



# Water resources within the Upper Orontes and Litani Basins

A balance, demand and  
supply analysis amid the  
Syrian refugees crisis

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Increasing refugee populations, industrial demands and agricultural activities have exacerbated water stress in Lebanon's Bekaa Valley. We have provided previously unavailable remotely sensed estimates of agricultural water consumption in the Upper Litani and Upper Orontes basins. We also quantified increases in domestic water demand and mapped water stress hotspots. Due to the distinction between demand, use and consumptive use, increased water demand does not have to mean water shortage. Increased consideration of this distinction is crucial for integrated water resources management planning and climate change adaptation.

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# Summary

The arrival of refugees from Syria has tripled the population in some areas of Lebanon's Bekaa Valley, increasing water demand for domestic use. Transient and resident populations also need water for agriculture, industry and other productive activities to support their livelihoods. This study focused on updating the available water balance figures for the Upper Litani Basin (ULB) and the Upper Orontes Basin (UOB).

We estimated water demand for domestic uses from population figures and refugee influxes. Agricultural water uses were estimated by mapping irrigated lands, surveying crops and calculating evapotranspiration requirements. In 2016, we mapped summer irrigation in Bekaa using a normalized vegetation index approach. We coupled the NDVI with an iso-cluster unsupervised classification scheme to analyse Sentinel-2 and Landsat Imagery.

We identified 35,500ha of irrigated agriculture in the ULB and 12,400ha in the UOB during the irrigation season (end of April–October 2016). Based on these findings, we estimated the volumes of water consumed by these lands in the two basins at 250 million cubic metres per year (MCM) for the Upper Litani and 81MCM for the Upper Orontes.

Major diversions for irrigation are estimated to be at least 35 per cent higher than the consumptive uses due to the spread of sprinkler irrigation in the region and surface irrigation on fruit trees irrigated from springs. Potatoes consume the most irrigation water of the Bekaa (43 per cent), followed by fruit trees and vegetables.

Overall, household demand for water (including for both Lebanese and displaced people) is small compared to agricultural demand. Our estimated water budget for the Litani is negative, whereas the water budget for the Upper Orontes is positive.

These basin-wide calculations mask hotspots of water stress at particular locations and times of the year. Springs are exploited for both irrigation and domestic uses, with surplus of water in some areas and deficit in others. Deterioration in water quality further reduces the availability of surface water for domestic and sometimes agricultural uses. This increases stress on the over-mined groundwater reserves.

We analysed hotspots for water stress by overlaying maps of water demand for domestic and agricultural uses, and comparing demand to supply. These hotspots include some areas where displaced people have been staying. The analysis reveals a need for further attention to strategies to increase domestic water supplies to the Lebanese and displaced populations, to adapt to climate change and to enhance integrated water management around the urban centres of Baalbeck, Zahle and Hermel areas.

## 1

## Background

Anthropogenic activities create a stress on water resources. Water has become scarcer in the Bekaa Valley due to population increase, including from an influx of displaced Syrians due to the conflict in Syria, and an increase in industrial and possibly agricultural activities (CCIAZ, 2014). Degrading water quality and global warming have made the situation worse. Re-visiting the water balance figures of the Bekaa can better assess the amount of water available for human use.

The Bekaa Valley is divided almost equally between two major river basins: the Upper Litani River (ULB) and the Upper Orontes (UOB) (Figure 1). Due to the crisis in Syria, hundreds of thousands of refugees have flooded into these two basins. In 2014, the Lebanese Ministry of Environment (MoE) and the UN Development Programme (UNDP) assessed the impact of Syrian conflict on the Lebanese environment. MoE-UNDP (2014) says the Bekaa is the most vulnerable area in Lebanon because it has the highest number of refugees and the highest water demand in terms of agriculture.

The objectives of this research are to:

1. Re-visit the water balance figures of both basins within the context of climate variability (given the recent flow data)
2. Assess consumption of water for irrigation following the Syrian crisis
3. Provide insights into the available water supplies (or lack thereof), and
4. Explore the effect of the arrival of refugees on the water balance of the two basins.

To achieve these objectives, we need to estimate the current domestic, industrial, and most importantly, agricultural consumption within the two basins. These water uses need to be assessed simultaneously as in most cases they draw water from the same sources and are frequently in conflict. The local balance between availability of water and demands for various uses should be considered in any strategic plan to balance water stress under climate change and population flux.

Springs and wells are the major source of water for the irrigated lands in Bekaa. These also remain the major sources for domestic and industrial use. The linkages between these uses will define any future attempts to prioritise/optimize water allocation in the Bekaa Valley.

In this paper we provide novel estimates of domestic and industrial demands at both the basin and municipal levels, while accounting for water demands of the displaced population. We also provide a new method to calculate agricultural water consumption and estimate diversions. This is based on a remote sensing technique that uses available satellite imagery and ground-truthing of the results via field surveys.

We explore estimates of renewable water resources in the upper parts of the two basins to map hotspots of water stress. This includes estimates of springs and river flows in addition to sectoral water demands and water availability. The work provides an innovative technical approach that is ready for use in other areas of the world facing water stress.

## 1.1 Water demand, supply and overall water balance

Water stress concerns the relationship between the availability of freshwater resources and the magnitude of water withdrawals for human use (see: [www.unwater.org/publications/publications-detail/ar/c/428727/](http://www.unwater.org/publications/publications-detail/ar/c/428727/)). After considering environmental water requirements (also known as water withdrawal intensity), previous researchers recommend estimating the quantity of water stress by focusing on the ratio between total freshwater withdrawn for all economic activities and total renewable freshwater resources. This would require measuring the volumes of water withdrawn for agriculture, manufacturing and electricity, as well as for collection, treatment and supply.

Water accounting and water budget studies have investigated the volumes of water extractions and availability in a range of basins in different parts of the world. Decision makers use these studies to review the share of available water resources consumed by different sectors. Policymakers and planners can then look for ways to reduce water stress by adjusting the allocation of water within or between sectors.

Not all water extractions will necessarily affect the overall water balance. The balance is usually assessed using some variation of the following equation (equation 1, Viessman and Lewis, 1995):

$$P - E - Q = \Delta S$$

Where  $P$  = precipitation,  $E$  = evapo(trans)piration,  $Q$  = outflow (measured at gauge stations) and  $\Delta S$  is the change in storage (net loss or gain in the aquifer and/or soil moisture).

According to this equation, changes in water storage due to groundwater depletion or recharge can be quantified by assessing precipitation, evapotranspiration and river flows. Therefore, estimating  $E$  (hereafter 'ET') is crucial for evaluating the changes in groundwater storage from falling groundwater levels. This is important in dry regions, where populations rely on water stored underground. In such situations, although direct observation and measurement of aquifer conditions is difficult, managers need to assess and regulate depletion and recharge rates.

The water balance equation highlights the main hydrological inputs and outputs. The term 'evapotranspiration' does account for water transpired by crops and evaporated from soil surfaces. However, it does not explicitly account for domestic and industrial water uses.

Domestic water reuse can be as high as 90 per cent with appropriate collection and treatment. Industrial water could also have a high recovery rate. Japan, for example, recovers about 78 per cent of its industrial

water (JFS, 2003). Domestic and industrial water uses may therefore constitute water diversions rather than consumptive uses.

### Domestic use and demand

Domestic water use is different than demand. Water authorities use demand to estimate the amount of water needed by the population. It is usually used for water networks design, master planning and other strategic demographic planning. Depending on infrastructure and other factors, however, the amounts of water that the population can actually use may differ from plans and projected demands.

The source for domestic water is usually groundwater, springs or river diversions. Any diversion to domestic water from springs and rivers will be reflected in the 'Q' term. Any diversion from groundwater will reflect in the  $\Delta S$  term.

### Agricultural water demand and consumption

The distinction between agricultural water demand and consumption is important. Agricultural water demand is gross water requirement, or the amount of water that needs to be diverted to the land to meet crop needs. It usually considers system efficiencies. Agricultural water consumption is the actual evapotranspiration that goes into the atmosphere, or net water requirement.

Agricultural water demand is usually calculated based on irrigation requirements. These are measured using crop coefficients and reference evapotranspiration, and added to possible system losses from runoff, wind drift and deep percolation. Agricultural water consumption can be estimated remotely using energy balance models (Allen et al., 2007; Anderson et al., 2013; Bastiaanssen et al., 1998). Agriculture is usually assumed to be the largest consumer of water worldwide (Hoekstra, 2013).

## 1.2 The study area

The Bekaa Valley is located in the northeastern part of Lebanon, bordering Syria to the North and East (Figure 1). The major groups recognised to make up the population of the Bekaa Valley in 2016 include Lebanese (69.8 per cent), Syrian refugees (29 per cent) and Palestinians (1.2 per cent). The Lebanese population data herein are for 2013. Changes since then are not quantified in this analysis.

The Bekaa is split between two main hydrographic basins, the Upper Litani (running south of Baalbeck city) and the Upper Orontes (running north of the city) (Figure 1). We have excluded Rachaya from our study; although Rachaya is part of the Bekaa governorate, it lies in the Hasbani Basin and not in the Litani Basin.

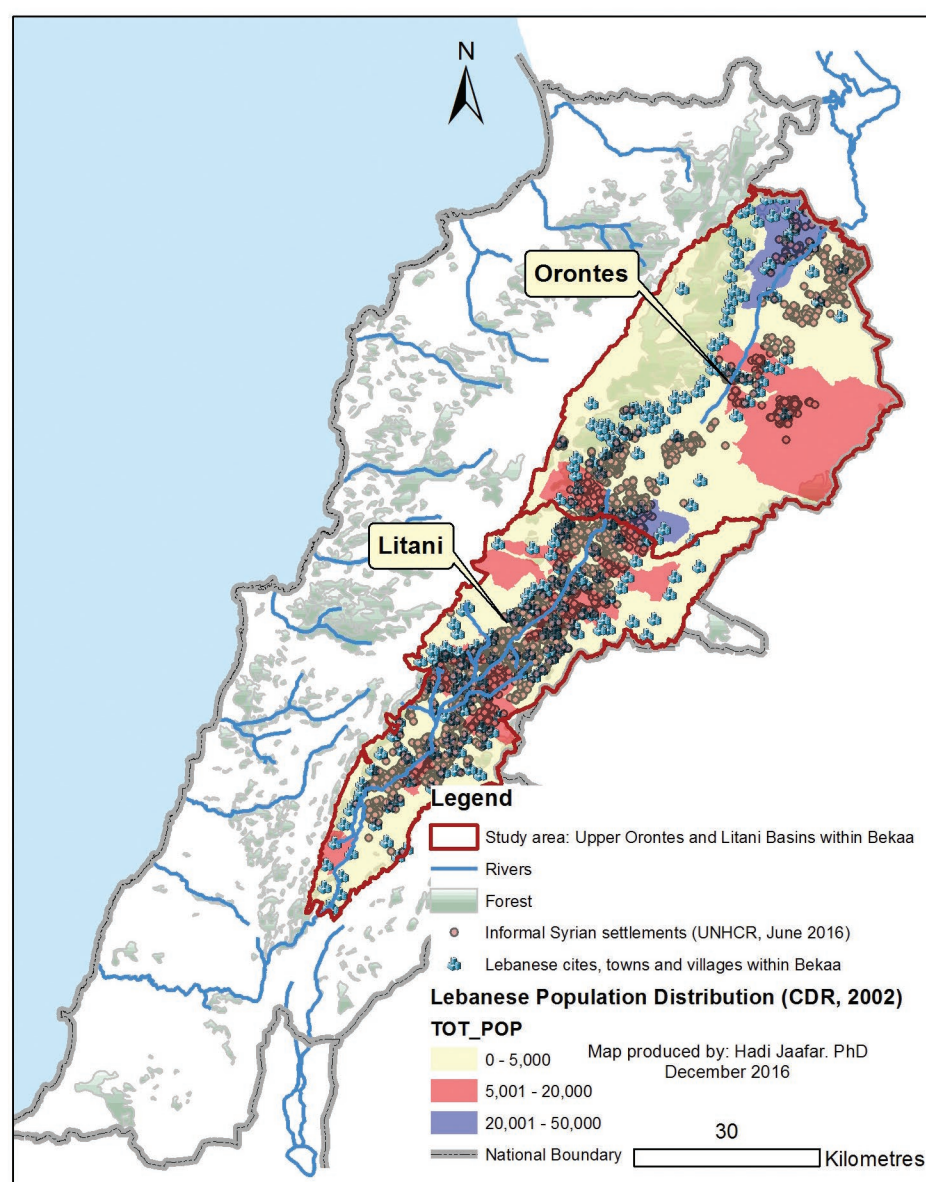


Table 1. Total population in Bekaa area

| GOVERNORATE/<br>DISTRICT | LEBANESE | PALESTINIANS | TOTAL<br>SYRIANS | TOTAL<br>POPULATION |
|--------------------------|----------|--------------|------------------|---------------------|
| BEKAA (excl. Rachaya)    | 498,947  | 12,835       | 275,307          | 787,089             |
| West Bekaa               | 134,798  | 4,975        | 70,283           | 210,056             |
| Zahle                    | 364,149  | 7,672        | 193,003          | 564,824             |
| BAALBEK-EL HERMEL        | 499,614  | 5,117        | 138,616          | 643,347             |
| Baalbek                  | 416,483  | 5,117        | 131,997          | 553,597             |
| El Hermel                | 83,131   | 0            | 6,619            | 89,750              |
| Total in Bekaa Valley    | 998,561  | 17,952       | 413,923          | 1,430,436           |

Source: Lebanese population figures: BWE, 2015; Syrian and Palestinian refugees: IAMP, 2016.

Figure 1. Study area showing Upper Litani Basin and Upper Orontes Basin



## 1.3 Water availability

### Precipitation

Precipitation in the form of snow and rain is the major source of water in the area. Rainfall ranges within the study area from a minimum of 200mm/yr in the Qaa (northern-most point of UOB) to above 1,400mm/yr at the western mountain peaks. To our knowledge, the amount of snowmelt that contributes to the waters of the two rivers is unknown.

We assume the rainfall map by Plassard (1971) considers the water equivalent of snowfall. Mean annual rainfall within the UOB and ULB are estimated at 969 and 1,000MCM/yr, respectively. For these figures, we took the digital version of Plassard's rainfall map (BWE, 2015), and multiplied the rainfall isohyets by their corresponding area. We averaged results after clipping by the watersheds' boundary.

Rainfall gauges in the area give a good indication of the amount of rain in the Bekaa Valley. Data from a weather station at the American University of Beirut (AUB) Agricultural Research and Education Center (AREC) show no significant trend in rainfall within the Bekaa since 1957. USAID (2011) confirms these data. Effect on snowfall is unknown due to lack of measurements. However, with a global warming trend, we expect faster melt of snow cover on the mountains of the basins.

Temperatures are expected to increase by around 2°C in the mainland by 2040 (RoL, 2015). By 2090, they will be 3.5°C and 5°C higher, respectively. At the same time, rainfall is projected to decrease by 10–20 per cent by 2040 and by 25–45 per cent by 2090 (see UNESCWA, 2013).

### Surface water

The mean annual flow rate in the Litani River before dam construction (1932–66) was 378MCM/yr. It decreased at an average rate of 1MCM/yr to an average of 331MCM between 1966–2011. According to available data for the Orontes River in Lebanon, gauge flow measurements are restricted to 1931–43, 1955–74 and 2000–present. Mean annual flows dropped from 13.86 cubic metres per second ( $\text{m}^3/\text{s}$ ) in the 1930s (which witnessed a drought), to 12.56 $\text{m}^3/\text{s}$  in mid-century, to 10.6 $\text{m}^3/\text{s}$  between 2000–14. Overall, mean annual

flows in the Orontes at Hermel station have decreased from an average of 13 $\text{m}^3/\text{s}$  (413MCM/yr) over 1932–74 to an average of 10.6  $\text{m}^3/\text{s}$  (~330MCM/yr) for 2000–14, a decrease of 16 per cent. All data are from Litani River Authority.

### Groundwater

The Orontes Basin discharges groundwater from the karstic Upper Cretaceous and Jurassic aquifers of the eastern slope of the western Lebanon Mountains and the western slopes of the Eastern Lebanon Mountains. The former are separated into a number of groundwater flow compartments. Groundwater discharge from the Upper Cretaceous aquifer section into Ain Yammoune (2.8 $\text{m}^3/\text{s}$ ) is caused by the Yammoune fault. To some extent, subsurface flow from the eastern mountain slopes reaches the Bekaa plain.

On the northeastern mountain sector east of the Yammoune fault, groundwater systems flowing northeast and south feed large springs within the Bekaa Valley (Zarqa spring). On the western slope of the northern part of the Eastern Lebanon mountains, groundwater discharges as the springs of Ras el Ain at Baalbek and the Laboue (Upper Cretaceous) (Jaubert et al., 2015; UN-ESCWA, 2013). Flows of these springs constitute the major surface flow of the Orontes Basin in Lebanon. Data for the Orontes at the Hermel station for 1975–99 are lacking.

The groundwater aquifer boundary between the Orontes Basin and the Litani Basin in the Bekaa Valley is the same as the surface water divide. Surface and groundwater movement starts to flow from 10km west of Baalbeck (Allaiq spring, currently dry) and then south-south-west. Within the Orontes Basin, groundwater flows north-north-west. Historically, the groundwater surface descended to around 700m above sea level (ASL) near Hermel at the northern end of the valley and to 800m ASL at Qaraoun in the south (Wagner, 2011).

A recent report on the groundwater situation in Bekaa focusing on the Upper Litani Basin was under the Litani River Basin Management Support Program. USAID (2011) estimates pumping for irrigation from the basin to be 120MCM/yr, and pumping for domestic supply to be 30MCM/year.



## 1.4 Previous water balance studies in the Bekaa

Precipitation is the major component of the hydrologic cycle. This has been reasonably measured within the two basins (more so in the ULB than in the UOB). However, evapotranspiration (the major outflow) has never been quantified at the basin scale. Extraction and demands for water by the population are also still not well understood. However, the falling groundwater table across much of the Bekaa suggests the water balance is negative.

A recent groundwater assessment (MoEW-UNPD, 2014) reports the groundwater balance of the aquifers of Lebanon (which may or may not correlate with the surface watersheds). This report mentions the number of private wells and the extraction rates from public and private wells are not adequately defined. Using the best available pumping figures from the Bekaa Water Establishment (BWE), the authors found a deficiency of 50MCM in a dry year.

MoEW-UNDP (2014) states that “due to over exploitation for irrigation, the South Bekaa Neogene-Quaternary Basin and the North Bekaa Neogene Quaternary Basin show deficiencies in their budgets of up to 45.7MCM and 34.2MCM respectively”. The report states that BWE pumps water from 209 wells at the rate of 33MCM/year; this estimate does not include the current increase in pumping rates due to the Syrian refugee crisis.

Conversely, USAID (2011) estimates that total groundwater recharge of the Upper Litani Basin is 210MCM/yr. It achieves this figure by estimating the percentage infiltration of precipitation (20 per cent in Carbonate aquifers and 10 per cent on Quaternary aquifers).

The Litani has an estimated recharge of 220MCM/yr and a spring discharge of 130MCM/yr. After building a groundwater model, the report concludes that aquifers underlying the Litani are being depleted at an average of 65MCM/yr. The model shows the change in groundwater levels between 1967–2010. Southern Bekaa shows little decline in groundwater levels (0–5m) compared to the northern and mountainous regions of the basin (10–25m). Aquifers in the Chmistar area witnessed a decline of 50m in groundwater levels. USAID (2011) provides evidence of decreasing groundwater storage within the Upper Litani Basin in Bekaa.

## Early research on ULB

The first study on the water balance of the ULB, Abdel Al (1943), shows that flows at the Mansoura station (1,429km<sup>2</sup> basin area) amounted to an average of 287MCM/yr. Several studies also estimated water use within the ULB. FAO (1972), for example, estimates that 15,800ha of irrigated lands consumed 122MCM annually (7,200m<sup>3</sup>/ha) upstream of Qarwan Lake. The Litani River is used for power generation, as well as agriculture, domestic and industrial uses (Jaafar, 2014; Jaafar et al., 2016). Waters of the Litani are diverted to the Awali after generating power in South Bekaa. Together with the waters of the Awali River in South Lebanon, this water generates power in another two plants and also delivers irrigation water to the southern coast (Jaafar, 1999).

The Litani project was also planned to supply water for 30,000ha of irrigated lands in south Lebanon (through a canal called Conveyer 800). Downstream of the reservoir, the 3,270ha Qasmieh project consumed 59MCM, and another 1,140ha in between the reservoir and the Qasmieh consumed 12MCM. This amounted to a total irrigation diversion from the river of 182MCM for 20,120ha. In 1969, the Litani authority estimated that 118.6MCM from the Litani River irrigated lands in Bekaa. USAID (2011) estimates that the 650MCM of the total precipitation (1,100MCM, estimated from FAO, 1972) evaporates between December and May. Flows in the ULB amounted to 400MCM between 1940–50, but have since decreased to 300MCM.

The operation of the Litani River for hydropower does not follow optimal operation rules (Jaafar, 1999). However, any water allocation upstream of Qarawn Lake has to respect water rights, as well as current and future allocations downstream.

For the Orontes River, BWE estimates total flow of 512MCM/year, of which 80MCM constitutes Lebanon's right (Brooks and Mehmet, 2000). World Bank (2003) identifies a flow of 656MCM/yr to Syria. If flows drop to less than 400MCM, then, according to a 1994 agreement between Syria and Lebanon, Lebanon's share will drop proportionally.

Concerning water extractions, Plan Bleu-UNEP (2001) estimates water demand in Bekaa to be 456MCM/yr (45MCM domestic, 402MCM irrigation and 18MCM industrial).

Domestic and industrial uses constitute water diversions from groundwater or surface water sources. In the Bekaa, the fate of water diverted for such uses is unknown. In other words, there are no records or studies that estimate the proportion of industrial or domestic water that goes back into the hydrologic cycle (either as deep percolation to recharge the aquifers or as surface water that returns to the river).

USAID (2011), for example, states that industrial water directly discharges used water either into the river or into the sewer networks that eventually flow into the Litani River. This includes water from industries such as dairy and food processing plants, water bottling, wineries, paper, dyeing/tanning, battery manufacturing and food packaging. As well, around 30 per cent of Bekaa towns are connected to sewer networks (that discharge untreated sewage into the river, with few minor exceptions) or use septic tanks (whose untreated sewage eventually reaches groundwater).

If untreated, these discharges may constitute a major source of water pollution. They could also render a significant amount of surface water unusable as well. USAID (2011) estimates domestic withdrawals in the ULB at 150l/day/capita (USAID 2011 cites a reference to Bekaa Water Authority figures).

USAID (2011) states that: "Neither the municipalities nor the BWE have information about the exact extraction rate for the public wells". Accordingly, well operators estimated domestic pumping based on either tank capacities or number of users multiplied by 180l/day – the water usage per capita from the last estimate by the Ministry of Energy and Water (MoEW). The number of users is calculated based on number of households connected to the water network (which was communicated by the water establishments) and multiplied by four (the size of the average household).

Irrigation withdrawals from the ULB have been estimated at 200MCM/yr (MoA, 1998), 130MCM of which is from groundwater. MoE-UNDP (2014) estimates that 115MCM of irrigation water comes from groundwater. None of the reports attempt to estimate the consumptive use part of that water.

## 2

# Domestic and Industrial Water Use/ Demand Analysis

In 2013, before most displaced people arrived, the BWE estimated current and projected domestic water demand in the Bekaa at 190,000m<sup>3</sup>/day or 69.6MCM/year (Table 2). In this section, we draw on the latest available secondary sources and updated population data to revise the estimates for domestic demand.

## 2.1 Lebanese population and domestic water demand

The Lebanese population in Bekaa is estimated to be more than 998,000 (Table 2), with more than 413,000 registered Syrian refugees (IAMP, 2016). This is considerably more than in 1959, when only 160,000 inhabited the Bekaa Valley (Abd-EL-Al, 1959). At that time, the water demand was estimated at 112l/day/capita, amounting to 18MCM/year.

Table 2 shows the projected future population and domestic water demand for the population. This is based on the BWE's estimated per capita demand of 180l/day/capita in 2013 (BWE, 2015). This figure is expected to increase to 195l/day/capita in 2035.

Water use data from institutions (mosques, hospitals) are not available, but are believed to be included within the domestic water demand. Many institutions have their own wells, and the actual water use is not possible without a ground survey.

Table 2. Current and projected domestic demand in Bekaa

| CAZA       | YEAR 2013            |                         | YEAR 2025            |                         | YEAR 2035            |                         |
|------------|----------------------|-------------------------|----------------------|-------------------------|----------------------|-------------------------|
|            | ESTIMATED POPULATION | WATER DEMAND (MCM/YEAR) | ESTIMATED POPULATION | WATER DEMAND (MCM/YEAR) | ESTIMATED POPULATION | WATER DEMAND (MCM/YEAR) |
| Hermel     | 83131                | 5.5                     | 102367               | 7.0                     | 121762               | 8.7                     |
| Baalbeck   | 416483               | 27.4                    | 512875               | 35.2                    | 610035               | 43.4                    |
| Zahle      | 364149               | 23.9                    | 448426               | 30.8                    | 533377               | 38.0                    |
| West Bekaa | 134798               | 8.9                     | 165992               | 11.4                    | 197441               | 14.1                    |
| Rachaiya   | 60342                | 4.0                     | 74309                | 5.1                     | 88382                | 6.3                     |
| Total      | 1058903              | 69.6                    | 1303969              | 89.5                    | 1550997              | 110.4                   |

Source: BWE, 2015.

## 2.2 Displaced people living in houses and flats similar to Lebanese population

More than one-fifth of the population living in Lebanon is Syrian (IFPRI, 2015; UNICEF, HAC). The population of Lebanese and Syrians living in the Bekaa is now roughly the same. Most Syrian refugees – about 269,000 – live with Lebanese host communities, mostly in Baalbeck and the Upper Litani Basin (Table 1). This fraction of the total refugee population in the Bekaa requires about 15.72MCM of domestic water annually (based on 160l/day/capita). The total domestic water demand in the two basins for the displaced Syrians not living in informal settlements is 15.72MCM (11MCM in the ULB and 4.72MCM for the UOB).

## 2.3 Displaced people living in informal settlements

One-third of Syrian refugees, or 145,000 in the Bekaa live in “informal settlements”, or IS. According to a recent survey (UNHCR, 2015), one-third of all Syrian refugees have access to tap water for more than two hours per day. Lack of a proper water accounting method, however, makes access to tap water (and other delivery methods) difficult to estimate. The best way to account for water usage is to estimate daily use on a per-capita basis. Since few data exist about the number of times that household/tent water tanks are filled, we assume one filling per day. By dividing the

water capacity of the tanks by the number of settlement inhabitants, we arrive at an approximate water use figure for the informal settlements within the Upper Orontes and Upper Litani basins: (120 and 160 l/capita/day, respectively).

We distinguish water demand from water use; use may be lower or higher than demand. Estimate of water allowance (which is also different than demand) for displaced people is controversial in Lebanon for political reasons. However, there are no plans for Syrians to remain as refugees in Lebanon indefinitely or to receive services not yet assured for much of the Lebanese population. Emergency water supply per capita can be as low as 15l/p/d (House and Reed, 1997). Minimum allocations for bathing, toilet flushing, laundry and other domestic uses need to be added to this estimate.

Many tanks within the tents are filled using water from boreholes. However, some are connected to the piped water supply network, which is more reliable than water from trucks. Still, trucks often fill the gap when water supply from other sources is interrupted.

As of June 2016, there were 10,613 tents in the Orontes Basin, distributed over 750 informal settlements, with more than 55,600 inhabitants (IAMP, 2016). We found total water storage capacity for the tanks of the tents was 6,630m<sup>3</sup>. Assuming tank filling once a day, total use would be 120l/per capita per day, equivalent to 2.4MCM annually.

The total number of tents as of June 2016 in the Litani Basin was 18,775, distributed over 1,900 settlements with more than 109,000 inhabitants. We calculated the total water storage capacity for the tanks surveyed by UNHCR for each tent at 17,220 m<sup>3</sup> (160l/capita/

day, assuming filling of tanks once per day equivalent to 6.4MCM annually). This is a small amount if we assume that displaced populations who live in the tents rely only on this water and are not able to purchase water from other sources.

Refugees in the ULB informal settlements use 30 per cent more water per capita than in the UOB. The total estimated yearly domestic demand for the settlements is believed to be 8.8MCM per year.

## 2.4 Total current domestic demand in the two basins

The 2016 estimate of domestic water demand in Bekaa (BWE, 2015) is 190,600m<sup>3</sup>/day or 69.6MCM/year. Table 3 shows estimated domestic water demand in the two basins of the Bekaa (excluding the Rachaya area, which is part of a different basin) at 90MCM per year (61MCM for the ULB and 29MCM for the UOB).

Table 3. Estimated domestic water demand (DWD) (MCM/yr) in 2016

|                                   | DWD FOR<br>LEBANESE | DWD FOR<br>PALESTIN-<br>IANS | DWD FOR<br>SYRIANS<br>IN IS            | DWD FOR<br>SYRIANS<br>NOT IN IS | DWD<br>FOR ALL<br>SYRIANS<br>IN<br>LEBANON | TOTAL<br>DWD |
|-----------------------------------|---------------------|------------------------------|--|---------------------------------|--|--------------|
| Per capita water demand (l/day)   | 180                 | 180                          | 120 in<br>Orontes and<br>160 in Litani | 160                             |  |              |
| West Bekaa (Litani)               | 9                   | 0                            | 1                                      | 3                               | 4  | 13           |
| Zahle (Litani)                    | 24                  | 1                            | 4                                      | 8                               | 11   | 36           |
| Subtotal: BEKAA                   | 33                  | 1                            | 5                                      | 10                              | 15   | 49           |
| Baalbek (Litani + Orontes)        | 27                  | 0                            | 3                                      | 4                               | 7  | 34           |
| El Hermel (Orontes)               | 5                   | 0                            | 0                                      | 0                               | 0  | 6            |
| Subtotal:<br>BAALBEK-EL<br>HERMEL | 33                  | 0                            | 3                                      | 5                               | 7  | 40           |
| Grand total in 2<br>basins        | 66                  | 1                            | 8                                      | 15                              | 23   | 90           |

## 2.5 Industrial water demand

There are reportedly 988 industries in the Bekaa (Industrial Guide of Lebanon, 2016), with more than 744 large establishments. Two-thirds lie within the ULB with the rest in the UOB (Figure 2). The main type of industries in the Bekaa are food (including bottling water from springs), dairy, wine, livestock, poultry, paper, ceramics, metal, plastic and chemicals.

In addition, there are at least 124 sand quarries and rock quarries, mainly limestone. Water use of these quarries is not documented. However, similar quarries in the United States can pump up to 26,000m<sup>3</sup> per annum (3.2MCM for the quarries).

In 2003, MoEW estimated industrial demand in Bekaa at 19MCM. Subscriptions of industrial establishments to public water are not documented. Meters are either not installed or may have been vandalised..

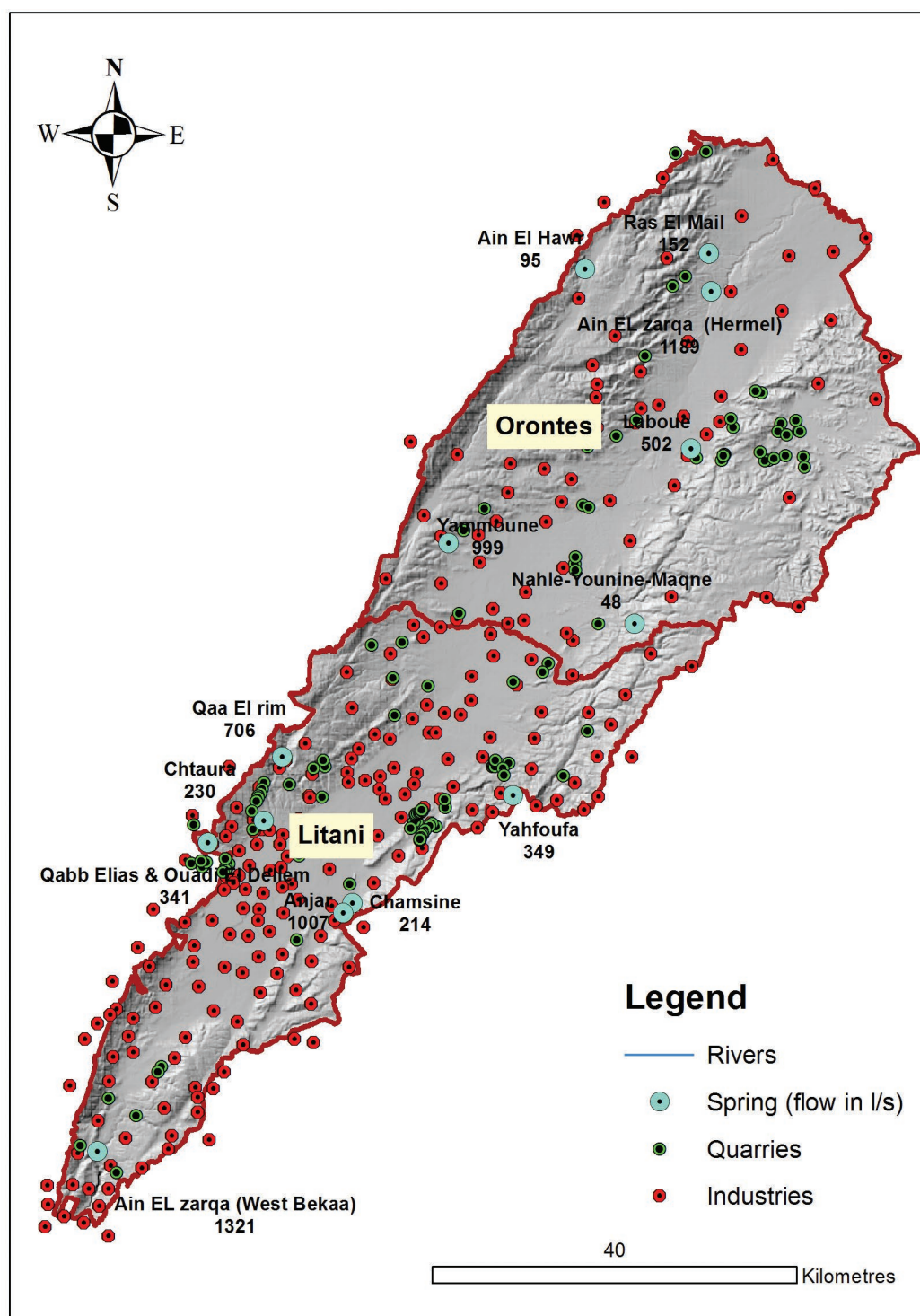
Industrial water demand has been estimated to be between 30–35 per cent of the domestic demand in Lebanon. We estimate 40 per cent because the Bekaa has a higher ratio of industry to domestic population due to its lower population density (Table 4). Using the 40 per cent figure and estimated volumes for domestic water use, the estimated total volume of industrial water use would be 30.6MCM/annum for the ULB and 14.4MCM for the UOB (Table 4).

Table 4. Estimated industrial water demands (MCM/yr) in 2016

|                                      | DOMESTIC DEMAND | INDUSTRIAL DEMAND<br>AS 40 PER CENT OF<br>DOMESTIC |
|--------------------------------------|-----------------|--|
| Subtotal: BEKAA (Litani)             | 49              | 19.6   |
| West Bekaa                           | 13              | 5.2  |
| Zahle                                | 36              | 14.4   |
| Subtotal: BAALBEK-EL HERMEL (Litani) | 40              | 16   |
| Baalbek (Litani + Orontes)           | 34              | 13.6   |
| El Hermel (Orontes)                  | 6               | 2.4  |
| Grand total in 2 basins              | 90              | 36   |



Figure 2. Industries and quarries within the Bekaa



Source: CDR-NLUMP, 2004.

# 3

## Agricultural Water Use

This section estimates the irrigation water demand in the Bekaa within the UOB and the ULB in the spring and summer of 2016. To do this, we develop a method that will enable continuous monitoring of irrigated agriculture within the Bekaa Valley using available satellite imagery.

We do so by following these steps:

- 1) Delineate irrigated lands using Sentinel-2 and Landsat satellite imagery to derive vegetation indices and perform image classification to identify the irrigated areas and cluster the irrigated lands over the growing season of 2016
- 2) Identify the existing crops and irrigation practices used in irrigated areas through field surveys and calculate the percentage of total irrigated area under each one
- 3) Calculate net water consumption by estimating the evapotranspiration rate over the season for each crop and calculate the total volume based on the area, and
- 4) Estimate the irrigation water demand as percentage of the net water consumption using knowledge of irrigation practice efficiency.

### 3.1 Satellite imagery analysis

Estimates of the extent of irrigated areas in the Bekaa Valley vary from 33,000ha (Plan Bleu-UNEP, 2001) to 45,000ha (MoEW, 2010).

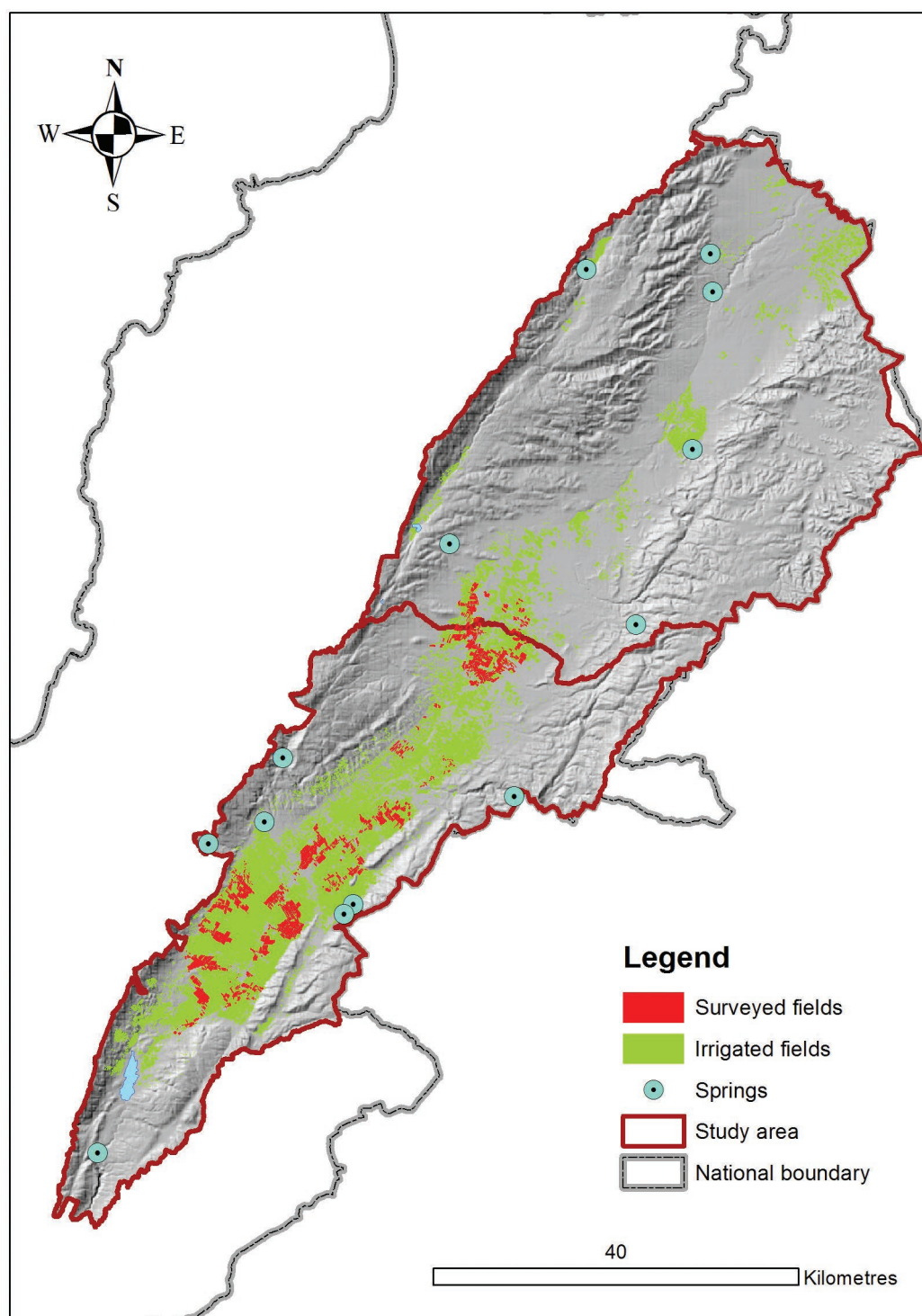
We mapped summer irrigation in Bekaa in 2016 with Sentinel-2 and Landsat imagery using a normalized difference vegetation index (NDVI). We coupled this approach with an iso-cluster unsupervised classification scheme to identify irrigated lands.

We followed this procedure:

- Delineated the general extent of cultivated areas from high-resolution (0.5m) Google Earth imagery
- Analysed 20 cloud-free (less than 10 per cent cloud cover) Landsat (15m resolution) and Sentinel-2 (10m resolution) scenes covering the area over April–September
- Derived the NDVI from the Surface reflectance product of the imagery, and
- Performed an image classification method (the ISO-cluster classification) on individual scenes to classify them into six different classes of NDVI ranges.

For each scene date, we converted the highest class to a polygon feature for which we calculated the area. The resulting feature class depicts the areas having the maximum vegetation for that date. This procedure is repeated for the 20 scenes. The result is the maximum vegetated areas at any given date. We merged the areas for the growing season of April–October, and the result estimates the total extent of irrigated areas in Bekaa (Figure 5).

Figure 3. Irrigated areas in the Upper Orontes (green) and Upper Litani basins (2016) and surveyed agricultural fields



Through this process, we calculated 45,700ha of irrigated agriculture in the Upper Litani Basin and 13,800ha in the Upper Orontes Basin during the irrigation season (April–October 2016). Furthermore, around 12,000ha of cereals have been cultivated in the Bekaa in the spring of 2016; 10,000ha are within the Upper Litani Basin, some of which is under supplemental irrigation. The net non-cereals irrigated areas are estimated at 36,000ha in the ULB and 12,000ha in the UOB.

Figure 6 presents the mean seasonal NDVI for the area. The highest NDVI values are near the major springs; Ain Zarqa Hermel, where topography does not allow irrigation of large areas, is the exception. Labwe region (UOB), Anjar (ULB) and Qab Elias (ULB) and the area downstream of Qab Elias in the ULB feature the most intensive agriculture. All of these schemes are mainly fed by the spring systems. Other irrigation in Bekaa relies on wells (locations not available).

## 3.2 Field survey

Table 5 identifies 1,488 fields for type of crop, growing stage and irrigation system used. We took eight field trips to the study area to determine the types of crops, the growing stages and irrigation methods. The survey covered 7,244ha of crops, of which 1,715ha are wheat and barley.

The most planted crop in the ULB is potato, followed by vegetables and fruit trees (Table 6). Analysis of the results revealed that major crops planted in summer in Bekaa are potatoes (43 per cent), vegetables (15 per cent), industrial crops (8 per cent), vines (12 per cent), fruit trees (12 per cent), corn (4 per cent) and legumes (3 per cent). The two major winter crops are wheat and barley (with an unknown portion of which is supplemental irrigation). There are considerable cannabis plantations in the upstream part of the ULB and the UOB. These are considered as industrial crops (Table 6).

## 3.3 Calculating net water consumption

To determine water use by these irrigated areas, we need to calculate the actual crop evapotranspiration (net water consumed by the crop and lost to the atmosphere). We can determine reference ET (Ref-ET) from weather parameters collected by an agrometeorological station using the Penman-Monteith equation. For the analysis herein, we determined reference ET values for the Bekaa using weather data from AUB's AREC station.

ET<sub>c</sub> – the actual evapotranspiration – cannot exceed the Ref-ET for a certain crop. ET<sub>c</sub> is either calculated ( $K_c \times \text{Ref-ET}$ ) or measured (usually remotely using energy balance approaches). ET<sub>c</sub> estimates from NDVI/energy balance estimate actual crop consumption. This is always less than gross demand that includes system inefficiencies and is calculated for non-restricting water conditions.

Table 5. Field trip dates and number of surveyed fields

| FIELD TRIP DATE | NUMBER OF SURVEYED FIELDS | AREA (HA) |
|-----------------|---------------------------|-----------|
| 6 June 2016     | 200                       | 1,074     |
| 13 June 2016    | 233                       | 1,046     |
| 16 June 2016    | 208                       | 940       |
| 21 June 2016    | 236                       | 963       |
| 23 June 2016    | 221                       | 1,211     |
| 20 July 2016    | 157                       | 671       |
| July 26 2016    | 77                        | 516       |
| August 8 2016   | 156                       | 841       |
| Total           | 1,488                     | 7,262     |

Table 6. Surveyed summer crop by field count and area (excluding wheat and barley)

| CROP CATEGORY    | CROP         | FIELDS | AREA (HA) | PER CENT OF TOTAL |
|------------------|--------------|--------|-----------|-------------------|
| Vegetables       | Vegetables   | 395    | 772       | 15                |
| Roots & tubers   | Potato       | 336    | 2,260     | 43                |
| Legumes          | Beans        | 21     | 46        | 1                 |
|                  | Peas         | 30     | 95        | 2                 |
| Cereals          | Corn         | 25     | 221       | 4                 |
| Grapes & berries | Grape vines  | 108    | 492       | 9                 |
| Fruit trees      | Stone fruits | 102    | 630       | 12                |
|                  | Plum         | 6      | 19        | 0                 |
| Industrial crops | Cannabis     | 91     | 560       | 11                |
|                  | Tobacco      | 52     | 168       | 3                 |

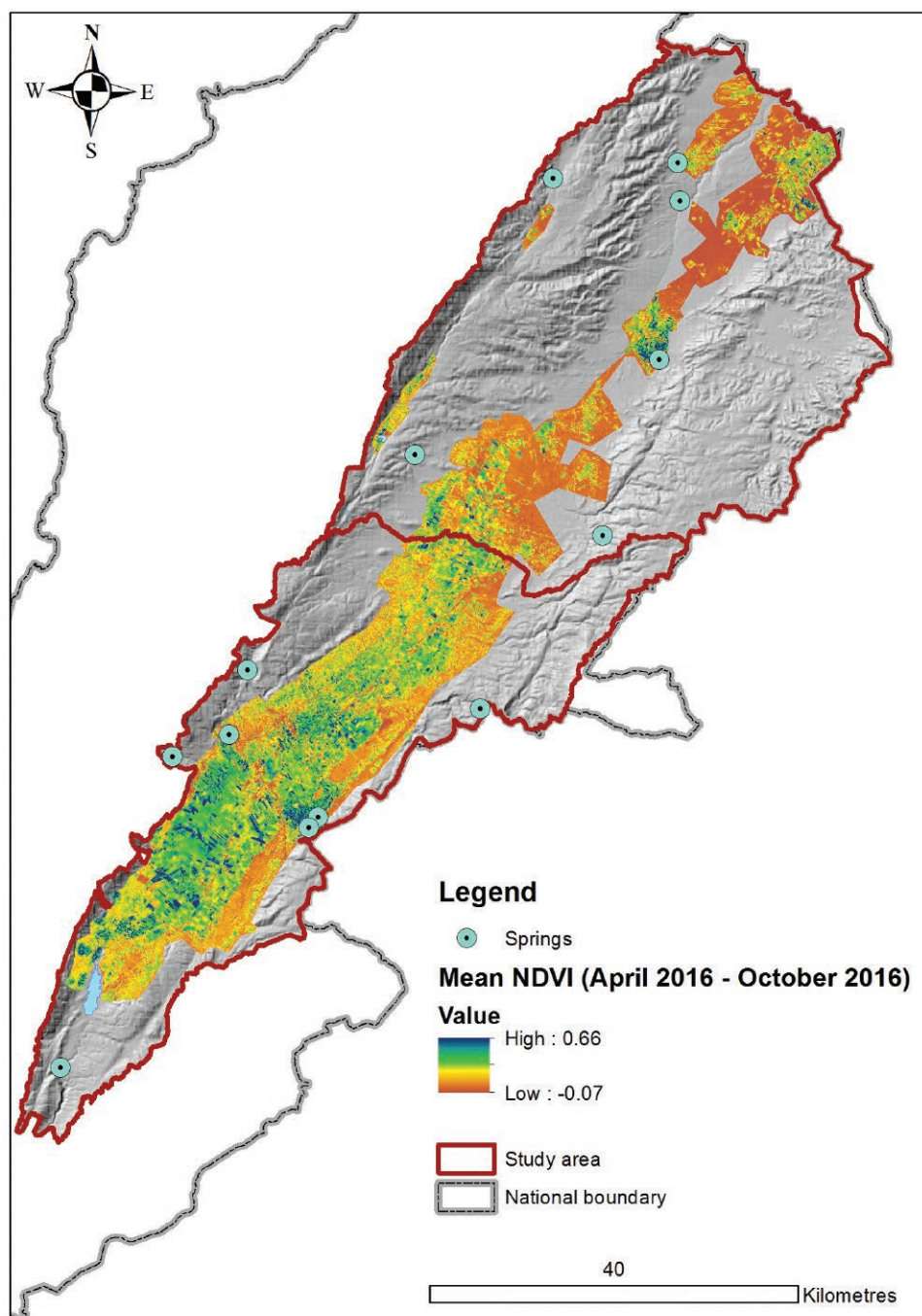


Estimating ET<sub>c</sub> from water balance approaches requires knowledge of the spatial distribution of precipitation, irrigation applications, the change in soil moisture content, runoff, deep percolation and contribution to soil moisture from the water table in areas of high water table.

DisALEXI ET (Anderson et al., 2013) is a diagnostic approach to calculate ET based on how much water evaporates to keep the land surface at the observed temperature. We applied the technique on an area in the Bekaa for crops planted in 2015.

In brief, the Landsat thermal infrared band was fused with the lower resolution ET measurements along with daily MODIS data. This produced a field scale estimate (30m) of ET<sub>c</sub>. Results show that mean cumulative seasonal ET<sub>c</sub> for agricultural areas was 364mm for the Upper Orontes and 415mm for the Upper Litani basins, respectively (21 April 2015 to 30 October 2015).

Figure 4. Mean seasonal (23 April–31 October) NDVI for 2016



### 3.4 Estimate of irrigation water demand

Water demand for irrigated areas is different than actual consumption. Demand is usually based on irrigation requirements that are calculated using crop co-efficients and Ref ET. Consumption can be estimated remotely using energy balance models (Allen et al., 2007, Anderson et al., 2013, Bastiannssen et al., 1998).

Due to management and sub-optimal irrigation factors, actual use is usually less than the Ref ET predicts. The diversion to the irrigated areas could be higher, however, due to losses in the transmission, distribution and on-farm system. Knowledge of the types of agricultural crops planted in the Bekaa is necessary both to estimate water requirements for the lands and to verify results of the satellite imagery.

Gross water application is greater than the net consumed water by a factor related to the irrigation system efficiency, field application uniformity, and losses in transmission and distribution. However, the DisAlexi model is based on Land ET in relation to the cover. It accounts for soil evaporation, most often regarded as a non-beneficial use.

Water lost to deep percolation and as runoff during irrigations may not always be lost from the system. Runoff water may return to the Litani or Orontes rivers for use by downstream users, for example. Deep percolation may also help recharge the water table aquifers in areas where the hydrogeology permits.

Given the hot and dry climate of the Bekaa summers, most cultivated crops during April–October are irrigated. Table 7 shows the irrigation practice of the surveyed areas (by method), based on the field survey. Most irrigation is sprinkler-based.

Given the windy conditions in Bekaa, efficiency of sprinklers is estimated at 65 per cent and micro-sprinklers at 75 per cent. Drip irrigation efficiency is estimated to be 80 per cent, and surface irrigation at 40 per cent. These estimates are crucial to evaluate the current irrigation abstraction in the Bekaa.

Table 7. Percentage of the surveyed areas by irrigation method

| IRRIGATION PRACTICE | PERCENTAGE |
|---------------------|------------|
| Drip                | 22         |
| Furrow              | 4          |
| Micro-sprinklers    | 6          |
| Rainfed             | 3          |
| Sprinkler           | 65         |

Table 8 summarises the percentage of the area for each crop by irrigation practice. Drip irrigation is used mostly in production of stone fruits and vegetables. Sprinkler irrigation is largely used to produce potatoes, cannabis, lettuce and onions.

Surface irrigation is evident on fruit trees irrigated via schemes with springs/canals as the major water source. Crop co-efficients were based on FAO-56 (Allen et al., 1998) for analysis of crop water requirement (ETc).

Table 8. Surveyed crops and their irrigation method

| GROUP            | CROP         | DRIP (%) | SURFACE (%) | SPRINKLER (%) | MICRO-SPRINKLERS (%) | RAINFED |
|------------------|--------------|----------|-------------|---------------|----------------------|---------|
| Vegetables       | Vegetables   | 3        | 17          | 75            | 4                    |         |
| Roots & tubers   | Potato       |          | 2           | 88            | 9                    |         |
| Legumes          | Beans        | 8        | 40          | 53            |                      |         |
|                  | Peas         | 6        | 39          | 89            | 1                    |         |
| Cereals          | Corn         |          | 4           | 96            |                      |         |
| Grapes & berries | Grape vines  | 82       |             | 2             | 9                    | 7       |
| Fruit trees      | Stone fruits | 66       | 31          | 1             | 1                    |         |
|                  | Plum         | 92       | 8           |               |                      |         |
| Industrial crops | Cannabis     | 3        | 22          | 58            |                      | 16      |
|                  | Tobacco      | 22       | 21          | 50            | 7                    |         |



We use Aquacrop for calculating water requirements for the Bekaa crops. Aquacrop, the FAO crop-water productivity model, calculates net irrigation requirements based on crop and weather data. This constitutes the net irrigation demand by crop at the field level.

We calculated irrigated areas by the monthly crop water requirements and then the seasonal sum. Aquacrop calculations indicate that mean seasonal requirements for irrigated areas are 600mm (based on AREC Weather Data and the Agricultural Survey in 2016). Reference ET from AREC station amount to 1,048mm for the same period. We multiplied the irrigated areas within each basin by the seasonal water requirements to arrive at the irrigation water use in MCM.

The total ETc volume for the areas in summer of 2016 would be 89MCM and 249MCM for the UOB and the ULB respectively, a total of 338MCM for the irrigation season of 2016. Table 9 shows the estimates of crop consumptive use according to different methods.

We conducted field measurements in Anjar to understand irrigation practices of stone fruits in Bekaa. Collected data show that farmers may apply up to 140mm/irrigation in ten hours of irrigation every three weeks using secondary canals and then flooding the field. (A management allowable deficit of 50 per cent and a root depth of 1.2m, and a water holding capacity of 150mm/m, would result in a maximum allowable depth not exceeding 90mm/irrigation. This depth can sustain the plants for about 15–18 days in summer in Anjar).

Applications of 140mm/irrigation indicate that farmers may be losing a percentage of the applied water to deep percolation. The Anjar spring feeds this system, and the safe yield for that spring is estimated at 1,007l/s (BWE, 2015), or 1m<sup>3</sup>/s (31.54MCM/year). This is enough to supply water for 1,000ha of irrigated lands if drip irrigation was used. Other references estimate the monthly flow in the range of 0.3–0.5m<sup>3</sup>/s (Telesca et al., 2013).

As noted earlier, average system efficiency is believed to be 65 per cent for sprinkler irrigation, 80 per cent for drip irrigation and 75 per cent for micro-sprinklers. Surface irrigation efficiency is believed to be much lower. Total efficiency is lower still as other losses (conveyance, distribution) at the project level need to be accounted for.

Based on the proportion of the irrigated crops by method, irrigation water requirements in the ULB and UOB are estimated at 415MCM and 148MCM, respectively, based on a total system efficiency of 60 per cent. A fraction of 20 per cent of total diversions (half of the non-consumptive diversions) is assumed to return to the system.

Table 9. Seasonal agricultural consumptive water use according to different estimates

| CUMULATIVE ET (IRRIGATION WATER CONSUMPTION) |                | LITANI ET (MM) | ORONTES ET (MM) |
|--|----------------|----------------|-----------------|
| NDVI method (approximation)                  | April–Oct 2016 | 754            | 655             |
| DisAlexi (provisional) (Energy Balance)      | May–Oct 2015   | 391            | 345             |
| ET <sub>PM</sub> -AREC                       | May–Oct 2013   |                | 1,046           |

## 4

# Assessment of water balance and availability vs. demand

## 4.1 Total water balance calculation and mapping the distribution of demand

Our estimated water demand for all sectors shows the proportion of water required for domestic uses in Bekaa is small (13 per cent of total demand) in comparison to the agricultural water demand (82 per cent of the total).

The total water demands in both basins are less than the total annual volume of rainfall that we calculated using the Plassard (1971) map. It has been estimated elsewhere that water stress occurs where total use exceeds 40 per cent of the available supply.

However, the water resources are not evenly distributed across the basins. Overall balance calculations at the level of each basin hide significant local

variations and hotspots of demand. In areas with more demand for water than available sources can supply, demands cannot be met or the water must come from groundwater. If the extraction of groundwater exceeds the annual recharge, it is considered to be over exploited.

The Litani Basin is experiencing an over exploitation of groundwater (87MCM/year on average, given the recent increase in domestic demand) whereas the Orontes is not. This has been observed previously (MoE-UNDP, 2014; USAID, 2011), and is evidenced by the falling groundwater table.

The proposed balances within the two basins consider downstream demand. Outflows include winter and summer ET, as well as flows into Qarawn Lake (Litani), and to Syria (Orontes) (Figure 5).

Table 10. Water demand in the Bekaa Valley in 2016\* (MCM/yr)

| Supply area <sup>i</sup> | DOMESTIC               |                             |                                 |                                     |                  |                      | INDUS-<br>TRIAL <sup>iv</sup> | AGRI-<br>CULTURAL <sup>v</sup> |
|--------------------------|------------------------|-----------------------------|---------------------------------|-------------------------------------|------------------|----------------------|-------------------------------|--------------------------------|
|                          | Lebanese <sup>ii</sup> | Palestinians <sup>iii</sup> | Syrians<br>in IS <sup>iii</sup> | Syrians<br>not in IS <sup>iii</sup> | Total<br>Syrians | Subtotal<br>domestic |                               |                                |
| West Bekaa               | 8.9                    | 0.3                         | 1.3                             | 2.8                                 | 4.1              | 13.3                 | 5.3                           | 162                            |
| Zahle                    | 23.9                   | 0.5                         | 3.4                             | 7.5                                 | 10.9             | 35.4                 | 14.2                          | 181                            |
| Baalbek                  | 27.4                   | 0.3                         | 2.5                             | 4.3                                 | 6.9              | 34.6                 | 13.8                          | 220                            |
| El Hermel                | 5.5                    | 0.0                         | 0.0                             | 0.3                                 | 0.4              | 5.8                  | 2.3                           | 8                              |
| Grand total              | 65.7                   | 1.2                         | 7.3                             | 15.0                                | 22.3             | 89.1                 | 35.7                          | 571                            |

<sup>i</sup> Rachaya was excluded from this study.

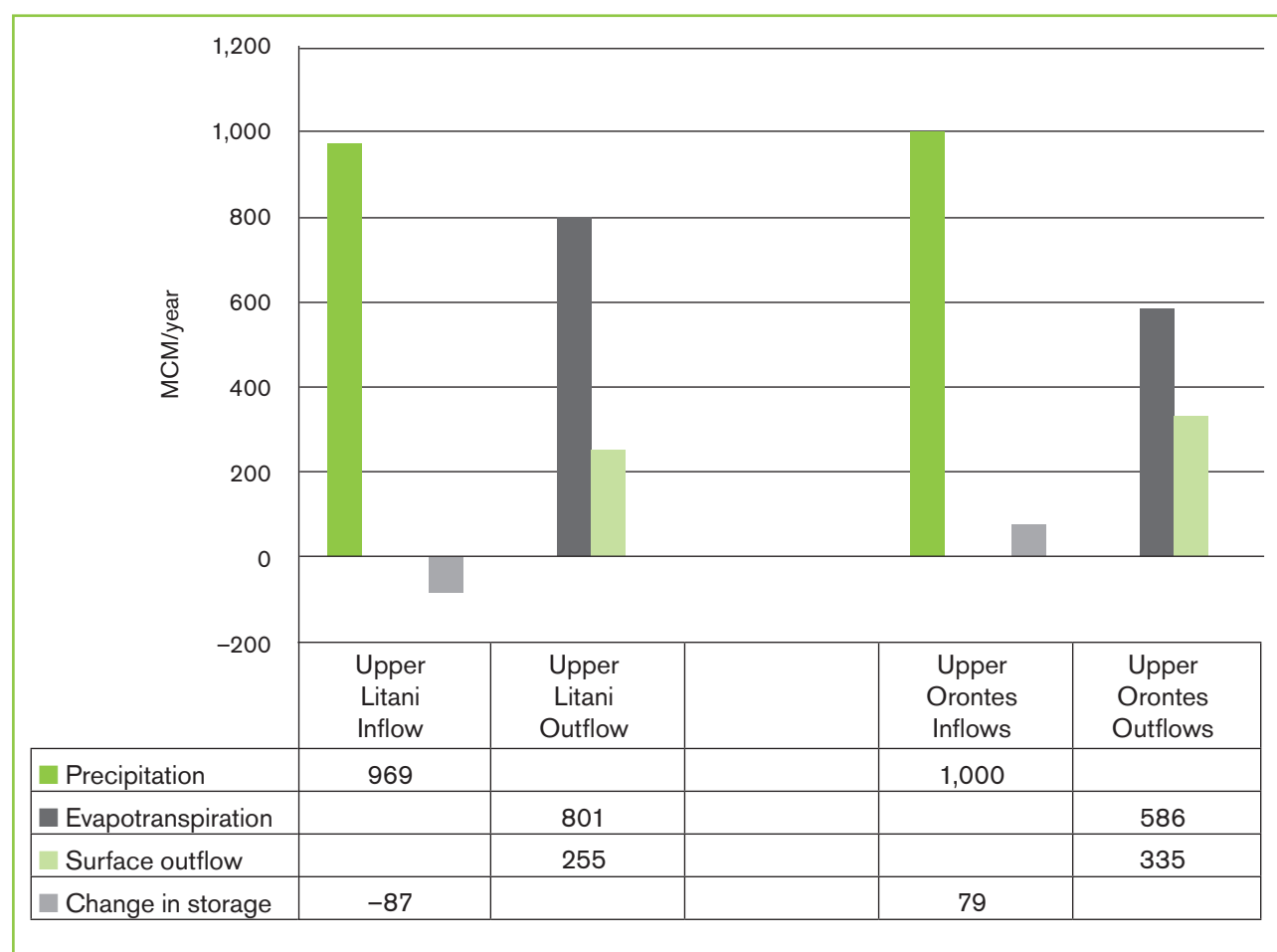
<sup>ii</sup> Based on BWE (2013) population estimates and consumption rate: 180l/c/day.

<sup>iii</sup> Based on IAMP population estimates and consumption rates of 160l/c/day (except for Syrians in Assi Basin, who use only 120l/c/day for reasons explained in the study).

<sup>iv</sup> 40 per cent of total domestic demand.

<sup>v</sup> Assuming 60 per cent project efficiency (total agricultural consumptive use = 343MCM/yr).

Figure 5. Hydrologic balances for the Upper Basins of the Litani and the Orontes in Lebanon (average year)



## 4.2 Mapping water demand at the municipal level

Figure 8 maps the domestic, industrial and irrigation requirements to highlight areas of highest water demand. Combining agricultural, domestic and industrial demand at the municipal level gives a clearer image of where demand is highest.

We used the following formula:

Domestic demand per municipality (based on Lebanese population + Syrian refugees outside informal settlements + Syrian refugees in informal settlements)

+

Irrigation demand (as calculated from the total irrigated area per municipality from the satellite imagery analysis multiplied by the crop water requirements per season)

+

Industrial demand per municipality (rated at 40 per cent of the domestic demand of the Lebanese population).

The result is presented in Figure 6. Total demand by municipality is shown in Appendix 1.

Barr Elias, Saarine, Baalbeck and surroundings and Zahle and surroundings, and Anjar area feature the highest water demand. We also present the percentage increase in water demand due to the Syrian crisis (Figure 7).

Figure 6. Current total water demand at the municipal level

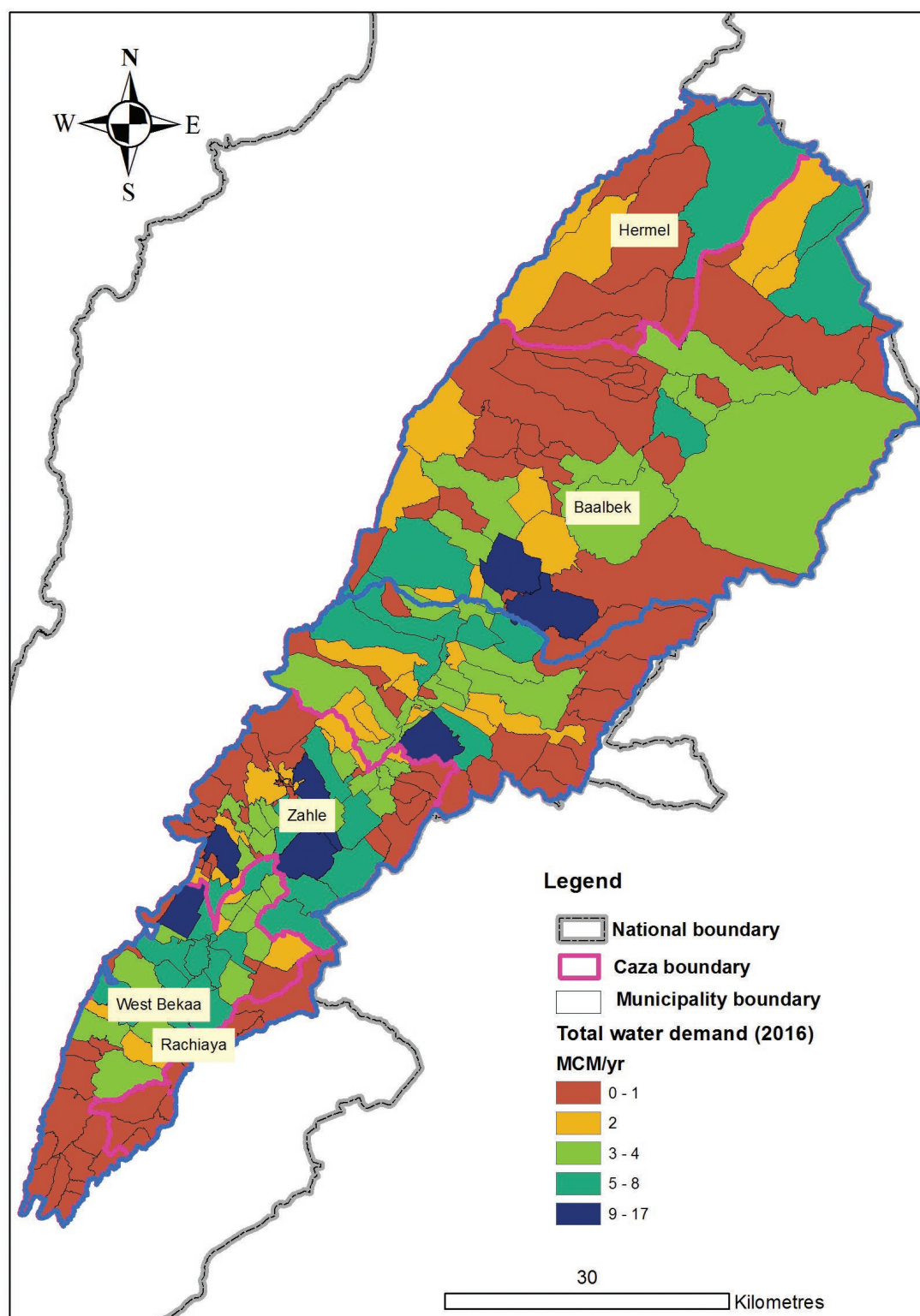
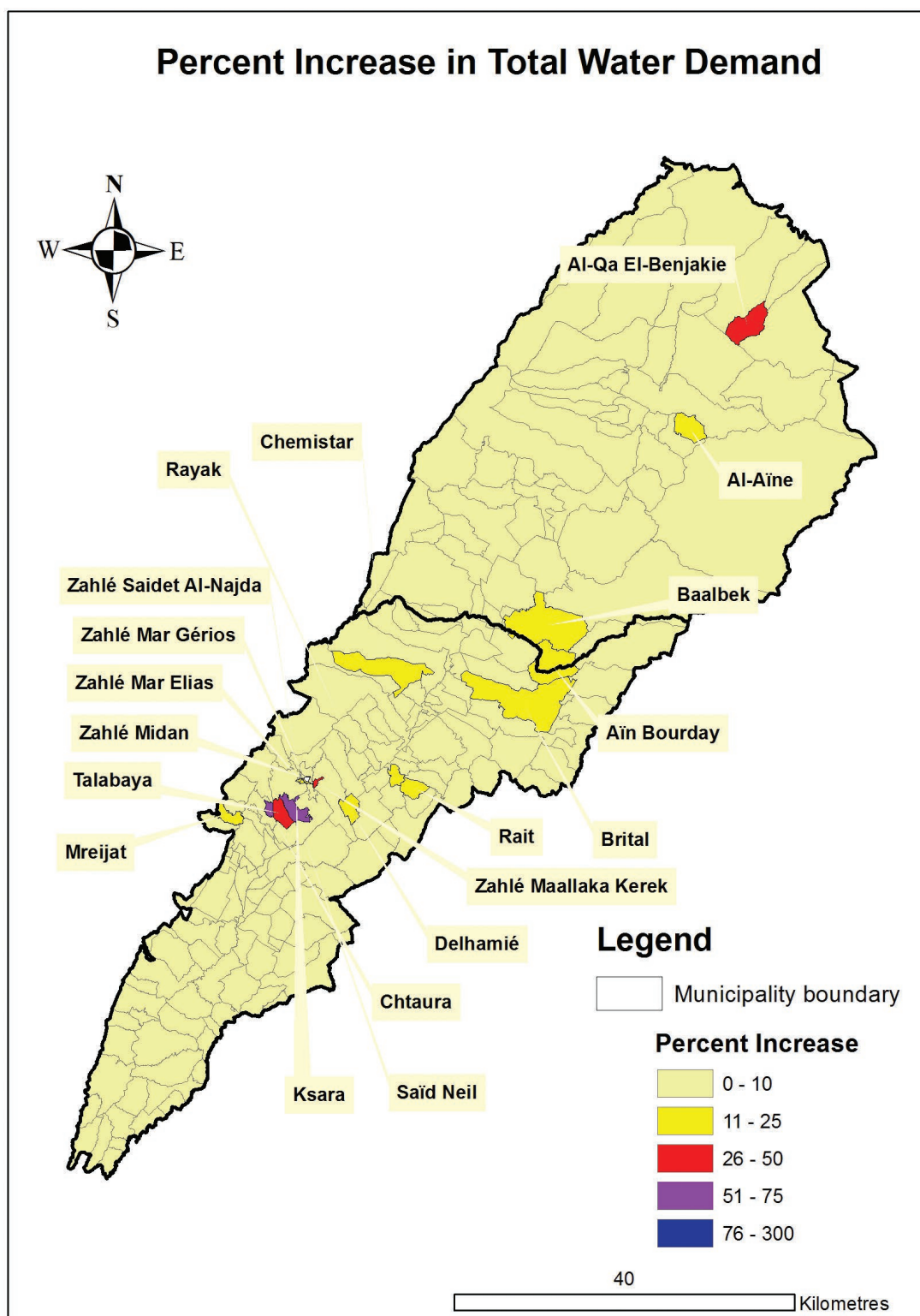


Figure 7. Percentage increase in total water demand since the beginning of the Syrian crisis





### 4.3 Comparing water flows and demands at supply areas and sources

The irrigation assessment report (BWE, 2015) lists 63 springs in Baalbeck Caza and 22 major springs in Hermel Caza. Hermel area spring flows amount to more than 1,540l/s (or 46MCM/year). Flows at the springs and demands for the service areas as reported in the BWE Master Plan are listed in Table 10.

The total flow of springs in Orontes Basin amounts to 3m<sup>3</sup>/s. (The average flow of the Ain-Zarqa spring is no less than 10m<sup>3</sup>/s. However, as the Orontes is a transboundary river, the Lebanese portion is limited by a bilateral agreement between Lebanon and Syria).

Demands are calculated based on the projected water demand of 195l/day/capita. Chamsine system (near Anjar) provides 214l/s. The Barr Elias area requires approximately 2.5MCM/year for domestic uses (around 80l/s) (Table 11). Including other demands (industrial and irrigation) shows that only Hermel has a surplus in spring water supply.

In addition to analysing domestic demand, it would be useful to compare availability of water at each spring to our data on agricultural water use. However, this would require further study to first identify which irrigated areas are supplied from which springs.

Table 11. Available spring flow and domestic demand in Upper Orontes Basin

| SYSTEM NAME                    | DOMESTIC DEMAND 2035 (L/S) * | FLOW (L/S) | DEFICIT/ SURPLUS |
|--------------------------------|------------------------------|------------|------------------|
| Ain eL Zarqa (Hermel)          | 164                          | 1,189      | 1,025            |
| Ras El Mail (Hermel)           | 145                          | 152        | 7                |
| Nahle-Younine-Maqne (Baalbeck) | 69                           | 48         | -21              |
| Laboue (Baalbeck)              | 269                          | 502        | 233              |
| Ain El Hawr (Hermel)           | 58                           | 95         | 37               |
| Yammoune (Baalbeck)            | 985                          | 999        | 14               |
| Total                          | 1,690                        | 2,985      |                  |

\*based on 195l/day/capita and excluding Syrian refugees  
Source: BWE, 2015.

Table 12. Available springs and domestic demand in Litani Study Area

| SYSTEM NAME                   | DOMESTIC DEMAND 2035 (L/S) | FLOW (L/S) | SUPPLY – DEMAND (L/S) |
|-------------------------------|----------------------------|------------|-----------------------|
| Anjar Spring                  | 327                        | 1007       | 680                   |
| Ain El Zarqa (West El Bekaa)  | 481                        | 1,321      | 840                   |
| Chamsine                      | 625                        | 214        | -411                  |
| Chtaura Spring                | 19                         | 230        | 211                   |
| Qabb Elias - Ouadi El Dellem  | 145                        | 341        | 196                   |
| Yahfoufa                      | 323                        | 349        | 26                    |
| Qaa El Rim - Berdaouni Spring | 425                        | 706        | 281                   |

Source: BWE, 2015.

## 5

## Discussion

Across the Bekaa and wider region, there is a need for improved understanding of overall water balance calculations, particularly agricultural water use and water demands for irrigation. In this study, we assessed irrigation water consumption following the Syrian crisis. We used an innovative approach that combines remote sensing with field survey data and available modelling tools. Our estimate suggests higher withdrawals from the ULB than previously reported.

### 5.1 An innovative approach

Given the absence of systems to measure water extractions for irrigation use, we combined remote sensing with field survey data and available modelling tools. This innovative approach enabled us to estimate volumes of water used in evapotranspiration and irrigation, and water demand. Our estimate suggests higher withdrawals from the ULB than have previously been estimated (e.g. in MoA, 1998).

We hope that by presenting and discussing these estimates, other researchers will be encouraged to critique our findings and use aspects of our work that could be relevant to them and to decision makers.

Our approach to analysis of agricultural water use provides a basis for a continuous agricultural water use monitoring system. This would enable better measurement and management of available water resources in the Bekaa. Such a system would allow bi-weekly agricultural water use analysis (actual consumption) via energy balance techniques based on remote sensing.

In this study we have provided, for the first time, a remotely sensed estimate of agricultural water consumption at the basin level in the Bekaa. We also quantified the recent increase in domestic water demand resulting from the Syrian refugee crisis. We mapped this increase spatially, allowing identification of water stress hotspots.

### 5.2 Observations and insights

From this work, we have gained insights concerning the availability, uses and demands for water supplies in different sectors, including agriculture, domestic supply and industry. This has helped us to better understand the observed lack of water and water stress in the Bekaa. For example, we can see that agricultural water demand and use volumes are likely far higher than domestic water demand and use volumes.

We have also observed that domestic and industrial water demands and uses do not necessarily remove water from the system and deplete the water balance. What matters more is the quality of water that returns to the system in the form of domestic and industrial wastewaters. If these return flows are polluted, they will also pollute the rivers, streams and lakes that they re-enter. This, in turn, will reduce the availability of usable freshwater in these water bodies, even while some level of flows in them may be maintained.

Concerning the effect of the arrival of refugees on the water balance of the two basins, we calculated the volume of additional demand, and pinpointed the municipalities with the most rapid increases. We have also identified the uneven spatial distribution on these increases and the types of agricultural demand that they will compete with at certain times of the year. Further analysis could help better understand the spatial and temporal concentration of these competing demands for water in particular municipalities.

### 5.3 Limitations

The demand-supply relation and the water balance calculations are intricate. Water accounting in the Bekaa is difficult for two reasons: lack of actual measurements of diversions for domestic and industrial use, and lack of sewage networks and operational wastewater treatment plants. Also, the lack of adequate snowfall measurement stations and snowmelt hydrologic studies of the basins make groundwater recharge estimates more uncertain.

The Orontes is a transboundary river, and the Orontes Basin has a limited share of 80MCM/yr. This means that increasing water demand within the Orontes River would require speeding up the Assi Dam construction to regulate use of this allocation.

A more detailed study would need to consider the temporal variability of the hydrologic inputs and outputs, as well as the intra-annual changes in the different water demands. It could possibly disentangle the local anthropogenic effects in the two basins from those of global climate change.

More remotely sensed estimates of evapotranspiration and rainfall (verified by rain gauges), as well as river gauge flow measurements, hold out potential for more accurate water balance estimates. The hydrologic balance approach is recommended to quantify the groundwater recharge/overdraft.

Groundwater reserves are believed to cover current deficits in water supply. The water diversions may be different than assumed. Yet sewage discharges into the Litani River, for example, will register as outflows into Qarawn Lake. Hence, they are not lost from the system. Flow measurements at Qarawn could arguably be re-used for the Litani Basin. Downstream uses should always be considered (hydropower demand, irrigation demand of South Lebanon).

We hope our methods and approaches will contribute to strategic thinking about water stress in Lebanon. They could be helpful for integrated water resources management planning in both basins, and in other parts of Lebanon. In the future, this work could also help with efforts to manage water in Syria as well.

## 6

# Conclusions

This paper has presented progress towards assessment of the water balance in the two major basins of the Bekaa Valley. This includes an innovative approach based on remote sensing to understand agricultural water consumption that is 'ready for use'. We hope that water resource planners and practitioners working in the Bekaa consider our approach in their ongoing work.

We also hope that sharing these methods and findings will stimulate debate and raise awareness among scientific and practitioner communities. MoEW should continue to improve water balance calculations by encouraging the approaches demonstrated in this paper. This should help enable progressive improvement of the water balance assessment, highlight knowledge gaps, and encourage researchers and other local actors to contribute to filling them.

## Distinct water supply issues within the two basins

There is a deficit of water supply within the Upper Litani Basin, but not the Upper Orontes (Figure 5). This deficit is believed to be covered from over exploitation of the groundwater table. Additional stress from Syrian refugees causes an increasing demand of 30MCM/year (subject to increase given the projected increase in Syrian refugee population).

Prior to the Syrian conflict, the MoEW estimated total demand for water in the Bekaa would be 513MCM in 2015 and projected increases of 5MCM per year (MoEW, 2010). The national strategy also estimates total supply in Bekaa at 399MCM/yr (206MCM/yr from surface water and 193MCM/yr from groundwater). The strategy does not explain how the deficit (supply minus demand = 114MCM/yr) is met. Our findings show demand is actually much higher (571MCM/yr for irrigation alone, excluding Rachaya). This is likely overdraft from groundwater reserves.

Domestic demand has also increased, but is still only 15 per cent of irrigation demand. Estimated domestic wastewater generated in Bekaa in 2007 (based on a population of 489,865) was 23.6MCM/year (World Bank, 2010). The amount is actually doubled with the most recent estimate of the Bekaa population (BWE, 2015). This non-conventional water could be another source of water supply if appropriate wastewater networks, treatment plants and treated sewage effluent networks are constructed, operated and maintained.

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# Appendices

| KADA    | MUNICIPALITY            | WATER DEMAND MCM/YR |
|---------|-------------------------|---------------------|
| Baalbek | Aadous                  | 0.841               |
| Baalbek | Aain Baalbek            | 0.900               |
| Baalbek | Aain Bourday            | 0.077               |
| Baalbek | Aain El-Barnaya         | 0.000               |
| Baalbek | Aain Es-Siyaa Chadoura  | 0.000               |
| Baalbek | Aamchki                 | 0.001               |
| Baalbek | Aarsal                  | 3.845               |
| Baalbek | Aaynata Baalbek         | 1.126               |
| Baalbek | Baalbek                 | 8.330               |
| Baalbek | Bajjaje                 | 2.405               |
| Baalbek | Bargha                  | 0.082               |
| Baalbek | Bechouat                | 0.085               |
| Baalbek | Bednayel Baalbak        | 2.922               |
| Baalbek | Beit Chama              | 0.910               |
| Baalbek | Bouday                  | 6.043               |
| Baalbek | Brital                  | 3.298               |
| Baalbek | Btedaai                 | 0.528               |
| Baalbek | Chaaibe                 | 0.000               |
| Baalbek | Chaat                   | 3.985               |
| Baalbek | Chlifa                  | 2.241               |
| Baalbek | Chmistar                | 1.351               |
| Baalbek | Dar El-Ouassaa          | 0.012               |
| Baalbek | Deir El-Ahmar           | 2.859               |
| Baalbek | Deir Mar Maroun Baalbek | 0.020               |
| Baalbek | Douris                  | 5.020               |
| Baalbek | Fekehe                  | 2.047               |
| Baalbek | Hadath Baalbek          | 4.067               |
| Baalbek | Halbata                 | 0.058               |
| Baalbek | Ham                     | 0.035               |
| Baalbek | haouch El-Dehab         | 1.696               |
| Baalbek | Haouch En-Nabi          | 0.531               |
| Baalbek | Haouch Er-Rafqa         | 2.832               |
| Baalbek | Haouch Snaid            | 2.970               |
| Baalbek | Haouch Tall Safiye      | 2.308               |
| Baalbek | Haouche Barada          | 2.810               |

*continues*

| KADA    | MUNICIPALITY           | WATER DEMAND MCM/YR |
|---------|------------------------|---------------------|
| Baalbek | Haour Taala            | 1.093               |
| Baalbek | Harabta                | 0.554               |
| Baalbek | Hizzine                | 1.857               |
| Baalbek | laat                   | 9.530               |
| Baalbek | Jebaa                  | 0.008               |
| Baalbek | Jenta                  | 0.044               |
| Baalbek | Kfar Dabach            | 1.189               |
| Baalbek | Kfar Dane              | 2.644               |
| Baalbek | Kharayeb El-Hermel     | 0.018               |
| Baalbek | Khodr Baalbek          | 1.307               |
| Baalbek | Khreibet Baalbek       | 0.104               |
| Baalbek | Kneisset Baalbek       | 1.782               |
| Baalbek | Laboue                 | 4.223               |
| Baalbek | litige                 | 0.000               |
| Baalbek | litige                 | 0.000               |
| Baalbek | Maaraboun              | 0.110               |
| Baalbek | Majdaloun              | 5.714               |
| Baalbek | Maqne                  | 1.161               |
| Baalbek | Mazraat beit Mchaik    | 0.000               |
| Baalbek | Moqraq                 | 0.078               |
| Baalbek | Mousraye               | 1.207               |
| Baalbek | Nabha Ed-Damdoum       | 0.185               |
| Baalbek | Nabi Chbay             | 0.001               |
| Baalbek | Nabi Chit              | 4.261               |
| Baalbek | Nabi Osmane            | 2.748               |
| Baalbek | Nahle baalbek          | 0.338               |
| Baalbek | Ouadi El-Aaoss         | 0.000               |
| Baalbek | Qaa Baalbek            | 1.902               |
| Baalbek | Qaa Baayoun            | 4.374               |
| Baalbek | Qaa Jouar Maqiye       | 7.279               |
| Baalbek | Qaa Ouadi El-Khanzir   | 1.885               |
| Baalbek | Qarha Baalbek          | 0.053               |
| Baalbek | Qsarnaba               | 1.582               |
| Baalbek | Ram Baalbek            | 0.041               |
| Baalbek | Ras Baalbek Ech-Charqi | 0.012               |
| Baalbek | Ras Baalbek Es-Sahel   | 0.942               |
| Baalbek | Riha                   | 0.218               |
| Baalbek | Saaide                 | 1.908               |
| Baalbek | Sbouba                 | 0.027               |
| Baalbek | Serraaine Et-Tahta     | 11.355              |
| Baalbek | Slouqi                 | 0.002               |

continues

| KADA       | MUNICIPALITY            | WATER DEMAND MCM/YR |
|------------|-------------------------|---------------------|
| Baalbek    | Taibet Baalbek          | 2.631               |
| Baalbek    | Talia                   | 3.622               |
| Baalbek    | Taraiya                 | 4.669               |
| Baalbek    | Temnine El-Faouqa       | 1.241               |
| Baalbek    | Temnine Et-Tahta        | 3.882               |
| Baalbek    | Yahfoufa                | 0.026               |
| Baalbek    | Yammoune                | 1.980               |
| Baalbek    | Youmine                 | 2.961               |
| Baalbek    | Zabboud                 | 0.787               |
| Hermel     | Charbine El-Hermel      | 0.632               |
| Hermel     | Hermel                  | 5.791               |
| Hermel     | Hermel Jbab             | 1.100               |
| Hermel     | Maaysra El-Hermel       | 0.008               |
| Hermel     | Michaa Mrajhine         | 1.106               |
| Hermel     | Ouadi Faara             | 0.032               |
| Hermel     | Ras Baalbek El Gharbi   | 0.130               |
| Hermel     | Ras Baalbek Ouadi Faara | 0.004               |
| Hermel     | Zighrine                | 0.151               |
| West Bekaa | Aain Et-Tine BG         | 0.119               |
| West Bekaa | Aain Zebde              | 1.255               |
| West Bekaa | Aammiq BG               | 9.812               |
| West Bekaa | Aana                    | 5.521               |
| West Bekaa | Aytanit                 | 0.626               |
| West Bekaa | Baaloul BG              | 1.029               |
| West Bekaa | Bab Mareaa              | 0.611               |
| West Bekaa | Chebrqiyet Aammiq       | 4.767               |
| West Bekaa | Dakoue                  | 2.840               |
| West Bekaa | Deir Aain Ej-Jaouze     | 0.380               |
| West Bekaa | Deir Tahniche           | 2.197               |
| West Bekaa | Ghazze                  | 4.863               |
| West Bekaa | Haouch El-Harime        | 3.509               |
| West Bekaa | Harime Es-Soughra       | 2.953               |
| West Bekaa | Jazira BG               | 2.718               |
| West Bekaa | Joubb Jannine           | 7.336               |
| West Bekaa | Kafraiya BG             | 2.612               |
| West Bekaa | Kamed El-Laouz          | 4.246               |
| West Bekaa | Khiara                  | 5.676               |
| West Bekaa | Khiara El-Aatiqa        | 1.649               |
| West Bekaa | Khirbet Qanafar         | 6.665               |
| West Bekaa | Lala                    | 2.314               |
| West Bekaa | Libbaya BG              | 0.216               |

continues

| KADA       | MUNICIPALITY           | WATER DEMAND MCM/YR |
|------------|------------------------|---------------------|
| West Bekaa | litige                 | 0.000               |
| West Bekaa | litige                 | 0.000               |
| West Bekaa | Loussa                 | 0.048               |
| West Bekaa | Machghara              | 0.657               |
| West Bekaa | Manara (Hammara) BG    | 0.949               |
| West Bekaa | Mansoura BG            | 5.138               |
| West Bekaa | Marj BG                | 5.048               |
| West Bekaa | Maydoun                | 0.000               |
| West Bekaa | Ouaqf BG               | 1.854               |
| West Bekaa | Qaraaoun               | 2.109               |
| West Bekaa | Qelaya                 | 0.063               |
| West Bekaa | Raouda (Istabel)       | 3.831               |
| West Bekaa | Saghbine               | 2.624               |
| West Bekaa | Sohmor                 | 0.426               |
| West Bekaa | Soltan Yacoub el Aradi | 0.397               |
| West Bekaa | Souairi                | 1.234               |
| West Bekaa | Soultan Yaacoub Faouqa | 3.942               |
| West Bekaa | Tall Znoub             | 4.154               |
| West Bekaa | Yohmor BG              | 0.174               |
| West Bekaa | Zilaya                 | 0.018               |
| Zahle      | Aain Kfar Zabad        | 0.250               |
| Zahle      | Aali En-Nahri          | 2.006               |
| Zahle      | Aanjar (Haouch Moussa) | 7.604               |
| Zahle      | Ablah                  | 2.524               |
| Zahle      | Barr Elias             | 16.003              |
| Zahle      | Bouarej                | 0.141               |
| Zahle      | Chebrqiyet Tabet       | 0.346               |
| Zahle      | Chtaura                | 0.779               |
| Zahle      | Dalhamiyet Zahle       | 3.244               |
| Zahle      | Deir El-Ghazal         | 0.246               |
| Zahle      | Fourzol                | 5.967               |
| Zahle      | Haouch El-Aamara       | 0.464               |
| Zahle      | Haouch El-Ghanam       | 1.337               |
| Zahle      | Haouch Es-Siyade       | 0.850               |
| Zahle      | Haouch Hala            | 2.947               |
| Zahle      | Haouch Mandara         | 2.420               |
| Zahle      | Haouch Qayssar         | 0.775               |
| Zahle      | Hazerta                | 0.206               |
| Zahle      | Hoshmosh               | 3.804               |
| Zahle      | Jdita                  | 2.515               |
| Zahle      | Kfarzabad              | 6.112               |

continues

| KADA  | MUNICIPALITY                 | WATER DEMAND MCM/YR |
|-------|------------------------------|---------------------|
| Zahle | Ksara                        | 0.158               |
| Zahle | litige                       | 0.000               |
| Zahle | Majdel Aanjar                | 6.310               |
| Zahle | Makse                        | 1.893               |
| Zahle | Massa                        | 0.510               |
| Zahle | Mazraat Er-Remtaniye         | 0.001               |
| Zahle | Mrayjat Zahle                | 0.164               |
| Zahle | Mzaraat Zahle                | 0.098               |
| Zahle | Nabi Ayla                    | 1.230               |
| Zahle | Nabi Ayla                    | 1.230               |
| Zahle | Nasriyet Rizk                | 0.921               |
| Zahle | Nasriyet Zahle               | 1.181               |
| Zahle | Niha Zahle                   | 1.149               |
| Zahle | Ouadi Ed-Delm                | 0.158               |
| Zahle | Ouadi El-Aarayech            | 0.382               |
| Zahle | Qaa Er-Rim                   | 0.173               |
| Zahle | Qabb Elias                   | 9.498               |
| Zahle | Qoussaya                     | 0.279               |
| Zahle | Raait                        | 0.912               |
| Zahle | Riyag                        | 2.111               |
| Zahle | Saadnayel                    | 2.906               |
| Zahle | Taalbaya                     | 2.902               |
| Zahle | Taanayel                     | 2.420               |
| Zahle | Tcheflik Edde Haouch         | 1.134               |
| Zahle | Tcheflik Qigano              | 1.384               |
| Zahle | Tell El-Akhdar               | 4.646               |
| Zahle | Terbol Zahle                 | 7.500               |
| Zahle | Touaite Zahle                | 0.106               |
| Zahle | Zahle Aradi                  | 1.585               |
| Zahle | Zahle El-Berbara             | 0.195               |
| Zahle | Zahle El-Maallaqa            | 1.409               |
| Zahle | Zahle El-Midane              | 1.285               |
| Zahle | Zahle Er-Rassiye             | 0.453               |
| Zahle | Zahle Er-Rassiye             | 0.453               |
| Zahle | Zahle Haouch El-Oumara       | 0.835               |
| Zahle | Zahle Haouch El-Oumara Aradi | 7.889               |
| Zahle | Zahle Haouch Ez-Zaraane      | 0.151               |
| Zahle | Zahle Maallaqa Aradi         | 9.147               |
| Zahle | Zahle Mar Antonios           | 0.000               |
| Zahle | Zahle Mar Elias              | 0.555               |
| Zahle | Zahle Mar Gerges             | 0.339               |

continues

| KADA  | MUNICIPALITY          | WATER DEMAND MCM/YR |
|-------|-----------------------|---------------------|
| Zahle | Zahle Saydet En-Najat | 0.031               |
| Zahle | Zebdoul               | 0.287               |

# Acronyms and Abbreviations

|                   |   |
|-------------------|---|
| ASL               | Above Sea Level   |
| AREC              | Agricultural Research and Education Center              |
| AUB               | American University of Beirut                           |
| BWE               | Bekaa Water Establishment                               |
| ET                | evapotranspiration                                      |
| ET <sub>c</sub>   | actual evapotranspiration                               |
| FAO               | Food and Agriculture Organization of the United Nations |
| ha                | hectares  |
| IS                | Informal Settlements                                    |
| l                 | litres  |
| l/s               | litres per second                                       |
| m <sup>3</sup> /s | cubic metres per second                                 |
| MoE               | Ministry of Environment                                 |
| MoEW              | Ministry of Energy and Water                            |
| MCM               | million cubic metres                                    |
| mm                | millimetres   |
| NDVI              | Normalized difference vegetation index                  |
| UNDP              | UN Development Programme                                |
| USAID             | United States Agency for International Development      |
| ULB               | Upper Litani Basin                                      |
| UOB               | Upper Orontes Basin                                     |
| yr                | Year  |



Increasing refugee populations, industrial demands and agricultural activities have exacerbated water stress in Lebanon's Bekaa Valley. We have provided previously unavailable remotely sensed estimates of agricultural water consumption in the Upper Litani and Upper Orontes basins. We also quantified increases in domestic water demand and mapped water stress hotspots. Due to the distinction between demand, use and consumptive use, increased water demand does not have to mean water shortage. Increased consideration of this distinction is crucial for integrated water resources management planning and climate change adaptation.

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