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ORIGINAL PAPER

Influence of snow cover on water capacity in the Qaraaoun Reservoir, Lebanon

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Abstract

Considerable amount of surface water in Lebanon is stored behind dams, and the Qaraaoun Reservoir (QR) is a typical example. It is the largest surface water body in Lebanon where it irrigates 27,500 ha and generates 22% of Lebanon's electricity. The reservoir is fed directly from the Litani River which receives water from several springs and from groundwater where both are replenished mainly from snowmelt. However, the relationship between snow cover area on the surrounding mountains and the water volume in the reservoir has not been investigated. This study aims at determining the influence of snow cover area as a water feeding source and the volume of water in the QR. The relationship between these two variables was calculated using satellite images (MODIS-Terra with 500 m spatial resolution) which enable retrieving measures each 8 days, and the in situ measuring instruments fixed in the QR. The investigated period was between 2001 and 2018. Results show that the water volume in the QR is substantially controlled by the snow cover area on the surrounding mountains. It was found that the average time period between snow accumulations on these mountains and the remarkable increase in water level in the QR is about 3 months, while the dynamic changes in snow cover (accumulation/melting) and the induced water level in the reservoir were calculated. In addition snow-water equivalent (SWE) was also determined. This study reveals the significance of snow cover, which either directly feeds the streams or indirectly replenishes the groundwater aquifers where both contribute in the water volume of the QR. Therefore, the catchment mountainous area where snow accumulates should be protected from human interventions which have been lately increased and impacted the hydrologic regime between snow cover and water volume in the QR.

Keywords Snowpack · Melting rate · Groundwater · Artificial lake · Environmental measures

Introduction

Water sector in Lebanon is witnessing unstable conditions and the supply/demand is totally imbalanced. This is reflected on the volume of water per capita which is continuously decreasing. This status has been exacerbated due to the recently existed physical and man-made challenges. In this respect, several investment projects are made to tap water resources in Lebanon; however, water shortage still exists and it is not exaggeration to say that all water resources in Lebanon are under depletion.

The precipitation rate in Lebanon ranges between 700 and 1500 mm (CNRS-L, 2015), while there are 14 rivers and more than 2000 springs with more than 25 l/s (Shaban 2020). The availability per capita is estimated at 1350 m^3/year, whereas water demand is less than 220 m^3/capita/year (Shaban 2011). Therefore, it is a paradox that Lebanon is considered a country under water stress. In this regard, poor management of water resources is still the main reason, especially that Lebanon possesses tremendous surface water resources (e.g., rivers, snow, lakes) as well as many aquiferous rock formations with considerable volume of water. Yet, many aspects of human interventions affect water regime (e.g., over pumping, pollution, deforestation), thereby altering the conditions for water replenishment (SNC 2011). The exacerbation of these activities in the absence of water conservation controls and laws

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resulted in the imbalanced supply/demand and supply shortage, and then water crisis occurred.

Surface water in Lebanon significantly controls the rate of water supply and per capita, and several sources of surface water are exploited whether on small- or large-scale projects. In particular, water harvesting becomes an alternative method to reduce water shortage, notably in the view of changing climatic impact (Jomaa and Shaban 2018). Thus, water harvesting in Lebanon has been adopted either on individual or on national levels. On the individual level, it is represented by the construction of mountain lakes (capacity of less than 1000 m^3 on average) to tap water from melting snow in the mountainous regions (Shaban 2020), while for water harvesting on the national level, there are a number of large-scale projects, and these are represented mainly by the construction of dams, such as Qaraaoun, Shabrouh, Janneh, and Beka'ata Dams.

The reservoir of the Qaraaoun Dam has been established in 1958, and the created reservoirs behind this dam became the largest surface water body in Lebanon. It is also considered the most successful water management project in the country (Shaban 2020). This project has been executed since more than 60 years ago in order to irrigate large agricultural lands and to generate electricity from the established hydro-power stations. Hence, the Qaraaoun Reservoir (QR) is fed either by direct inflow of the Litani River or from the snowmelt along streams plus from the replenishment from groundwater water which is also fed from snow.

There are several studies done on the QR, and all these studies focused specifically on the crisis of water pollution which became lately a national problem (e.g., El-Goul 2004; Assaf and Saadeh 2008; Korfali and Jurdi 2011; Abou-Hamdan et al. 2014; Amacha et al. 2015; Nehme and Haidar 2018), while the volumetric estimates were not determined in these studies. Likewise, the hydrologic regime, groundwater characteristics, and the feeding mechanism to the QR have not also been determined. In addition, only the direct inflow from the primary course of the Litani River into the QR is calculated, while the volume of water that seeps into the QR from groundwater was not calculated.

There is always a debate whether the QR is fed from the primary course of the Litani River or there are other sources that contribute in the water volume of the reservoir. In this regard, some researchers consider that the Litani River contributes with the total water volume in the QR where the direct inflow is the only hydrologic process (Ramadan et al. 2013; Nassif et al. 2014), while others believe that springs are the only sources feeding the river then the QR (IDRC 2007; Baydoun et al. 2015). Besides, little concern is given to groundwater as a source for the QR (Metni et al. 2004; Darwich et al. 2011).

In this respect, the authors applied a number of studies based on field surveys, and investigated the existing rock formations (Shaban 2003; Shaban et al. 2013; Telesca et al. 2014; Shaban et al. 2014; Shaban 2020). It was found that groundwater is seeping from the surrounding mountains, and then it feeds the springs at the foot slopes where these springs are the primary source providing water to the Litani River, whereas these springs are mainly fed from snow. This in turn motivated applying this research to investigate the role of snow as a major source of water in the region.

Therefore, the study aims at identifying the relationship between the snow cover area, on the catchment of the mountainous region surrounded the QR, and the water level in the reservoir, where the latter is a function of water volume. In particular, the contribution of snowmelt to the water volume in the QR will be calculated to deduce the lag time between snow accumulation and the increase in the water level of the reservoir.

The structure of this paper implies introductory part including description of the study area and mechanism of water replenishment in the QR. Then, used tools were shown including mainly satellite images and the instruments for measuring water level, whereas the methodology discusses the processing of satellite images and the relevant data preparation, and then the statistical correlation approaches. Consequently, results showed the calculated time lag for water replenishment, dynamic trends, and snow/water equivalent, and finally the conclusion and discussion were illustrated.

For this purpose, a miscellany of advanced measuring tools have been used including space techniques (i.e., satellite images of 8-day retrieve interval) to monitor the snow cover area, while records from water level sensors were used to measure the changing surface water level in the reservoir. Therefore, the obtained measurements were manipulated by applying statistical methods for data correlation.

The study area

The Qaraaoun Dam was constructed in a low-land terrain (i.e., depression topography) in order to restrict surface water that runs along several dissipated tributaries of the Litani River and accumulates in this depression, which later on formed the QR.

The QR is located in the middle part of the Lebanese territory between the major two mountain chains (the so-called Mont-Lebanon and Anti-Lebanon), and more specifically in the Bekaa Plain, which is a depression with an average width of about 8 km (Fig. 1). These mountain chains are composed of rugged topography where carbonate rocks are the major rock lithology.

The OR is located near Qaraaoun village, and specifically between the following geographic coordinates:

$$33°35'37''N, 33°32'53''N \text{ and } 35°40'56''E, 35°42'26''E$$

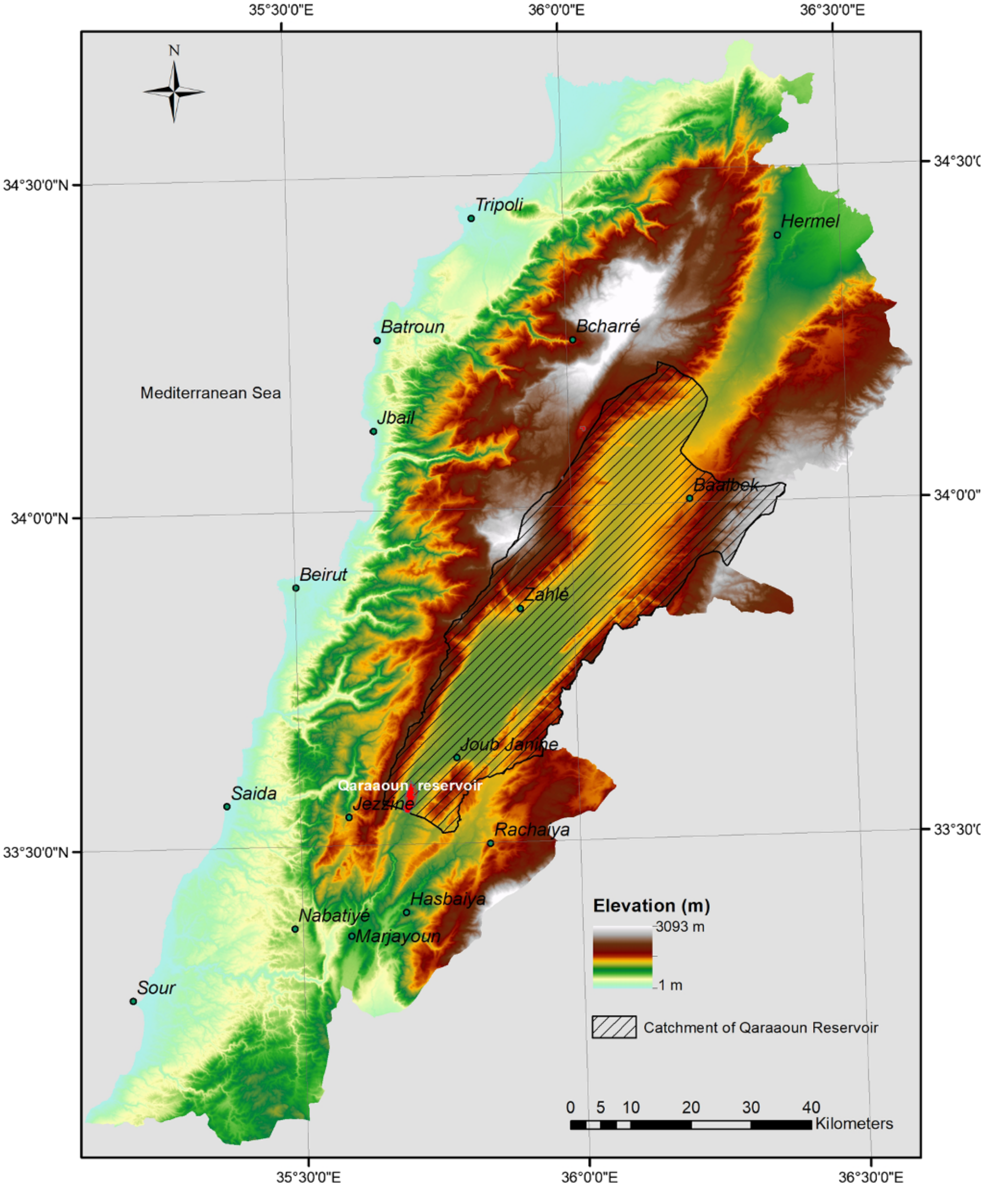


Fig. 1 Location maps of the Qaraaoun Reservoir and its catchment

The majority of climatic and hydrologic measurements of the QR, similarly to the middles part of the Bekaa Plain, is illustrated in Table 1.

The Qaraaoun Dam is 62 m high, 1090 m long, and 162 m wide (Fadel et al. 2017), while the QR is situated at the elevation of about 850 m above sea level, where the maximum depth is 60 m (LRA 2020). The surface level of water in the reservoir is often changing, and this is controlled by seasonal meteorological variation and the oscillating climatic conditions. Thus, the area of the surface reservoir ranges between 6 and 9 km^2 (Shaban and Nassif 2007).

The discharge (i.e., conveying water downstream) from the QR is man-made regulated, and this depends on the water inflow in the reservoir and water demand for irrigation.

Table 1 Average monthly climatic and hydrologic data for the QR area

	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Precipitation (mm)	182	158	95	60	14	0	0	0	35	62	108	210
Temperature (°C)	10.5	15.8	16.5	19.3	21.4	24.8	28.5	30.2	22.5	18.4	16.8	14.5
Discharge (m^3/s)	10.2	17.6	54.7	16.9	9.3	6.4	1.5	3.4	4.1	4.6	5.7	6.2

Thus, the average annual discharge ranges between 360 and 480 million m^3, and then averaging about 420 million m^3/year, while the average capacity of water in the reservoir is estimated at 220 million m^3 (LRA 2020).

In addition to irrigation, stored water in the QR is also used for hydro-power generation. Hence, water from the reservoir is conveyed to downstream regions along the Litani River floodplain and its surrounding where cultivated lands are dominant, and therefore, canals (i.e., several kilometers long) were constructed to convey water and to irrigate about 27,500 ha. Nevertheless, water in the reservoir has become totally polluted due to uncontrolled dumping of solid and liquid wastes in the Litani River, and this created a national geo-environmental problem instead of becoming a successful national project.

The flow of water from the reservoir is connected with Markaba and Al-Awali hydro-power stations. These two plants generate electrical energy of about 500 MW, which is equivalent to 22% of Lebanon's electricity demand (Shaban and Hamzé 2018).

The QR can be considered the junction between the Upper Litani Sub-basin (ULSB) and the Lower Litani Sub-basin (LLSB) where these two sub-basins have different hydrological characteristic, and they are characterized by diverse geological and hydrogeological setting as well as different water flow mechanisms.

The catchment area (surface water basin) of the ULSB, which represents the catchment area of the QR, occupies an area of about 1826 km^2. This is equivalent to 17.5% of the Lebanon's surface area (Fig. 1).

Water replenishment in the QR

The feeding mechanism of water in the QR is controlled mainly by the hydrological and hydrogeological elements; thus, water runs directly from the Litani River and its tributaries to the reservoir, or indirectly through groundwater seeps from the surrounding mountains. It is, therefore, fed from several sources with different feeding mechanisms (Fig. 2). These are as follows:

1. Direct precipitation on the reservoir surface (average area of 8 km^2), where the average precipitation rate is about 710 mm/year as calculated from TRMM (Abdulrazzaq et al. 2019), and thus, the reservoir receives a total precipitated water volume of about 5.68 million m^3/year. Besides, water volume estimated at about 4 million m^3/year, is returned to the atmosphere as direct evaporation from the surface of the reservoir (CNRS-L 2015).
2. Inflow from the primary watercourse of the Litani River of the ULSB, where the contact point of this inflow is located in the northern part of the reservoir (840 m altitude and coordinates: 33° 35′ 25″ N and 35° 41′ 46″ E). The inflow ranges between 2.5 m^3/s (minimum) and 54.7 m^3/s (maximum), and averaging about 11.7 m^3/s (LRBMSP 2011). Therefore, the estimated total inflow is about 368 million m^3/year. In this respect, the main flow in the ULSB is from major springs (e.g., Ghzayel-Anjar, Chamsine, Berdaouni, Khrayzat) which are located mainly at the foot slope of the surrounding mountains. The average estimated discharge from these springs is about 270 million m^3/year (Fig. 2).
3. Melting water from snow which is accumulated on the surrounding mountain chains and extending to the east and west of the Bekaa Plain, where the average altitude of these mountain chains is 1300 m. Thus, snow remains for couple of months (i.e., 5–8 months) on these chains. Hence, water from snowmelt uniformly percolates into the substratum, and then it feeds groundwater in the carbonate rocks (i.e., limestone and dolomitic limestone).

Materials and methods

The majority of research methodology and tools include space techniques and in situ measurements, which were prepared and investigated using different approaches of analysis. Figure 3 shows the flowchart for the main components of this research.

Materials

In order to elaborate for the relationship between snow cover and water level in the QR, two variables should be primarily calculated. These are as follows: the snow cover area which is a function of groundwater entering the reservoir after snow melts, and the water level in the reservoir, as an evidence of water volume. In this respect, two types of measuring tools were used to calculate these two variables. These are:

1. Satellite images to calculate the snow cover area within the catchment surrounded the RQ. The available images were for the period between 2001 and 2018. For this purpose, the Moderate Resolution Imaging Spectroradiometer products named MODIS-Terra (MOD10A2) were used. It, with MODIS-Terra, views the entire Earth's surface every day, acquiring data in 36 spectral bands, or groups of wavelengths (0.4 to 14.5 μm) with spatial resolutions of 250 m (bands 1–2), 500 m (bands 3–7), and 1000 m (bands 8–36). These data improve the understanding of global dynamics and processes occurring on land and oceans. The swath width (scene size) of MODIS images is 2030 km × 1354 km (rows/columns).

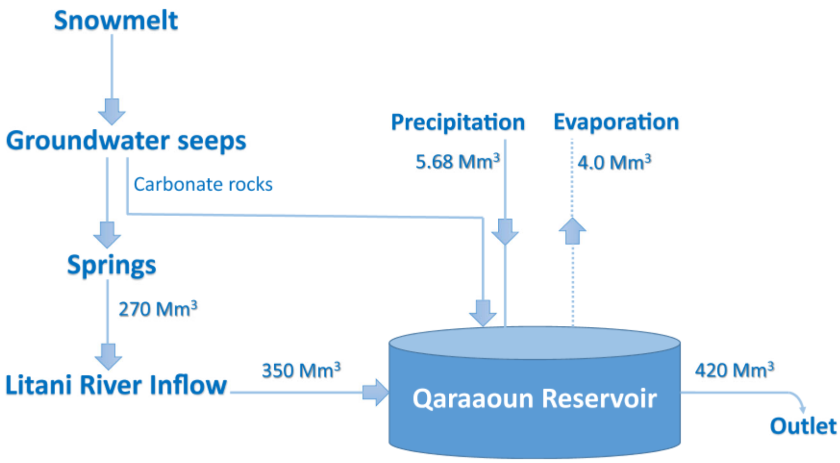


Fig. 2 Scheme for the water cycle of the Qaraaoun Reservoir

The selection of MODIS-Terra images is attributed to the availability of these images on daily basis, and this in turn enables applying detailed monitoring approaches for snow cover over short time periods. In addition, snowpack can easily be observed on MODIS-Terra images, whereas snow can be discriminated from clouds when the later exist.

2. Measurements, from instruments for calculating water level in the reservoir, were used to estimate water capacity. These instruments are installed by the Litani River Authority (LRA) which is under the mandate of the Ministry of Power and Water. These include water-level sensors manufactured by *Rittmeyer Brugg* (Fig. 4). In addition, data from observation wells for monitoring the fluctuation of the water surface were also utilized. Vibrating wire piezometers (VWP) with data logger and software are also utilized, and they were installed to monitor monthly and even daily (when surface water level exceeds 857 m) reservoir surface level changes.

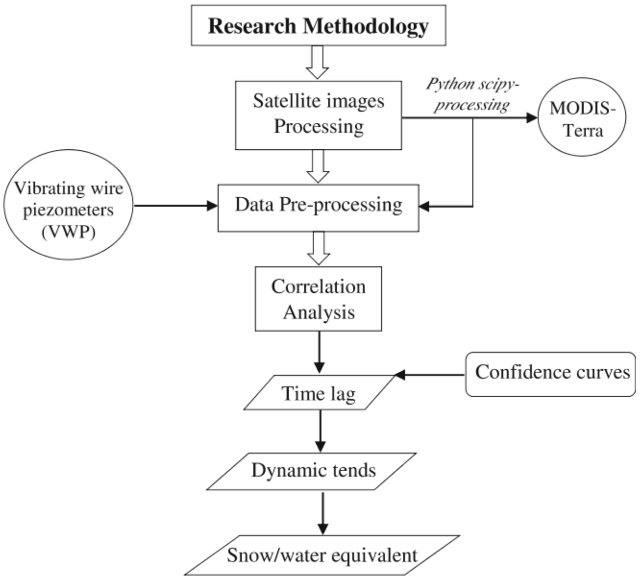


Fig. 3 Main components of the applied research

Methods

Satellite images processing

Added to their availability, the selection of MODIS satellite images implies a number of advantages that fit with the purpose of the study. This includes the spatial resolution (500 m) which fits recognizing the snowpack spread over the catchment of the QR. In addition, the duration for image retrieval

Fig. 4 Water level sensor fixed in the Qaraaoun Reservoir

(i.e., short re-visit time) with 8 days is also significant and applicable.

For image analysis, Python SciPy-processing tools were used to digitally process the Moderate Resolution Imaging Spectroradiometer (MODIS-Terra). MODIS-Terra images were downloaded from Goddard Space Flight Center “DISC” website of NASA. For snowpack identification, MODIS data identification depends on reflectance criteria in the visible and near-infrared (NIR) spectral bands. The identification of snowpack can be induced from the global criteria for snow recognition, entitled as “Normalized Snow Difference Index (NSDI).” Therefore, any pixel passes that group of identification; then, it is recognized as snowpack (Fig. 5).

Nevertheless, differentiation between snowpack and clouds was done from the combination between the two MODIS products (i.e., MODIS-Terra and MODIS-Aqua).

The selection of this period (2001–2018) depends on MODIS data availability as well as the consistency with the available data for water level of the QR. Thus, MODIS-Terra data was retrieved daily over the whole time period, when the area of snow cover was calculated in order to induce the dynamics of snow accumulation and melting.

Data pre-processing

The available data sets were on 8-day and 5-day intervals for snow cover and water level; respectively; thus, data were converted to be analyzed on monthly basis. The conversion approach was based on the concept that the influence of snow cover takes relatively long time interval to be observed in the water level in the reservoir after it passes several hydrological processes (e.g., melting, infiltration, seeps), while using daily comparison will not represent the actual snow influence and it may result in small fluctuations. Moreover, data sets of yearly basis were also used for more general assessment in this study.

The investigated period for snow cover is between 26/2/2001 and 2/2/2018 (17 years), and it was between 1/1/2002 and 2/2/2018 (16 years) for water level in the reservoir (Table 2). Therefore, series of data sets have been prepared for correlation analysis.

In this study, the snow cover measurements have been reported 1 year (i.e., 2001) before the water level measurements (i.e., 2002) for the QR. This is in order to compare the influence of accumulated snow cover on water level. Therefore, the prepared data sets become consistent for the optimal correlation method since the snow cover, as a feeding source for the QR, preceded the water level in the reservoir.

For snow cover and due to its dynamic changes (i.e., sublimation, accumulation, and melting), however, the average snow cover area was calculated for the analysis, because it represents the majority of water volume that can contribute feeding the water in the reservoir.

Correlation analysis

In this study, the relationship between snow cover and water level in the QR was investigated by using the cross-correlation method based on confidence curves. The obtained confidence curves were based on the Fourier-transform method surrogates of the snow cover series or the water level series, starting with a randomized shuffle of the series. Shuffling eliminates as much of the original correlation structure in a series as possible. Hence, the desired spectral amplitudes from the

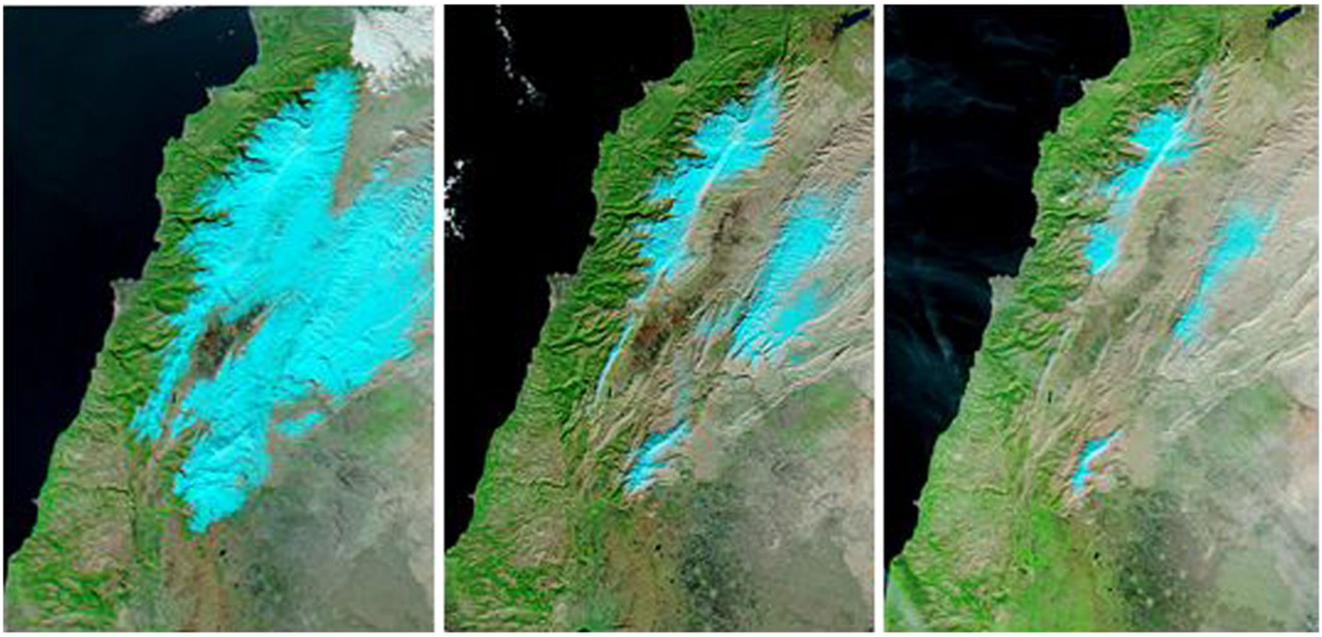


Fig. 5 Examples of snow identification (turquoise color) from MODIS-Terra images at different dates

Table 2 Used tools and the retrieved data sets for correlation analysis

Data type	Tools of measurement	Measuring period	Measuring interval	Number of measures
Snow cover	Satellite images (MODIS-Terra)	2001–2018	8 days	776
Water level	Water-level sensors, wells and wire piezometers	2002–2018	5 days	1168

original series were imposed to get the same cyclic auto-correlation as the original series (Little et al. 2006). After generating 1000 surrogates, the cross-correlation function of each surrogate of the series with the other one was calculated. The range of values that contain 90% of the cross-correlation coefficients for a given time lag is the 90% confidence interval for that time lag. Then, cross-correlation will help to identify if variations in snowmelt can significantly contribute to variations in water level of the reservoir. In this case, the maximum monthly snow cover over the surrounding mountain of the QR and the maximum monthly level of the water of the reservoir were cross-correlated.

Results

Time lag for replenishment

Table 3 shows the maximum (peak) snow cover area over the catchment of the QR. It was calculated from MODIS-Terra images. This represents the month the area of snow cover was maximum. Also the table shows the months when the maximum water level was registered Therefore, it was obvious that the peaks of snow cover often exist in months 1 and 2 (January and February), while the maximum water level occurs in months 4 and 5 (April and May). Therefore, the lag time (i.e., replenishment time) varies between 1 and 5 months. While if the peaks (maxima) are considered for both variables (months 1 and 2 for snow cover and months 4 and 5 for water level), thus, a general replenishment period of 3 months is dominant and the frequency of delay was also calculated as 23.5, 41, 29.5, and 6 for the months 2, 3, 4, and 5, respectively (Table 3).

The above results on the replenishment time period reveal that the water cycle, which starts when water exists from snowmelt until it reaches the reservoir, takes about 3 months. During these 3 months, the majority of water journey passes through different hydrological and hydrogeological processes. This can be summarized as follows:

1. Melting snow either flows directly along the slopes, as overland flow towards the QR catchment, or infiltrates through the carbonate rocks of the limestone and dolomite where the presence of impermeable layers of marl among the carbonate rocks plays a significant role in groundwater flow regime along the bedding planes of the Jurassic and Cretaceous rocks (Fig. 6). Thus, groundwater flows along the inclined rock beds (i.e., dip angle 12–18°) towards the reservoir (Shaban 2003). Hence, snowmelt provides the largest water volume to the major springs (e.g., Berdaouni, Ghzayel-Anjar, Chamsine, Kob EliaS) in the ULSB in which these springs feed the Litani River and then the QR.
2. The flow of groundwater towards the QR is supposed to be faster when rock deformations exist. This is well pronounced in the area surrounding the QR, where the existed carbonate rocks are dominant with karstic features (e.g., conduits, galleries) and intensive rock defects (e.g., faults, fissures, joints). It is well known that the carbonate rocks in this region are highly fractured due to the presence of the regional fault of Yammounah in the proximity of the QR (Fig. 6).

Table 3 Simplified manifest showing the maximum snow cover besides the water level in the QR

Year	Maximum snow cover (km^2)	Month*	Maximum water level (m)	Month	Year	Maximum snow cover (km^2)	Month	Maximum water level (m)	Month
2001	389	2	-	-	2010	1599.3	12	857.7	3
2002	1754.1	1	853.8	6	2011	629.9	3	857.9	5
2003	1542.6	12	858.4	5	2012	1706.0	3	858.1	5
2004	1165.2	11	858.2	3	2013	1742.0	1	858.0	4
2005	976.8	2	856.7	4	2014	257.8	2	839.2	4
2006	944.6	2	854.1	5	2015	1750.4	1	853.8	5
2007	895.8	2	852.3	5	2016	895.1	1	849.5	4
2008	1707.3	2	846.7	4	2017	1348.9	1	849.9	5
2009	453.6	2	855.2	5	2018	722.2	1	844.1	4

*Months of maximum (peak) calculated snow cover and water level

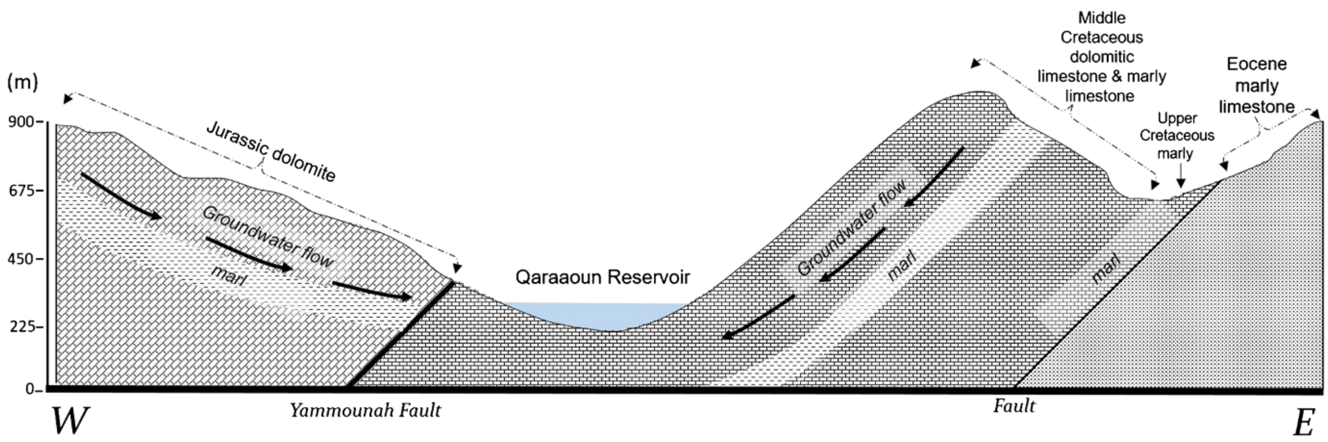


Fig. 6 Schematic geologic section showing the representative rock succession around the QR

Dynamic trends

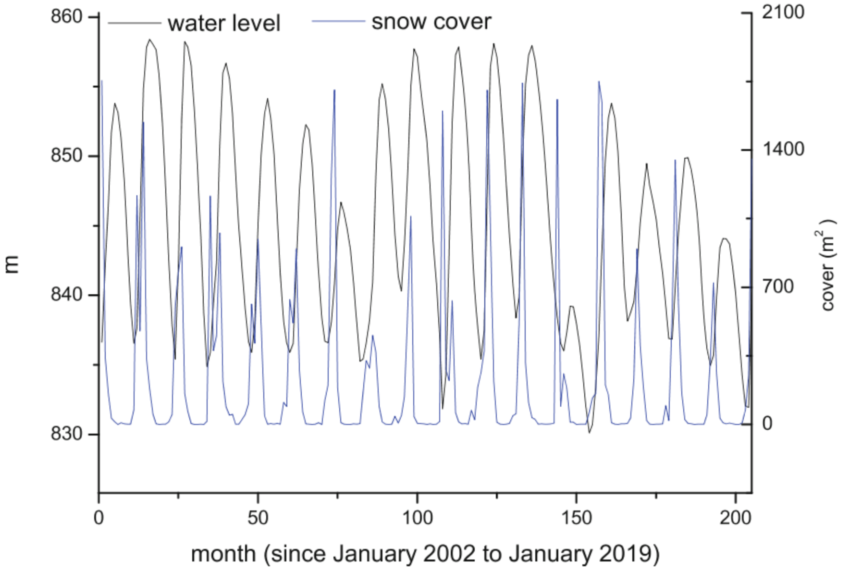
To determine the behavior (i.e., dynamic trend) of snow accumulation/melting besides the increase/decrease of water level in the QR; however, the time variation of the maximum snow cover and the water level in the QR are synoptically shown in Fig. 7. The water level in the QR varies between 830 and 860 m, while the snow cover area changes between 0 and 1800 km^2. Both time variations of snow cover area and water level show a clear annual modulation. During the whole observation period, most of snow cover peaks (i.e., maximum accumulation) precede the increased water level, evidencing a clear relationship between both variables.

The annual cycle of water level is characterized by the presence of only one peak corresponding to the largest amount of water collected by the dam, while the snow cover sometimes shows the presence of two peaks (Fig. 8). This can be linked to the occurrence of more than one snow storm (within the same year) for Lebanon (Telesca et al. 2014). Moreover, when the annual cycle of the snow is characterized by two peaks, the crests of peaks are always different. This is normal hydrological phenomenon when sometimes two snow events occur in the same year in Lebanon, and then each of them has different level of impact (Fig. 8a, b).

Given the peak shape, that of the snow cover is quite spiky, but that of the water level is smoothly curved (Fig. 9). This is because snow events come abruptly and snow cover may increase hundreds of square kilometers within hours. While the water level in the reservoir almost needs few months to form, it shows noticeable level increase since the reservoir is mainly fed from groundwater where the latter provides water the reservoir very gently.

The cross-correlation along with the 90% confidence curve (red dotted line) is shown in Fig. 10. The highest values of the cross-correlation are at 3–4 months. At these lags, the cross-correlation is also significant at 90% confidence. This result is in agreement with the higher percentage of delay times

Fig. 7 Synoptic variation of snow cover area and water level in the QR.



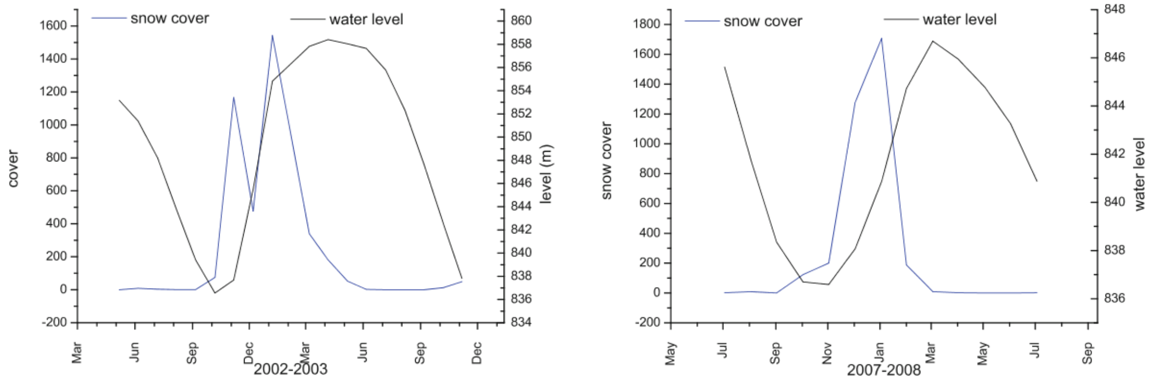


Fig. 8 Example showing the existence of peaks in snow cover area and water level in the QR

between the two peaks in snow cover and water (Table 4), and the delay of 3 and 4 months accounts for 56.25% of the total number of the observed delays.

Snow/water equivalent

Following watershed modeling approaches (e.g., Guiamel and Lee 2020) to calculate the rate of the changing volume of water in the reservoir as a result of dynamic changes in the area of the accumulated snow on the catchment surrounding the QR, however, the average annual snow area and the difference between the maxima and minima of water level were calculated (Table 5). Thus, the units adopted were in km^2 for the snow cover and in *cm* for the water level in the reservoir. In addition, Table 5 reveals the estimated water volume in the QR after considering the average surface area of the reservoir at 8 km^2.

It was obvious that water volume in the QR is influenced by the changing snow cover area, as deduced from the investigation of the 17 years for both measurements in this study. The influence was numerically presented and it was found that each 1 km^2 of the spatial extent of snow will raise the water level in the QR between 3.7 and to 14.1 cm, and thus averaging about 8.6 cm over the entire investigated years (Table 5).

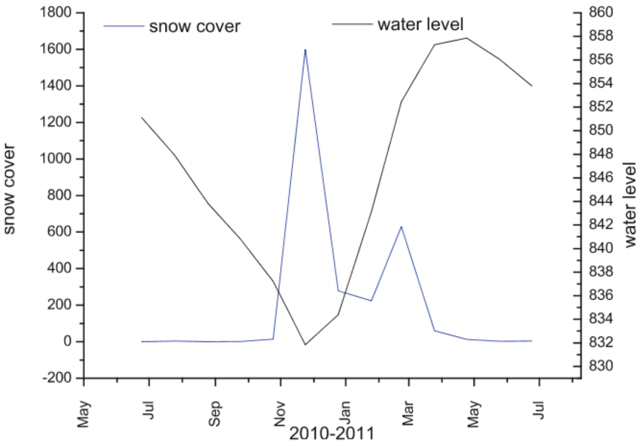


Fig. 9 Peak shapes for snow cover area and water level in the QR

By considering the average surface area of the QR, which is 8 km^2, thus, each 1 cm increase in the water reservoir level will result in:

$$= \text{Area (in m) x level increase of 1 cm (in m)}$$
$$8 \text{ x } 10^6 \text{ x } 1/100 = 80000 \text{ m}^3$$

Therefore, the average estimated snow cover area with respect to the water volume in the reservoir is approximately 68,423 m^3/km^2. In other words, each 1 km^2 of snow cover when it is melted, it will contribute to about 68,423 m^3 in the OR (Table 5).

Conclusion and discussion

Without snow, Lebanon will lose large percentage in its water budget, which can be estimated to more than 60%, and this will affect the surface and groundwater resources. In fact, rain water flows rapidly, due to the steeping slopes of the Lebanese terrain, and then outlets into the sea with no/or minimal benefit, while snowpack takes enough time to melt and then it uniformly feeds the rock stratum. This makes snow as the

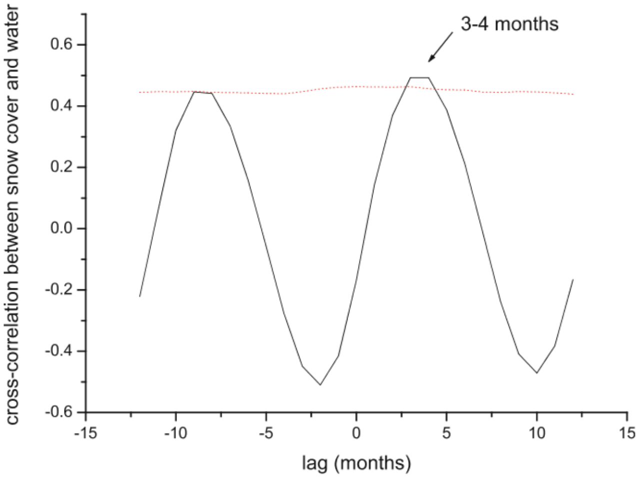


Fig. 10 Cross-correlation between snow cover area and water level in the QR

Table 4 The delay intervals between the maximum snow cover and water level in the QR

Month of maximum snow cover	Month of maximum water level	Delay*	Month of maximum snow cover	Month of maximum water level	Delay
2	-		12	3	3
1	6	4	3	5	2
12	5	4	3	5	2
11	3	4	1	4	3
2	4	5	2	4	2
2	5	3	1	5	4
2	4	2	1	5	4
2	5	3	1	4	3

*Time needed for water from the melted snow to reach the QR

principal feeding source of water for the largest water bodies in Lebanon such as the QR. However, the interrelation between the snow cover and water volume in the QR was not determined in all the obtained studies. Hence, this study focuses on identifying the correlation between snow cover area, which was calculated from satellite images (MODIS-Terra) and the water level measured by the fixed sensors in the QR.

This study is unlike other applied studies done in Lebanon where innovative methods of calculating snow cover area and correlating it with ground measures for the water volume. Hence, the use of satellite images enabled analyzing geospatial and hydrological data, especially the geographic.

The QR is fed mainly from rain and snow, but rain water recharges the reservoir directly by precipitation process which takes only few hours or as much as few days; therefore, the response of increased water level in the reservoir due to rain is rapidly observed. Nevertheless, the snow cover feeds the reservoir slowly and the replenishment time, as it was estimated in this study, is about 3 months. This facilitates discriminating the impact of snow from rain which is evidenced on the surface level of water in the reservoir.

It is obvious from the snow measurements over the catchment of the QR, for the investigated 17 years (2001–2018), that there is considerable snowpack accumulation, notably that the catchment is located between two elevated regions

Table 5 The maxima (peaks) difference for snow cover and water level in the QR

Year	Average snow cover (km^2)	Maximum water level (m) Lmax	Minimum water level (m) Lmin	Lmax − Lmin	Snow area/water level equivalent cm/km^2	Snow area/water volume equivalent (m^3)
2002	296.6	853.8	836.6	17.2	5.8	46,400
2003	271.9	858.4	835.4	23.0	8.5	68,000
2004	288.5	858.2	834.9	23.4	8.1	64,800
2005	219.5	856.7	835.9	20.8	9.5	76,000
2006	230.2	854.1	835.9	18.3	7.9	60,800
2007	174.3	852.3	836.5	15.7	9.0	72,000
2008	306.9	846.7	835.3	11.4	3.7	29,600
2009	120.8	855.2	838.2	17.0	14.1	112,800
2010	277.4	857.7	831.9	25.9	9.3	74,400
2011	146.8	857.9	834.4	23.5	16.0	128,000
2012	327.7	858.1	837.5	20.6	6.3	50,400
2013	325.1	858.0	838.4	19.6	6.0	48,000
2014	76.2	839.2	830.1	9.1	11.9	95,200
2015	336.1	853.8	837.1	16.7	5.0	40,000
2016	182.9	849.5	836.9	12.6	6.9	55,200
2017	212.6	849.9	834.9	15.0	7.0	56,000
2018	113.3	844.1	831.9	12.1	10.7	85,600
		Average			8.6	68,423

of the Mount Lebanon and Anti-Lebanon. Therefore, the calculated maximum coverage over the QR is 1754.1 km^2 (in 9/1/2002), while the average calculated maxima over the investigated 17 years was 1182 km^2, which is equivalent to 65% of the entire catchment area.

Based on previous field verifications (e.g., sampling for calculating snow density, depth) done by the authors on the surrounding area of the QR (Shaban et al. 2013; Shaban et al. 2014), the average snowpack depth (S_d) on the catchment of the QR was estimated at 0.36 m and snow-water equivalent (SWE) was 61%. Therefore, the water volume derived from snowmelt (Ws), as it was calculated for the first time, for the catchment of the QR will be:

$$\mathrm{Ws} = \mathrm{A} \times \mathrm{S_d} \times \mathrm{SWEWs} = \left(1182 \times 10^6\right) \times 0.35 \times 62/100 = 256 \times 10^6\ \mathrm{m}^3$$

Therefore, the catchment of the QR receives about 256 million m^3 of surface water from snowmelt annually, and this volume is greater than the reservoir capacity itself (i.e., 220 million m^3). This reveals the significance of snowmelt in feeding source water of the QR. Nevertheless, part of this amount is sublimated, evaporated, or enters another aquifers.

However, the current study evidenced that each 1 km^2 of snow cover will produce about 68,423 m^3 of water in the reservoir. Given the total area of the Qaraaoun catchment, which is about 1826 km^2, therefore, the total volume of water derived from snow into the reservoir will be:

$$= \text{Catchment area (in m)} \times \text{Water volume from snow for each of 1 km (in m)} 1826 \times 10^6 \times 68,423 = 125\ \text{million m}^3$$

This volume was not calculated before and only descriptive estimations were put to the contribution of snow to the QR. Hence, it was mentioned that the snowmelt is partially feeding the QR (Nassif et al. 2014), and some researchers reported that less than 10% (< 22 million m^3) of the water volume in the QR is derived from snow (Darwich et al. 2011).

Out of 256 million m^3 of water included in the snowpack over the QR catchment, about 49% of this volume seeps into the QR. Thus, the rest ratio (51%) is lost as sublimation and evapotranspiration and seeps into aquiferous rocks which do not belong to the QR.

The estimated volume of water that derived from snow in the QR (125 million m^3) exceeds half capacity of the reservoir (220 million m^3) and equals to about 57% of the estimated capacity. This also shows the significance of snow as a major feeding source for water in the QR.

Moreover, the results show that the time needed for the hydrologic cycle since the snow accumulates then melts and infiltrates to the rocks and eventually flows to the QR, is about 3 months. From the hydrogeologic point of view, time lag can be considered relatively moderate to rapid, and this can be attributed to the following:

- Exposure of the snowpack to sunlight is dominant in the catchment area of the QR, and this accelerates the melting rate.
- There is rapid infiltration rates in the exposed rocks, because the majority of exposed rocks is known by the presence of fractured and karistified limestone and dolomite.
- There is relatively rapid groundwater flow due to the dip of the bedding planes which exceeds 15° in most rock beddings, as well as the intervening of impermeable rock layers which enhances water seeps (Fig. 6)

Based on the above discussion, the importance of snowpack is clearly evidenced in this study, and the QR reveals a typical example for the contribution of snow to water resources in Lebanon. Therefore, concern must be given to this aspect of water resources; notably the people in Lebanon believe that rainfall is the main water source. For this reason, new approaches to conserve snowpack in the mountainous regions should be adopted, such as designating these regions as protected areas.

In this respect, it is worth mentioning that the increased human activities mess hydrogeologic regime of melting water from snow to reach the QR. In particular, the excavation and quarrying processes that have been recently exacerbated in the region (notably the catchment of the QR) significantly affected the mechanism of water feeding. Hence, environmental legislations and controls must be adopted in order to protect this aspect of water resources.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12517-020-06295-6.

Nomenclatures CNRS-L, Conseil National de la Recherche Scientifique- Liban; DISC, Data and Information Services Center; LLSB, Lower Litani Sub-basin; LRA, Litani River Authority; LRBMSP, Litani River Basin Management Support Program; MODIS, Moderate Resolution Imaging Spectroradiometer; NC, National Commission; NSDI, Normalized Snow Difference Index; QR, Qaraaoun Reservoir; Sd, snowpack depth; SWE, snow-water equivalent;

TRMM, Tropical Rainfall Mapping Mission; ULSB, Upper Litani Subbasin; VWP, vibrating wire piezometers; Ws, water derived from snow

References

Abdulrazzaq Z, Hadi R, Aziz N (2019) Integrated TRMM Data and Standardized Precipitation Index to monitor the meteorological drought. Civ Eng J 5(7)

Abou-Hamdan H, Ismail H, Amacha N, Chalak L, Jomaa R, Kamar M, Kobaissi A, Baydoun S (2014) Preliminary assessment of macrophytic community in Qaraaoun Reservoir, Lebanon. Int J Sci Res 2319–7064

Amacha N, Saadeh M, Karam F, Eter R, Jomaa R, Koubaissi A, Baydoun S (2015) Spatial-temporal characterization of water quality indicators of the open irrigation Canal 900 of Qaraaoun Reservoir, Lebanon. Int J Recent Sci Res 6(2):2611–2615

Assaf H, Saadeh M (2008) Assessing water quality options in the Upper Litani Basin, Lebanon, using an integrated GIS-based decision support system. Environ Model Softw 23:1327–1337

Baydoun S, Darwich T, Nassif M, Attalah T, Puig J, Kamar M, Amacha N, Molle F, Closas A (2015) Spatial and temporal variations in groundwater quality in Upper Litani Basin. Paper presented at Les Troisièmes Journées Franco-Libanaises JFL3: La Recherche au Service de la Communauté, Lebanese University, Beirut, 29–31 October 2015, p 7

CNRS-L (National Council for Scientific Research, Lebanon) (2015) Regional coordination on improved water resources management and capacity building. Technical Report. Regional project. GEF, WB, p 146

Darwich T, Atallah T, Francis R, Saab C, Jomaa I, Shaban A, Sakka H, Zdruli P (2011) Observations on soil and groundwater contamination with nitrate: a case study from Lebanon, Eastern Mediterranean. Agricultural Water Management 99(11):74–89

El-Goul Z (2004) Sources and transportation mechanism of pollutants in the Qaraaoun Lake, Lebanon. M.Sc. Thesis. Lebanese University. Beirut

Fadel A, Lemaire BJ, Vinçon-Leite B, Atoui A, Slim K, Tassin B (2017) On the successful use of a simplified model to simulate the succession of toxic cyanobacteria in a hypereutrophic reservoir with a highly fluctuating water level. Environ Sci Pollut Res Int:1–15. https://doi.org/10.1007/s11356-017-9723-9

Guiamel S, Lee H (2020) Watershed modelling of the Mindanao River Basin in the Philippines using the SWAT for water resource management. Civ Eng J 6(4)

IDRC (International Developing Research Center), CNRS, LRA and DSA (Development Studies Association) (2007) Towards an ecosystem approach to the sustainable management of the Litani watershed. Technical report, 143pp. Lebanon-East Mediterranean. Agric Water Manag 99:74–84

Jomaa I, Shaban A (2018) Improving water use efficiency and productivity in the Litani River Basin. In: Lebanon: an assessment and current challenges, vol 85. Springer International Publisher, Berlin. https://doi.org/10.1007/978-3-319-76300-2

Korfali S, Jurdi M (2011) Speciation of metals in bed sediments and water of Qaraaoun reservoir, Lebanon. Environ Monit Assess 178:563–579

Little MA, McSharry PE, Moroz IM, Roberts SJ (2006) Testing the assumptions of linear prediction analysis in normal vowels. J Acoust Soc Am 119(1):549–558. https://doi.org/10.1121/1.2141266

LRA (Litani River Authority) (2020) The official site for the Litani River Authority, Lebanon. Water level in the Qaraaoun Reservoir. Available at: https://www.litani.gov.lb/en/

LRBMSP - Litani River Basin Management Support Program (2011) Water balance Report, Draft, US Agency for International Development, Beirut, Lebanon, February 2011. NC (National Communication, 2nd edn). 2011. Submitted to the UNFCCC. Ministry of Environment. GEF. UNDP, New York, 191pp

Metni M, El-Fadel M, Sadek S, Kayal R, Lichaa-El Khoury D (2004) Groundwater resources in Lebanon: a vulnerability assessment. Int J Water Res Dev 20(4):475–492

Nassif N, Kchour H, Shaban A (2014) Temporal changes in the Lebanese Litani River: hydrological assessment and recommended actions to handle with the human and global change impacts. J Sci Res Rep 4(5):313–327

Nehme N, Haidar C (2018) The physical, and chemical and microbial characteristics of Litani River water. In: The Litani River, Lebanon: an assessment and current challenges. Springer, Berlin 179 p

Ramadan H, Beighley R, Ramamurthy A (2013) Temperature and precipitation trends in Lebanon's largest river: the Litani basin. J Water Resour Plan Manag 139(1):86–95

Shaban A (2003) Etude de l'hydrogéologie au Liban Occidental: Utilisation de la télédétection. Ph.D. dissertation. Bordeaux 1 Université. 202p

Shaban A (2011) Analyzing climatic and hydrologic trends in Lebanon. J Environ Sci Eng 5(3)

Shaban A (2020) Water resources of Lebanon. Springer International Publisher, Berlin. https://doi.org/10.1007/978-3-030-48717-

Shaban A, Hamzé M (2018) The Litani River, Lebanon: an assessment and current challenges. Springer International Publisher, Berlin, p 85. https://doi.org/10.1007/978-3-319-76300-2

Shaban A, Nassif N (2007) Pollutants in Qaraaoun Lake, Central Lebanon. Environ Hydrol 15(11):2007

Shaban A, Faour G, Khawlie M, Abdallah C (2004) Remote sensing application to estimate the volume of water in the form of snow on Mount Lebanon. Hydrol Sci J 49(4):643–653

Shaban A, Darwich T, El-Hage M (2013) Studying snowpack and the related terrain characteristics on Lebanon Mountain. Int J Water Sci 2(6) 1-10 pp

Shaban A, Darwich T, Drapeau L, Gascoin S (2014) Climatic induced snowpack surfaces on Lebanon's mountains. Open Hydrol J 2014(8):8–16

SNC (2011) Second National Communication to the UNFCCC . Climate change vulnerability and adaptation. Ministry of Environment & GEF & UNDP, Beirut, Lebanon, p 288

Telesca L, Shaban A, Gascoin SL, Darwich T, Drapeau L, El-Hage M, Faour G (2014) Characterization of the time dynamics of monthly satellite snow cover data on mountain chains in Lebanon. J Hydrol 519(2014):3214–3222