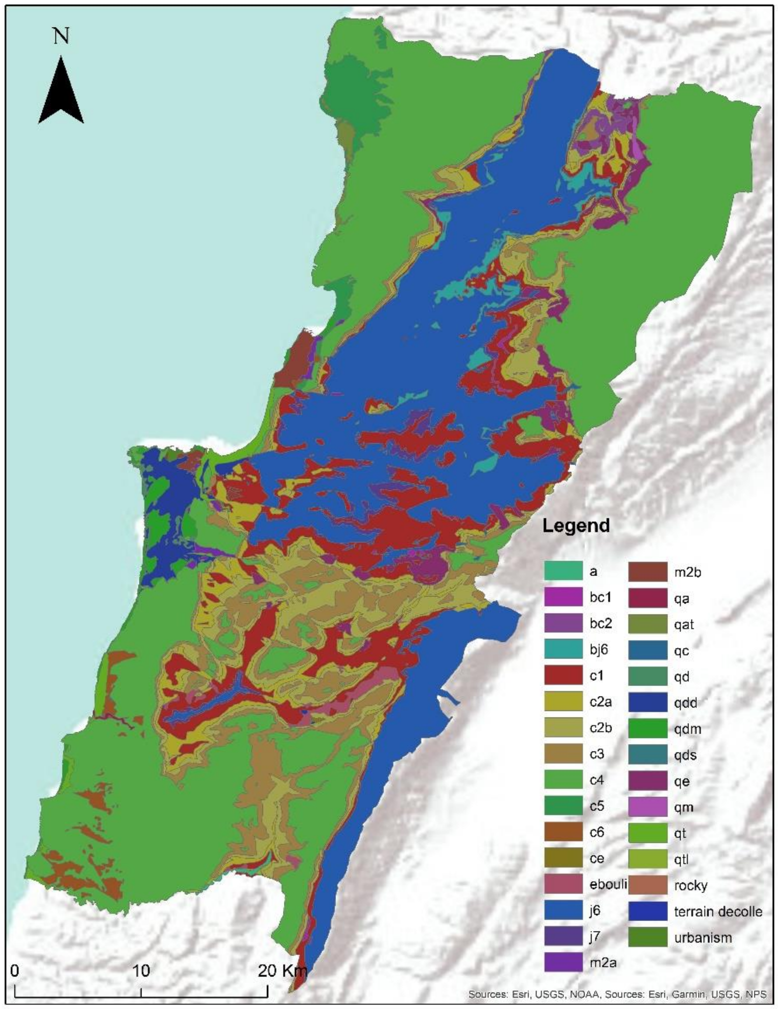

Figure 10 Geology in the Study Area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

The prevalence of karstic rocks in the study area is a strong factor of natural groundwater recharge. In fact, the presence of relief in Lebanon is favorable for karst development, with a predominance in areas with important difference of altitude such as in Mount Lebanon (UNDP and Cedro, 2014). Groundwater recharge is high in areas located on karstic formations. As depicted in Figure 11, a major part of the study area is located on karstic rocks with very high permeability, notably towards the north and the south of the study area.

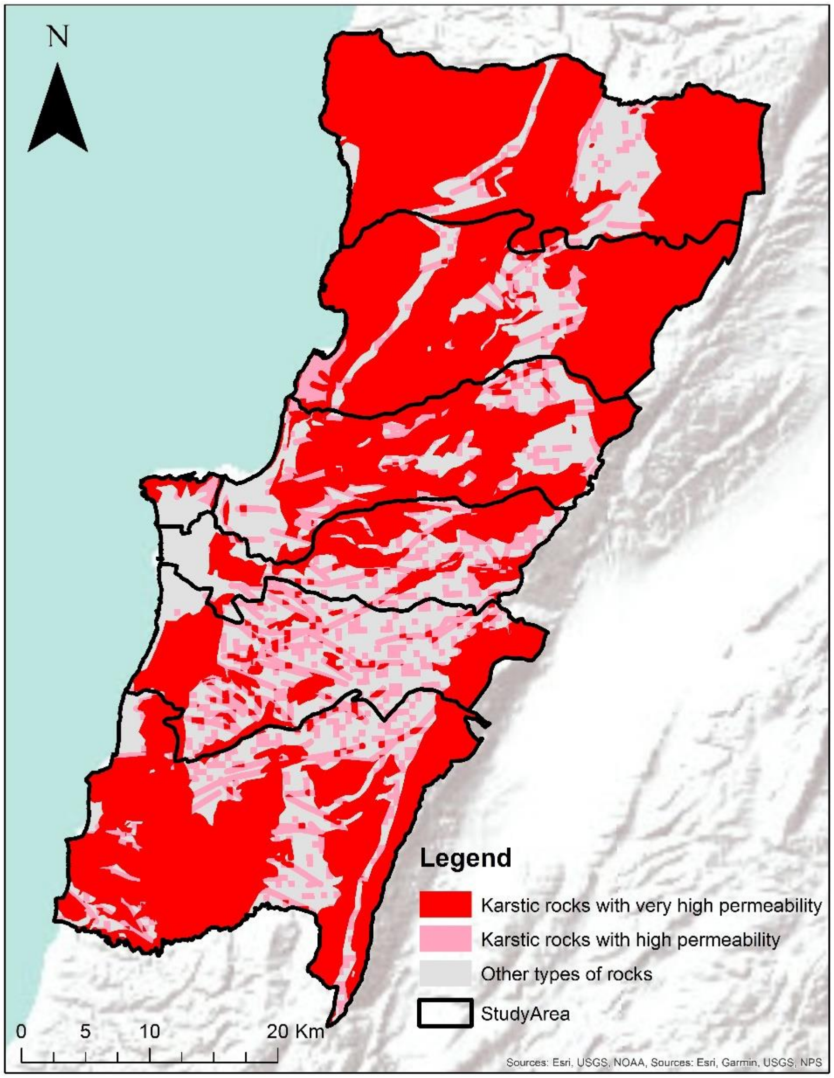

Figure 11 Karstic Rocks Permeability
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

Second, rivers are important areas of groundwater recharge. Groundwater recharge is estimated around 3,200 MCM in Lebanon, of which 2,500 MCM constitute the base flow of rivers (FAO, 2008). Many rivers and seasonal streams are found in the Greater Beirut and Mount Lebanon, with more than 10 main rivers (as shown in Figure 12) existing within the study area including Nahr Aaray (1), Nahr Awali (2), Nahr Barouk (3), Nahr Beirut (4), Nahr Bisri (5), Nahr Bou Zebli (6), Nahr

Charoun (7), Nahr El Damour (8), Nahr El Hammam (9), Nahr El Kalb (10), Nahr El Safa (11) and Nahr Ibrahim (12).

Figure 12 Main Rivers and Streams in the Study Area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

Precipitation also plays a role in water infiltration and groundwater recharge. During and after rainfall events, water infiltrating into the soil first meets the soil moisture deficiency if any, and then moves vertically downwards reaching groundwater table as recharge water (Abdullahi and Garda, 2015). Snowmelt and rainwater percolation are the two main sources of groundwater recharge in Lebanon (MoE and UNDP, 2011). In the study area, rainfall ranges between 600 and 1000 mm per year in coastal area, and between 1000 and more than 1400 mm per year in mountainous areas. The area with the highest yearly precipitation rate is located in the mountainous area between the districts of Jbeil and Keserwan (Figure 13).

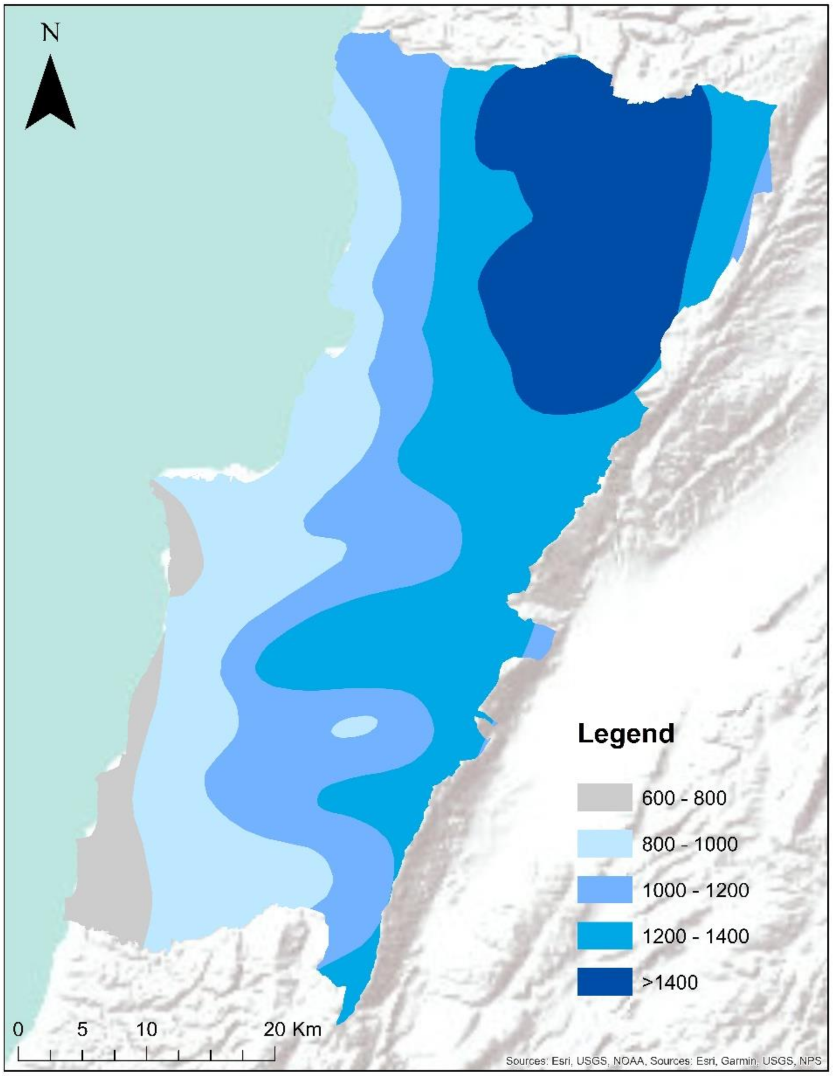

Figure 13 Rainfall in the Study Area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

Third, in the case of groundwater recharge though soil strata, topography and slope have an important effect on water infiltration. A shallow slope slows down the runoff flow allowing it to have more time to remain on the surface and to slowly percolate into the subsurface. In areas where slopes are steep, the runoff flow is faster and has less time to infiltrate into the soil. Accordingly, the groundwater recharge potential is low in areas with steep slopes and high in areas with shallow slopes. Likewise, in the case of groundwater recharge through river beds, if the slope of the streams channel is steep, the water is likely to flow faster on the surface as runoff, without infiltrating to the ground. On the other hand, gentler slopes slow down the water flow and rainwater is given time to percolate into the ground. Figure 14 shows the slopes (contour lines of 50 m) coupled with main streams in the study area.

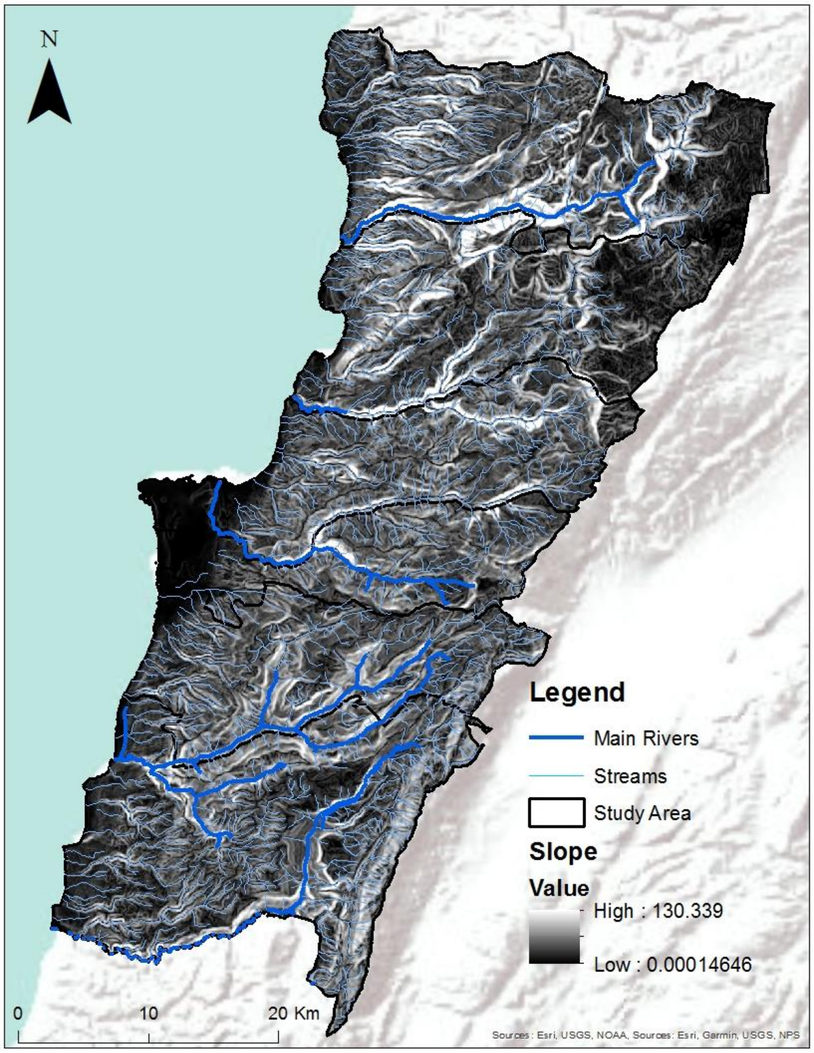

Figure 14 Slopes and Streams in the Study Area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

In addition, groundwater recharge rates are also determined by the land use and land cover in a given area. Figure 15 shows that the land use in the study area comprises of built-up areas (urban developments and infrastructure), green areas (mainly pine and oak forests, and sporadic urban green areas), agricultural lands, industrial and commercial zones, water bodies (rivers, stream and lakes) and vacant lands (mainly rocky lands). Figure 14 also shows that a major part of the study area is forested or urbanized, and to a lesser extent agricultural.

The vegetative cover determines the rate of groundwater recharge. Gee et al. (1992) claim that areas covered with deep-rooted vegetation such as forests have lower groundwater recharge rates than areas of shallow-rooted vegetation. But in general, the biological decomposition of the roots helps loosen the rock and soil allowing water to easily percolate to the subsurface of the earth. Vegetative cover also prevents direct evaporation of water from soil since the roots of a plant absorb water and prevent water loss (Yeh et al., 2008).

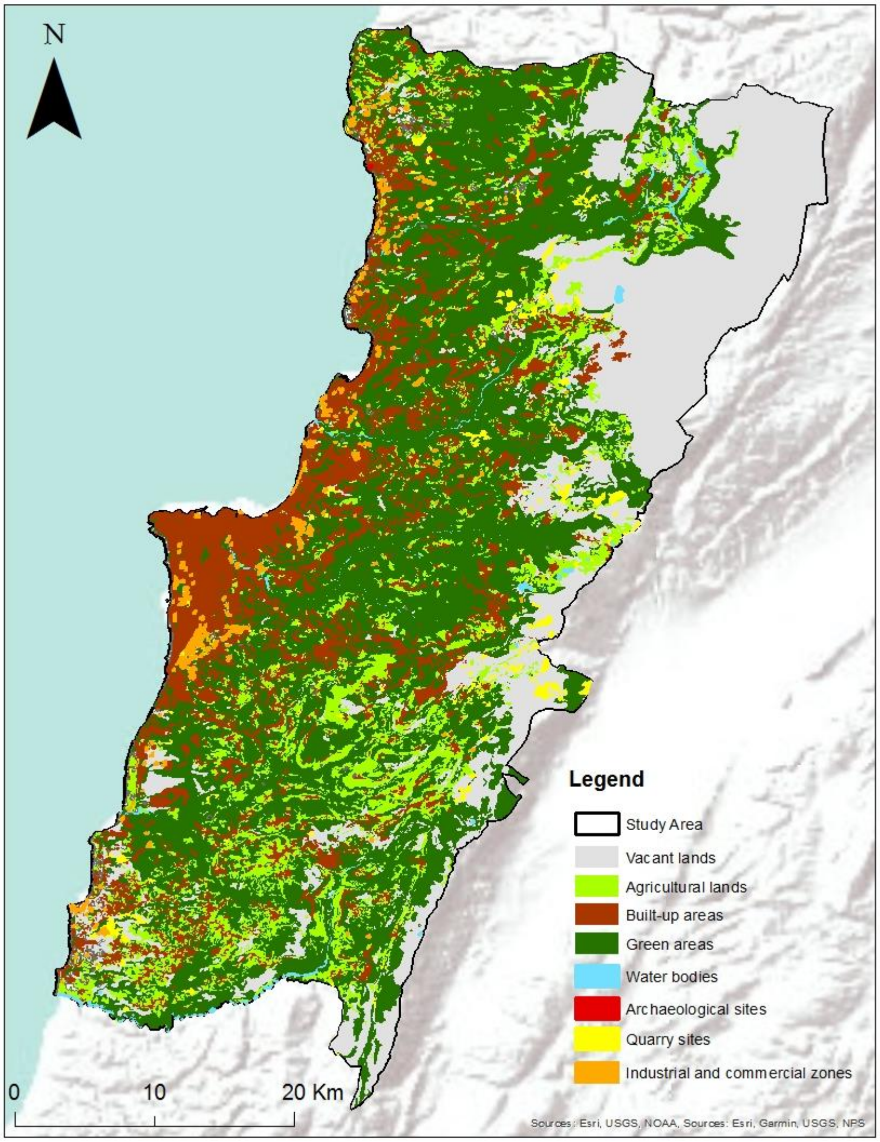

Figure 15 Land Use and Cover in the Study Area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

3.3.4 Sources of Groundwater Pollution

Groundwater resources are highly exposed to contamination, particularly in karstic and permeable geological settings. In fact, the study area is subjected to various sources of pollution associated with human activities. The main sources of pollution are saltwater intrusion, agricultural activities, industrial wastewater and municipal sewage discharge in the environment and open dumping of domestic solid waste. Groundwater pollution can be direct, but it might be induced indirectly as well by contaminants making it to the hydrological cycle or accumulating in the soil and subsequently reaching groundwater tables. To start with, saltwater intrusion is very common in coastal zones in the study area. Saltwater intrusion is a natural process in most coastal aquifers due to the hydraulic dynamic between groundwater and seawater. However, the process becomes abnormal when groundwater resources are overexploited in coastal aquifers, as the water pressure of freshwater is reduced. And since the water pressure and density of saltwater are higher than freshwater, the former can push inland and contaminate the latter (Johnson, 2007).

In addition, sources of contamination from agricultural and industrial activities are many. Agricultural sources include but are not limited to animal manure and the extensive use of fertilizers and pesticides washed downwards with runoff water and reaching groundwater tables. Some of the common nutrients present in fertilizers are nitrogen, phosphorus and potassium (NKP). They also contain secondary plant nutrients such as calcium, sulphur and magnesium. pesticides contain chemical substances such as phosphamidon, lindane, chlorpyrifos, heptachlor and malathion (National Portal of India, 2011). Nitrate from agriculture is the most common chemical contaminant in the world's groundwater aquifers (WWAP, 2013). Livestock excreta contain considerable quantities of nutrients, oxygen depleting substances and pathogens and, in intensive livestock systems, also heavy metals, drug residues, hormones and antibiotics (FAO, 2017), which accumulate in the soil. Irrigation can speed up the infiltration of above mentioned pollutants and salts through the soil, resulting in groundwater contamination and salinization. On the other hand, industrial effluents are also major sources of groundwater pollution. Industrial wastewater quantities are highly variable and depend on the type of industry as well as the industrial process itself (Karam et al., 2013). Industrial wastewater and sludge contain a wide range of pollutant including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), oils, heavy metals, suspended solids, phenols, cyanide, fluorides, sulfates, organic chemicals, acids and. The study area comprises large, medium and small industries and generated effluents are to a large extent discharged in the environment untreated.

Moreover, municipal sewage and waste are important sources of groundwater contamination when directly discharged in the environment without proper treatment or disposal. 35 to 50% of untreated municipal wastewater are estimated to infiltrate into aquifers, in the presence of nonoperational or obsolete wastewater networks and wastewater treatment plants (MoE, 2004). Untreated sewage contains chlorides, microorganisms, organics, trace metals, pathogens, nutrients, heavy metals and others that may seep into the groundwater system (Rail, 1989). As for municipal waste, open dumping is common in Lebanon and municipal waste is disposed as is in licensed landfills. Concentration of heavy metals (Cd, Cr, Cu, Fe, Ni, Pb and Zn) and microbiological pollutants (total coliforms and faecal coliform) as well as concentrations of Cl^{-}, NO_3^{-}, SO_2^{4-}, NH_4, Phenol, Fe, Zn and COD in groundwater indicate that groundwater resources are significantly affected by leachate infiltration (Mor et al., 2006).

Water resources, in particular groundwater resources, are heavily exposed to the above mentioned sources of pollution found in the study area. In addition, storage reservoirs have been identified as a new source of pollution in Beiut, whereby around 94% of samples taken from tap water in Beirut and the Litani River showed the presence of microplastics. Although Lebanese households do not drink tap water, but the latter is commonly used for cooking. Also, since public water supply is intermittent and water is stored before consumption, water contamination by microplastics from storage reservoirs is more probable especially if the latter are placed on roofs and are exposed to the sun.

CHAPTER 4

DATA COLLECTION

4.1 Greater Beirut Area: Population, Existing Groundwater Infrastructure and Available Resources

4.1.1 GBA Population

The Greater Beirut and Mount Lebanon area includes the governorates of Beirut and Mount Lebanon and covers the 7 districts of Aaley, Baabda, Beirut, Chouf, Jbeil, Keserwan and Metn. The study area occupies an area of around 2,000 km^2 and covers almost 550 different towns. The area of Beirut and Mount Lebanon is highly populated as compared to other regions of the country. In fact, around 50% of Lebanon's population lives in the GBML area. The population of Beirut and Mount Lebanon evolved and grew over the years, with the exception of the slight falloff between 1980 and 1994 explained by the Lebanese civil war that extended over 15 years (1975-1990).

There is no official delimitation of the area's boundaries, as it has not stopped expanding over the years. No population census has been carried out in the GBA, while a lot of studies estimate it between around 940,000 and 1.3 million, and some even estimate it at 2.2 million. The wide ranging estimation of GBA's population could end in both an underestimation and an overestimation of population in the absence of a particular reliable data source. The current extent of the GBA shows that the latter currently covers more than 100 cadastral units and an area of around 236 km^2 (or 320 km^2 taking into account the entire cadastral area of all municipalities within the GBA).

Table 4 Area and number of localities per district

District	Area	Number of Localities
Aley	106.95	26
Baabda	48.06	17
Beirut	21.26	12
Chouf	45.71	7
El Metn	89.86	45
Keserwan	8.67	1
Total	**320.51**	**108**

In this thesis, historical and projected population data from World Population Review for the Greater Beirut Area based on data from the UN-DESA was used as population data, as shown in Table 5.

Table 5 GBA Historical and Projected Population (Source: UN-DESA)

Year	Population	Growth Rate
2015	2,228,705	0%
2019	2,406,875	1.94%
2020	2,424,425	0.73%
2025	2,379,326	-0.37%
2030	2,311,062	-0.58%
2035	2,303,801	-0.06%

Table 5 shows a decline of the GBA population as of the year 2020. In fact, the projected decline in the urban population in Lebanon can be explained by the different factors. According to Fol and Cunningham-Sabot (2010), the decline of urban population can be associated with the aging of the population, reduced fertility, smaller and single-person households, the rising rate of women in the workplace and the delayed childbearing because of the growing number of dual-income households remaining childless for longer periods.

On the other hand, population growth per district was calculated for the population data shown above based on 2004 population percentages per district deduced from the last NPMPLT report published in 2004 (**Error! Not a valid bookmark self-reference.**).

Table 6 Population data per district in GBA in 2004 (NPMPLT, 2004)

District	Population	Population Percentage
Aley	**131,506**	**9%**
Baabda	**485,889**	**34%**
Beirut	**403,338**	**28%**
Chouf	**11,630**	**1%**
El Metn	**376,645**	**26%**
Keserwan	**19,192**	**1%**
Total	**1,428,200**	**100%**

Based on the above mentioned approach, population and population density were calculated for the years of 2019 and 2035 for the 6 districts in the GBA (Table 7).

Table 7 Population and population density in the GBA in 2019 and 2035

District	Area	Number of Localities	2019 Population	2035 Population	2019 Population Density (persons/km2)	2035 Population Density (persons/km2)
Aley	106.95	26	216618.75	207342.09	2025	1939
Baabda	48.06	17	818337.5	783292.34	17027	16298
Beirut	21.26	12	673925	645064.28	31699	30342
Chouf	45.71	7	19519.76	18683.83	427	409
El Metn	89.86	45	649856.25	622026.27	7232	6922
Keserwan	8.67	1	28641.81	27415.23	3304	3162
Total	**320.51**	**108**	**2,406,899**	**2,303,824**		

4.1.2 Public and Private Wells in the Study Area

In regards to groundwater-based supply, both public and private wells help meet the water demand in the study area. Based on data provided from the the MoEW, 358 public wells are found in the study area. Among them, 282 are operational and 76 are out of service (Figure 16). The distribution of the 282 operational public wells per kaza within the study area comes as follows: 68 operational public wells in Chouf, 64 in Aaley, 57 in Baabda, 44 in Metn, 23 in Keserwan, 26 in Jbeil and none in Beirut. Coordinates were provided for only 280 operational public wells. The two remaining wells are therefore not located on the below map. As shown in Figure 16, the majority of wells that are out of service are located near the coastline, which is explicitly illustrated in the Metn district. This observation can be indicative of saltwater intrusion in coastal aquifers, although, coastal wells are still operational in the Chouf district based on data provided from the MoEW.

As for well depth and abstraction rates, data was not provided for all the wells existing in the study area. Out of 282 operational public wells, 220 have depth data and 136 have abstraction rates data. Based on available data, depth of operational public wells varies between 12 and 710 m, and abstraction rates vary between 1.8 and 650 m^3/h. An average depth of 296 m and abstraction rates of 1896 m^3/day for every well are recorded in the study area.

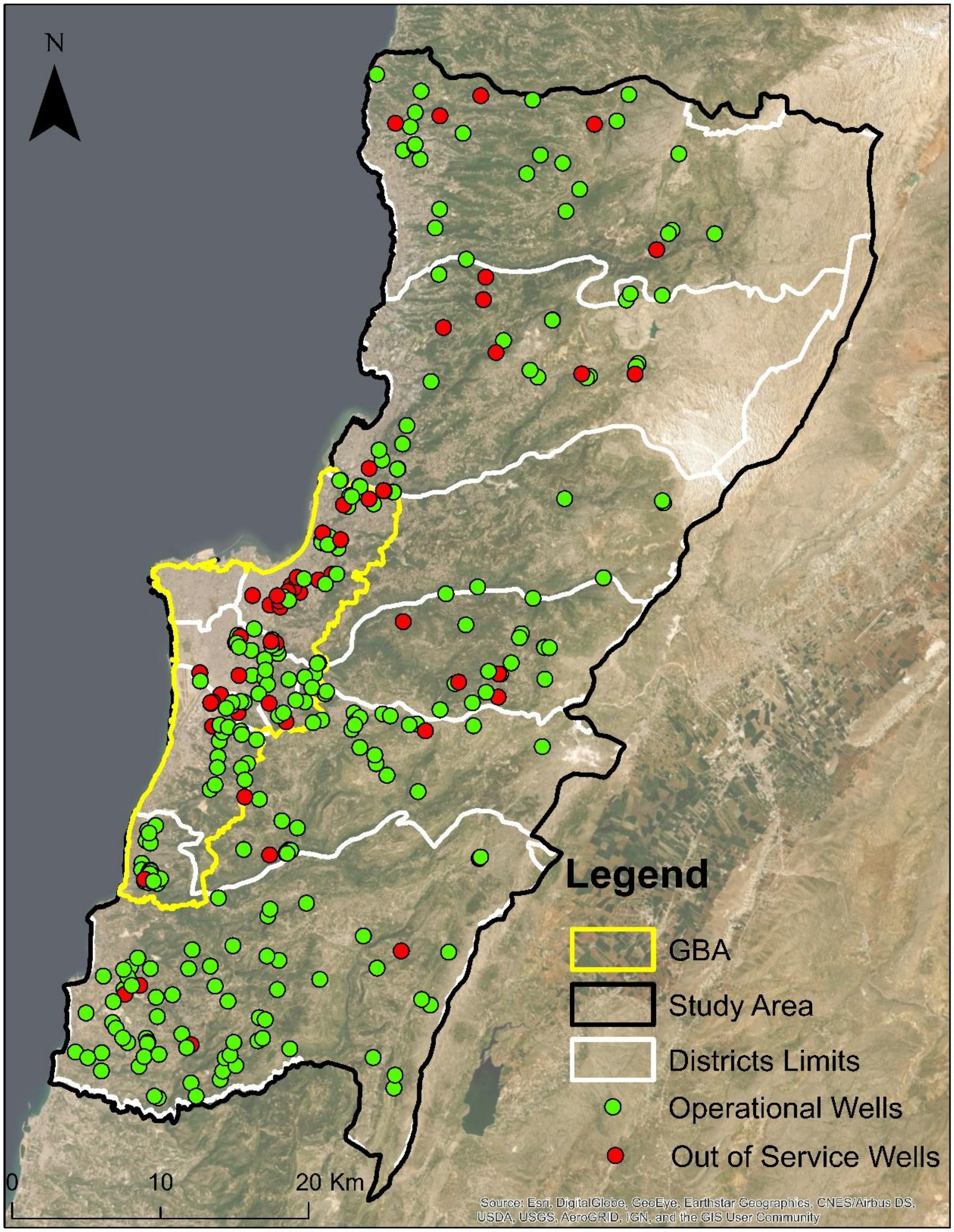

Figure 16 Current Status of Public Wells in the Study Area
(Basemap Source: ESRI, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

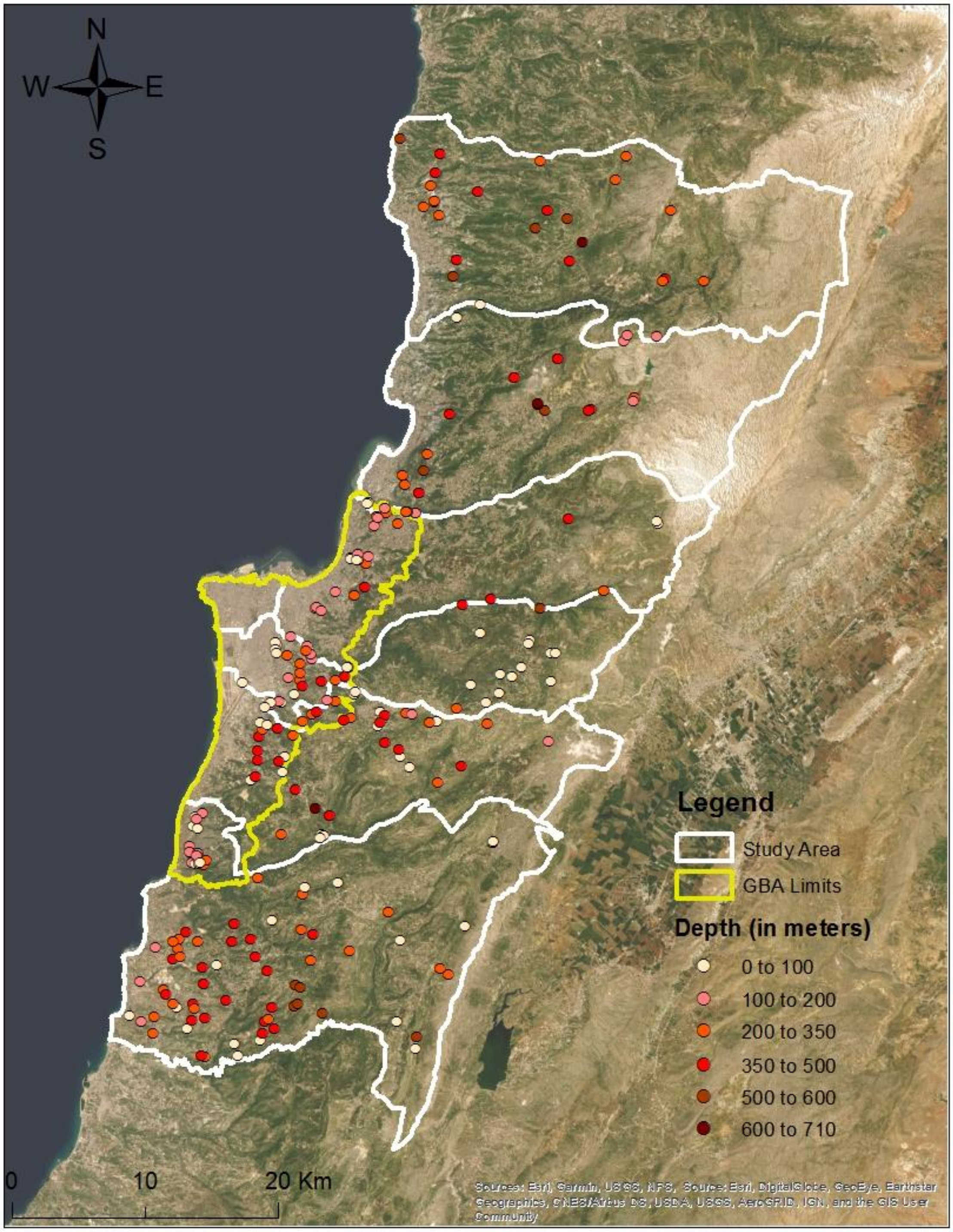

Figure 17 Depth of Public Wells
(Basemap Source: ESRI, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

Table 8 Depth of Public Wells

Well Depth (In Meters)	Aley	Baabda	Chouf	Metn	Keserwan	Jbeil
0 to 100	3	8	5	6	1	0
100 to 200	3	21	3	12	5	2
200 to 350	10	10	22	15	4	11
350 to 500	17	5	21	3	8	7
500 to 600	2	0	6	0	2	4
600 to 710	0	0	0	0	2	2
N/A	29	13	11	8	1	0
Total	**64**	**57**	**68**	**44**	**23**	**26**

Figure 18 Abstraction Rates of Operational Public Wells
(Basemap Source: ESRI, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

Table 9 Abstraction Rates of Operational Public Wells

Abstraction Rates (In M^3/Hour)	Aley	Baabda	Chouf	Metn	Keserwan	Jbeil
0 to 25	3	7	3	3	4	10
25 to 50	5	9	4	2	7	11
50 to 100	4	13	3	7	6	1
100 to 200	1	5	1	15	0	2
200 to 400	1	0	0	4	2	1
400 to 650	1	0	0	0	1	1
N/A	49	23	57	13	3	0
Total	**64**	**57**	**68**	**44**	**23**	**26**

Private wells are another important source of water to compensate for water shortage in the area, whether for agricultural or domestic use. The number of private wells far surpasses the number of public wells in the study area. Farmers and individuals have resorted to drilling private wells in order to fill the gap left by water resources mismanagement and unavailability. According to UNDP's groundwater assessment study in 2014, 20,537 private wells were officially registered all over the country until January 2012 based on data from the MoEW, of which more than 50% are located in the area of Beirut and Mount Lebanon (over 10,000 licensed private wells). The study also claims that the number of unlicensed private wells in Lebanon is almost 3 times the number of licensed ones, and was estimated at about 55,000 to 60,000 wells based on interviews and discussions with representatives from local authorities, local community and local drillers (UNDP, 2014). Based on numbers provided by the MoEW, 16,538 private wells are found within the study area, being officially registered until June 17, 2019. Among those private wells, 14,538 are located in the governorate of Mount Lebanon and 2,000 in Beirut. Unfortunately, there are no detailed data for private wells in terms of depth and abstraction rates.

4.1.3 Springs in the Study Area

Hydrogeological formations in Lebanon are classified into three main groups: karstic aquifers, porous or semi-aquifers, and aquicludes. The two main aquifers are the Kesrouane Jurassic and the Sannine - Maameltain aquifers which are mainly composed of karstic carbonate rocks and cover about 5590 km^2 of the Lebanese territory, which is more than 50% of the country's area (UNDP, 2014). More than 50 main springs exist in Greater Beirut and Mount Lebanon, some of them being seasonal and others being permanent. The majority of existing springs in the study area are found in the districts of Jbeil and Keserwan, as depicted in Figure 19.

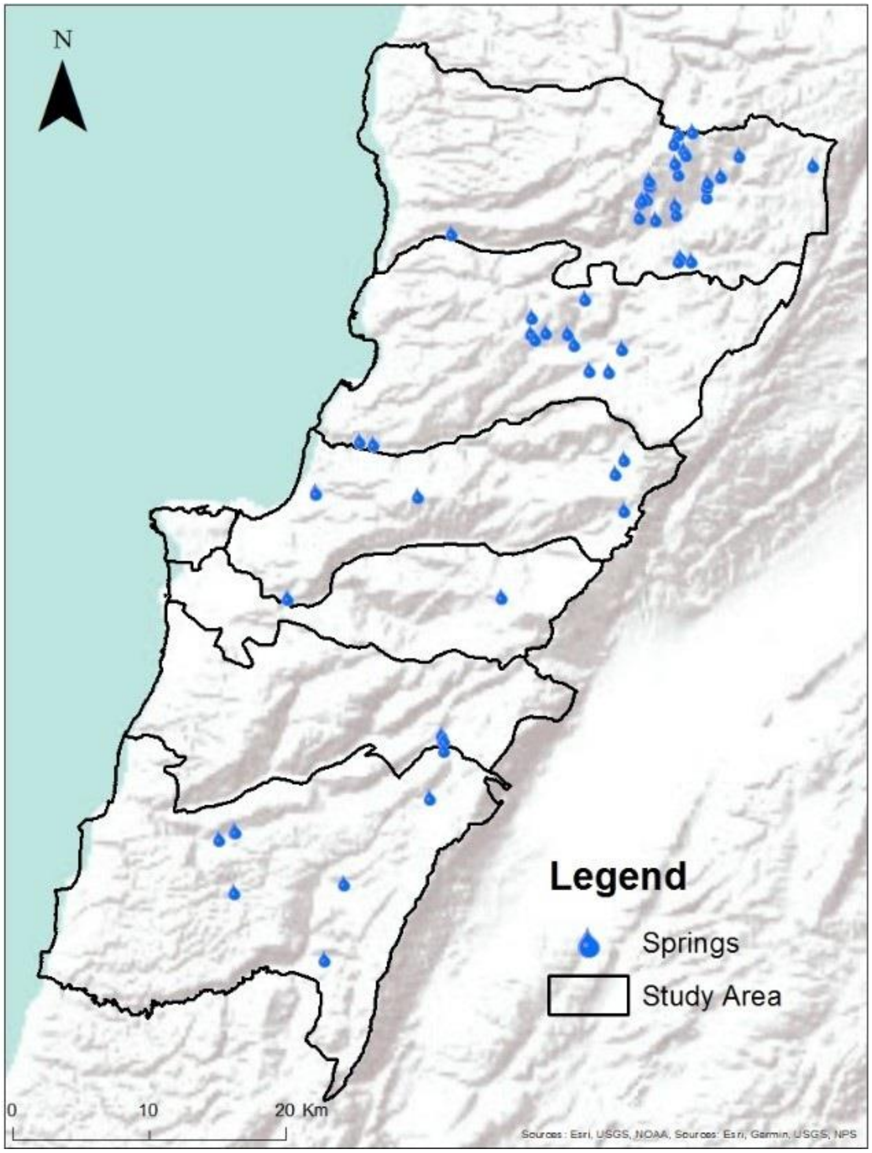

Figure 19 Main springs in the study area
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

The Jeita spring groundwater catchment is one of the main spring catchments in the study area. It is located between the districts of Jbeil, Keserwan and Metn, but mostly in Keserwan, within the Nahr Ibrahim surface water catchment. The catchment extends over an area of around 400 km^2, providing drinking water to more than 75% of Beirut (Schuler and Margane, 2014).

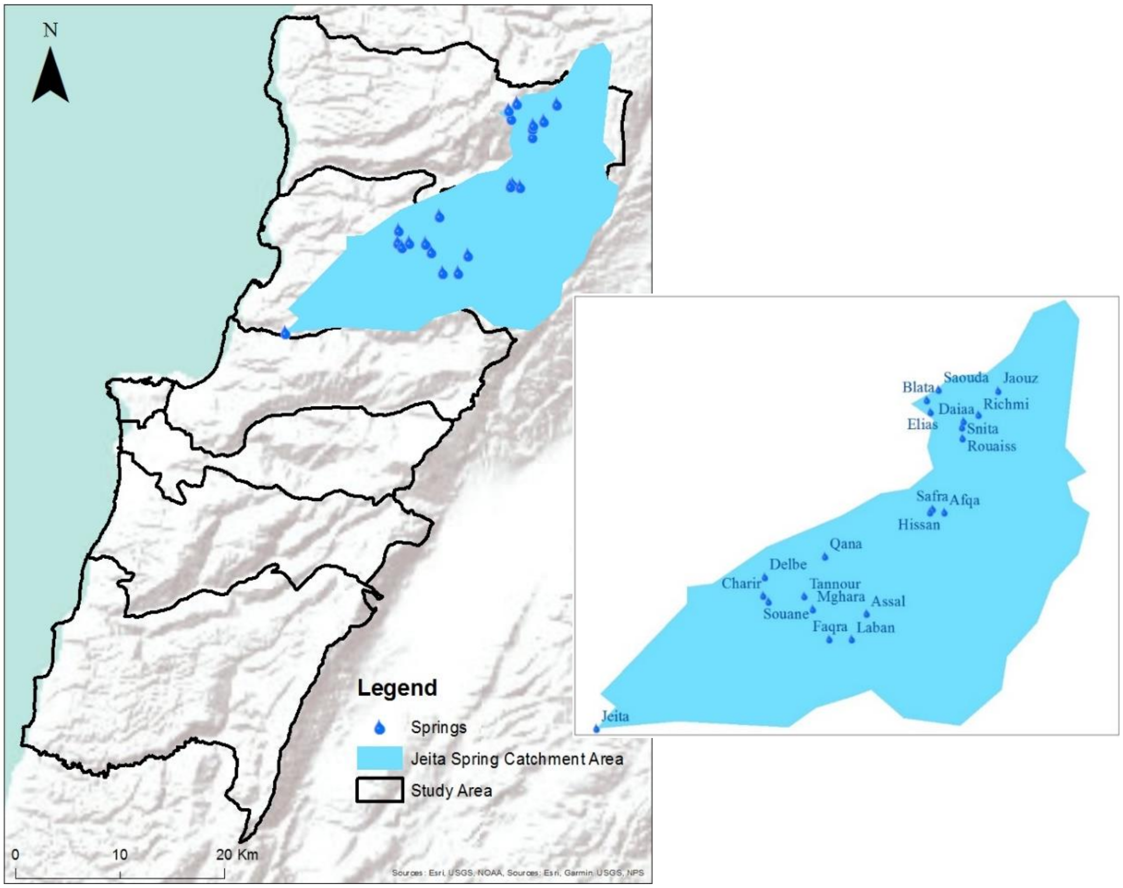

Figure 20 Jeita spring catchment and existing springs
Basemap Source: Esri, USGS, NOAA, Garmin, NPS.

The Jeita spring catchment consists of formations which are part of the Jurassic (J) or Cretaceous (C). 70% of the Jeita spring catchment area is covered by limestone with high degrees of karstification. Karstification is extreme at higher altitudes, especially on the high plateau, in the Sannine Formation (C4), where more than 2,000 dolines are found, allowing rain and snow to rapidly infiltrate into the soil and resulting in an extremely high groundwater recharge of around 81% during snowmelt (Schuler and Margane, 2013). The Jeita spring catchment also comprises the entire groundwater catchments of the Afqa, Assal, Labbane and Rouaiss springs, which all discharge from the Upper Aquifer C4 (Raad and Margane, 2013). Out of 50 springs in the study area, 21 are concentrated in the northern part of the study area, as part of the Jeita spring groundwater catchment (Figure 20). According to Margane and Makki (2010), the springs located within the catchment evidently contribute to Jeita spring discharge, which ranges between 150 MCM in the dry season and more than 250 MCM during the rainy season. Whereas based on a study conducted by Doummar et al. (2014), the Jeita spring discharge ranged between 1.5m^3/s in September 2010 and 2011 (low flow period) and 8m3/s in March 2011 (high flow period), equivalent to a discharge ranging between 47 and 252 MCM per year. The average long-term discharge of Jeita spring for the entire groundwater catchment of the spring is estimated at 172 MCM per year (Raad and Margane, 2013). Based on data provided by the MoEW, the flow rate used from Jeita spring by the Beirut and Mount Lebanon Water Establishment (BMLWE) for supply purposes is around 110.41 liters/second, equivalent to 3.48 MCM per year. The water quality of springs discharging from the Upper Aquifer is higher than springs discharging from the Lower Aquifer (J4), since they are less exposed to sources of pollution and contamination (Raad and Margane, 2013). The BGR claims that the Jeita spring could supply the entire GBA with water. Other important springs are found in the study area and are exploited by the BMLWE for water supply purposes. The Kashkoush spring, for example, is located approximately half a kilometer downstream of Jeita, and discharges into the Nahr el Kalb and/or into the Jeita-Dbayeh conveyor. The groundwater catchment of Kashkoush spring has not yet been delineated and data on discharge and flow rates is still rare. However, based on data provided by the MoEW, the BMLWE water supply provided from the Kashkoush spring is estimated at an average discharge of 130.7 liters/second, equivalent to 4.12 MCM per year. However, the spring's average discharge recorded 54.1 MCM in water year 2010/2011 and 84.0 MCM in water year 2011/2012, as measured by the BGR (Margane and Stoeckl, 2013), forming an average of 69 MCM. Another important spring in the study area is the Dayshounieh spring, located between the districts of Metn and Baabda. Based on data provided by the MoEW, the BMLWE water supply provided from the Dayshounieh spring is estimated at an average discharge of 228.6 liters/second, equivalent to 7.21 MCM per year. However, no studies were conducted to quantify or even estimate the average discharge of the Dayshounieh spring. Nevertheless, many other important springs are found in the study area. According to UNDP (2014), Nabaa Al Roueiss located in the High Central Mount Lebanon Basin records an average minimum discharge of 0.144 m3 per second, equivalent to 4,5 MCM per year. Nabaa Fouar Antelias also records an average minimum discharge of 0.2 m3/second, equivalent to 6.3 MCM per year.

CHAPTER 5

RESULTS

Water demand was estimated by multiplying district population by different scenarios of daily water demand. According to Doummar (2014), each person consumes around 150L of water per day. According to WHO (2003), 100 to 200 L/day/capita are needed to secure an optimal supply. According to FAO (2009), each person in Lebanon needs between 200 and 250 L/day during the wet and dry season respectively. In the absence of a reliable references on water demand per day per capita, water demand was estimated using different scenarios of daily consumption per capita for each cadastral unit in the GBA. Water demand scenarios were chosen based on available literature and come as follows:

- Scenario 1: 100 L/day/capita
- Scenario 2: 120 L/day/capita
- Scenario 3: 150 L/day/capita
- Scenario 4: 200 L/day/capita
- Scenario 5: 250 L/day/capita

Based on the calculations (Table 10), a water demand ranging between 89.1 and 222.6 MCM was needed to fulfill the needs of the 2019 population for a demand ranging between 100 and 250 L/day/capita. As the GBA population is expected to decrease by 2035 according to World Population Review, water demand is also expected to decline and range between 85.2 and 213.1 MCM to meet the water needs of the 2035 population for a demand ranging between 100 and 250 L/day/capita. As shown in Table 5, 2020 will record the highest population and water demand with the latter ranging between 89.7 and 224.3 MCM for a demand ranging between 100 and 250 L/day/capita (detailed calculations for cadastral water demand are found in Appendix 2).

Table 10 Yearly Water Demand per District in MCM

District	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
2019					
Aley	8.0	9.6	12.0	16.0	20.0
Baabda	30.3	36.3	45.4	60.6	75.7
Beirut	24.9	29.9	37.4	49.9	62.3
Chouf	0.7	0.9	1.1	1.4	1.8
El Metn	24.0	28.9	36.1	48.1	60.1
Keserwan	1.1	1.3	1.6	2.1	2.6
Total	**89.1**	**106.9**	**133.6**	**178.1**	**222.6**
2020					
Aley	8.1	9.7	12.1	16.1	20.2
Baabda	30.5	36.6	45.7	61.0	76.2
Beirut	25.1	30.1	37.7	50.2	62.8
Chouf	0.7	0.9	1.1	1.5	1.8
El Metn	24.2	29.1	36.3	48.4	60.6
Keserwan	1.1	1.3	1.6	2.1	2.7
Total	**89.7**	**107.6**	**134.6**	**179.4**	**224.3**
2025					
Aley	7.9	9.5	11.9	15.8	19.8

Baabda	29.9	35.9	44.9	59.9	74.8
Beirut	24.6	29.6	37.0	49.3	61.6
Chouf	0.7	0.9	1.1	1.4	1.8
El Metn	23.8	28.5	35.7	47.5	59.4
Keserwan	1.0	1.3	1.6	2.1	2.6
Total	**88.0**	**105.6**	**132.1**	**176.1**	**220.1**
2030					
Aley	7.7	9.2	11.5	15.4	19.2
Baabda	29.1	34.9	43.6	58.1	72.7
Beirut	23.9	28.7	35.9	47.9	59.9
Chouf	0.7	0.8	1.0	1.4	1.7
El Metn	23.1	27.7	34.6	46.2	57.7
Keserwan	1.0	1.2	1.5	2.0	2.5
Total	**85.5**	**102.6**	**128.3**	**171.0**	**213.8**
2035					
Aley	7.7	9.2	11.5	15.3	19.2
Baabda	29.0	34.8	43.5	58.0	72.5
Beirut	23.9	28.6	35.8	47.7	59.7
Chouf	0.7	0.8	1.0	1.4	1.7
El Metn	23.0	27.6	34.5	46.0	57.5
Keserwan	1.0	1.2	1.5	2.0	2.5
Total	**85.2**	**102.3**	**127.9**	**170.5**	**213.1**

Most aquifers in Lebanon are karstic, which allows rainwater and snowmelt to be the main sources of natural groundwater recharge and to feed deep groundwater tables. Data on existing wells, population and water demand was collected and is herein combined in a simple mathematical calculation, in order to demonstrate whether or not existing resources can supply the 2020 population, since 2020 is expected to be the year with the highest population according to World Population Review projections. In addition, this section is based on Scenario 5 (water demand of 250 L/day) of the year 2020 as the figures reflected represent the worst case scenario of our study. Taking into account discussed numbers for Jeita (172 MCM), Daychounieh (7.21 MCM), Kashkoush (69 MCM), Fouar Antelias (6.3) and Al Roueiss (4.5) springs, a minimum discharge of 259 MCM is secured yearly. Accordingly, discussed springs can definitely cover the maximal water demand of 224.3 MCM to be reached in 2020. As mentioned in the previous section, up to 50 major springs are found in the study area, and the ones discussed in this thesis are only some of them, not to mention important groundwater basins such as the Kneisseh Basin of which the spring discharges still have not been well measured and might be underestimated, and the Sarafand-Khalde Basin (Damour, Awali and Ghadir rivers) currently facing high exploitation and saltwater intrusion issues. (UNDP, 2014). Thus available resources are even more abundant and are able to supply the GBA with enough water to fulfill the water demand of the GBA population over the coming years.

On the other hand, after making sure that the area is self-sufficient in terms of groundwater resources, it is important to examine whether existing well infrastructure can convey the water needed to meet the demand. 256 operational public wells are currently found in the study area, excluding the ones located in Jbeil since the district is not part of the GBA. Abstraction rates were provided by an anonymous source in m3/hour. The average of provided abstraction rates is estimate at 91.6 m^3/hour. According to the World Bank, the average public water supply stands at 6 hours per day in the summer season and 9 hours in the winter season; accordingly, this thesis adopts an average of 7.5 hours of public water supply per day. Accordingly, multiplying 91.6 m^3/hour by 7.5 hours of public water supply per day results in daily public water supply of around 687 m^3/day per public well (equivalent to around 0.25 MCM/year per public well). Since the year 2020 is the one with the highest calculated water demand, Table 11 below summarizes the water supply provided by currently existing wells in the GBA.

Table 11 Water Demand and Supply in 2020 under Scenario 5

District	2020 Water Demand in MCM (Scenario 5)	Wells per District	Average Yearly Abstraction per well (in MCM)	Yearly Water Supply from Public Wells	Deficit
Aley	20.2	64	**0.250755**	16.04832	-4.15168
Baabda	76.2	57		14.293035	-61.90697
Beirut	62.8	0		0	-62.8
Chouf	1.8	68		17.05134	15.25134
El Metn	60.6	44		11.03322	-49.56678
Keserwan	2.7	23		5.767365	3.067365
Total	**224.3**	**256**		**64.19328**	**-160.1067**

As shown in Table 11, for a water demand of 250L/day/capita, the yearly water demand in 2020 under Scenario 5 will reach 224.3 MCM in 2020. The yearly water supply from public wells was calculated, taking into consideration the numbers of wells per district and multiplying them by the yearly public water supply calculated based on the daily public water supply deduced in the previous paragraph. It is important to note that those results were calculated based on assumptions and do not exactly reflect the real public water supply. A preliminary observation of the results shows a serious deficit in public water supply in the districts of Aley, Baabda, Beirut, El Metn and Keserwan, as opposed to an excess of public water supply in Chouf. What can be deduced from analyzed data is the following:

- The maximum water demand to be reached in the GBA is 224.3 MCM in 2020;
- A yearly public water supply of 64.19 MCM is ensured from 256 public wells located within the GBA;
- A maximum deficit of 160 MCM is needed to be supplied to meet the demand of the 2020 GBA population;
- The calculated deficit is the maximal and can be supplied by existing springs in the study area;
- Private wells can help covering demand for the industrial, hospitality and agricultural sectors.

In terms of water storage infrastructure, 66 operational water reservoirs are found in the GBA to date, with a total capacity of around 70,666 m^3, equivalent to 70,666,000 L or 0.07 MCM, according to data provided from an anonymous source (Table 12).

Table 12 Capacity of Existing Reservoirs and 2020 Daily Water Demand in GBA under Scenario 5

District	Operational Reservoirs In GBA		Daily Water Needs In 2020 For Scenario 5 (In MCM)
	Quantity	Total Capacity (in MCM)	
Aley	33	0.0367	0.0558
Baabda	4	0.0040	0.2062
Beirut	0	0	0.1712
Chouf	11	0.0103	0.0049
El Metn	17	0.0195	0.1598
Keserwan	1	0.0003	0.0082
Total	**66**	**0.0706**	**0.6061**

As shown in Table 12, more reservoirs are required to accommodate the daily water needs of the GBA population, particularly in the districts of Aley, Baabda, Beirut, Metn and Keserwan. As for the Chouf district, numbers show an excess of storage capacity compared to the maximum daily water needs.

CHAPTER 6

DISCUSSION

Based on the results presented in the previous sections, and based on the thorough literature review conducted in this thesis, existing groundwater resources are sufficient to provide a decent water supply to the GBA assuming a water demand of 250L/day/capita. However, new wells and storage reservoirs and network improvements are needed to convey existing resources to meet calculated water needs. The costs of the required infrastructure are high, but not as high as the cost of construction and maintenance of the proposed dams intended to supply the area. It is important to note that the above results were calculated based on projections for 2020's GBA population and based on the scenario of a water demand of 250 L/day/capita. Results would be even more conclusive in case of decrease of demand and decrease of losses related to network leakage rates.

Below is a summary of the main deductions and findings of this thesis:

- The calculated deficit can be reduced from existing public well infrastructure if abstraction hours are prolonged;
- The calculated deficit can be reduced from existing public well infrastructure if abstraction rates are increased;
- Abstraction rates can be better determined if discharge measurements are done for springs existing in the study area, for a better assessment and a

more sustainable use of existing resources and in order to quantify the capacity of assessed water sources to supply this or that area or localities of the GBA;

- New public wells can be installed to ensure an efficient and fair distribution of public wells in the GBA and to minimize distribution network costs to convey public water over long distances;
- New storage reservoirs shall be constructed to store the water needs of the GBA;
- Private wells can help covering demand for the industrial, hospitality and agricultural sectors;
- The entire water distribution network shall be renewed to reduce water leakage.

Water sector-related issues in Lebanon are many and mainly include poor management and protection of resources, specifically groundwater resources. The public network water supply is irregular and unstable; whereby daily water supply drops from 13 hours during the wet season to only 3 hours during the dry season. The outdated public water network, most of it dating back to the 1960s, is leaking to a rate of 50 percent on average, reaching up to 80 percent in some areas (Riachi, 2014). Due to the deficit between water demand and water supply, households have resorted to other sources of domestic water supply including but not limited to off-network water supply providers of water jugs, bottled water and water tanks, in addition to drilling private wells.

Groundwater in Lebanon is currently overexploited, resulting in the depletion of the water tables, salt water intrusion in coastal areas, and higher contamination and pollution of resources. In order to secure a sustainable source of water for GBA residents, ensuring a viable protection against overexploitation and pollution of groundwater resources shall be guaranteed through the strict enforcement of new laws and regulations and the identification of new and updated groundwater protection zones where groundwater resources are depleted and/or exposed to heavy sources of contamination. Domestic wastewater, industrial effluents, agricultural fertilizers and pesticides and dumpsites, among others, are the main sources of groundwater pollution existing in the study area. Mitigating groundwater depletion and pollution is possible, yet a long process.

With the aim of mitigating the overexploitation of groundwater resources, existing groundwater policies shall be enforced and new firmer texts shall be initiated based research in the fields of geology, hydrogeology and environment to assess and quantify groundwater resources in order to prohibit drilling new wells in stressed aquifers and set clear withdrawal limits for already existing wells and future ones. A combination of regulatory, economic and collective action policy making should be employed in order to be less restrictive and more efficient. In addition, frequent maintenance of wells is also important to preserve groundwater quality whereby well owners or operators shall periodically check the conditions of the well. Water quality testing shall also be carried out to monitor water quality (microbiological, chemical and heavy metals tests). Tests shall be done regularly if water quality is stable, or more often if changes in taste or color were observed. Moreover, groundwater recharge can mitigate the decline of water quantity and quality by injecting water into aquifers on the first hand and diluting contaminated groundwater and dropping them to lower concentrations on the second hand. The government is the main party responsible of controlling and monitoring public wells, and determining groundwater protection zones. Concerned authorities shall also consider adopting a polluter-pays principle and mitigation measures to restore depleted and contaminated resources.

Groundwater recharge has been proven to protect groundwater from seawater intrusion by displacing the saltier groundwater, thus allowing the conservation of groundwater resources (Karam, 2002). Groundwater recharge occurs either naturally or artificially. Natural and artificial groundwater recharge are important measures to increase resources and mitigate contamination and depletion. Natural recharge of groundwater is a relatively slow process and is unable to mitigate depletion alone under excessive and continued exploitation of groundwater resources (Shakti Bhawan and Marg, 2007). Artificial methods help speed up the recharge process. Different water sources can be used for recharge, including, surface water bodies, surface runoff, rainwater, treated wastewater and others. Although artificial recharge is still an uncommon practice in Lebanon, the Project d'Etude des Eaux Souterraines au Liban, a joint project between UNDP, FAO and the Lebanese government, undertook the recharge of the Hadath Cenomanian coastal aquifer in 1961 by injecting water from the Beirut river through the Deychouniyeh irrigation canal into two injection wells in the Hadath area, resulting in an increase in the water level in the targeted aquifer (Massaad, 1971). Groundwater recharge in coastal areas can mitigate saltwater intrusion and reestablish the water pressure of freshwater in coastal aquifers. Those aquifers shall not be exploited, and their role shall be to prevent saltwater from intruding again.

On the other hand, groundwater protection is important to secure sustainable and decent resources. Delineating new groundwater protection zones can help protect aquifers from potential sources of pollution. Lebanon's karst aquifers have specific characteristics that render them highly vulnerable to contamination. Geological, hydrological and hydrogeological characteristics, as well as polluting activities in karst environments must be investigated in order to preserve karst groundwater. The establishment of new groundwater protection zones is highly important to guarantee the preservation of groundwater resources, based on comprehensive hydrogeological investigation and studies. Groundwater protection zones can involve highly contaminated aquifers, or important groundwater reservoirs. Groundwater protection not only consists of delineating vulnerable or highly valuable aquifers, but must also include the nomination of independent experts or an advisory board of experts in the fields of geology, hydrology, hydrogeology and environment who would be responsible for determining potential groundwater zones to be protected and for the follow-up of established protection zones. Experts shall become predominant actors in the water sector and must be involved in all decisions and interventions directly or indirectly related to groundwater and undertaken by other actors involved in the water sector.

A tangible solution would be opting for hybrid water supply systems consisting of a combination of both centralized and decentralized systems of water supply through the use of localized rainwater tanks, storm water harvesting and wastewater treatment and reuse, in addition to centralized systems. Centralized water systems have provided adequate urban water supply, sanitation and drainage services over the years. However, in view of current changes in demographic patterns, socio-economic factors, climate change, water supply and water demand, in addition to the ageing of water infrastructure, pressure on these urban water systems has been increasing. Hybrid water supply systems would require a better integration of these systems by improved network design, as well as well-planned operation and maintenance mechanisms (Sapkota et al., 2015) but would generate more sustainable and resilient urban water systems.

CHAPTER 7

CONCLUSION

To sum up, water shortage is perceived as a reality to tackle with engineering solutions, while the major problem is a matter of management, along a futile regulatory framework. Also, there is a clear disregard for groundwater resources to the benefit of large-scale dam projects. The analysis of existing wells, springs and water demand in the study area showed that existing resources are more than enough to cover the needs of the GBA and that existing public well infrastructure shall operate based on hydrogeological investigation and studies. Calculations were done for the year 2020 as it will record the highest population (2,424,425 residents) according to UN-DESA projections, whereby population in the GBA will start declining and reach 2,303,801 persons by 2035. Calculated water demand for 2020 ranges between 89.7 MCM and 224.3 MCM for a demand ranging between 100 and 250 L/day/capita. In contrast, in the final ESIA elaborated for the GBWSAP, a population growth and an increasing water demand between 2010 and 2035 is shown and highlighted, with an unsupported depiction of a constant yearly available water resources to showcase the need for and promote proposed dams (Appendix 1), namely the Bisri dam.

Water scarcity, as promoted by politicians and decision makers, is hypothetical and the need for large infrastructure projects such as dams is simply a game of power and corruption. Groundwater flow velocities are much slower than surface water flow velocities, except in limestone karst formations (Barackman and Brusseau, 2002). Consequently, dams are very likely to fail in meeting their objectives. Developed countries all around the world are now questioning the efficiency and sustainability of dams, while the developing world is still planning and adopting dams to solve water shortage problems. As long as the efficiency and associated benefits of a dam are not proved to outweigh its environmental and social impacts, the dam option is either not the suitable solution, or requires further studies and investigation. In Lebanon, dams are being promoted as a result of the flow of finds by international donors. Opting for dams became automatic, short of sufficient and proper investigation and exploration of more sustainable and affordable alternatives.

One of the major issues in the water sector in Lebanon standing in the way of a proper protection and management of groundwater resources in Lebanon is the lack of managerial, environmental and technical awareness and expertise which is explicitly reflected by the reality of water supply in the GBA. Protection, management and technical improvements of the existing public water supply network emerge as crucial levels of intervention in the water sector to secure a decent and sufficient water supply to the GBA. The lack of staff and the many vacancies in important positions in the public water sector is a major driver of mismanagement. The main actors in the water sector, namely the MoEW, shall hire adequate expert and technical personnel to ensure groundwater protection and management. The development and empowerment of the Groundwater Office of the Groundwater and Geology Department at the MoEW can allow the office to cover more tasks and to take on further protective measures to prevent groundwater related issues including but not limited to:

- Detailed assessment of water demand to quantify the needs per district and per cadaster and accordingly propose new public wells or higher abstraction rates from existing public wells.
- Well surveys to monitor groundwater abstractions;
- Spring discharge measurements to determine abstraction rates based on resources and supply capacity of each spring;
- New studies addressing the fluctuations of both demand and supply during summer and winter seasons.
- The delineation of new groundwater protection zones;
- Water quality monitoring
- Closer collaboration with water establishments to ensure the maintenance and the efficiency of public well infrastructure and public water supply networks;
- Improvement of the public water supply and creation of incentive mechanisms to encourage private well owners to shift to public supply;
- Introduction of water meters with scaled tariffs to keep record of water consumption and ensure a fair pricing for all consumers;
- Thorough studies for the licensing requests of private wells;

- System of penalties to abide by in case of any violations.

In addition to the above mentioned measures and interventions at the level of the water sector and the MoEW specifically, protective measures shall be considered in different sectors and fields potentially affecting water resources including urbanization, industrialization, tourism, agriculture and waste disposal activities, among others. These measures shall allow and facilitate the protection of groundwater resources and shall include the following:

- Adequate regulations and zoning for urban planning and land use (settlements, houses, buildings, roads, industrial plants, grazing activities, etc.) taking into account existing water resources;
- Regulated production, storage and use of fertilizer, pesticide and animal manure;
- Proper collection, storage and treatment of solid waste management;
- Prohibition of the direct or indirect disposal of liquid wastes, wastewater and solid wastes into groundwater;
- Treatment of wastewater and liquid wastes; and
- Renewal and/or construction of municipal sewage networks and wastewater treatment plants.

Throughout my research, limitations were expected. This thesis incorporates data that ranges from general to specific, from available to obtainable, from qualitative to quantitative. One limitation was related to interviews conducted with public officials but also related to data collection. The administrative steps to follow at the MoEW with the aim of getting the approval to conduct interviews with public officials and of acquiring data from the ministry were time consuming. In particular, I had to address several letters to the General Director of the ministry, requesting is approval to obtain data on public and private wells existing in the governorates of Mount Lebanon and Beirut. Once my different letters were approved by the general director, they were sent to the different departments and offices involved in my requests to get their respective approvals. As a result, this administrative procedure delayed the data collection phase. On the other hand, interviewed public officials were very helpful and provided as much data and insights as possible, however, interviewees could not provide answers to all my questions, including some critical ones that were of relevance and importance to my study. Although this is totally understandable, it somehow affected the data collection phase of my study. Finally, detailed data about registered private wells in the study area (such as location, coordinates, abstraction rates and well depth) were not provided for unknown reasons, which did not allow me to elaborate an even description of public and private wells in the study area. Also, data on well depth and abstraction rates of public wells was not complete and not really accurate, which forced me to make some assumptions specially regarding abstraction rates and certainly affected my findings. In addition, the absence of recent and detailed population data for the GBA forced me to use general data from the UN for 2019 and UN-DESA projections for 2020, 2025, 2030 and 2035. Also, the distribution of the population among districts and cadastral units was taken from the NPMPLT's 2004 population data as population percentages and applied to other years based on UN population projections. Accordingly, the lack of detailed and up to date data forced me to make assumptions, which affected my findings to a certain extent.

In conclusion, limitations are unavoidable and the findings of this thesis are still reasonable. Alternatives shall be considered before opting for any dam project, especially that resources and infrastructure already exist. Serious investigation shall be conducted to quantify the water budget in Lebanon by independent parties to avoid conflicts of interests and provide credible results. This thesis attempts to shed the light on available groundwater resources in the GBA to prove that existing springs can supply the yearly water demand of the GBA population, but further studies are needed to firmly demonstrate it. To conclude, this is a primary study covering several aspects of groundwater management in the GBA. More comprehensive research addressing the groundwater-based supply is encouraged to produce more complex plans of action. Seasonal fluctuations in water availability shall be also addressed in dedicated studies and research, especially under the influence of climate change and its effects on both surface and groundwater resources. Delving into the feasibility of hybrid water supply systems in Lebanon and in the GBA in particular is an important subject of interest to investigate in future studies.

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APPENDICES

Appendix 1 – GBA Domestic, Industrial and Agricultural Water Balance between 2010 and 2035 according to the World Bank as claimed in the ESIA for the Greater Beirut Water Supply Augmentation Project.

Water Demand & Supply for GBA		**2010**	**2015**	**2020**	**2025**	**2030**	**2035**
Demand	Domestic & Industrial Water Demands	225	240	260	290	320	340
	Reduced Domestic & Industrial demands	225	210	180	190	210	230
	Agricultural Water Demands	80	90	100	105	105	105
TOTAL DEMANDS (without losses reduction)		**305**	**330**	**360**	**395**	**425**	**445**
TOTAL DEMAND (with reduction)		**305**	**300**	**280**	**295**	**315**	**335**
Supply	Currently available water resources	100	100	100	100	100	100
	Awali Conveyor (GBWSP) future contribution	-	40	40	40	40	40
TOTAL SUPPLY		**100**	**140**	**140**	**140**	**140**	**140**
WATER BALANCE (with no losses reductions and no GBWSP)		**-205**	**-230**	**-260**	**-295**	**-325**	**-345**
WATER BALANCE (GBWSP implemented and with losses reductions)		**-205**	**-160**	**-140**	**-155**	**-175**	**-195**
Expected Water Deficit Reduction		**0%**	**30%**	**46%**	**47%**	**46%**	**43%**

Appendix 2 – Detailed population data and estimated water demand scenarios in 2020

District	Cadastral Unit	Total Area (in km2)	Population	Population Percentage (in %)	Population Density (persons/km2)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Aley	Chouaifat Amroussyat	5.2	90,855.67	3.75	17,472.25	9,085,567.49	10,902,680.98	13,628,351.23	18,171,134.97	22,713,918.72
	El-Kahaleh	1.9	3,573.32	0.15	1,880.69	357,331.93	428,798.32	535,997.90	714,663.86	893,329.83
	Chouaifat Oumara	4.3	8,241.55	0.34	1,916.64	824,155.12	988,986.14	1,236,232.67	1,648,310.23	2,060,387.79
	Aley	8.5	28,196.12	1.16	3,317.19	2,819,612.05	3,383,534.46	4,229,418.07	5,639,224.09	7,049,030.12
	Bsous	2.5	1,943.68	0.08	777.47	194,368.20	233,241.84	291,552.30	388,736.40	485,920.50
	Houmale	0.8	1,943.68	0.08	2,429.60	194,368.20	233,241.84	291,552.30	388,736.40	485,920.50
	Bdedoune	1.4	2,410.51	0.10	1,721.79	241,050.52	289,260.62	361,575.78	482,101.04	602,626.30
	Bleibel	1.1	926.86	0.04	842.60	92,685.62	111,222.75	139,028.43	185,371.24	231,714.05
	Chouaifat Qobbat	9.2	35,602.48	1.47	3,869.84	3,560,248.25	4,272,297.90	5,340,372.38	7,120,496.50	8,900,620.63
	Ain Al Remmeneh	0.4	183.33	0.01	458.34	18,333.42	22,000.10	27,500.13	36,666.84	45,833.55
	Ain Aanoub	4.1	3,603.88	0.15	878.99	360,387.50	432,465.00	540,581.25	720,775.00	900,968.75
	El-Kamatiyeh	0.9	6,145.09	0.25	6,827.88	614,509.07	737,410.88	921,763.60	1,229,018.13	1,536,272.67
	Aitat	2.4	1,858.81	0.08	774.50	185,880.51	223,056.61	278,820.76	371,761.01	464,701.26
	Bmakkine	1.1	735.03	0.03	668.21	73,503.43	88,204.12	110,255.15	147,006.87	183,758.58
	Deir-Koubel	2.7	3,084.43	0.13	1,142.38	308,442.81	370,131.37	462,664.22	616,885.62	771,107.03
	Bchamoune	6.3	9,350.04	0.39	1,484.13	935,004.40	1,122,005.28	1,402,506.61	1,870,008.81	2,337,511.01
	Chamlane	1.5	482.10	0.02	321.40	48,210.10	57,852.12	72,315.16	96,420.21	120,525.26
	Aramoun	11.7	9,923.81	0.41	848.19	992,381.22	1,190,857.46	1,488,571.83	1,984,762.44	2,480,953.04
	Sarahmoul	2.1	1,016.83	0.04	484.20	101,682.58	122,019.09	152,523.87	203,365.16	254,206.44
	Ainab	3.3	1,385.19	0.06	419.76	138,519.17	166,223.01	207,778.76	277,038.34	346,297.93
	Ain Drafile	2.7	-	-	-	-	-	-	-	-
	El-Fsaikine	1.5	1,904.64	0.08	1,269.76	190,463.86	228,556.63	285,695.79	380,927.72	476,159.65
	Remhala	3.7	1,989.52	0.08	537.71	198,951.55	238,741.87	298,427.33	397,903.11	497,378.89
	Ain Ksour	1.9	665.44	0.03	350.23	66,543.52	79,852.23	99,815.28	133,087.05	166,358.81
	Baouarta	6.4	711.27	0.03	111.14	71,126.88	85,352.25	106,690.32	142,253.76	177,817.20
	Abey	4.3	2,816.22	0.12	654.93	281,621.70	337,946.04	422,432.55	563,243.39	704,054.24
	Dakkoun	3.4	305.56	0.01	89.87	30,555.70	36,666.84	45,833.55	61,111.40	76,389.25
	Kfar Matta	11.6	3,381.50	0.14	291.51	338,149.74	405,779.69	507,224.61	676,299.48	845,374.35
Baabda	Forn El-Chobbek	1	22,052.73	0.91	22,052.73	2,205,272.73	2,646,327.28	3,307,909.10	4,410,545.47	5,513,181.83
	Chiah	8.8	341,568.58	14.09	38,814.61	34,156,858.42	40,988,230.10	51,235,287.63	68,313,716.84	85,392,146.05
	Baabda	8.7	51,518.61	2.12	5,921.68	5,151,860.69	6,182,232.82	7,727,791.03	10,303,721.37	12,879,651.72
	Haret Horeik	1.8	110,747.44	4.57	61,526.35	11,074,743.52	13,289,692.23	16,612,115.28	22,149,487.05	27,686,858.81
	Hadace	5.5	41,005.75	1.69	7,455.59	4,100,574.87	4,920,689.84	6,150,862.31	8,201,149.74	10,251,437.18
	Borj Al Barajneh	3.3	196,025.00	8.09	59,401.51	19,602,499.74	23,522,999.69	29,403,749.61	39,204,999.48	49,006,249.35
	Louaizeh	1.8	3,266.06	0.13	1,814.48	326,606.48	391,927.77	489,909.72	653,212.95	816,516.19
	Chouit	2.1	1,831.64	0.08	872.21	183,164.44	219,797.33	274,746.66	366,328.89	457,911.11
	Araya	3.5	4,085.98	0.17	1,167.42	408,597.60	490,317.12	612,896.41	817,195.21	1,021,494.01
	Tahouitat-el-Ghadir	2.5	13,157.62	0.54	5,263.05	1,315,762.37	1,578,914.84	1,973,643.56	2,631,524.74	3,289,405.93
	Laylaki	0.4	14,931.55	0.62	37,328.88	1,493,155.18	1,791,786.22	2,239,732.77	2,986,310.36	3,732,887.95
	Wadi Chahrour el Soufla	2.4	3,530.88	0.15	1,471.20	353,088.08	423,705.70	529,632.12	706,176.17	882,720.21
	Haret -el-Sit	0.9	1,882.57	0.08	2,091.75	188,257.06	225,908.47	282,385.59	376,514.12	470,642.65
	Boutchay	0.6	1,965.75	0.08	3,276.25	196,575.00	235,890.00	294,862.50	393,150.00	491,437.50
	Mardachat	0.2	555.10	0.02	2,775.48	55,509.52	66,611.42	83,264.28	111,019.04	138,773.80
	Kfarchima	2.8	11,076.44	0.46	3,955.87	1,107,644.11	1,329,172.93	1,661,466.16	2,215,288.21	2,769,110.27

	Wadi Chahrour el Olia	0.7	3,822.86	0.16	5,461.23	382,285.75	458,742.90	573,428.63	764,571.50	955,714.38
	Bsaba Wadi Dlab	0.9	1,790.90	0.07	1,989.89	179,090.35	214,908.42	268,635.52	358,180.70	447,725.87
	Beirut Central District	0.6	-	-	-	-	-	-	-	-
	Medawar	2	11,030.61	0.45	5,515.30	1,103,060.75	1,323,672.90	1,654,591.13	2,206,121.50	2,757,651.88
	Minet el-Hosn	0.6	2,571.77	0.11	4,286.29	257,177.14	308,612.56	385,765.71	514,354.27	642,942.84
	Port	1	6.79	0.00	6.79	679.02	814.82	1,018.52	1,358.03	1,697.54
	Ain el-Mreisseh	1	11,465.18	0.47	11,465.18	1,146,517.75	1,375,821.30	1,719,776.62	2,293,035.49	2,866,294.37
	Ras Beyrouth	2.5	81,802.70	3.37	32,721.08	8,180,270.01	9,816,324.02	12,270,405.02	16,360,540.03	20,450,675.03
Beirut	Zoukak el-Blatt	0.5	26,459.54	1.09	52,919.08	2,645,953.82	3,175,144.59	3,968,930.73	5,291,907.64	6,614,884.55
	Saifeh	0.4	5,377.80	0.22	13,444.51	537,780.31	645,336.37	806,670.47	1,075,560.62	1,344,450.78
	Remeil	1	56,460.14	2.33	56,460.14	5,646,014.25	6,775,217.10	8,469,021.37	11,292,028.50	14,115,035.62
	Moussaytbeh	4.1	153,520.32	6.33	37,443.98	15,352,032.19	18,422,438.63	23,028,048.28	30,704,064.38	38,380,080.47
	Bachoura	0.5	26,984.08	1.11	53,968.16	2,698,407.77	3,238,089.33	4,047,611.66	5,396,815.54	6,746,019.43
	Achrafieh	3.2	116,305.18	4.80	36,345.37	11,630,517.75	13,956,621.30	17,445,776.62	23,261,035.49	29,076,294.37
	Mazraa	3.8	192,697.82	7.95	50,709.95	19,269,782.12	23,123,738.55	28,904,673.19	38,539,564.25	48,174,455.31
	Naamat	6.7	12,622.90	0.52	1,884.01	1,262,289.90	1,514,747.88	1,893,434.84	2,524,579.79	3,155,724.74
	Damour	10	1,799.39	0.07	179.94	179,939.12	215,926.94	269,908.68	359,878.24	449,847.80
	El-Mouchref	3.9	928.55	0.04	238.09	92,855.38	111,426.45	139,283.06	185,710.75	232,138.44
Chouf	Kfar Matta	1.8	-	-	-	-	-	-	-	-
	Deir Baba	2	1,173.00	0.05	586.50	117,299.94	140,759.92	175,949.90	234,599.87	293,249.84
	Debbiyeh	16.6	758.80	0.03	45.71	75,879.99	91,055.98	113,819.98	151,759.97	189,699.97
	Dmite	3.6	2,459.73	0.10	683.26	245,973.38	295,168.06	368,960.07	491,946.76	614,933.45
	El-Moghaireh	1.1	-	-	-	-	-	-	-	-
	Zouk Khrab	2.5	12,103.45	0.50	4,841.38	1,210,345.21	1,452,414.25	1,815,517.81	2,420,690.41	3,025,863.02
	Dbayeh	1.8	4,221.78	0.17	2,345.43	422,177.91	506,613.50	633,266.87	844,355.83	1,055,444.79
	Mar Abda El-Mchammar	0.4	-	-	-	-	-	-	-	-
	Deir Tamiche	0.8	1,768.84	0.07	2,211.04	176,883.55	212,260.26	265,325.32	353,767.10	442,208.87
	Kornet-El-Hamra	2.3	3,889.06	0.16	1,690.90	388,906.15	466,687.38	583,359.23	777,812.31	972,265.38
	Zekrit	1	1,127.17	0.05	1,127.17	112,716.58	135,259.90	169,074.87	225,433.16	281,791.45
	Haret El-Belleni	0.9	5,752.96	0.24	6,392.18	575,295.92	690,355.10	862,943.88	1,150,591.84	1,438,239.80
	El Freikeh	0.8	1,127.17	0.05	1,408.96	112,716.58	135,259.90	169,074.87	225,433.16	281,791.45
	Mazraet Yachou	1.7	8,995.26	0.37	5,291.33	899,525.84	1,079,431.01	1,349,288.76	1,799,051.68	2,248,814.60
	Mazraet El-Hadira	0.8	3,690.45	0.15	4,613.06	369,044.95	442,853.94	553,567.42	738,089.90	922,612.37
	Mazraet Deir Aoukar	0.6	1,400.47	0.06	2,334.12	140,046.96	168,056.35	210,070.43	280,093.91	350,117.39
El Metn	Dik El-Mehdi	0.7	2,806.03	0.12	4,008.62	280,603.17	336,723.81	420,904.76	561,206.35	701,507.93
	Mazraet Beit Chaar	0.6	6,123.02	0.25	10,205.04	612,302.27	734,762.72	918,453.40	1,224,604.53	1,530,755.67
	Naccache	2.5	17,763.05	0.73	7,105.22	1,776,304.66	2,131,565.60	2,664,456.99	3,552,609.33	4,440,761.66
	Hebouss	0.3	397.22	0.02	1,324.08	39,722.41	47,666.89	59,583.61	79,444.82	99,306.02
	El-Mtaileb	1.4	6,454.04	0.27	4,610.03	645,404.27	774,485.13	968,106.41	1,290,808.55	1,613,510.69
	Beit El Koukou	0.3	2,042.14	0.08	6,807.13	204,213.92	245,056.71	306,320.89	408,427.85	510,534.81
	Ain Aar	0.4	1,850.32	0.08	4,625.79	185,031.74	222,038.08	277,547.60	370,063.47	462,579.34
	Kornet Chahouane	4.6	12,967.50	0.53	2,819.02	1,296,749.94	1,556,099.92	1,945,124.90	2,593,499.87	3,241,874.84
	Ain-Alak	0.8	1,960.66	0.08	2,450.82	196,065.74	235,278.89	294,098.61	392,131.48	490,164.35
	Antelias	2	22,419.40	0.92	11,209.70	2,241,939.57	2,690,327.49	3,362,909.36	4,483,879.15	5,604,848.93
	El Atchaneh	1	1,524.39	0.06	1,524.39	152,438.99	182,926.79	228,658.48	304,877.98	381,097.47
	Mezher	0.7	3,262.67	0.13	4,660.96	326,266.97	391,520.36	489,400.45	652,533.94	815,667.42

	Nabiyeh	3.9	3,794.00	0.16	972.82	379,399.94	455,279.92	569,099.90	758,799.87	948,499.84
	Jal-el-Dib	0.9	15,817.67	0.65	17,575.19	1,581,766.71	1,898,120.05	2,372,650.06	3,163,533.42	3,954,416.77
	Majdoub	1.3	2,291.68	0.09	1,762.83	229,167.75	275,001.30	343,751.62	458,335.49	572,919.37
	Bsalime	1.4	3,316.99	0.14	2,369.28	331,699.09	398,038.91	497,548.64	663,398.19	829,247.73
	Wata Amaret Chalhoub	0.6	5,554.35	0.23	9,257.25	555,434.72	666,521.66	833,152.07	1,110,869.43	1,388,586.79
	Bkennaya	0.7	4,413.60	0.18	6,305.14	441,360.10	529,632.12	662,040.16	882,720.21	1,103,400.26
	El-Zalka	0.9	22,472.02	0.93	24,968.91	2,247,201.94	2,696,642.33	3,370,802.91	4,494,403.89	5,618,004.86
	Borge Hammoud	2.6	128,785.48	5.31	49,532.88	12,878,548.32	15,454,257.98	19,317,822.47	25,757,096.63	32,196,370.79
	Mar Chaya et Mzakki	2.2	2,688.90	0.11	1,222.23	268,890.16	322,668.19	403,335.23	537,780.31	672,225.39
	Jouret-El-Ballout	1.6	2,261.12	0.09	1,413.20	226,112.18	271,334.61	339,168.26	452,224.35	565,280.44
	Baouchariat	3.9	110,969.81	4.58	28,453.80	11,096,981.28	13,316,377.54	16,645,471.92	22,193,962.56	27,742,453.21
	Biakout	1	5,790.31	0.24	5,790.31	579,030.51	694,836.61	868,545.76	1,158,061.01	1,447,576.26
	Jodaidat	1.7	27,591.80	1.14	16,230.47	2,759,179.66	3,311,015.60	4,138,769.49	5,518,359.33	6,897,949.16
	Kanabet Broummana	1.1	1,768.84	0.07	1,608.03	176,883.55	212,260.26	265,325.32	353,767.10	442,208.87
	Roumieh	5.1	4,332.12	0.18	849.44	433,211.92	519,854.30	649,817.88	866,423.83	1,083,029.79
	Senn el Fil	2.3	58,991.17	2.43	25,648.34	5,899,117.29	7,078,940.75	8,848,675.94	11,798,234.59	14,747,793.23
	Broummana	3.9	13,364.72	0.55	3,426.85	1,336,472.34	1,603,766.81	2,004,708.52	2,672,944.69	3,341,180.86
	Dekouanet	1.9	41,148.34	1.70	21,657.02	4,114,834.20	4,937,801.04	6,172,251.30	8,229,668.39	10,287,085.49
	Fanar	2.1	16,715.67	0.69	7,959.84	1,671,566.52	2,005,879.82	2,507,349.77	3,343,133.03	4,178,916.29
	Ain Saade	5.5	6,321.63	0.26	1,149.39	632,163.47	758,596.17	948,245.21	1,264,326.94	1,580,408.68
	Mar Roukose et Dahr El-Hossain	2.2	2,128.71	0.09	967.60	212,871.37	255,445.65	319,307.06	425,742.75	532,178.43
	Beit Mery	8.5	14,632.78	0.60	1,721.50	1,463,278.50	1,755,934.20	2,194,917.75	2,926,556.99	3,658,196.24
	Mkallesse	1.6	1,369.91	0.06	856.20	136,991.39	164,389.66	205,487.08	273,982.77	342,478.47
	El-Mansouriyeh	2.6	18,596.54	0.77	7,152.51	1,859,653.82	2,231,584.59	2,789,480.73	3,719,307.64	4,649,134.55
	El-Dechouniyeh	1.3	604.32	0.02	464.86	60,432.38	72,518.86	90,648.58	120,864.77	151,080.96
Kasrouane	Zouk Mousbeh	4.7	28,360.78	1.17	6,034.21	2,836,078.17	3,403,293.81	4,254,117.26	5,672,156.35	7,090,195.43
	Mazraet El Ras	1.1	921.76	0.04	837.97	92,176.36	110,611.63	138,264.54	184,352.72	230,440.90
	Jeita	2.9	3,296.62	0.14	1,136.77	329,662.05	395,594.46	494,493.07	659,324.09	824,155.12
Total		**320.5**	**2,424,425**	**100%**	**Total in Liters/day**	**242,442,500**	**290,931,000**	**363,663,750**	**484,885,000**	**606,106,250**
					Total in MCM/year	**88.4915125**	**106.189815**	**132.7372688**	**176.983025**	**221.2287813**