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## The water resources of Lebanon - A review to support water security

Mohammad Merheb<sup>a,b,\*</sup>, Roger Moussa<sup>c</sup>, Chadi Abdallah<sup>d</sup>, Jalal Halwani<sup>b</sup>,  
Christophe Cudennec<sup>a</sup>

<sup>a</sup> Institut Agro, INRAE, SAS, 65 Rue de Saint Brieu, 35000, Rennes, France

<sup>b</sup> Water and Environmental Sciences Laboratory, Lebanese University, Tripoli, P.O. Box 6573/14, Lebanon

<sup>c</sup> LISAH, Univ Montpellier, AgroParisTech, INRAE, Institut Agro, IRD, Montpellier, France

<sup>d</sup> National Council for Scientific Research, 59, Zahia Salmane Street, Jnah, P.O. Box 11-8281, Beirut, Lebanon

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### ABSTRACT

This work reviewed a large and fragmented body of academic and grey literature on water resources in Lebanon. The objective was to assess and curate the existing knowledge base that reflected the importance of water-related concerns. Studies were classified into four topics: water balance, quality, management and governance, each of which was subdivided into sub-topics. Bibliometric analysis was performed, the content was summarised and discussed, and future directions were proposed. In terms of water balance, precipitation requires more research, as available rainfall maps are outdated. Despite an increase in the number of weather stations, their spatial distribution and data continuity remain problematic. Snow cover area and duration differed among studies; thus, it also requires more research. Estimates of evapotranspiration lack comprehensive coverage and often focus on specific crops. Surface-water studies are rare and have low temporal resolution. River flows have high temporal and spatial variability, emphasizing the importance of groundwater, which is overexploited. No consistent trends in climate change impacts were detected. More research is needed in all of the hydrological cycle components. On the other hand, water quality is degrading rapidly with microbiological pollution in most rivers. Groundwater degradation, saltwater intrusion, nitrate pollution, and pesticide contamination pose significant challenges. In addition, emerging pollutants are also being detected. In terms of water management and governance, Lebanon's water framework is complex, involving many laws, institutions, and international partnerships. Despite reforms, challenges remain. Water management has evolved from being state-centred to having increased involvement by international organisations and the private sector. Access to public water networks has improved but remains intermittent. Wastewater networks are expanding, but treatment capacity remains limited. Finally, this work made it possible to quantify the research work and projects carried out in each Lebanese basin, which made it possible to identify gaps in study topics and areas. We hope that this work contributes to the ongoing debate about water security and serves as a resource to support water security and solutions for researchers, educators and policy makers.

### Abbreviations

BMLWE	Beirut and Mount Lebanon Water Establishment
BWE	Beqaa Water Establishment
CDR	Council for Development and Reconstruction
CFD	Central Fund for the Displaced
COS	Council of the South
ET	Evapotranspiration
ETO	Reference Evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations

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GDE	General Directorate of Exploitation
GDHER	General Directorate of Hydraulic and Electrical Resources
LRA	Litani River Authority
MCM	Millions Cubic Meters
MENA	Middle East and North Africa
MoA	Ministry of Agriculture
MAP	Mean Annual Precipitation
MAQ	Mean Annual Runoff
MODIS	Moderate Resolution Imaging Spectro-radiometer
MoE	Ministry of Environment

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\* Corresponding author. Institut Agro, INRAE, SAS, 65 Rue de Saint Brieu, 35000, Rennes, France.

E-mail addresses: [mohammadmerheb1987@gmail.com](mailto:mohammadmerheb1987@gmail.com), [mohammad.merheb@agrocampus-ouest.fr](mailto:mohammad.merheb@agrocampus-ouest.fr) (M. Merheb).

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MoEW	Ministry of Energy and Water
MoF	Ministry of Finance
MoPH	Ministry of Public Health
MRHEL	Ministry of Hydraulic and Electrical Resources
NGO	Non-governmental organisation
NLWE	North Lebanon Water Establishment
NWSS	National Water Sector Strategy
RMSE	Root Mean Square Error
RWE	Regional Water Establishment
SDG	Sustainable Development Goal
SLWE	South Lebanon Water Establishment
SWE	Snow Water Equivalent
UN	United Nations
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNHCR	United High Commissioner for Refugees
US	United States of America
USAID	US Agency for International Development
USBR	United States Bureau of Reclamation
WEF	World Economic Forum
WEF nexus	Water-Energy-Food nexus
WMO	World Meteorological Organization

## 1. Introduction

Lebanon is considered to have more abundant water resources than neighbouring countries in the Mediterranean basin and those in the Middle East and North Africa (MENA). Nevertheless, with a long turbulent history, an ongoing multidimensional crisis, and the increasing impacts of global change, Lebanon's water security faces many accelerating challenges (de Waal et al., 2023; ESCWA, 2022; UNICEF, 2021; World Bank, 2017) of a systemic character (Silmann et al., 2022; WEF, 2022).

Water security relates to a strong complexity that includes hydro-climatic and socio-hydrological co-evolutions, feedback loops, compartment interfacing, upstream-downstream regulations, geographic heterogeneity, temporal and frequential variabilities, infrastructure development and management, socio-economic and technical choices and trends, and robustness and resilience in response to eventual extreme events and shocks (Blöschl et al., 2019; Di Baldassarre et al., 2019; UNESCO, 2022; Young et al., 2015), and it lies at the heart of the complexity of the Anthropocene syndrome (Bai et al., 2016; Brondizio et al., 2016; Cudennec et al., 2024; Steffen et al., 2011). Lebanon is a particular hotspot and scene in the materialisation and contextualisation of the Anthropocene syndrome. Its past, current, and potential trajectories, and its MENA context, make its water security a highly critical challenge in many respects (de Waal et al., 2023). The United Nations' (UN) Agenda 2030 (UN, 2015), in particular Sustainable Development Goal 6 (SDG6) and its interlinkages, provides a framework that simplifies this complexity into targets, supports assessment and monitoring of progress using indicators, and provides a pace for action (UN Water, 2022; 2020; UNESCO, 2018), and it appears that Lebanon is not on track to meet these targets (SDG database, 2023).

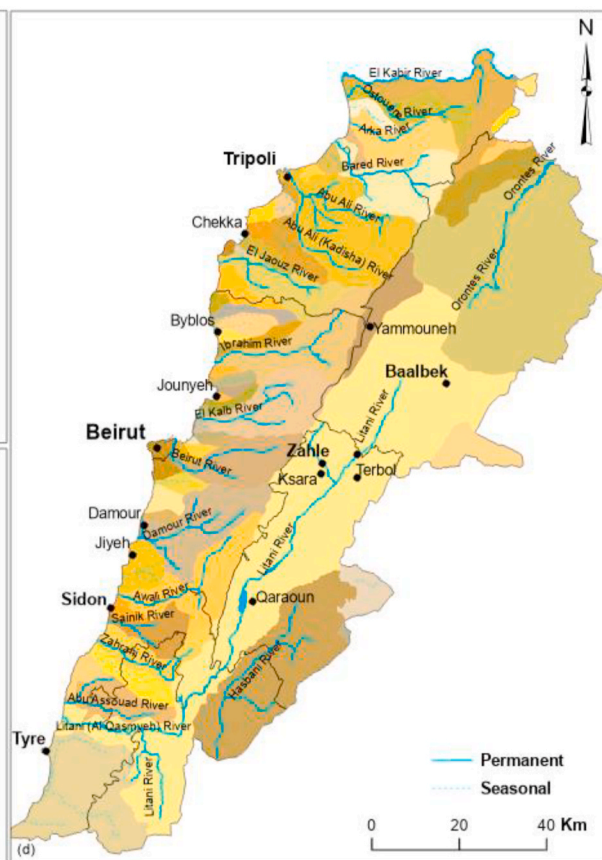
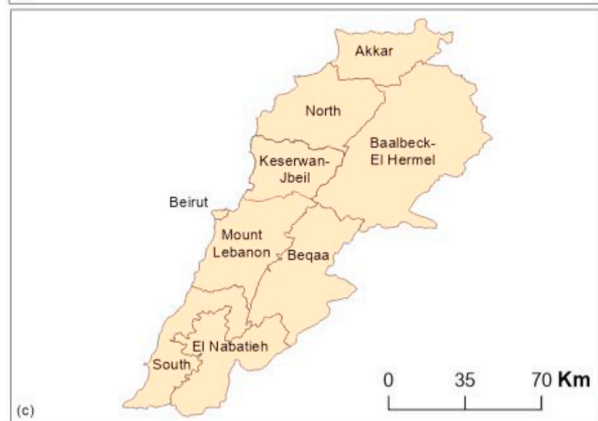
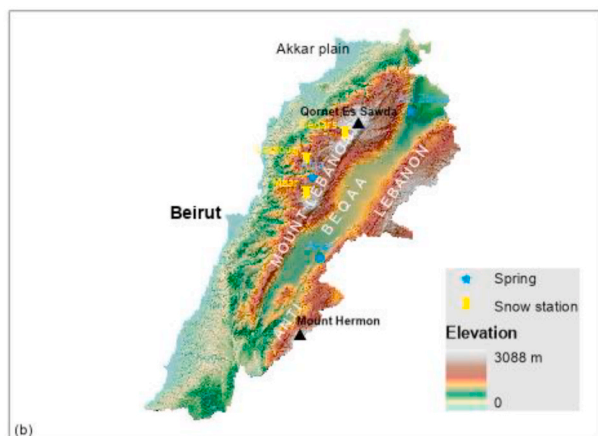
Hydrological processes and pressures need to be understood and assessed to appreciate current and potential water resources, and to use and manage them, assess the state of water-resource systems, and put them into perspective for the future (Bai et al., 2016; Ceola et al., 2016; McMillan et al., 2016). One of Lebanon's strengths is that its hydro-graphic and hydrogeological consistencies have created a highly consistent hydrology, which is rare for a non-island country. However, water-related knowledge of Lebanon needs to be improved to help towards water security by consolidating, curating, managing, and advancing knowledge in order to support awareness, understanding, and evidence-based decisions of stakeholders (ISC, 2023; Jiang et al., 2021; Misstear et al., 2022; UNESCO, 2023). This review summarises the currently available, yet fragmented, knowledge in order to provide a

basis for revising the chains of data-information-knowledge and data-products-services, and related principles (Cudennec et al., 2020, 2022a; Kootval and Soares, 2020; WMO, 2021a, 2021b, 2022), and for identifying improvement paths. With this objective, this review was driven by the overall principle that a scientific collection, review and summary of available information and knowledge are needed even when data are rare and imprecise (Dixon et al., 2022; Hrachowitz et al., 2013), to contribute to assessment from a self-organised scientific perspective (ISC, 2023) and thus support decision making for the benefit of Lebanon's population, society, and wider geopolitics. This review collates scientific and academic information and knowledge in peer-reviewed articles (Cudennec and Hubert, 2008; Koutsoyiannis et al., 2016) and the grey literature (especially reports by funding and project agencies and consulting firms) to make the best use of all information, even when doing so introduces uncertainties (Strobl et al., 2020). This inclusive approach to managing knowledge towards solutions is inscribed in the Open Science paradigm to serve society (Arheimer et al., 2024; Cudennec et al., 2022a, 2022b; UNESCO, 2021); is consistent with the ambitions of the action plan for hydrology of the World Meteorological Organization (WMO, 2023); aims at supporting immediate and mid-term improvements in water-resource management; and should further help identify paths for improving the knowledge base itself, from hydrometry to resource assessment, solution implementation, state reinforcement, polycentric governance, and citizen engagement (Arheimer et al., 2024; de Waal et al., 2023; Dixon et al., 2022; ISC, 2023; Nardi et al., 2022; Ostrom et al., 1999; Tauro et al., 2018; UNESCO, 2023).

## 2. Study area

Located on the shore of the eastern Mediterranean Sea (Fig. 1a), Lebanon is a small mountainous country with an area of 10,452 km<sup>2</sup>. It contains two mountain ranges – Mount Lebanon and Anti-Lebanon – that run parallel to the sea in a south-north direction, separated by an elevated depression – the Beqaa valley, the most important agricultural area in the country – and delineate a narrow coastal plain (Fig. 1b). This orography creates a quasi-consistent hydrography for the entire country. All rivers that flow west down the Mount Lebanon range lie completely in the country, as does the Litani River, which drains the Beqaa valley, whereas three rivers are transboundary: the El-Kabir River, which forms the northern border with Syria; the Orontes River, which flows north towards Syria and reaches the Mediterranean Sea in Iskenderun (southern Turkey); and the Hasbani River, which drains the western flanks of Mount Hermon and runs towards the Upper Jordan River, forming a tributary of the Jordan River.

The mountainous terrain of Lebanon, which reaches high elevations and neighbours the Mediterranean Sea, causes relatively high precipitation, with much of it falling as snow (see Ulbrich et al. (2012) and Merheb et al. (2016) for a Mediterranean perspective; and Feki et al. (2017), Silvestri et al. (2022), and Slimani et al. (2007) for analysis of mountain effects in other Mediterranean areas). The country's highest elevation is 3088 m, at Qornet Es'Sawda in northern Mount Lebanon (Fig. 1b), and about 50% of Lebanon lies above 1000 m, and 20% lies above 1800 m. Indeed, the geomorphology of the country largely impacts precipitation distribution and temperatures. Fig. 2d shows the spatial distribution of mean annual precipitation over Lebanon. Rainfall ranges between 700 and 1000 mm on the coast. It increases on the western flanks of Mount Lebanon to reach more than 1400 mm on its central part. Mean annual precipitation decreases inland due to the rain shadow effect of Mount Lebanon. It reaches its lowest value in north-eastern Lebanon (around 200 mm). In addition to its high spatial variability, precipitation features high intra and inter-annual variability characteristic of the Mediterranean climate. It usually occurs between November and April. The type of precipitation is altitude dependent with areas above 1800 m receiving mostly snow. Temperatures are the lowest in winter, and the highest in summer. Increasing elevation results



**Fig. 1.** Lebanon's (a) location, (b) geomorphology, (c) administrative divisions, and (d) distribution of streams and catchments. The maps show sites of interest mentioned in the text.

in decreasing temperatures. The effect of Mount Lebanon also affects temperature causing continental tendencies in the Beqaa valley and Anti-Lebanon.

The geological substratum of Lebanon, composed mainly of highly karstified carbonate rocks (Fig. 2b and c), favours infiltration; thus, groundwater is the most important water resource, as reflected by the many springs distributed throughout the country. The larger springs lie at the head of the country's 16 permanent rivers and maintain river

flows during the long dry summers. Some springs also discharge below sea level, forming submarine springs along the entire Lebanese coast (Bakalowicz, 2014; Bakalowicz et al., 2007; Ghannam et al., 1998; Kareh, 1966). The country thus exhibits a strong hydrogeological consistency. Little groundwater enters Lebanon, while annual groundwater outflows to neighbouring countries is estimated at 280 million m<sup>3</sup> (MCM) out of total internal renewable water resources estimated at 4800 MCM (AQUASTAT, 2023).



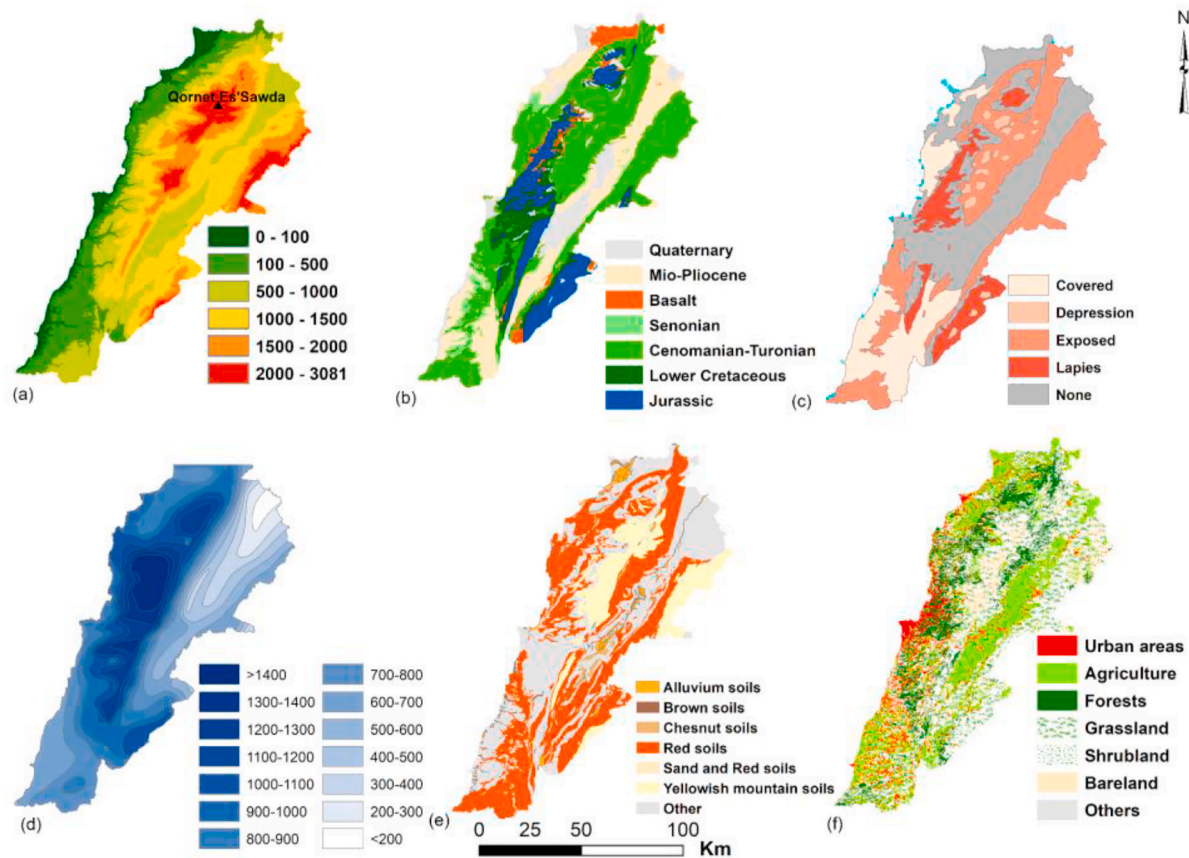


Fig. 2. Maps of a) elevation classes (m), b) geology (Dubertret, 1955), c) karst, d) mean annual rainfall (Plassard, 1972), e) soils (Geze, 1956), f) and land use (CNRS, 2010) in Lebanon.

Land cover/use in Lebanon shows a high concentration of urban areas on the narrow coastal strip (Fig. 2e). Urban areas are 8% of Lebanon's surface. Agricultural areas (23% of total surface area) are mostly located in the Beqaa valley and the Akkar plain. Parts of southern coastal Lebanon and some areas in Mount Lebanon also features agricultural activities. Forests represent around 13% of Lebanon's area and are mostly on the western slopes of Mount Lebanon. The remaining areas are mostly shrublands characteristics of the Mediterranean area and barren lands on the highest altitude. The distribution of land use classes also influences water use. Water demand for domestic use is the highest in the coastal area coinciding with the highest population density. This is also true for industrial water demand. The highest agricultural water demand is in the Beqaa valley, followed by the Akkar plain.

Lebanon's population was estimated at ca. 5.6 million people in 2021 (World Bank, 2023), which creates a high population density (550/km<sup>2</sup>), most of whom live in coastal urban areas. Lebanon is among the most urbanised countries in the MENA region, with 87% of the population living in urban areas (World Bank, 2010). According to the UN's High Commissioner for Refugees (UNHCR, 2023), Lebanon is estimated to harbour more than 1.5 million refugees, which results in the largest number of refugees per capita and per square kilometre in the world. The refugees come mainly from Syria (>1 million) due to the ongoing Syrian civil war, but also from Palestine, dating back to Arab-Israeli conflicts and their descendants (ca. 180,000). Lebanon's political and socio-economic situation is strongly shaped by the unstable geopolitics of the Middle East, which also materialised in the long Lebanese civil war (1975–1990). These events have cast shadows over all socio-economic sectors and the governance of resources, including the water sector. Thus, monitoring of water processes and resources is highly fragmented in time, with gaps in hydro-meteorological records that correspond to major conflicts in the country. In addition, the Syrian

refugee crisis has increased domestic water demand by 20% and agricultural water use in summer by 10% (Jaafar et al., 2020). AQUASTAT (2023) reported that Lebanon's total freshwater withdrawals were 1800 MCM/year in 2020, which represents 37.5% of internal renewable water resources. These total freshwater withdrawals are higher than the water demand of 1500 MCM/year estimated by the Ministry of Energy and Water (MoEW) (MoEW, 2020) and divided into 38.5% domestic, 55.9% agricultural, and 5.6% non-domestic. These percentages agree with the World Bank's public expenditure review of Lebanon's water sector (World Bank, 2010). The SDG database (2023), fed by national reporting, indicates that the degree of water stress in Lebanon was 59% in 2020. In addition, only 46% of the population has safely managed drinking water, while as little as 26% has safely managed wastewater. In addition, only 50% of the water monitored has good ambient quality (SDG database, 2023). Estimates of Lebanon's water-balance components are controversial, and different sources report different estimates (El-Fadel et al., 2000; Fawaz, 1992; Jaber, 1993; MoEW/UNDP, 2014; UNDP, 1970).

### 3. Methodology

#### 3.1. Research strategy

This review is based on a collection of 378 documents, of which 238 are academic and 140 non-academic. The academic documents consist of 171 peer-reviewed articles, 14 conference papers, 32 theses (mostly doctoral), 12 books and book chapters, and 9 maps. The non-academic documents are mainly reports (118 documents) and other types of documents (26), including notes, working papers, and feasibility studies. The majority of non-academic reports are from international organisations namely the World Bank and various UN agencies, or foreign ones

such as USAID. Most of the documents are in English (Fig. 3a).

The peer-reviewed articles and book chapters were identified by searching Google Scholar for a set of key words related to different subfields of water-resource studies along with the key word “Lebanon”. The search was done in January 2023 for the period extending from 1920 to 2022.

To find grey literature documents, we searched websites of Lebanese Ministries involved in the water domain, such as the Ministry of Energy and Water (MoEW), Ministry of Environment (MoE), and Ministry of Agriculture (MoA). We also searched websites of UN agencies that operate in Lebanon, mainly the UNDP and the Food and Agriculture Organization (FAO), as well as the World Bank, and other foreign agencies such as USAID. Other important sources for grey literature included the website of the Lebanese Council for Development and Reconstruction (CDR). Another source of mainly non-academic documents was the Lebanese Water Actors Platform (<https://www.lewap.org/news/>). Grey literature was also collected by searching ResearchGate profiles of colleagues who worked in the water sector and through personal connections.

### 3.2. Analysis methods

To facilitate the analysis, the collected documents were classified into four general topics: water balance, water quality, water management, and water governance (Fig. 3b). Each general topic was further subdivided into specific sub-topics. Water balance was divided into precipitation, evapotranspiration (ET), surface hydrology, groundwater hydrology, climate, and hazards. Water quality was divided into general hydrogeochemistry, physico-chemical characteristics, isotopes, heavy metals, seawater intrusion, microbiological pollution, ecological pollution, emergent pollutants, and pesticides. Water management was divided into water supply and wastewater, water-resource management, agriculture, renewable energy, Water-Energy-Food (WEF) nexus, Syrian crisis, hazards, and climate. Water governance was divided into national strategies, hydrosocial studies, economy, transboundary water, water laws, water authority, and water sector. See the Supplementary Material A for a complete list of the documents classified by document type, language, year of publication, general topic, sub-topic, theme, study area, and reference.

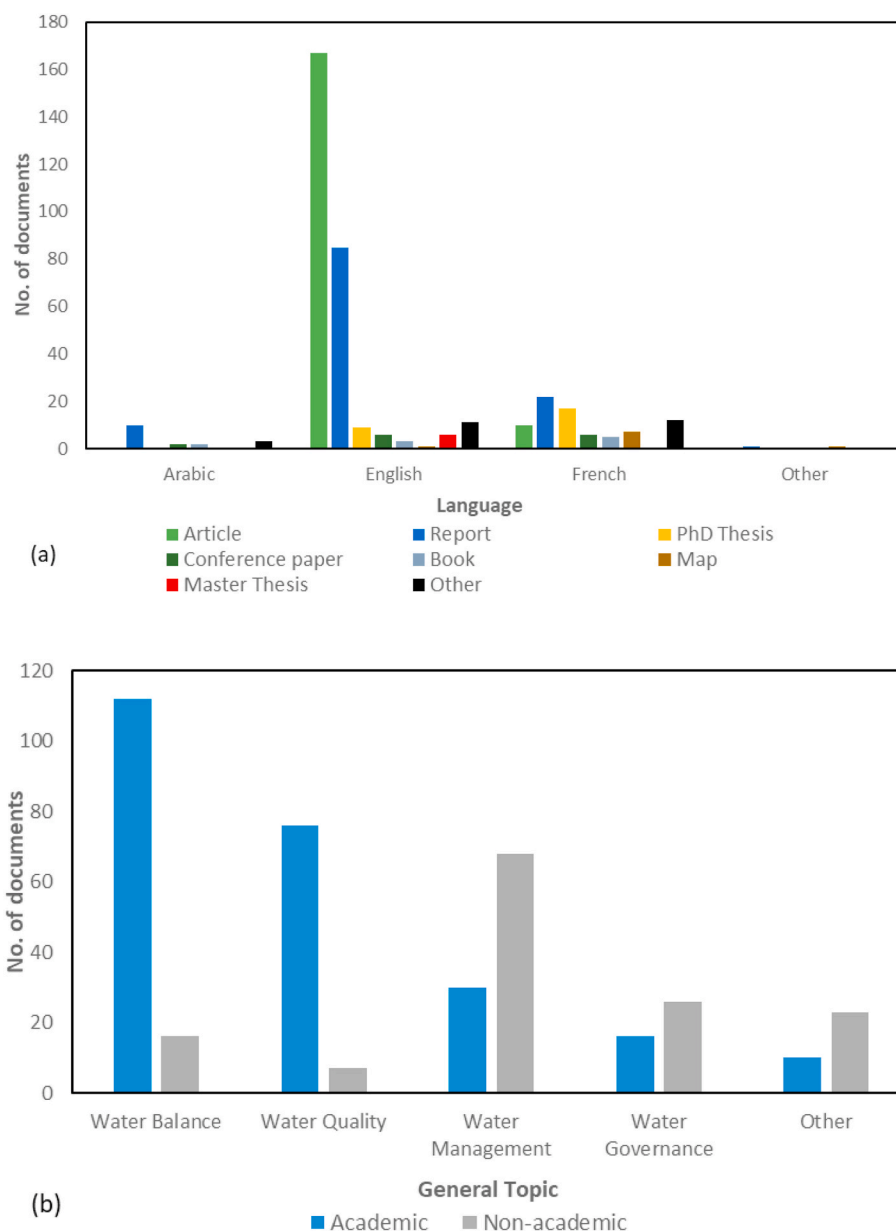


Fig. 3. Distribution of studies by (a) language and document type and (b) topic and study type.

The documents were classified as academic or non-academic. For water balance and water quality, there are many more academic documents than non-academic documents, whereas for the other topics, it was the opposite.

We first analysed the temporal and spatial distribution of water-resource studies in Lebanon by document type and topic. Then, for each general topic and its sub-topics, we summarised the research findings. We end by discussing the state of knowledge of water resources in Lebanon while highlighting the gaps and focusing on geopolitical and global impacts. We also identify paths for future research.

## 4. Results

### 4.1. Bibliometric analysis

#### 4.1.1. Temporal and spatial distribution of studies

The studies were subdivided by document type (Fig. 4a) and general topic (Fig. 4b). We analysed documents among nine periods of Lebanese history: pre-1920 (pre-French mandate), 1920–1943 (French mandate), 1944–1974 (independence to civil war), 1975–1990 (civil war), 1991–2000 (reconstruction to the end of Israeli occupation in southern Lebanon), 2001–2005 (to the end of Syrian presence), 2006–2010, 2011–2019 (start of Syrian civil war and refugee crisis), and 2020–2023 (huge financial crisis). All types of documents gradually increased in

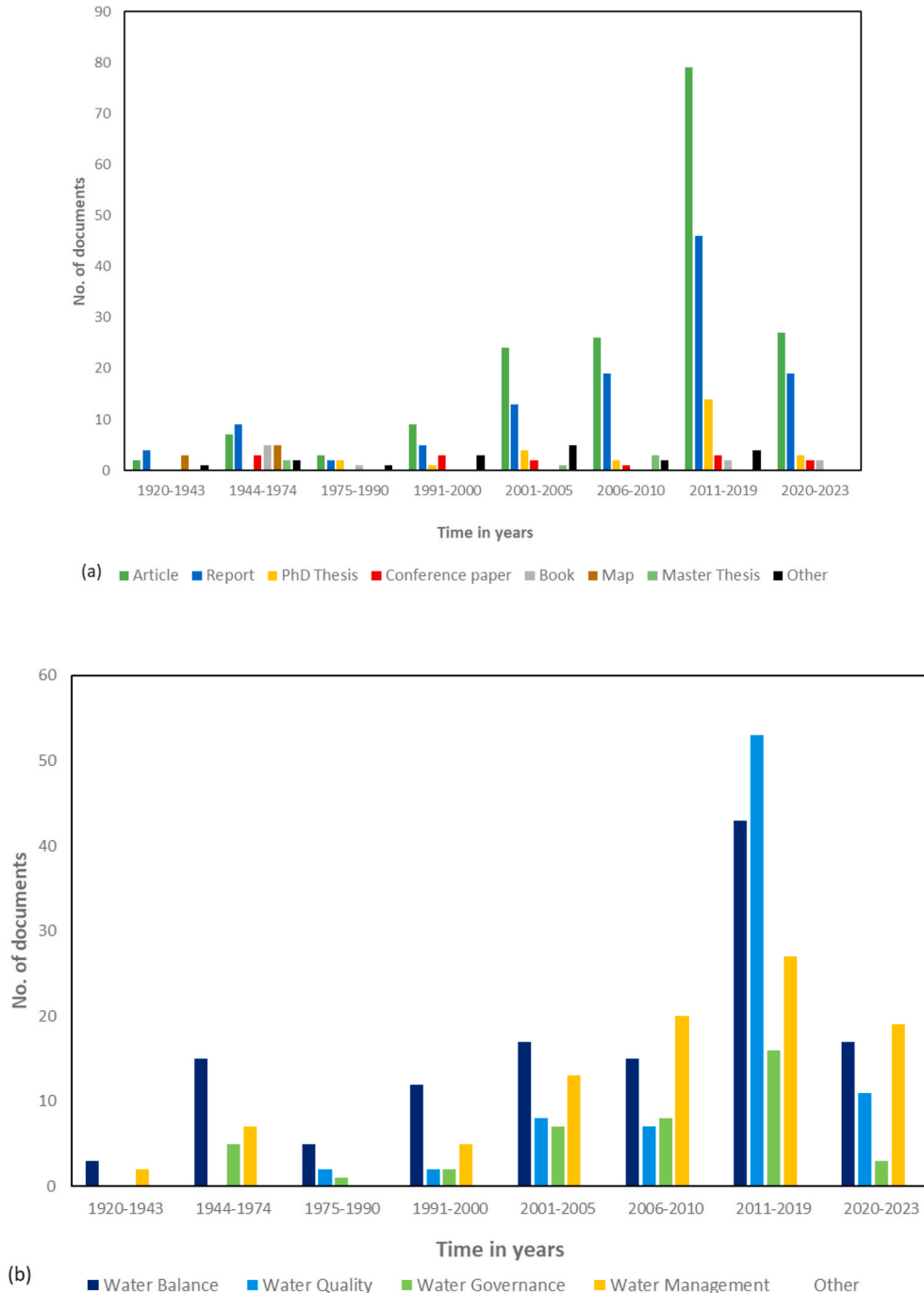


Fig. 4. Distribution of studies over time by (a) document type and (b) study topic.

number during the 20th and 21st centuries, peaking from 2011 to 2019. Water-balance and water-management studies dominated until 2010, after which the number of water-quality studies increased greatly.

Lebanon's relatively small area makes most studies national in scale, especially those on water balance, water management, and water governance, although most water-quality studies are local (Fig. 5). The Beqaa valley and its main source of irrigation water, the Litani River, have been studied the most. Other common subjects of water-quality studies include Qaraoun Lake (a reservoir on the Litani River), the Mount Lebanon range, the Akkar plain (a coastal agricultural zone), Beirut and its southern suburb (around Damour), and Tripoli (the second largest city).

#### 4.1.2. Topics

**4.1.2.1. Water balance.** Water-balance studies (125 documents) include all those related to any component of the water cycle, the climate, or natural hazards (e.g. floods). The number of water-balance studies classified by sub-topic varies temporally (Fig. 6a) and spatially (Fig. 6b). Most water-balance studies focus on precipitation, especially snow, mainly due to advances in remote sensing, which greatly increased the number of water-balance studies in the past decade. Groundwater studies are also abundant, due to the importance of Lebanon's groundwater resources, whereas surface-water studies, especially of ET, are less common.

Most water-balance studies cover all of Lebanon or the Mount Lebanon range, especially precipitation-based studies and some groundwater-hydrology studies. In contrast, surface-hydrology studies focus more on specific river basins, while ET studies are concentrated in the Beqaa valley.

**4.1.2.2. Water quality.** Water-quality studies (81 documents) appeared relatively late, increased greatly from 2011 to 2019, and continue to

increase. The first studies concerned mainly seawater intrusion and microbiological pollution, but multiple types of biological and chemical pollution have been studied more recently (Fig. 7a). The geographic distribution of these studies reflects the importance of agricultural areas (e.g. Beqaa valley, Litani basin and its Qaraoun Lake, Akkar plain) and urban areas (e.g. Beirut and its southern suburbs, Tripoli) as major sources of pollution (Fig. 7b).

**4.1.2.3. Water management.** The 97 water-management studies classified by sub-topic also varies temporally (Fig. 8a) and spatially (Fig. 8b). Water-management studies also increased over time. Spatially, many of the studies are at the national scale, while the Beqaa valley and Litani basin are the geographic areas most frequently studied. Most of these studies are non-academic reports related to a wide variety of projects.

Studies in the water supply sub-topic examined mainly domestic water supply (Salamé & Associates, 1992; CDR/ELARD, 2010; Kazma, 2008; MoEW, 1996; World Bank, 2014), drinking water supply (Abd-El-Al, 1959; Ayoub and Malaeb, 2006; Massoud et al., 2010; MoEW, n.d., n.d., n.d., n.d.; Semerjian and Dennis, 2007), and drinking water quality (Abbas et al., 2023), but also irrigation water supply (Gibert, 1949; Hydraulic Study Board, 1930; Jaafar et al., 2015; Makhoul, 1999; McCrory, 1948; SCP/SOGREAH/CADRES, 1996; USAID, 2016) and water inventories (Daher, 2011; Makhoul, 1999, 1998, n.d.; MoEW, n.d.). Many studies report on water-supply and wastewater support programmes and master plans (Kredo/DAI/USAID, 2015; MSC-Water, 2006; USAID, 2021, 2015, 2011; USAID/BWE, 2014) and the situation of the wastewater sector (Bakchan et al., 2020; ELARD/CDR, 2015; KCC, 2021; Machayekhi et al., 2014; MRHEL/UNDP, 1973).

The agriculture sub-topic includes mainly irrigation studies (FAO, 2020a, 2008; IRWA, 2002; Karam et al., 2009; Karam and Nangia, 2016; UNDP/CDR, 2009; World Bank, 1994) but also general sector reviews (Dal et al., 2021; Sanlaville, 1963), agricultural sector national

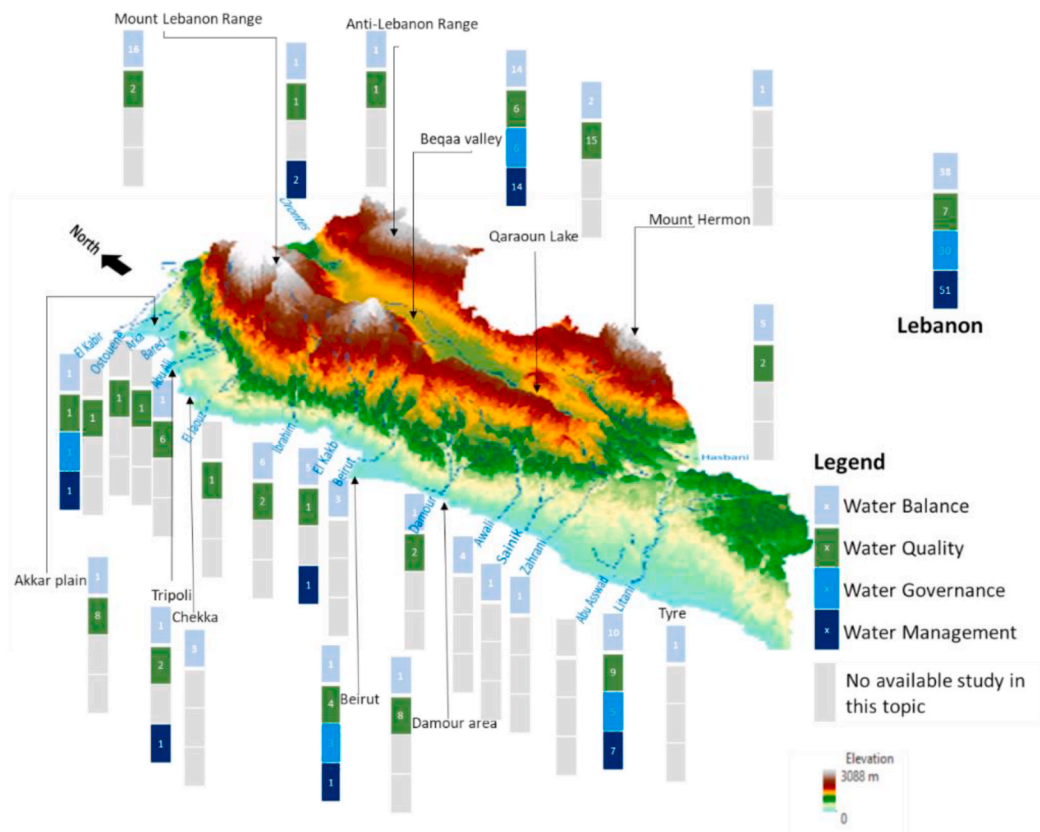


Fig. 5. Distribution of studies by topic and geographic area of Lebanon. A detailed table describing this figure is available in Supplementary Material B.1.



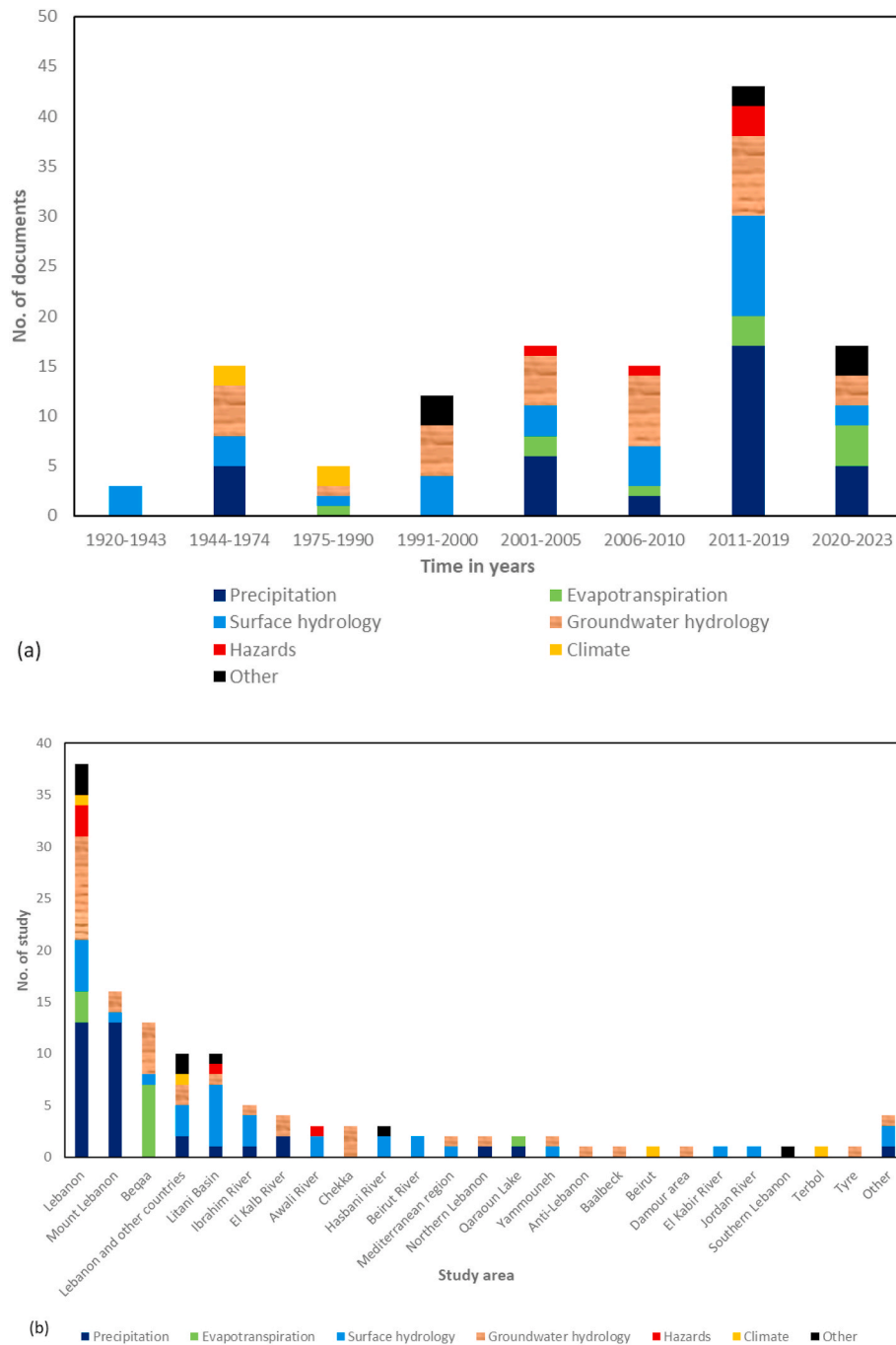


Fig. 6. Distribution of water-balance study sub-topics by (a) period and (b) study area. Only study areas where at least 2 studies are available are shown. Other study areas are referred to as “Other”.

strategies (MoA, 2020, 2010), studies of agricultural potential (Kubursi, 2005), and farmer satisfaction surveys (USAID, 2014b).

The hazards sub-topic includes a variety of studies of natural and anthropogenic hazards, such as floods (Abdallah et al., 2013; Abd-El-Al, 1940; Khawlie, 1994; USAID, 2010a), climate change impacts (Khawlie, 2001; MOE/UNDP/GEF, 2022, 2019, 2016, 2011; Nasreddine, 2001; Osman Elasha, 2010; Plan Bleu, 2008; UNDP, 2021), droughts (Verner et al., 2018; Ziade, 2009), desertification (MoA, 2003), and groundwater vulnerability (Metni et al., 2004; MORES, 2010; Saadeh, 2020). The renewable energy sub-topic includes studies of river hydropower (Hourii, 2006; McCrory, 1948; Sanlaville, 1965), hydropower potential of non-river sources (UNDP/CEDRO, 2013a, 2013b), solar-powered pumping (Hajj Shehadeh, 2015) and geothermal resources

(UNDP/CEDRO, 2014). The water-resource management sub-topic included water resources management studies (Doummar et al., 2009; El-Fadel et al., 2001; FAO, 2021; JICA, 2004; Makdisi, 2007; USAID, 2014a, 2012a), integrated water-resource management (Gharios, 2009), sustainable water-resource management (LRA/L-NCRS/DSA, 2007), and the WEF Nexus (FAO, 2020b; IUCN, 2019; Karnib and Alameh, 2020). In this topic, we also included socio-economic studies (MoE/UNDP, 2018; UNDP et al., 2020), studies of impacts of the ongoing Syrian refugees crisis (GVC, 2016; Hussein et al., 2020; Jaafar et al., 2020; MoE/EU/UNDP, 2015; UNDP, 2022), management of transboundary waters (Cadham Hayes Systems, 2006; Conker and Hussein, 2020), and legal and policy aspects of water management (Ghiotti, 2004, 2005).

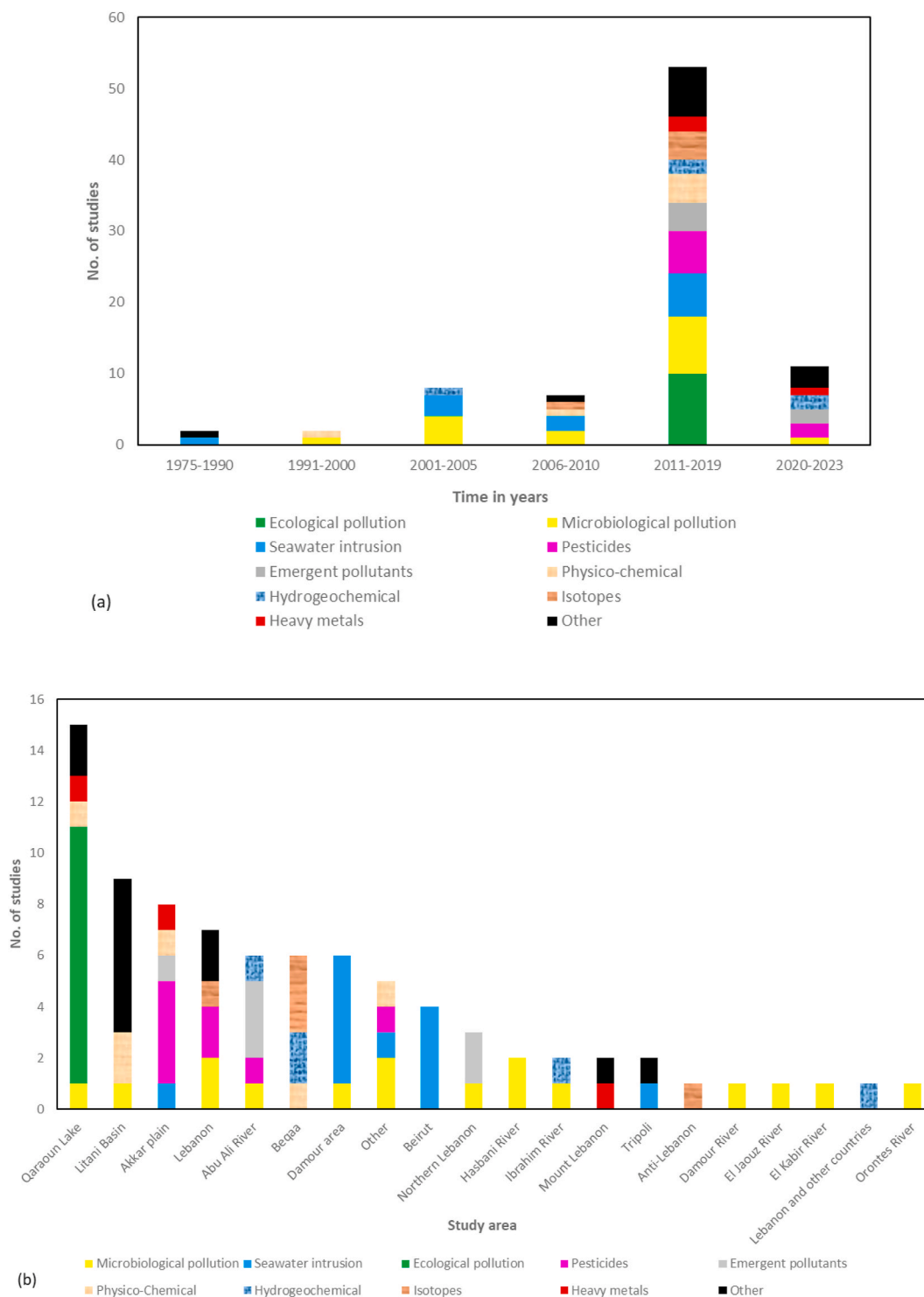
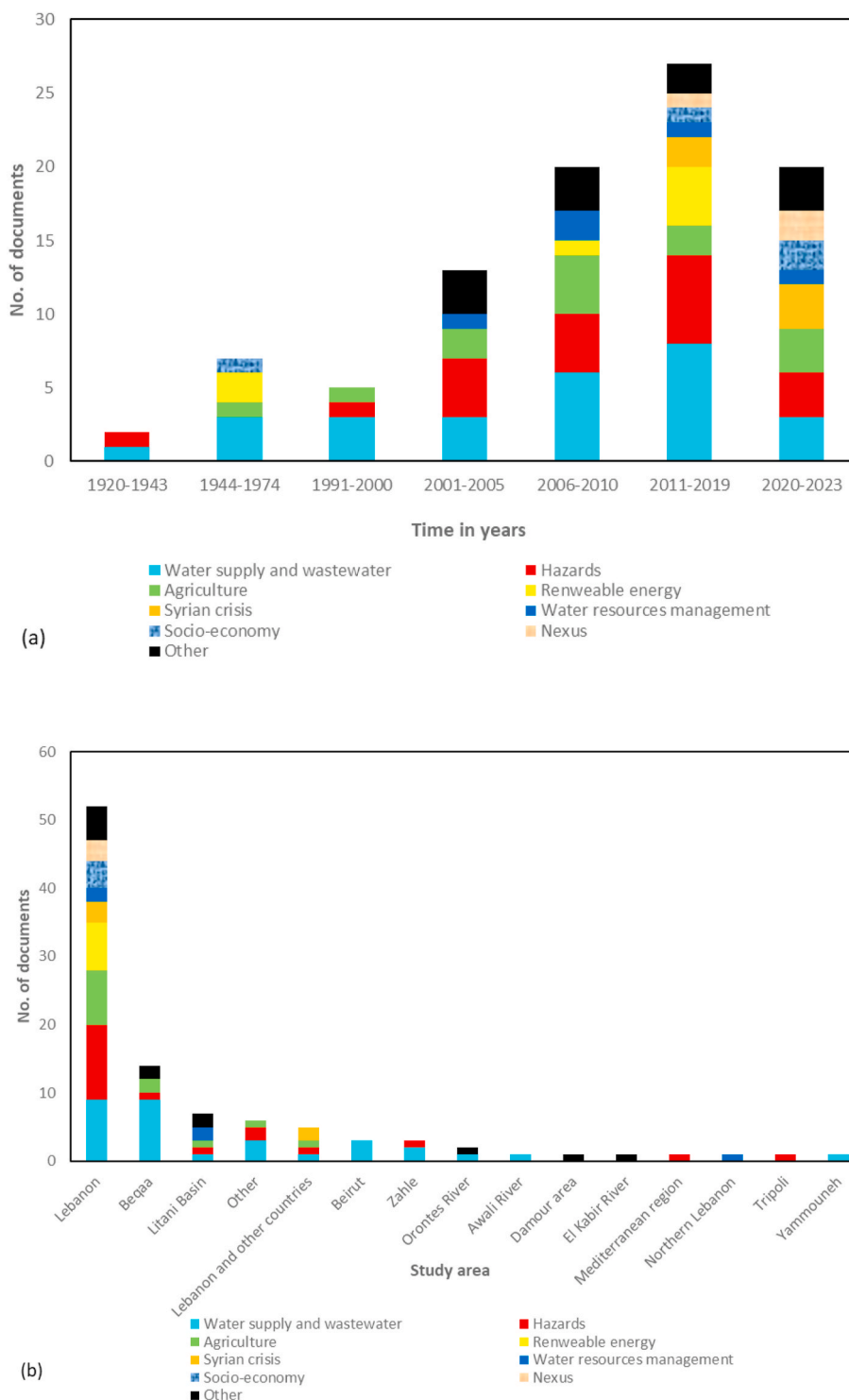


Fig. 7. Distribution of water-quality study sub-topics by (a) period and (b) study area. Only study areas where at least 2 studies are available are shown. Other study areas are referred to as "Other".

4.1.2.4. *Water governance.* The 42 water governance studies classified by sub-topic vary temporally (Fig. 9a) and spatially (Fig. 9b). The number of studies has increased since 1975, but many of them were produced from 1944 to 1975, when Lebanese intellectuals emerged who envisioned Lebanon through the development of its water sector (Gemayel, 1952, 1954, 1955). Spatially, nearly all of the studies are at the national scale.

There are more non-academic studies (26 reports) than academic studies (16 books and articles), mostly reports by government

authorities that address aspects of governance, such as national strategies and plans (Comair, 2009; DAR-LAURIF, 2004; FAO, 2016; Gemayel, 1952; IRFED, 1963; MoEW, 2020, 2010, 2005a, 2005b; World Bank, 2012), socio-economic aspects (Mallat, 1982; Plan Bleu, 2011; USAID, 2012b; World Bank, 2010, 2009), water laws (Darwish, 2004; Farajalla et al., 2015; Gharios, 2020; Gharios et al., 2021; Ghiotti and Barakat, 2006; Ghiotti and Riachi, 2013; Thomas et al., 2003), water-sector investment and water-authority restructuring and capacity building (Catafago, 2005; Doumit, 2018; Konigk, 1999; MoEW, 2005a; MRHEL,



**Fig. 8.** Distribution of sub-topics of water-management studies by (a) period and (b) study area. Only study areas where at least 2 studies are available are shown. Other study areas are referred to as “Other”.

1970; USAID, 2021, 2015, 2014a, 2013, 2012b, 2012c, 2010b; Verdeil, 2008), and transboundary waters (AFIAL, 2014). Other studies address specific issues, such as groundwater governance (Molle et al., 2017; Riachi, 2016), irrigation (World Bank, 2003), private-sector involvement (EUWI-Med/OCDE, 2010), pollution prevention (Farajalla and Khoury, 2007), the involvement of international donors in Lebanon’s water sector after the civil war (Eid-Sabbagh, 2015), and changes in water governance and management in Lebanon since the 19th century (Riachi, 2013).

**4.1.2.5. Other water-related topics.** Finally, we identified 33 studies in which water was only one of several components, such as those that reported actions of international programmes in Lebanon (e.g. the UNDP), development plans, the Syrian crisis, Lebanon’s country profile (Collelo, 1989; Darwich, 2009; Dussaud et al., 1941; Fish, 1944; Gemayel, 1960; UNDP, 2016, 2014), geopolitical aspects of water conflict in the region (Borgomeo et al., 2021), and climate change impacts (MoE/URC/GEF, 2012). They also include additional reports on UN Millennium Development Goals and Sustainable Development Goals

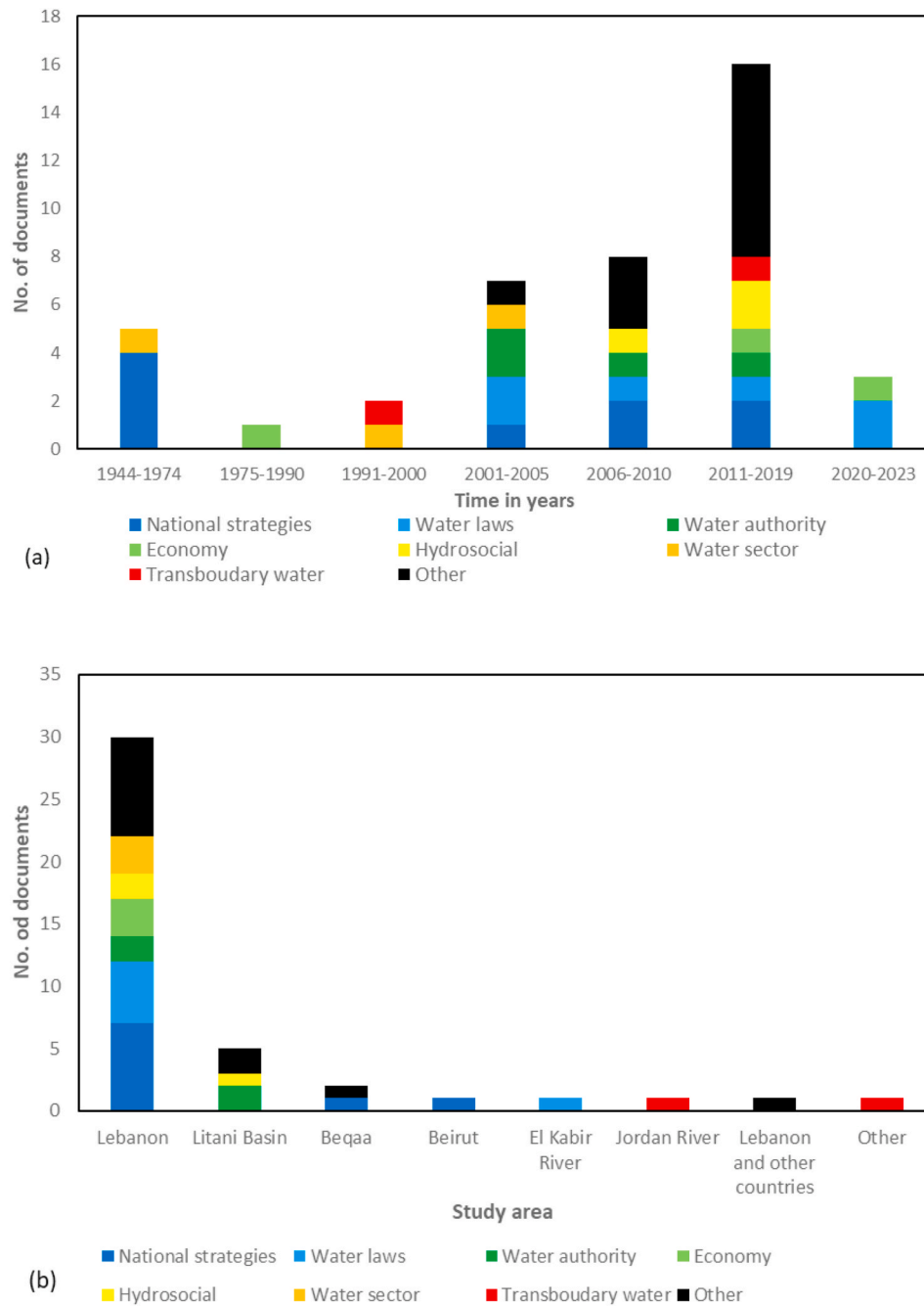


Fig. 9. Distribution of water-governance study sub-topics by (a) period and (b) study area. Only study areas where at least 2 studies are available are shown. Other study areas are referred to as “Other”.

(UNDP, 2008), other sustainable development studies, and studies that assess trends in environmental degradation and its socio-economic costs (CAS, 2006; ECODIT, 2002; MoE/EU/UNDP, 2014; MOE/UNDP/ECODIT, 2011; Sarraf et al., 2004; UNDP, 2022; UNDP et al., 2020).

## 4.2. Water balance

### 4.2.1. Precipitation

**4.2.1.1. Rainfall.** Precipitation in Lebanon varies greatly in space and time. Spatially, mean annual rainfall ranges from 200 mm in the north-east to more than 1400 mm in north-central Mount Lebanon (Blanchet, 1976; Plassard, 1972; Traboulsi, 2010), due to the Mediterranean climate, which has high temporal and spatial variability in precipitation

(Cudennec et al., 2007; García-Ruiz et al., 2011; Merheb et al., 2016). Lebanon’s geomorphology places the western slopes of the Mount Lebanon range on the windward side, and its eastern slopes, the Beqaa valley and the northern Anti-Lebanon range in the rain shadow, while the southern end of the range (Mount Hermon) receives abundant rainfall due to the lower elevation of Mount Lebanon. Unfortunately, studies of temporal and spatial variability in rainfall in Lebanon are rare.

Two studies are considered reference works on this subject: the 1:200,000 rainfall map of Lebanon by Plassard (1972) and a doctoral thesis on the weather of Lebanon by Blanchet (1976). Plassard’s (1972) map was not the first, as it was preceded by four other rainfall maps (Atlas Climatique du Liban, 1966; Combiér, 1945; Fish and Dubertret, 1946; Rey, 1955). Traboulsi (2010) also published a rainfall map but used the same data as Plassard (1972). Plassard’s (1972) map is still



considered a reference work in Lebanon because it reflects the high spatial coverage of the weather network (140 stations) and the fact that rainfall records at most stations stopped in 1975. All of these maps are annual rainfall maps, as no daily or even monthly maps exist for Lebanon. The weather-station network was re-established in the 1990s, but with many fewer stations and thus smaller spatial coverage and lower density, and, to our knowledge, there have been no attempts to update Plassard's (1972) map. There is certainly a need to extend the meteorological network and to develop new up to date spatial rainfall maps at various time scales.

**4.2.1.2. Snow.** Blanchet (1976) highlighted snow as a major type of precipitation in Lebanon. The Cedars weather station (elevation of 1925 m) experiences ca. 55 snowy days and has a coefficient of snowiness (number of snowy days/total precipitation days) of 65.2%, which is higher than that of the French Alps at the same elevation. Snow cover remains for 118 days at this elevation, up to 9 months at higher elevations, and even for the entire year on the highest peaks.

In recent decades, advances in remote sensing increased the number of snow-related studies: 20 snow-related articles have been published in the Lebanese literature since 2002. Only one study (Aouad-Rizk et al., 2004) is based solely on field measurements, while the rest are mainly remote sensing studies, most of which used mainly Moderate Resolution Imaging Spectro-radiometer (MODIS) TERRA/AQUA satellite images (Alonso-Gonzalez et al., 2021; Darwish et al., 2015; Mhaweij et al., 2014; Saleh and Faour, 2016; Shaban et al., 2014a, 2021; Telesca et al., 2014). Other satellites used included RADARSAT (Corbane et al., 2005), ENVISAT (Bernier et al., 2003; Corbane et al., 2005), Landsat OLI/TIRS (Doumit and Sakr, 2019), Landsat ETM+ (Mhaweij et al., 2014), and SPOT-4 (Shaban et al., 2004). Other studies used drones and cameras (Abou Chakra et al., 2019, 2020; Somma et al., 2014). Finally, some studies combined remote sensing and field measurements (Aouad-Rizk et al., 2005; Corbane et al., 2005; Fayad, 2017; Fayad et al., 2017; Fayad and Gascoin, 2020; Mhaweij et al., 2014; Shaban et al., 2013, 2014a).

Most satellite-based remote sensing studies were applied to the entire country. Estimates of snow cover areas and snow water equivalent (SWE) differ among studies – sometimes within the same study – for a given period. Shaban et al. (2014a) used 500 m resolution MODIS TERRA images to study snow cover over Lebanon. Telesca et al. (2014) used both MODIS TERRA and AQUA. Estimates of snow's contribution to Lebanon's water budget also vary greatly, ranging from 31% (Telesca et al., 2014) to 58.5% (Shaban et al., 2014a). Using an enhanced 500 m resolution "TERRA-AQUA Combined" (TAC) product, Mhaweij et al. (2014) estimated mean snow cover as ca. 1000 km<sup>2</sup> per year for 2002–2012. Regarding SWE, Mhaweij et al. (2014) estimated that snow contributes a mean of ca. 26% of the water budget. The number of snowy days varies less among studies. However, the numbers reported by recent studies are much lower than those of Blanchet (1976). All authors agreed that snow in Lebanon starts falling in October/November and stops falling in May, and observed that some snow patches persist until June at higher elevations.

Except for Shaban et al. (2013) all field-measurement studies are local and concentrated in north-central Mount Lebanon. Aouad-Rizk et al. (2005) studied physical properties of snow in the headwater catchment of the El Kalb basin. Fayad et al. (2017) published the first datasets of snow depth, SWE, and snow density in Lebanon based on data from weather stations in three headwater catchments (El Kalb basin, Ibrahim basin, and Abu Ali basin). Snow density was highest in the El Kalb basin. Fayad and Gascoin (2020) predicted SWE for the same three headwater catchments using SnowModel (Liston and Elder, 2006) from 2013 to 2016.

Local studies that used remote sensing cameras and drones highlighted the accuracy of these techniques and their applicability, especially for monitoring snowmelt in sinkholes (Abou Chakra et al., 2019, 2020). This is of particular importance in Lebanon, given the role of

sinkhole snow in recharging aquifers during the long dry summer.

Field-measurement studies are limited to the Mount Lebanon range, except for one study at Mount Hermon in the Anti-Lebanon range by (Gil'ad and Bonne, 1990), who combined Landsat images, aerial photographs, and measurements of snow depth and SWE at several sites at elevations of 1500–2100 m. They estimated a mean snow cover of 166 km<sup>2</sup> from 1977 to 1986 and a mean SWE of 100–650 mm at 1500 and 2100 m, respectively. They estimated that Mount Hermon snowmelt contributes only 10% of the total annual discharge, and 30% of the dry-season discharge, of the Upper Jordan River.

Finally, snow measurement in Lebanon is quite limited with a high dependency on remote sensing technologies. The snow contribution to the water budget is yet to be fully estimated. There is a need for more snow monitoring stations in Mount Lebanon and Anti-Lebanon ranges.

#### 4.2.2. Evapotranspiration

All ET studies were performed in the Beqaa valley. Karam et al. (2007, 2005, 2003) measured ET for three crops (i.e. maize, soya bean, and sunflower) using lysimeters. ET for other crops, such as pepper (Karam et al., 2009), maize, cotton, and eggplants (Karam and Nangia, 2016), have also been estimated.

Bachour et al. (2013) compared a regionally calibrated version of the Hargreaves method for estimating ET to estimates from the reference Penman-Monteith equation using data from the Beqaa valley (Terbol weather station). The former predicted ET better and thus can be used in Lebanon, where fewer data are available.

More recently, studies have focused more on using remote sensing to estimate ET. Jaafar and Ahmad (2020) estimated monthly ET over the entire Beqaa valley for 1984–2017 using local weather data and Landsat thermal images and surface-reflectance products. The study did not identify any trends in ET from 1984 to 2017. In addition, the more agriculturally intensive centre of the Beqaa valley had higher spatial variability in ET than its northern parts. This spatial variability was also observed by Mhaweij et al. (2020), who predicted ET for winter cereals in the Beqaa valley for the 2017–2018 season. Predicted ET ranged from 300 mm to 600 mm. Similarly, Caiserman and Faour (2021) used the PYSEBAL model to predict spatial variability in ET in the Beqaa valley.

Only one study investigated evaporation alone, estimating monthly evaporation from Qaraoun Lake in the Beqaa valley from 2009 to 2015 and comparing it to that from pan evaporation at a nearby weather station (Bou-Fakhreddine et al., 2019). Mean monthly evaporation at Qaraoun Lake during the dry season (May–October) ranged from 162 mm in October to 327 mm in July.

Finally, evapotranspiration studies in Lebanon remain scarce and largely based on remotely sensed data. They are also concentrated in the Beqaa valley. There is definitely a need for measurements and for more studies in different locations.

#### 4.2.3. Surface hydrology

Different authors studies the hydrological characteristics of the Lebanese catchments starting from the 1940s with the work of Abd-El-Al (1959, 1951, 1949, 1949, 1948a, 1948b, 1947, 1944, 1943, 1940, n.d.). In recent decades, Sene et al. (2001, 1999) studied temporal and spatial variations in water flows in five catchments and the regional distribution of maximum instantaneous flows for 55 gauging stations in Lebanon. Despite the high temporal and spatial variability in river flows across the country, they found a regional pattern, distinguishing three regions in Lebanon based on maximum daily flow (Sene et al., 2001). This was further highlighted by Merheb (2015), who classified Lebanese catchments as a function of their physical and hydrological response characteristics. He detected a similar pattern, which further highlighted the ability to detect regionalization potential in a country with high spatial heterogeneity and little data. In addition, many Lebanese catchments, especially in western Lebanon, had a runoff ratio in the ranges of those observed in north-western Mediterranean catchments (Merheb, 2015) (Fig. 10). Indeed, Fig. 10 shows the Lebanese catchments as compared to

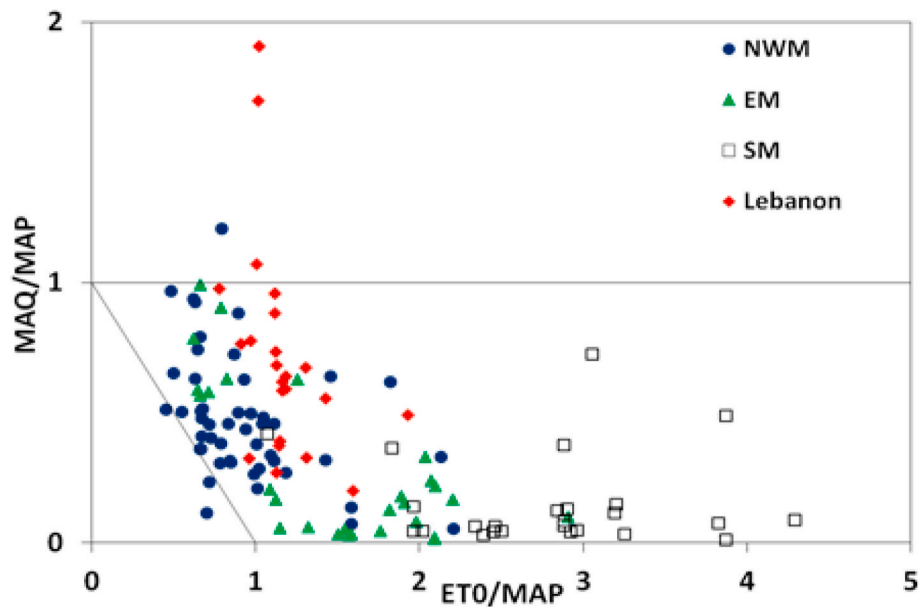


Fig. 10. Mass balance data on the Andréassian and Perrin variant of the Budyko diagram, which plots the mean annual runoff coefficient (MAQ/MAP) as a function of the aridity index ( $ET_0$ /MAP), for catchments in Lebanon (Merheb, 2015; Merheb et al., 2016) and others in the eastern, north-western, and southern Mediterranean (EM, NWM, and SM, respectively). The horizontal line (MAQ/MAP = 1) and diagonal line (MAQ = MAP -  $ET_0$ ) represent water and energy limits, respectively. The catchments falling outside these lines are either gaining or losing water (see Andréassian and Perrin (2012) for a more detailed explanation of the variant of the Budyko diagram).

other Mediterranean catchments on a hydrological variant of the Budyko diagram (Andréassian and Perrin, 2012). Conservative catchments lie within the water (MAQ = MAP), energy ( $Q = MAP - ET_0$ ) and measurements (MAQ = 0) limits. Catchments falling above the water limits are “gaining” water. This is the case of Ibrahim basin and its 2 headwaters sub-basins where hydrogeological boundaries do not correspond to the hydrological ones. Similarly, catchments falling outside the energy limits are “leaking” or losing water. The majority of Lebanese catchments falls within the conservation of mass limits albeit with high to very high runoff ratio and lower dryness index when compared to other eastern Mediterranean catchments. This can be explained by the results of studies (Shaban and Houhou, 2015; Telesca et al., 2019) that detected sub-humid to humid and even very humid conditions. River flows in Lebanon also have high inter- and intra-annual variability (Merheb, 2015; Sene et al., 1999), and the former follows precipitation dynamics. Nevertheless, the type of precipitation (rain or snow) and physical characteristics of the catchment strongly influence the intra-annual variability in river discharges, whose monthly flow peaks from February–May depending on the rain/snow input. Another influential factor is the geological substratum, as all Lebanese rivers are spring-fed and sustained through the dry season by karstic springs. An extreme example of the influence of a karstic spring is the Orontes River, which despite being in the semi-arid northeast, has a stable discharge rate of ca.  $11 \text{ m}^3/\text{s}$  because it is sustained by a karstic spring connected to a large aquifer (El-Hakim and Bakalowicz, 2007). The large contribution of snow and karstic springs to the water balance of Lebanon’s catchments becomes clearer when comparing Lebanese catchments to other Mediterranean catchments. On a Budyko diagram, Lebanese catchments have wetter conditions than others in the eastern Mediterranean and are more similar to those in the north-western Mediterranean (Fig. 11). Thus, when modelling the hydrological response of Lebanese rivers, hydrogeological factors should be included, but this is seldom done (Bou-Fakhreddine et al., 2018; Hdeib et al., 2018; Hreiche, 2003; Hreiche et al., 2006; Merheb, 2015, 2010; Merheb and Abdallah, 2022; Hamzeh H. Ramadan et al., 2012).

Few hydrological modelling studies exist at the event scale. Sene et al. (2001) is the only peer-reviewed article with estimated peak flows

for Lebanese catchments, but similar information is available in the grey literature, such as a report by (Abdallah et al., 2013) on mapping flood risks in Lebanon. Peak flows estimated by Sene et al. (2001) (from datasets from before the civil war) range from  $14 \text{ m}^3/\text{s}$  in small catchments in the Beqaa valley to up to  $748 \text{ m}^3/\text{s}$  in catchments in Mount Lebanon. Merheb et al. (2016) found that these peak flows lay within the range of those of other eastern Mediterranean catchments. The paucity of event-scale studies stems from the lack of high-resolution data. To counter this, Hdeib (2019) and Hdeib et al. (2018) developed a framework for modelling floods in ungauged basins using a coupled hydrological-hydraulic model and post-flood observations and applied it to the Awali basin. In comparison, Shaban et al. (2009) relied on remote sensing, using correlation between MODIS TERRA and TRMM images to extract flood-response characteristics of western Lebanon catchments, such as lag time, which was estimated at 1–4 days, with a mean of 2.5 days.

Daily and monthly hydro-meteorological data also have large gaps. To attempt to fill them, Bou-Fakhreddine et al. (2018) compared a two-phase constructive fuzzy inference hybrid model to a fuzzy system model. The former model yielded more accurate predictions, especially of extreme flows. The academic literature also contains traditional continuous streamflow modelling. Hreiche (2003) developed a conceptual model specifically for Mediterranean conditions – MEDOR – and applied it to six catchments in Lebanon and France. Later, Hreiche et al. (2006) developed a hydrological model (based partly on MEDOR) and combined it with a standard energy-balance approach and a degree-day snowmelt model to represent the contribution snow to the El Kalb and Ibrahim basins. Aouad-Rizk et al. (2005) used Landsat images (TM5), a digital elevation model, and field measurements to estimate snow cover area. Allam and Najem (2017) used tree time-delay artificial neural network models to model the streamflow of the Ibrahim basin, with a focus on the snow-dominated plateau. The model yielded satisfactory predictions but did not outperform MEDOR. Streamflow of the Litani basin was also modelled (Ramadan et al., 2012) using the Hillslope River Routing model (Beighley et al., 2009) at both daily and monthly time steps. The model was then used to generate a long series (1900–2008) of discharge data that was used to analyse trends.

Despite its small surface, catchment hydrological responses in Lebanon are quite heterogeneous. However, regional patterns governed mainly by precipitation amount and type and also the geological substratum do exist. Hydrological modeling studies are concentrated on specific basins and are generally at a daily or monthly time step given the data availability. More modeling studies are certainly needed. One can envisage tailored models for multiple groups of similar catchments.

#### 4.2.4. Groundwater hydrology

Groundwater is an extremely important water source in Lebanon. Groundwater resources in the country are abundant (Bakalowicz et al., 2008; Edgell, 1997) and have been exploited for millennia (Bakalowicz et al., 2002). Of the 51 groundwater basins identified by the MoEW/UNDP (2014), 45 are productive basins in different aquiferous and semi-aquiferous geological formations, and 6 are aquicludes. This number is larger than the 39 groundwater basins identified by Khair et al. (1992) and, more interestingly, than the 32 groundwater basins identified by the UNDP (1970). The former divided Lebanon into three hydrogeological provinces (i.e. West Lebanon, Beqaa, and Anti-Lebanon), each subdivided into basins and then sub-basins, while the latter divided the country into two provinces (Mediterranean and interior), which MoEW/UNDP (2014) retained. Another large difference lies in the estimated annual groundwater recharge rate: 3000 MCM (UNDP, 1970), 2542 MCM (based on mean annual rainfall) (Khair et al., 1992), or 5209 MCM (averaged over 2008–2012) (MoEW/UNDP, 2014). These differences highlight the difficulties in accurately estimating the water resources of Lebanon in general and groundwater in particular. Nevertheless, these studies agree that infiltration rates in Lebanon are high (Shaban et al., 2006) but also have high spatial variability. (Khair et al., 1992; MoEW/UNDP, 2014) agree that central Mount Lebanon has the largest estimated groundwater infiltration, the highest estimated maximum annual surface flow, and highest precipitation, but these flows are not necessarily reflected in spring discharge.

The springs in Lebanon with the largest discharge are located in the interior provinces (i.e. Beqaa and Anti-Lebanon). Lebanon contains at least hundreds (El-Fadel et al., 2000) and likely more than 2000 springs (MoEW, 2020). The MoEW/UNDP (2014) classified 409 springs by their magnitude: 7 have discharges of 1–10 m<sup>3</sup>/s, while 158 have discharges of 0.01–1 m<sup>3</sup>/s. According to Edgell (1997), Lebanon contains at least four first-magnitude karst springs, all in the interior provinces. El-Hakim and Bakalowicz (2007) classified four karstic aquifers in Lebanon (i.e. connected to the springs of Afqa, Ain Anjar, Chamsine, and Ain Zarqa. With the exception of Afqa, the springs were found to have large to very large storage capacities. The presence of carbonate aquifers with such large storage capacities can be explained by a deep strongly karstified phreatic zone that is partially or completely confined under impermeable sediments (Bakalowicz, 2015). The large storage capacities, especially for Ain Zarqa, are responsible for the low intra-annual variability in discharge of the Orontes River, and in the rest of Lebanon, emphasise the great importance of groundwater. Groundwater contribution to surface flow is crucial: the baseflow index for 1968–1972 (Sene et al., 1999) represents more than 70% of the total flow at most stations in northern Lebanon and especially those in the interior provinces, where it can reach more than 90%.

Other studies also identified characteristics of aquifers at the local scale. Ukayli (1971) studied the transmissivity and recharge rates of the karstified Cenomanian aquifer in the Beirut area. Mroueh et al. (1996) estimated the effective water volume of the Eocene and Cretaceous aquifers in south-western Lebanon at 107 and 175 MCM/year, respectively. More recently, Dubois et al. (2020) and Doummar et al. (2018) used hydrogeological modelling to study climate change impacts on the karstic springs of Qahsqoush and El Assal in Mount Lebanon. They predicted that the aquifers have good storage capacities that sustain relatively stable discharges, but that climate change would decrease these discharges. Several studies used isotopes to identify groundwater recharge areas and the main contributor (rain or snow) to recharge

(Awad, 2014a, 2014b, 2011a, 2011b).

Some relatively unexplored groundwater resources in Lebanon are its submarine karstic springs, which discharge offshore (Bakalowicz, 2014; Bakalowicz et al., 2007; Ghannam et al., 1998; Kareh, 1966). The most famous one lies offshore of the town of Chekka (Kareh, 1966). Ghannam et al. (1998) estimated the minimum annual discharge of this spring and another offshore of the city of Tyre at 650 MCM. (Shaban et al., 2005b) identified 10 offshore and 17 littoral springs using an airborne thermal infrared survey of the northern Lebanese coast combined with analysis of Landsat 7 ETM + images. Four of the submarine springs lay offshore of Chekka. Bakalowicz (2014) identified six permanent submarine springs 5–30 m below sea level and six seasonal submarine springs from 35 to 104 m that form a cluster near Chekka. Estimated mean discharge from these springs varies from 2 m<sup>3</sup>/s (Hajj, 2008) to more than 30 m<sup>3</sup>/s (Kareh, 1966). Karstic galleries, faults, and tilted strata were found to contribute the most groundwater seepage to the sea (Shaban et al., 2005b). Recently, El Hage et al. (2020) highlighted the influence of faults using Landsat thermal images (2013–2015), concluding that “faults act as conduits to channel rainwater and snowmelt from the surrounding mountains before seeping into the sea”.

Groundwater is the most important water source in Lebanon. However, hydrogeological studies are quite rare and the main ones are reports from international organisations. The advancement in remote sensing provides new opportunities for research especially for the under-exploited and potentially important submarine springs. Moreover, the development in 3D hydrogeological modelling can pave the way to a better understanding and characterization of groundwater resources in Lebanon.

#### 4.2.5. Hydro-climatic trends

Regarding climate change impacts, several studies analysed precipitation and temperature variations and trends for the entire country (Mahfouz et al., 2016; Shaban, 2009, 2011) or specific areas, such as western Lebanon (Shaban and Houhou, 2015), northern Lebanon (Arkadan, 2008; Lovallo et al., 2013) or the Litani basin (H. H. Ramadan et al., 2012; Ramadan et al., 2013). Except for Shaban (2009), who reported a 12% decrease in mean annual rainfall from 1967 to 2005, the studies highlighted no trends in annual rainfall. Trends in the temporal variability in snow cover differ among studies. Shaban et al. (2014a) and Telesca et al. (2014) identified no trends, but Shaban (2011, 2009) identified a decrease in snow cover caused by faster melting due to increasing temperature. Mahfouz et al. (2016) highlighted changes in intra-annual rainfall, with an increase in September–October, a decrease starting in February, and an increase in the frequency of extreme droughts. In addition, Shaban and Houhou (2015) and Telesca et al. (2019) detected a prevalence of humid and sub-humid conditions at most stations in western Lebanon but arid conditions at stations in the Beqaa valley.

More locally, Ramadan et al. (2013) identified a decreasing rainfall trend in the Litani basin based on more than 100 years (1900–2008) of rainfall data generated from multiple sources. They found decreasing annual rainfall precipitation at a rate of 1.1 mm/decade, with the maximum decrease in December. No significant temperature trend was found for the same period. For a subset of the data (1970–2008), they found no rainfall trend, except for an increase of 0.2 mm/decade in autumn, while temperature showed a strong warming trend of 0.2 °C/decade. In a previous study, Ramadan et al. (2012) correlated the Litani basin's temperature and rainfall series with different regional and global circulation patterns, and found moderate correlations with some indices that could explain some of the inter- and intra-annual variability.

For hydrological trends, Ramadan et al. (2013) found a significant decrease in discharge of 0.1–0.8 m<sup>3</sup>/s per decade, which was positively correlated with a decreasing rainfall trend. Similar trends were found by Shaban et al. (2014b), who used singular spectrum analysis to assess streamflow fluctuations in the Litani River from 1920 to 2009, but with



gaps in the data. They attributed the decrease mainly to climate factors but did not exclude human impacts. Similarly, land cover/use change was found to increase curve numbers in the Awali basin in southern Lebanon (Al Sayah et al., 2019). At the scale of the entire country, Shaban (2009) found that surface water decreased by 23% from 1965 to 2006.

Spring discharges in Lebanon are tending to decrease (Shaban, 2009), but few studies specifically investigated their dynamics (Shaban et al., 2014b). Groundwater depletion was also detected. Massoud et al. (2021) detected groundwater depletion signals in the Beqaa valley from 2002 to 2017, and estimated spatially varying rates of groundwater storage (i.e. from  $-11$  to  $+8$  mm/year). Similarly, Caiserman and Faour (2021), estimated a groundwater recharge deficit of  $-60$  MCM for 2017 in the Beqaa valley.

Finally, there is certainly a decrease in river discharge, and probably an increase in temperature. Precipitation trends studies provide conflicting results. Thus, the impact of climate change on Lebanon's water resources is not yet fully understood.

### 4.3. Water quality

#### 4.3.1. Surface water

**4.3.1.1. Eutrophication.** For surface water quality, Qaraoun Lake, the largest freshwater reservoir in Lebanon, is a major focus of research. These studies, seemingly from the same group of authors (Atoui et al., 2013; Fadel, 2014; Fadel et al., 2014, 2015, 2016, 2017; Sharaf et al., 2018, 2019; Slim et al., 2014), deal primarily with the problem of cyanobacteria development in the lake due to contamination of the Litani River by human activities. Fadel et al. (2014) reviewed the status of Qaraoun Lake 49 years after it was constructed and compared it to other lakes in the Mediterranean region; they found it to be "hyper-eutrophic, with low phytoplankton biodiversity and regular blooms of toxic cyanobacteria". Compared to other Mediterranean lakes, Qaraoun Lake shares the same annual toxic algae blooms but has lower phytoplankton biodiversity (Fadel et al., 2014). The methods used to study Qaraoun Lake include sampling for physico-chemical parameters, nutrients, and phytoplankton along with chemical analysis and microscopic identification of several species (Atoui et al., 2013; Fadel et al., 2014, 2015; Slim et al., 2014); sampling combined with remote sensing (Fadel et al., 2016; Sharaf et al., 2019); and hydrodynamic and ecological modelling (Fadel et al., 2017; Sharaf et al., 2018). Results of these studies confirmed the (hyper)eutrophic conditions of Qaraoun Lake, which cause toxic cyanobacteria blooms to form and decrease phytoplankton biodiversity, a situation that is worsened by increasing temperature trends in the region (Slim et al., 2014). On a technical level, hydrodynamic and ecological models of Qaraoun Lake yielded good predictions, and satellite images appear promising for monitoring it.

An earlier study of Qaraoun Lake (Jurdi et al., 2002) aimed at assessing its water quality (e.g. physico-chemical parameters, major ions, nitrate, phosphate, heavy metals) and comparing it to international guidelines. The study concluded that it was "fit for multipurpose uses, namely, drinking, domestic, recreational activities, irrigation, fisheries, livestock and industrial". As Fadel et al. (2014) state, its "nutrient and metal concentrations would not prevent the use of Qaraoun reservoir for a drinking water supply". However, the main issue is ecological eutrophication, which cannot be captured by chemical measurements alone. Even though high concentrations of metals were found in its sediments (Korfali et al., 2006), a later speciation study of the metals in its water and sediments (Korfali and Jurdi, 2011) showed a low percentage of toxic free-hydrated metal ions in its water. Studies also investigated physico-chemical parameters, microbiological contamination, and heavy metal concentrations of the upper Litani River (Haydar et al., 2014) and lower Litani River (Nehme, 2014; Nehme et al., 2014), and observed low water quality, especially in the dry season.

Three other ecological studies were performed on the Orontes, Hasbani, and El Jaouz Rivers (Khalaf et al., 2007; Slim et al., 2005, 2013). Slim et al. (2013, 2005) also included hydrochemical analysis, while Khalaf et al. (2007) considered only biodiversity. The Orontes River study found a gradient of decreasing water quality and biodiversity from upstream to downstream caused by human activity. A similar gradient of decreasing biological water quality was found in the El Jaouz River due to wastewater discharge into the river and changing hydro-climatic conditions (Khalaf et al., 2007). According to Slim et al. (2013), from an ecological viewpoint, the Hasbani River is polluted only from October–December, due to residues from olive oil production.

In summary, eutrophication is a serious problem affecting surface water quality in Lebanon, mainly in the Qaraoun lake. Other water bodies are also witnessing an important decline in ecological parameters that correlate well with increasing human activities.

**4.3.1.2. Chemical and microbiological pollution.** Various rivers were the focus of research in terms of chemical and microbiological pollution. Daou et al. (2018) compared the surface water quality of the Abu Ali, Ibrahim, Orontes, and Damour Rivers, and found that the Orontes has the highest water quality, followed by the Damour. Both the Abu Ali and Ibrahim Rivers are polluted, albeit by different sources (i.e. agricultural/domestic return flow and marble production, respectively). For all rivers, pollution increases from upstream to downstream due to increasing human activities as distance from the headwater increases. In a previous study, Daou et al. (2013) compared the surface water quality of the Ibrahim and El Kalb Rivers, and found that the downstream section of the Ibrahim is polluted by minerals from industrial activity, whereas the El Kalb is polluted more by human inputs. Similarly, Massoud (2012) studied the temporal and spatial variability in surface water quality on a downstream section of the Damour River used mainly for recreational activities. Although the water quality index indicated good water quality overall, which decreased slightly downstream, high concentrations of faecal bacteria were present in the samples. Similar results were found in the Abu Ali River by (Merhabi, 2019; Merhabi et al., 2019), who studied physico-chemical and microbiological parameters of its water at 12 points on lower sections in 2017. The results indicated good quality based on the physico-chemical parameters, but faecal bacteria exceeded the limit for recreational activities, especially at lower elevations. Microbiological contamination, with extremely high concentrations of faecal bacteria, was also found in the El Kabir River (Hamze et al., 2005). Organic pollutants (i.e. polycyclic aromatic hydrocarbons (PAHs)), were also identified at the mouths of the El Kabir, El Bared, and Abu Ali Rivers (Amine et al., 2018). More recently, Jabali et al. (2021) measured PAH concentrations at multiple sites along the Abu Ali River, and found that PAHs were absent upstream, but their concentrations increased gradually downstream, where they peaked. Another recent study (Dagher et al., 2021) found the presence of microbiological pollution in more than 90% of rivers in Lebanon. Relatively high concentrations of some heavy metals (i.e. Fe, Zn, Cu, Pb) were found at some sites on the Ibrahim River (Korfali and Davies, 2003). In contrast, analysis of the Oustouene River showed no heavy metal pollution (Bouaoun & Nabbout, 2016).

Finally, chemical and especially microbiological pollution pose a serious threat to surface water quality in almost all of the Lebanese rivers. Like with ecological pollution, it is highly associated to human activities.

**4.3.1.3. Pesticides.** Several types of pesticides, some of which are on priority pollutant lists of the US Environmental Protection Agency and the EU, were detected in various Lebanese rivers. The concentrations, which were monitored for 12 months in the Litani River, Qaraoun Lake, and the Orontes River (Kouzayha et al., 2013), varied by season due to agricultural activities. A review of the data available on polychlorinated biphenyls and organochlorine pesticides in Lebanon (Helou et al., 2019)



highlights the extent of pesticide pollution in the Litani, Ibrahim, and Hasbani Rivers. Concentrations of DDE (dichlorodiphenyldichloroethylene) were much higher in Lebanese rivers than in those of other countries. High concentrations of pesticides were also measured, and bacteria (e.g. faecal coliform, salmonella) were found in the Hasbani River (Badr et al., 2014).

Although the studies are scarce, pesticides are being detected in the surface water of major Lebanese rivers especially in agricultural areas. This certainly calls for a monitoring program and more studies to better assess the situation.

#### 4.3.2. Groundwater

**4.3.2.1. General hydrogeochemistry.** Groundwater quality is a major research topic in Lebanon. Regarding general hydrochemical characteristics, most of the dominant groundwater hydrochemical facies are calcium-magnesium-bicarbonate (MoEW/UNDP, 2014), because Lebanon's aquifer-forming rocks are composed mainly of calcite ( $\text{CaCO}_3$ ) and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). This is the case for most groundwater samples analysed from springs and wells in eastern Mount Lebanon, Beqaa, and Anti-Lebanon provinces by Awad (2011) and El Hakim (2005), most Ibrahim basin groundwater samples (Hanna et al., 2018), the Damour aquifer (Khadra et al., 2017), and most Abu Ali basin groundwater samples (Al-Haj, 2021). The facies shift towards mixed calcium-magnesium-sulphate or sodium-chloride appears as the degree of saltwater intrusion increases (El-Fadel et al., 2014; Halwani et al., 2001; Khadra et al., 2017; Khadra and Stuyfzand, 2018; Masciopinto, 2013).

**4.3.2.2. Saltwater intrusion.** Saltwater intrusion is a major concern in coastal aquifers, especially near large urban areas, and is common in the entire Mediterranean basin (Balzan et al., 2020). Signs of salinisation were detected in Beirut's coastal aquifer in the 1980s (Lababidi et al., 1987) and were verified by more recent studies (Acra and Ayoub, 2001). Saltwater intrusion was also detected in Greater Beirut and its southern suburbs (Moujabber et al., 2006; Saadeh, 2008; Samad et al., 2017), cities further south (e.g. Damour) (Khadra et al., 2017; Khadra and Stuyfzand, 2018; Masciopinto, 2013), other coastal cities (e.g. Tripoli (El Moujabber et al., 2013; Kalaoun et al., 2016) and Byblos (El Chami et al., 2009), and coastal plains such as Akkar (Halwani et al., 2001). Saltwater-intrusion studies have also simulated the extent and behaviour of saltwater-affected groundwater (Kalaoun et al., 2016; Khadra and Stuyfzand, 2018; Masciopinto, 2013).

Almost all groundwater quality studies in coastal areas point to a problem of saltwater intrusion driven by the increasing demographic pressure on the Lebanese coasts.

**4.3.2.3. Chemical pollution.** Pollution by trace elements has been investigated and detected in several aquifers across Lebanon. Darwish et al. (2008) detected high concentrations of minor ions in the Beqaa valley. Similarly, high concentrations of heavy metals were detected in a coastal aquifer near Damour (Khadra et al., 2017). High concentrations of cadmium were detected in several parts of Mount Lebanon (Halwani et al., 2020). In contrast, low concentrations of heavy metals were found in the aquifer of the Akkar plain (Halwani et al., 2001; Moustafa et al., 2019). Radiometric pollution in the form of radon was also investigated by Abdallah et al. (2007), who found that all 20 samples analysed had concentrations lower than those in the EU and US guidelines.

In summary, the number of studies on heavy metals and radiometric pollution in groundwater is low, most likely due to the cost. However, when studied, heavy metals are being detected, while radiometric pollution appears to be absent.

**4.3.2.4. Nitrate and pesticide pollution.** Pollution from agricultural activity (e.g. nitrate, pesticides) is another major concern for groundwater

quality in Lebanon. Nitrate pollution was observed in aquifers on the Akkar plain (Halwani et al., 2000), Tripoli (El-Hoz et al., 2014), and in the central Beqaa valley (Assaf and Saadeh, 2009; Darwish et al., 2008). Several types of pesticides have been detected in many aquifers, including on the Akkar plain (Chbib, 2017; Chbib et al., 2018, 2020; El Osmani et al., 2014), Tripoli (Jabali et al., 2020), and southern Litani basin (Youssef et al., 2015). Kouzayha et al. (2013) analysed groundwater samples collected from villages in northern Lebanon, eastern Beqaa (Terbol), and a village (Zawtar) in southern Lebanon for 67 pesticides from multiple classes. Overall, 28 pesticides were detected in some or all the samples studied. Some of the frequently detected pesticides are organochlorines, which are persistent organic pollutants that tend to bioaccumulate in organic tissues and have been prohibited in Lebanon since 1992. In addition, PAHs have been detected in the groundwater of Abu Ali basin (Jabali et al., 2021).

Finally, the available studies point towards a serious problem related to nitrate and pesticides pollution in agricultural areas all over Lebanon.

**4.3.2.5. Microbiological pollution.** Microbiological pollution has been detected in groundwater samples across Lebanon. For example, faecal coliform bacteria were detected in groundwater from Beirut (Citton et al., 2020), Tripoli (El-Fadel et al., 2014; El-Hoz et al., 2014), the Damour area (Masciopinto, 2013) and a village in southern Lebanon (Baalbaki et al., 2019). Groundwater in Lebanon is highly susceptible to pollution, as the karstified nature of the outcropping geological formations favours rapid infiltration (Metni et al., 2004).

Finally, and despite the relatively low number of studies, one can conclude that microbiological pollution is a cause of concern for groundwater in Lebanon.

#### 4.4. Water management

##### 4.4.1. Assessment of water resources

As famously stated, "you can't manage what you don't measure", and this is perhaps the main issue for water management in Lebanon. The first weather stations pre-date the establishment of Lebanon: 1875 for the station at the American University of Beirut and 1906 for the Ksara observatory, operated by the Université Saint Joseph, and the number of stations increased during and after the French mandate. By 1940, Lebanon had 31 weather stations (Merheb, 2015), whose number peaked in 1970 at 139. Unfortunately, the civil war ended observations (except for those at the Beirut Airport, Tripoli, and Zahle). The network was reconstructed after the war, beginning in 1994, but only 37 stations were operational by 1997. These stations are operated by the Lebanon Meteorological Service, but Lebanon has many other weather stations operated by other government authorities or private institutions. For example, the Lebanese Agricultural Research Institute (LARI) reports 80 operational weather stations (<http://www.lari.gov.lb/>) (but the national water-sector strategy (NWSS) (MoEW, 2020) indicates 60 stations, with only 30 operational). However, most these stations were installed after 2009 and thus cannot yet provide long time series. Currently, Lebanon has 135 weather stations, but not all are operational (MoEW, 2020). The spatial extent of the network is also problematic, as few stations exist at high elevation or in the Lebanon's eastern mountains, which causes precipitation to be underestimated.

Similarly, the hydrometric network started in 1931 with stations on the Litani and Orontes Rivers. The number of stations increased gradually, especially in the 1960s, and peaked just before the civil war, with 150 hydrometric stations on multiple rivers, springs, and canals. However, the civil war destroyed the network, and reconstruction did not start until 1990. By 2016, Lebanon had 138 operational hydrometric stations. Like the weather stations, however, the hydrometric network has highly fragmented time series and relatively low-quality measurements. The hydrometric stations are managed by the LRA and RWEs.

Surface-water storage consists of 13 reservoirs (excluding hill lakes)

that have a total static and dynamic storage of 220 and 364 MCM, respectively. Of the 13, four supply drinking water; two supply irrigation water; four supply both drinking and irrigation water; and three supply drinking water, irrigation water, and hydropower.

Regarding groundwater, Lebanon has more than 2000 springs (MoEW/UNDP, 2014), of which 275 are tapped (MoEW, 2020). The latter report estimates that springs in Lebanon have an annual discharge of more than 2000 MCM and states that there are 1193 operational public wells (and 422 non-operational), which have a total flow of 1.5 MCM/day. However, there is a large, but unknown, number of illegal wells, which have an estimated density of more than 5 wells/km<sup>2</sup> (MoEW/UNDP, 2014). If this estimate is correct, then Lebanon has more than 50,000 illegal wells. Hydrogeological studies are spatially scattered and still-based on older 1:50,000 scale geological maps, which makes it difficult to estimate Lebanon’s groundwater resources accurately.

The measurement problem is obvious when trying to determine Lebanon’s water balance, because estimates differ greatly among sources. The MoEW (2020) NWSS report provides water balances from nine sources. While estimates of precipitation vary among sources, the main difference is the estimate of ET. Precipitation estimates vary from 7830 MCM for a dry year to 11,932 MCM for a wet year. Many sources estimate it at ca. 8600 MCM (FAO, 2008; Plassard, 1972), while the World Bank (2003) estimates it at 9800 MCM. The MoEW (2020) NWSS report chose a water-balance approach that estimated annual precipitation at 8559 MCM/year and ET as only 30% of it, which is much lower than the ET estimate of the MoEW (2010) NWSS report. This change results in more precipitation available for surface (25%) and groundwater flow (45%) and thus more available water resources, estimated at 4225 MCM/year, which is much higher than earlier estimates, such as the FAO’s (2008) 2080 MCM/year. The MoEW (2020) NWSS report also differs from the general post-war narrative of water scarcity, stating that available water resources in Lebanon can cover the projected demand until at least 2035, even with increasing climatic and demographic

pressure.

In summary, the fragmented nature of hydro-meteorological measurements in Lebanon constitute a major challenge for an accurate estimation of the water resources of the country. While the number of stations increased in the recent years, the records are still short and the spatial distribution of the stations is not coherent. In addition, snow monitoring and evapotranspiration measurements remain scarce. There is an urgent need to extend and enhance the observation network.

#### 4.4.2. Water supply and wastewater

The CDR (2018) mapped the extents of the water-supply and wastewater networks in Lebanon (Fig. 11a and b).

Although these maps are now slightly outdated, the water-supply network covers most of Lebanon, but this does not directly reflect the percentage of the population connected to it. The percentage of households or the population connected to it (in 1998 (Riachi, 2013) or 2020 (MoEW, 2020), respectively) varied among regions and seems to have decreased in areas other than the BMLWE (Table 1).

**Table 1**

Percentage access to the water supply network of Lebanon’s regional water establishments in 1998 (Riachi, 2013) and 2020 (MoEW, 2020). BMLWE: Beirut and Mount Lebanon Water Establishment, NLWE: North Lebanon Water Establishment, BWE: Beqaa Water Establishment, SLWE: South Lebanon Water Establishment.

Sources	MASL	NWSS
Year	1998	2020
Unit	Households	Population
BMLWE	85.5%	92%
NLWE	68.3%	67%
BWE	76%	48%
SLWE	77.2%	34%

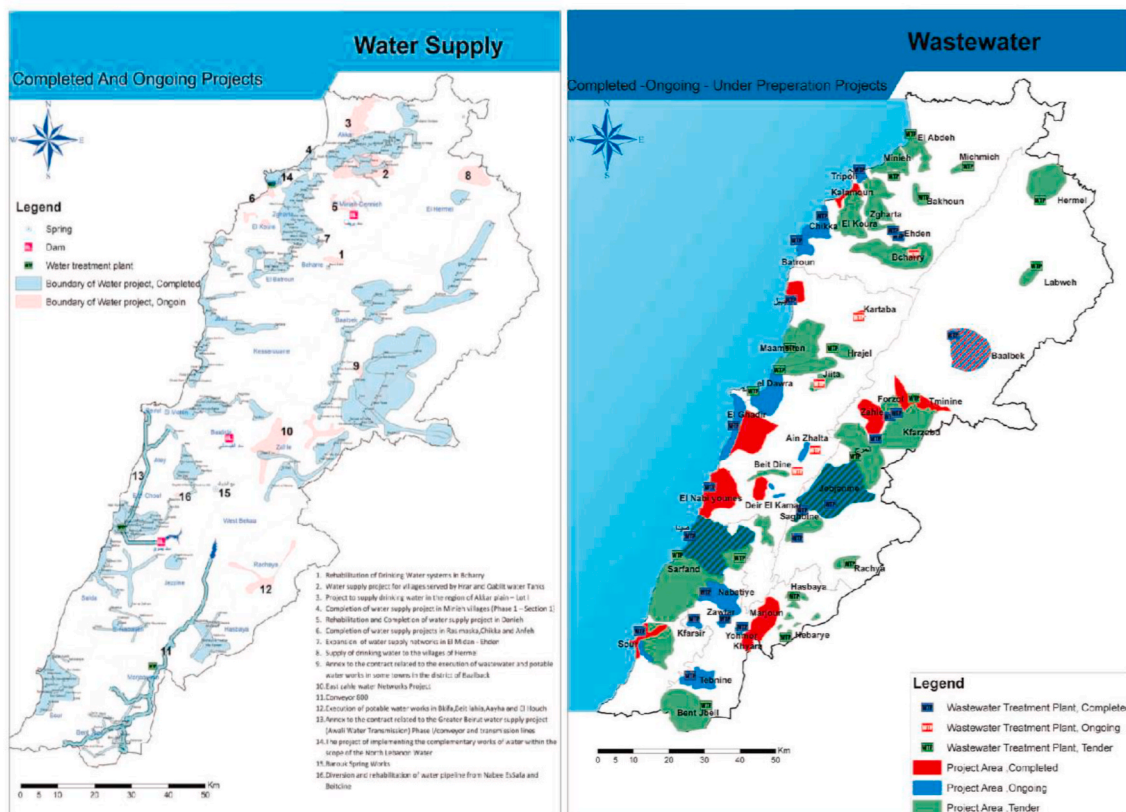


Fig. 11. Current and completed projects of the (a) water-supply network and (b) wastewater network in Lebanon. Source: (CDR, 2018).

The problem is not the supply itself, which is higher than the MENA region mean, but its intermittence, which degrades water quality because it requires people to store water; thus, drinking water quality is a major issue in Lebanon. El-Fadel et al. (2003) reported alarming statistics from the Lebanon's Ministry of Health indicating microbiological contamination of 40% of 863 and 24% of 450 water samples collected from drinking water networks and water vending companies, respectively, across Lebanon. The study also analysed 65 water samples collected from water vendors in the southern suburbs of Beirut and found total faecal coliform contamination in 37% of them. The intermittent supply worsens this situation. Ayoub and Malaeb (2006) studied effects of travel distance on chlorine decay in Beirut's water supply, and highlighted that the intermittent supply created variable chlorine concentrations, which greatly degraded water quality and could cause potential health problems. Rural areas in Lebanon also face challenges in accessing safe drinking water (Massoud et al., 2010). According to the UN SDG database, 2023, only 46% of the Lebanese population have access to safely managed drinking water; consequently, 40% of the population drink bottled water (Riachi, 2013).

Similarly, although the wastewater network covers most of Lebanon, only 26% of Lebanese population have safely managed wastewater, perhaps because the network does not discharge into a wastewater treatment plant. According to MoEW (2020), 53 out of 75 existing wastewater treatment plants are operational, which treat 30% of the wastewater volume generated. Moreover, 85% of the waste is treated only at a primary level.

In summary, while the water supply and wastewater networks expanded in the recent decades, access to the services is still limited especially in rural areas. Moreover, the intermittent nature of the supply and the absence of adequate wastewater treatment plants pose serious public health concerns.

#### 4.4.3. Irrigation

McCroly (1948) reported that 44,000 ha were irrigated in Lebanon, with another five projects being planned or under construction that would increase the irrigated area by 40,000 ha. Two of the projects, Yammounh (13,000 ha), which began operating in the early 1930s (Hydraulic Study Board, 1930), and Qasmiyeh (5000 ha), were already functional and being expanded. The remaining three were being planned in southern Beqaa valley (15,000 ha), the Akkar and El Mineyh area (13,500 ha), and El Qaa in north-eastern Lebanon (6000 ha). The report also indicated that another 44,000 ha were to be irrigated later, putting the total irrigated area at 128,000 ha, which is similar to the current irrigated area in Lebanon (MoA/FAO, 2012).

According to MoA/FAO (2012), Lebanon exploits 232,200 ha of agricultural land, of which 49% (ca. 113,000 ha) are irrigated, an 8% increase since 1998. However, the area of irrigated land varies among sources. The CDR (2018) indicates that ca. 100,000 ha are irrigated, mainly in the Beqaa valley (66%) and the north (23%), and the NWSS (MoEW, 2020) reports a similar area.

The MoA/FAO (2012) survey details that 39.2% of the irrigated land use surface water (i.e. rivers and springs), 49.8% use groundwater (i.e. from wells), and the rest uses water from cisterns (6.6%), hill lakes (2.9%), and other sources, which further highlights the importance of groundwater in Lebanon. Of the irrigated land, 49.5% use traditional surface irrigation, and the rest is divided almost equally between sprinkler and drip irrigation. The survey does not report the volume of water used for irrigation, but the NWSS (MoEW, 2020) reports ca. 1684 MCM/year of irrigation water (i.e. a mean of 8435 m<sup>3</sup>/ha/year). Irrigation requirements vary spatially, however, ranging from 6500 m<sup>3</sup>/ha in the more humid Mount Lebanon province to 9000 m<sup>3</sup>/ha in the Beqaa valley. The percentage of agricultural land that is irrigated also varies spatially, with the agricultural Beqaa valley having the highest percentages (i.e. from 55% in the north to 72% in the centre and south) and the second-most-important agricultural area, the Akkar plain, having only 44% (MoA/FAO, 2012).

Finally, it appears that irrigated lands area in Lebanon remained relatively stable over the history of independent Lebanon. Furthermore, groundwater is the main water source for irrigation, further highlighting its importance.

#### 4.4.4. Hydropower

Hydropower production is an essential component of water projects in Lebanon. The first hydropower plant was constructed on the Abu Ali River in 1929. Later, McCroly (1948) reported two main plants that produced 16,700 kW, along with other small plants, and mentioned plans to build another four plants on Yammounh Lake and the Orontes, Litani, and Ibrahim Rivers, for a total production of 89,300 kW. However, the plant on the Orontes was not built, likely for geopolitical reasons. Nevertheless, the number increased gradually, and by 1975, there were 16 hydropower plants on eight rivers. These plants produced ca. 70% of all electricity produced in Lebanon (Moore and Collins, 2020). Sanlaville (1965) reported that hydropower produced more electricity in Lebanon than thermal production did, but he also highlighted its limitations in Lebanon given the country's steep terrain and strong seasonality of river discharges, which has a phase opposite to that of energy consumption.

The main hydropower plants are located on the Litani River, and currently, Lebanon has only 12 plants on five rivers (Houry, 2006). Hydropower production now represents only 4–7% of all electricity produced in Lebanon (Moore and Collins, 2020). Hydropower production in Lebanon also has high inter-annual variability (Kinab and Elkhoury, 2012), which limits using it as a primary source of electricity.

Finally, the share of hydropower in Lebanon's electricity decreased over the years. Although the country has ample water resources, a combination of both natural and socio-political factors resulted in a reduced dependency on hydropower.

#### 4.5. Water governance

##### 4.5.1. Legal framework

Several laws, decrees, and orders govern Lebanon's water sector (Supplementary Material B.2). The first modern legislative text on water use came from Ottoman civil law in 1877. Before this date, water use was governed by customs derived primarily from Islamic law. This was followed by the Ottoman irrigation code in 1913 (Farajalla et al., 2015; Riachi, 2013). Elements of these laws still exist in Lebanon's water-sector legislation to this day (MoEW, 2020). Although Ottoman civil law acknowledged that all people had the right to drinking water, it did allow ownership of water rights by private individuals. This was further asserted by an order issued in 1920 by the French-mandate government, whose authorities wanted to encourage investment in water projects by focusing on individual water rights. In the same spirit, order no. 320 of 1926 allowed private property owners to dig wells without prior authorisation if the discharge was less than 100 m<sup>3</sup>/d. This particular legislation was problematic as it greatly increased the number of private wells, even though it was amended by a decree in 1970 that regulated groundwater exploration. Well installation did not require a licence until 2010.

Laws and decrees were passed to regulate aspects of the water sector, including the creation of multiple water authorities and the relations between them. In this context, the Ministry of Hydraulic and Electrical Resources (MRHEL) was created in the 1960s but many water offices and local water and irrigation authorities were created before it, in particular the Litani River Authority (LRA), created in 1954.

Lebanese water laws were amended greatly after the civil war, in 2000 and in 2001. These laws changed the structure of Lebanon's water sector by merging many water authorities into four semi-autonomous regional water establishments (RWEs) responsible for Beirut and Mount Lebanon (BMLWE), Northern Lebanon (NLWE), Beqaa (BWE), and South Lebanon (SLWE). Along with these RWEs, the LRA remains operational and has a similar status. These water authorities are



supervised by the General Directorate of Exploitation of the MoEW (changed from the MRHEL). During the same period, a law for national privatisation was also passed to favour the involvement of the private sector in all projects, including in the water sector. Recently, a new Lebanese water code was set in 2018 and amended in 2020. In addition, many laws and decrees that regulate water quality, both for drinking water and environmental protection, also exist in the legislative literature of Lebanon's water sector.

In summary, a complex framework of laws, decrees, and orders that evolved over time influenced by historical and political factors governs the water sector in Lebanon. Despite several attempts that were made to modernize this framework, law enforcement remains subject to the complicated sectarian politics of the country.

#### 4.5.2. Institutional framework

A complex institutional framework currently governs Lebanon's water sector (Fig. 12), but it is recent, having been reformed in the early 2000s. The previous framework had been shaped progressively and in a fragmented manner with the development of several water offices in the major cities. In the 1930s, the Hydraulic Study Board was established under the supervision of the Ministry of Public Affairs, which remained the case until the MRHEL was established and made responsible for the water sector.

By the 1970s, Lebanon had more than 20 water authorities (Riachi, 2013), which created difficulties for governing the sector. The government planned to merge them into five RWEs, but the civil war halted this project until the early 2000s. The RWEs were designed as semi-autonomous bodies governed like a company with an administrative board (Eid-Sabbagh, 2015) to increase efficiency and the budget, which were the main problems that faced the previous local water authorities. However, the situation is more complicated, as not only do the MoEW and RWEs govern the water sector, so do the Ministries of Agriculture, Public Health, Public Works, Environment, and Finance. However, the main institution in the water sector is the CDR, which

serves as a kind of "super-ministry".

The World Bank (2010) identified five entities as the main investors in the water-supply and wastewater sectors: the CDR (created in 1977 to help reconstruct Lebanon), MoEW, Council of the South (created to help citizens of southern Lebanon after Israeli occupation), Central Fund for the Displaced (CFD, created to help displaced people return home after the civil war), and the LRA. Three of these entities reflect Lebanon's turbulent past.

The CDR is the main investor in the water-supply and wastewater sectors. From 1994 to 2008, the CDR signed a mean of 42 contracts per year worth US\$98 million per year (World Bank, 2010). The CDR website provides a portal that shows all of its contracts (<https://portal.cdr.gov.lb/contracts>). From 1991 to 2023, the CDR took on more than 450 water-supply projects (total value of US\$1.206 billion), more than 400 wastewater projects (total value of US\$686 million), and 99 irrigation projects (total value of US\$76.8 million) (Supplementary Material B.3).

The CDR is responsible for performing all major infrastructure projects in Lebanon, including those in the water sector (Fig. 12). The MoEW delegates projects to the CDR, which in turn hires private companies to build the projects. The CDR should work closely with the RWEs and local authorities, mainly municipalities, but this is not the case, as cooperation among actors of the water sector is weak. Once completed, the projects that the CDR managed are placed under the authority of the RWEs, which face major difficulties in operating and maintaining the projects (MoEW, 2020). The CDR is financed mainly by donations and loans from international donors, which not only finance water projects but also provide technical support to the MoEW and capacity building for RWEs, the LRA, local municipalities, and actors in the water sector.

Similar to the legal framework, the institutional framework that governs the water sector in Lebanon is complex. Despite the modernization restructuring made in the recent decades, the roles of different institutions remain overlapping, unclear and sometimes redundant. A particular aspect however, is the increasing reliance on the private

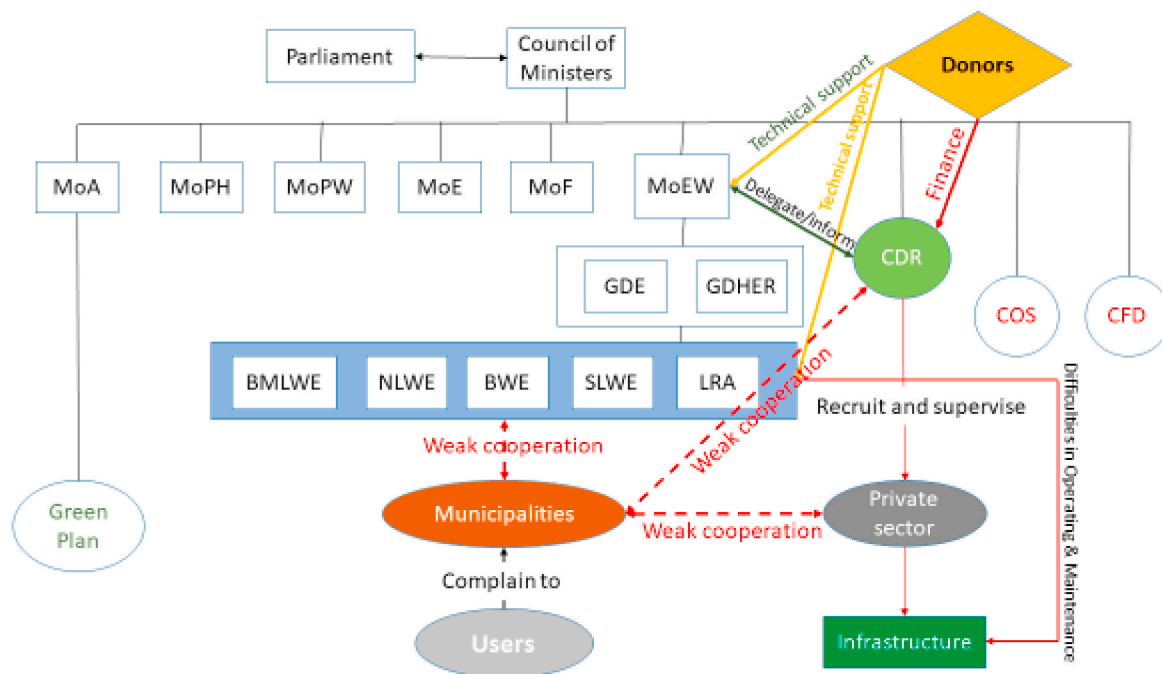


Fig. 12. Institutional framework of the water sector in Lebanon. Based on (Eid-Sabbagh, 2015; MoEW, 2020). MoA: Ministry of Agriculture; MOPH: Ministry of Public Health; MoE: Ministry of Environment; MoF: Ministry of Finance; MoEW: Ministry of Energy and Water; GDE: General Directorate of Exploitation; GDHER: General Directorate of Hydraulic and Electrical Resources; CDR: Council of Development and Reconstruction; BMLWE: Beirut and Mount Lebanon Water Establishment; NLWE: North Lebanon Water Establishment; BWE: Beqaa Water Establishment; SLWE: South Lebanon Water Establishment; LRA: Litani River Authority; COS: Council of the South; CFD: Central Fund for the Displaced; Green Plan: a support program by the MoA. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



sector for project implementation.

#### 4.5.3. International cooperation

The involvement of international partners in the governance and management of Lebanon's water sector is older than the country itself. As mentioned, Protestant and Jesuit missionaries established the first weather stations on the territories of what would become Lebanon. In the 1870s, a British company established the first water-supply project in Beirut, and many hydraulic and irrigation projects were built during the French mandate; however, we focus on the period since Lebanon's independence in 1943.

Soon after independence, Lebanon applied for a loan from the World Bank, which it received in 1952, after a report for the World Bank (McCrorry, 1948) that assessed the situation of Lebanon's water sector, especially its irrigation and hydropower projects. Later in the 1950s, a huge project of the US Bureau of Reclamation (USBR, 1954, 1951) assessed each of 10 major Lebanese rivers by installing gauging stations and producing detailed reports with an estimated water balance, hydrometric study, economic assessment, and potential projects. The project focused in particular on the Litani River, with the aim of transposing the Tennessee Valley Authority model of catchment management (Sneddon and Fox, 2011), which was reflected by the establishment of the LRA during this period.

In the 1960s, a UNDP project performed a detailed hydrogeological assessment of Lebanon that inventoried 1481 wells, 1031 boreholes, and 1121 springs; provided hydrochemical analysis and geophysical assessment; and estimated a national water budget (UNDP, 1970). Another important project was a cooperation between the MRHEL and UNDP in 1973 to perform the first assessment of Lebanon's wastewater sector (MRHEL/UNDP, 1973).

The involvement of international partners increased greatly after the civil war, as reflected by the influence of the "International Development Complex" (Eid-Sabbagh, 2015) in governing Lebanon's water sector. This shift towards a water sector that is heavily financed by international donations and loans, but that also has greater involvement by the private sector, follows a worldwide paradigm shift in the management of water resources from the public to the private sector, due to the increasing dominance of neo-liberal policies (Eid-Sabbagh, 2015; Riachi, 2013). This is reflected by the large investment of international donors in Lebanon's water sector: the CDR received US\$2.36 billion for water projects from 1991 to 2023 (Supplementary Material B.4). This amount excludes investment by other international partners (e.g. US and UN agencies), who worked with other water-sector actors, such as the MoEW, Ministry of Environment, and RWEs or authorities.

The World Bank is one of the main donors to Lebanon's water sector, becoming involved as early as the 1940s and its influence increased after the civil war. In 1994, it loaned the CDR funds to reconstruct water infrastructure destroyed during the war (World Bank, 1994). The World Bank went beyond providing loans, by producing reports on Lebanon's water sector, including a policy note on sustainability of the irrigation sector (World Bank, 2003), a public expenditure review (World Bank, 2010), social impact analysis (World Bank, 2009), environmental and social impact assessment of the Beirut water-supply project (World Bank, 2014), assessment of Lebanon's water-sector strategy (World Bank, 2012), and the book *Droughts and Agriculture in Lebanon* (Verner et al., 2018).

Similarly, the USAID funded the Lebanon Water Project (2015–2020) (US\$65 million) to increase access to clean and reliable water sources, the Litani River Basin Management Support Project (2009–2015) to help the LRA improve sustainable management of the basin, and the Lebanon Water and Wastewater Support Program (2009–2015). The UNDP also funded several water-sector projects in Lebanon, such as a groundwater assessment report (MoEW/UNDP, 2014). Projects of the UNDP (and its associates) also focus on Lebanon's overall environmental situation (UNDP et al., 2020) and the impact of emerging crises, such as the Syrian refugee crisis (MoE/EU/UNDP, 2015; 2014).

In the end, international cooperation was always an important element in the governance of the Lebanese water sector. However, one should highlight the huge increase in the role of international organisations in financing and implementing water projects since the end of civil war.

## 5. Discussion

This work is not the first attempt to characterize some aspects of Lebanon's water resources. Indeed, many academic studies have been published in recent decades. Earlier studies focused on the volume of water resources (Bou-Zeid and El-Fadel, 2002; El-Fadel et al., 2000) and human impacts (Khair et al., 1994). More recently, the book *Water Resources of Lebanon* (Shaban, 2020) presented the knowledge on the Lebanese water resources from the available data. Lebanon was also included in several studies of the Mediterranean region, such as those of water-resource management (Correia, 1999), global-change impacts (García-Ruiz et al., 2011; Milano et al., 2013), drought variability (Cook et al., 2016), hydrological response characteristics (Merheb et al., 2016), catchment classification (Allam et al., 2021), climate trends (Alpert et al., 2008; Philandras et al., 2011), and groundwater hydro-geochemistry (Al Haj et al., 2023). Lebanon was also included in studies of the Middle East (Chenoweth et al., 2011; Izdebski et al., 2016; Kushnir and Stein, 2019).

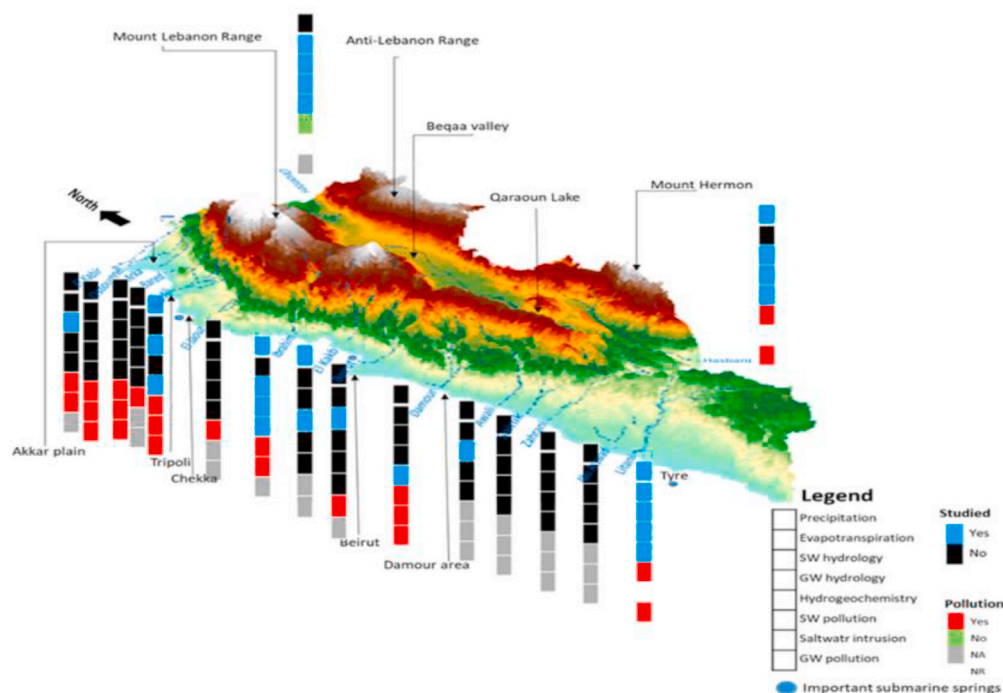
This work is, to our knowledge, the first attempt to synthesize the current state of knowledge with regards to not only the hydrological cycle, but also water quality, management and governance through a literature review of peer-reviewed and grey literature. Fig. 13 summarises the main findings and the following discusses the main results in terms of current state of knowledge and possible future directions.

### 5.1. Current state of knowledge

Precipitation in Lebanon has been understudied. No updated rainfall map of Lebanon exists; the most reliable one is for annual rainfall and dates from 1972 (Plassard, 1972). Similarly, the only thorough statistical analysis of temporal variability in rainfall also dates from the 1970s (Blanchet, 1976). The available information on snow cover and its contribution to Lebanon's water budget varies among authors (Mhaweij et al., 2014; Shaban et al., 2014a; Telesca et al., 2014). Several studies relied heavily on remote sensing to monitor snow and estimate SWE because continuous measurements are limited to only three stations in north-central Mount Lebanon. As mentioned, the number of weather stations has increased greatly in recent years. There are currently ca. 135 stations (MoEW, 2020), but they are managed by several authorities, and most do not provide long time series. Their spatial distribution remains asymmetrical, with a higher density of stations in central Lebanon and a lower density on the highest peaks and in eastern Lebanon.

Estimating ET is another issue. All studies of ET were limited to the Beqaa valley, and most were crop-specific. Using remote sensing helps estimate ET, but the studies that used it also had a small geographic extent. Nevertheless, the available information indicates high spatial variability in ET. Most ET comes from blue water due to irrigation during the dry season. Thus, the percentage of precipitation lost to ET is lower than the 50% generally reported in the literature, as ET peaks when there is no rainfall. MoEW/UNDP (2014) estimated real ET as 16% of total annual precipitation from 2008 to 2012, which the recent NWSS (MoEW, 2020) considered when it estimated ET as only 30% of total precipitation.

Surface-water studies are rare, due to gaps in flow measurements and especially their low temporal resolution. Most are available only at a daily time step, which limits studies to continuous flow modelling, water-resource management, or trend analysis. Flood-response characteristics are another challenge, as peak-flow estimates are available only for pre-civil war data. In recent decades, post-flood studies were used to estimate peak flows, but they were limited to a few catchments. River



**Fig. 13.** Summary of knowledge about Lebanon's water balance (top five compartments per bar) and water quality (bottom three compartments per bar), by river basin (each bar). The colours indicate "Yes", "No", "not applicable" (NA), or "not researched" (NR), SW: surface water, GW: groundwater. A detailed description of this figure is available in Supplementary Material B.5 (a) and (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

flows in Lebanon have high temporal and spatial variability (inter- and intra-annual). Base flow is crucial and is the only water input component during the dry season. Groundwater resources are extremely important, but they have yet to be fully assessed and appear to be overexploited. Some aquifers have unusually high storage capacity that can maintain high discharges throughout the year, and a large volume of groundwater flows as submarine springs. Unfortunately, both surface and groundwater resources exhibit signs of depletion, mainly due to human impacts.

Regarding climate change impacts, precipitation, ET, and snow cover showed no trends in inter-annual variability, and only one study (Mahfouz et al., 2016) reported a shift in intra-annual rainfall. That study noted that the number of snowy days and the duration of snow cover were half those of Blanchet (1976) and of recent studies, especially for areas above 1500 m; thus, this subject requires more research. If this decrease is accurate, it would indicate an enormous shift in the precipitation pattern of the country. Most contemporary studies report that snow patches remain on the Mount Lebanon range until June, which differs from earlier reports (Blanchet, 1976; Russell, 1950) and from recent studies that report snow later in the year (Abou Chakra et al., 2019, 2020).

The quality of water resources in Lebanon is degrading rapidly. Most rivers exhibit some degree of pollution that increases from upstream to downstream. Dagher et al. (2021) found that nearly all Lebanese rivers have microbiological pollution. An extreme example of water-quality degradation is Qaraoun Lake, which experiences hypereutrophic conditions and frequent blooms of toxic cyanobacteria (Fadel, 2014). Groundwater pollution is also a major problem, with most coastal aquifers experiencing saltwater intrusion. Nitrate and pesticide pollution are starting to become a problem in agricultural areas, and emergent pollutants (e.g. organic pollutants) are being detected in surface and groundwater bodies (Helou et al., 2019; Jabali, 2017; Jabali et al., 2020, 2021).

Lebanon's water governance framework is complex, involving many laws, institutions, and international partners. Reforms in the early 2000s

aimed at streamlining and improving sector governance, but challenges remain, particularly coordination among entities. International cooperation remains crucial for addressing Lebanon's water-related challenges and developing sustainable water-management practices.

Water management in Lebanon experienced two phases: pre-civil-war, with more state-centred projects, and post-civil-war, with a huge increase in the number of projects funded by international donors and the private sector. Nevertheless, access to a public water network increased, despite its intermittent supply. However, the current economic crisis in Lebanon has caused fuel shortages, which have decreased the number of hours of water supply. This intermittent supply degrades water quality and forces people to drink bottled water. The wastewater network is also improving and being extended to most rural areas and suburbs; however, wastewater treatment plants remain below the capacity needed, and most are limited to primary treatment. Lebanon has good hydropower potential, albeit with limitations due to the seasonality of discharges. However, the percentage of electricity produced from hydropower remains low. Nevertheless, water management in Lebanon still faces major challenges, mainly inadequate data collection, water-quality concerns, and regional differences in access to water supply and wastewater treatment. Despite improvements in recent decades, management of water resources remains complex, and Lebanon's available water resources continue to be a subject of debate.

The complex geopolitical situation in the Middle East places further strains on water-resource management in Lebanon, as does mismanagement, which decreases its ability to ensure adequate water services (Makdisi, 2007). Lebanon shares three catchments with neighbouring countries: the Orontes and El Kabir basins (Shaban et al., 2005a) with Syria and the Hasbani basin (Comair et al., 2012), which lies in the Upper Jordan basin, with Israel. Syria's power over Lebanon gave it the upper hand in sharing transboundary water resources, especially the Orontes River (Conker and Hussein, 2020). In comparison, the conflict between Lebanon and Israel is reflected by the large difference in estimated water withdrawal in the Hasbani basin (Merheb, 2010; Merheb and Abdallah, 2022; Shentsis et al., 2021). Even rivers completely

within Lebanon, especially the Litani River, were subject to geopolitical conflicts (Amery, 1993). The Syrian crisis has created an influx of refugees that strengthened the local discourse of water crisis and scarcity in Lebanon (Hussein et al., 2020). Although the crisis has decreased water demand for irrigation in the Syrian part of the Orontes River (Jaafar et al., 2015), it has increased water stress in Lebanon by 6% (Jaafar et al., 2020).

### 5.2. Future directions

Although the review is limited by the inability to access and analyse all water-resource studies performed in a given area, even one as small as Lebanon, we hope that it can help educators teach about water resources in Lebanon and that the information that it summarises can help researchers address scientific priorities and study specific aspects of Lebanon's water resources, and all stakeholders co-design knowledge-based solutions for water security. Some particularly important research paths relate to the study of precipitation patterns in Lebanon, as knowledge of the temporal and spatial characteristics of precipitation needs to be updated. More rainfall and snow measurements are needed, as is more analysis of the existing data, especially to update the existing rainfall map and produce new maps at multiple time scales. Statistical analysis of temporal variability in rainfall is needed to understand the precipitation pattern in Lebanon and compare it temporally (using available historical data) and spatially to those of other Mediterranean countries. Another important research path is to study ET. The development of tailor-made hydrological model that can help understand the hydrological response characteristics of Lebanese catchment is also an important research avenue. Detailed hydrogeological studies that precisely delineate groundwater basins and estimate their water balance are also needed. More surface and groundwater quality studies are needed for all pollutants. In addition, most water-governance and water-management studies are reports by government and international partners. More peer-reviewed research of these topics is needed, especially on solutions for water-related problems. Furthermore, water related studies are not distributed equally. Some regions are studied rigorously while other are hardly studied at all. Thus, more local studies that take into account local challenges but also knowledge are also needed. This is particularly important in the context of the UN SDGs and the new Science for Water Solutions decade (2023–2032) of the International Association of Hydrological Sciences: “*Hydrology engaging local people in one global world*” (Arheimer et al., 2024).

On the national scale, expanding the observation network, installing snow monitoring stations, creating a single database for water-resource data, producing new larger-scale geological and hydrogeological maps to assess groundwater resources better and establishing a new water-quality monitoring programs along with modernizing the governance and management frameworks are needed. These recommendations join the conclusion of a recent NWSS (MoEW, 2020) that assessed the current status of water resources in Lebanon. This NWSS differs from previous NWSS, especially in estimating much larger available water resources than before, without explaining why particularly well. It predicts that water resources will still be able to satisfy future demand, even when considering impacts of climate change and the refugee crisis. This optimism, which deviates from previous official discourse, is based on the new estimated water balance and a series of water projects, including many dams and wells, that the strategy envisions. A shortcoming of the NWSS is that it is based mainly on technical studies and reports, and thus does not refer to the relatively large number of peer-reviewed studies. Hence, we hope that this review will feed the debate on water-resource management in Lebanon and help push Lebanon towards the water-related goals and targets conceptualised and prioritised in Agenda (2030) and its related SDGs (even if they cannot be reached by 2030).

This review aimed at decreasing the fragmentation and unFAIRness of data, information and knowledge in the water sector (Cudennec et al.,

2020, 2022a) which currently limit the ability to address Lebanon's large water-security challenges. This is particularly consistent with the three epistemic ambitions of the WMO's Action Plan for Hydrology (i.e. “High quality data supports science”, “Science provides a sound analysis for operational hydrology”, and “Sustainable development is supported by hydrological information”), apply directly to its three integrative ambitions (i.e. “We have a thorough knowledge of the water resources”, “Water quality is known”, and “Hydroclimate and meteorological data support the food security agenda”) that support its two ambitions about variability and extremes (i.e. “No one is surprised by a flood” and “Everyone is prepared for drought”) (WMO, 2023). Consequently, all documents used in this review are listed by topic in the Supplementary Material for sake of curation.

## 6. Conclusions

A relatively large body of literature related to multiple aspects of water resources exists in Lebanon. This knowledge base, albeit fragmented, shed much-needed light on the country's water situation and helped us to highlight several critical findings and challenges. First, estimating total precipitation in Lebanon, which currently has few continuous measurements, requires more research. The available rainfall maps and data are outdated, which emphasizes the need for more comprehensive rainfall and snowfall measurements and analyses. Despite an increase in the number of weather stations, spatial distribution and data continuity remain problematic. Snow cover area and duration differed among studies and thus require more research. Estimation of ET, which is focused primarily on the Beqaa valley, lacks comprehensive coverage and often considers only specific crops. Surface-water studies are rare, and their flow measurements have low temporal resolution. Because river flows have high temporal and spatial variability, groundwater is an important resource that is overexploited and requires more research. Regarding climate change impacts, no consistent trends in inter-annual variability were detected, although a potential shift in intra-annual rainfall was detected. Water quality in Lebanon is degrading rapidly, with microbiological pollution in most rivers. Groundwater pollution, saltwater intrusion, nitrate pollution, and pesticide contamination pose significant challenges. Emerging organic pollutants are also being detected in surface water and groundwater. Lebanon's water governance framework is complex, involving many laws, institutions, and international partnerships. Despite reforms, coordination remains challenging. Water management in Lebanon has evolved from state-centred projects to increased international and private-sector involvement. Access to public water networks has increased, but water supply remains intermittent, which decreases water quality. Wastewater networks are expanding, but treatment capacity remains limited. A new NWSS that emphasises data collection, water-quality monitoring, and capacity building was recently enacted, but challenges related to political complexity, corruption, and regional geopolitical tensions add uncertainty to water-resource management. We hope that this review will contribute to the ongoing water resources and water security debates in Lebanon and abroad. It can serve as a starting point for future research and initiatives and inspire other similar reviews in different geographic and climatic contexts.

### CRedit authorship contribution statement

**Mohammad Merheb:** Writing – original draft, Visualization, Methodology, Conceptualization. **Roger Moussa:** Writing – review & editing, Methodology, Conceptualization. **Chadi Abdallah:** Writing – review & editing, Visualization, Resources. **Jalal Halwani:** Writing – review & editing, Resources. **Christophe Cudennec:** Writing – review & editing, Visualization, Resources, Conceptualization.



## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.pce.2024.103683>.

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