Climate effects on the Litani basin watershed in Lebanon

Hamzeh H. Ramadan

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By: Hamzeh H. Ramadan

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Signed by the final examining committee:

Dr. S. Bergler, CSE, Chair

Dr. S. Gaskin, CE, McGill University, External Examiner

Dr. M.R. Soleymani, ECE, External to Program

Dr. A. Athienitis, BCEE, Examiner

Dr. Z. Chen, BCEE, Examiner

Dr. A.S. Ramamurthy, BCEE, Thesis Co-Supervisor

Dr. R.E. Beighley, CE, San Diego State University, Thesis Co-Supervisor

Approved by

____
Chair of Department or Graduate Program Director

____________ ______________________________
Dean of
Faculty

Abstract

The hydrological sensitivity of a mid-size basin in the Mediterranean region to global and regional climate patterns is presented in the current study, based on a methodology to generate a basin-scale, long-term monthly surface temperature and precipitation time series that permits modeling the basin's runoff. To this end, the case of the Litani Basin was selected. This basin is located in Lebanon and is situated east of the Mediterranean Basin. It is known to have a diverse regional environmental setting. This selection was made, first, to point out the importance of the physical and topographical characteristics that cover coastal versus mountainous regions of the basin on its hydro-climatological response and, also to demonstrate the opportunity for conducting related studies in areas with limited long-term measured climate and/or hydrological data. Monthly precipitation and temperature data were collected from different resources including grid based, satellites and gauging stations. The Hillslope River Routing (HRR) model was selected to generate the basin's discharges.

Due to the lack of long-term runoff data, synthetic daily precipitation data were generated from the available monthly data using a two-part gamma distribution and mixed exponential models in order to produce and examine the resulting watershed runoffs. The Litani Basin is shown to maintain a dry trend in the period between 1900 and 2008. In addition, different climate pattern teleconnections in correlation with basin response were illustrated. The results show significant correlation between many global and regional circulation patterns and Litani's hydro-climatology. To this end, the basin's streamflow regime was investigated subject to the effects of various hypothetical and predicted climate change scenarios. The results suggest a significant effect of the combination of

temperature rise and precipitation decrease on the streamflow regime of the Litani. The results of this study will support water managers, planners and river agencies incorporating the impacts of climate change on watershed hydrology during the development of the basin planning process.

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To My Father's Loving Memory: Hussein Khalil Ramadan

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List of Abbreviations

AO	Arctic Oscillation
ASCE	American Society of Civil Engineers
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CRU TS-Prcp	Climate Research Unit Time Series - Precipitation
CRU TS-Temp	Climate Research Unit Time Series - Temperature
DEM	Digital Elevation Model
EA	East Atlantic
EA/WR	East Atlantic/Western Russia
EMRO	Eastern Mediterranean Regional Office
ENSO	El Niño South Oscillation
EP-NP	East Pacific-North Pacific
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GCM	General Circulation Model
GHG	Greenhouse Gases
GIS	Geographic Information System
IDCR	The International Development Research Centre
IPCC	Intergovernmental Panel for Climate Change
LRA	Litani River Authority
MOAC	Mediterranean Oscillation Algiers Cairo

MODIS	Moderate Resolution Imaging Spectroradiometer
MOI	Mediterranean Oscillation Index
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NNRP	NCEP/NCAR Reanalysis Project
PNA	Pacific/North American
POL	Polar/Eurasia
PT	Pacific Transition
RCM	Regional Climate Models
RICAMARE	Research In global Change in the Mediterranean: A Regional Network
SCA	Scandinavia
SRTM	Shuttle Radar Topography Mission
SST	Sea-Surface Temperature
TNH	Tropical/Northern Hemisphere
TRMM	Tropical Rainfall Measuring Mission
UD-Prcp	University of Delaware Precipitation
UD-Temp	University of Delaware Air Temperature
UNEP	United Nation Environment Programme
WBM	Water Balance Model
WMO	World Meteorological Organization

WP	West Pacific

1 OVERVIEW

1.1 General Introduction

The global increase in water resources demand due to lifestyle change and population growth is encountered by freshwater scarcity throughout the planet. Meanwhile, the potential effects of climate change on water resources availability pose further challenges on the sustainability of this meager yet life-dependent substance; this is in addition to the complexity of the prospect of climate's natural variability and its eventual reserved effect on the water balance cycle. As this is a decades old subject of ongoing discussion in the global scientific community, the Intergovernmental Panel for Climate Change (IPCC) recently emphasized the need for directing climate variability and change impacts on water resources studies toward regional and local dimensions. This allows for the creation of competent mitigation solutions to be interconnected with local population demands and priorities. However, it is also of considerable importance to distinguish the effect of natural climate variability, which is characterized by global and regional climate patterns, on watershed regime behavior. This would allow the relation between natural climate variability and the watershed's hydro-climatology performance to be seen, and thus differentiate it from other anthropogenic-induced climate change outcomes. The IPCC has therefore required water managers and related authorities to account for the potential cumulative impacts of climate change on hydrology for different regions of the globe.

The problematic issue of linking climate variability to watershed regime alteration is due primarily to the various responses that may be established at different temporal and spatial dimensions. This elicits the need for greater focus in the regional and local dimensions. The East Mediterranean region (Figures A-1, A-2, A-3, A-4 and A-5) has historically suffered from water resources shortage, which makes the region more vulnerable to any additional threat to freshwater accessibility and sustainability. Despite this fact, very few studies have been conducted in this region, and so these combined effects are not yet well illustrated. Lebanon (Figure A-6), considered one of the "luckiest" countries in the region in relative "richness" of its water resources, currently undergoes water stress which is projected to amplify due to climate change.

In addition to its aesthetic and recreational value, streamflow represents one of the most important sources of renewable freshwater supply. The Litani River (Figures A-7, A-8 and A-9) is considered to be the largest source of perennial stream water in the country. Its basin covers approximately 20% of the Lebanese territories, with 800Mm^3 of yearly discharge being used for domestic water supply, agriculture and power generation. The Litani River is therefore considered vital to the Lebanese economy and population development. However, no studies have been conducted which investigate the link between hydro-climatological response of this basin and climate variability.

1.2 Literature Review

Knowledge about the variability of hydrological systems at the basin or watershed level due to climate patterns and climate change inference is important. Studying the coarser hydrological resolution of an area from a global to regional scale is beneficial, because it provides insight into the general water balance features of an area. However, a closer look at the unique attributes of the local scale remains vital, because of the substantial hydrological, temporal and spatial variability occurring at a larger scale. Hence, a simple methodology is needed to generate basin-scale climate variation in terms of three interrelated factors: temperature, precipitation and runoff. This knowledge will assist policymakers and stakeholders in positive decision-making and in developing long-term adaptation policies for the hydrology of a basin-scale system.

Stern (2007) stated the impossibility of avoiding the climate change that will take place in the next couple of decades. He mentioned the possibility of protecting our societies and economies from its impact by: providing information and planning; working on mitigation measures; and taking strong immediate actions using the necessary proactive measures, which include the latest cutting-edge technology and knowledge. However, Bates et al. (2008), in their recent comprehensive assessment, stated the incessant need for filling in the gaps in such knowledge. They outline the improvements required to build a relationship between climate change and the hydrological cycle at scales relevant to decision making. The Intergovernmental Panel on Climate Change (IPCC 2007a) published the findings of many General Circulation Models (GCMs), which imply a global increase in precipitation and evapotranspiration. Similarly, there is strong evidence of a possible shift in the global climate system during the 1970s, which may have resulted in a stronger Pacific-mid-latitude link during the past three decades (Wuethrich 1995)**.** Trenberth et al. (2007) and Smith and Reynolds (2004) agreed to consider the 1901-2005 average global trend of the sea-surface temperature (SST) change at about 0.0067^{o}C/decade. Trenberth et al. (2007) computed the land-near-surface temperature global trend to be between 0.068 and 0.084^{o}C/decade. Nevertheless, IPCC (2007a) indicated that global results are subject to spatial and temporal variations which make it necessary to investigate smaller scales (regional and local). For example, most GCM simulations show smaller changes of precipitation in mid to low latitudes compared to high latitudes as a response to greenhouse gas concentration change (Orsolini & Sorteberg 2009).

Mohkov (2008), as a result of many simulations using the “best” climate models of global circulation, noted good correlations of positive trends for annual-mean surface air temperature in Alaska and the Antarctic Peninsula. He noted, however, negative regional temperature trends even for the regions with the highest rate of regional warming at the end of the 20th Century. Labat et al. (2004), in a study of 20th Century climate change related to the hydrologic behavior of 221 rivers around the world, suggested that for each 1°C rise in temperature, a 4% increase in global runoff will occur. However, it was stated that this tendency has to be examined on the regional scale, where increasing as well as decreasing trends may occur. In addition, the consequences of climate change vary for different basins. The unique and existing climatic and physiographic conditions of a basin influence, directly or indirectly, the water quantity and quality of the basin itself. Relating hydrologic performance to climate change and/or relevant issues for different basins located in the same regional continent may have varying and even conflicting results (Chang 2003).

Many studies showed that the effect of climate change on the hydrological behavior of watersheds or basins differs significantly depending on various local and regional factors (Pociask-Karteczeka 2006). In the last couple of decades, the detection of hydrologic trends and their sensitivity to climate variability have been the focus of numerous studies for different regions [Lettenmaier et al. (1994), Lines and Slack (1999), Dettinger and Diaz (2000), Rimbu et al. (2002) and Masih et al. (2009)]. The European Meuse River Basin (France, Belgium and the Netherlands) hydrological trends have been studied by Tu (2006). He linked streamflow trends to precipitation changes and climate pattern changes such as the North Atlantic Oscillation (NAO). For Canadian Rivers, George (2007) noted a strong yet not uniform relationship between precipitation and temperature changes and streamflow variability. Birsan et al. (2005) analyzed streamflow trends in Switzerland (1931–2000) and noted that mountain basins were more sensitive to climate change.

The measure of climate variability is considered to be the same as the measure of climate change (Geer 1996). Earth scientists standardized some climatological phenomena by the invention of different climate indices (e.g. Climate and Global Dynamics, 2011). These indices, known as teleconnections or climate patterns, describe the natural variability modes of the climate on a large region of the globe. Hence, more attention has been given lately to the influence on rivers streamflow of large-scale climatic patterns such as El Niño South Oscillation (ENSO), North Atlantic Oscillation (NAO) and others. This may explain the natural climate variability effect on rivers hydrology. Several similar studies have been conducted on the continental and regional scale as well as in other parts of the globe, especially for European and American territories.

Links between observed changes in climate to hydrological cycle have been a matter of intensive studies in the last couple of decades. Bates et al. (2008) in their comprehensive work discussing the potential effects of climate change on water resources at global and regional levels presented an extended list of references showing the exhaustive effort recently directed to that subject. According to recent IPCC (2007a) findings, it is likely that shifts in magnitude and timing of temperature, precipitation and runoff will be experienced due to anthropogenic interferences causing consistent global warming; this has serious consequences on water resources management, distribution and availability worldwide. It has been concluded that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC 2007b). Observed temperature and precipitation trends have revealed a significant rise in global temperature accompanied by a variable increase of precipitation in

Northern Europe, the eastern parts of North and South America, and Northern and Central Asia; there has meanwhile been a decrease in the Mediterranean, Sahel and Northern and Southern Africa. These effects are likely to be amplified when combined with other factors such as the consequences of human growth and socio-economical development, like land use changes and urbanization expansion (IPCC 2007a).

The future implications of climate change on the water resources of many watersheds have been investigated worldwide: Bae et al. (2008) forecasted a reduction of runoff by 2100 in the spring and summer seasons and an increased runoff in fall and winter for many basins located in South Korea (43-2293 km^2); Thodsen (2007) suggested an increase of 12% by 2100 in mean annual runoff for many Danish basins (23-814 km^2); Andreásson et al. (2004) predicted an increase in the northern Swedish basin's runoff and a decrease in the southern basin's by the 2030s (1100-6000 km^2); Loukas et al. (2002) reported an increase in fall and winter runoff and a decrease in spring and summer runoff for many rainfall-dominated, mid-sized basins in British Columbia, Canada, and an increase in winter runoff for snowmelt dominated basins between 2080 and 2100 (1150-1194 km^2); George (2007) predicted, however, that anthropogenic activities will not result in water flow scarcity of the Winnipeg River Basin, while Frei et al. (2002) predicted a runoff increase of 10% to a decrease of 30% for the Catskill Mountains in New York, USA (1180 km^2).

Many review studies have been conducted for modeling results on the hydrological response to climate change. Arora and Boer (2001) and Arnell (1999) have concluded that low- and mid-latitude regions and the sub-tropics will be likely to witness a general decrease in runoff, in contrast to high-latitude regions such as Equatorial Asia and Africa and Southern Asia, which will be likely to witness an increase. Pal et al. (2004) indicated that projected changes in precipitation due to climate change will be followed by significant changes to river flow. Chiew

& McMahon (2002) predicted a roughly double fold change in runoff percentage compared with precipitation modifications in the Australian catchments. They noted that the percentage change in runoff can be even more than four times the percentage change in precipitation in ephemeral catchments. Najjar (1999) reported in Pennsylvania, USA a double sensitivity of watersheds runoff compared to precipitation due to climate change, while Chang (2003) predicted more runoff when temperature and precipitation increase; however, he emphasized the effect of physiographic conditions of each basin and its correlation to the variable reactions to climate change. Similarly, Sun et al. (2000) expected increases in runoff and evapotranspiration whilst Sharma et al. (2000) reported an increase of temperature and precipitation for the Himalayas, accompanied by a decrease in runoff. Nevertheless, Arnell and Liu (2001) argued that the effect of climate change on rivers regime may not be apparent, as other factors may have been more influential on watersheds runoff. They suggested that smaller watersheds may be more sensitive to changes among others.

The Mediterranean region climate was the center of numerous studies in the last decade. In the Mediterranean during the last decade, many researchers have concentrated their efforts on studying climate variability over the whole region or in the western region. However, Lionello et al. (2006) described the presentation of the Mediterranean Sea area as one solid region that is "absolutely unrealistic" due to its diverse climate characteristics. In order to illustrate the varied characteristics of the region, Figures A-1 to A-5 (Appendix A) show regional orographic and climatic characteristics of the Mediterranean basin elevations; five sets of maps present the elevation range of countries surrounding the Mediterranean, as well as temperature and precipitation distribution throughout the region during the wet and dry seasons of 2008. These maps were produced using ArcGIS software. The elevation data used was sourced from ESRI

Software, which is based on a GTOPO30 grid with 1 km horizontal resolution at the equator. Development of precipitation and air temperature maps for the Mediterranean region involved two stages: data preparation and data mapping. The climate data was sourced at the University of Delaware, 2008 with data resolution of 0.5 degrees.

The Mediterranean is a water-deficit region with a history of conflicts over land and water resources, especially in the eastern basin region (Al-Kashab 1958, Amery 1987 and Beaumont 1998). Currently, around 60% of the world's water-poor population lives in the Mediterranean region, concentrated mainly in the eastern and southern countries, with less than 1000 m^3 per capita per year. For this region in general the expected changes in climate will produce a decrease of freshwater availability. This was emphasized earlier by IPCC (2007a), who stated that developing Mediterranean countries face potential adverse impacts of climate change on freshwater quantity and quality. The threat to the availability of freshwater is considered as one of the most critical issues, adding another bitter challenge to the numerous issues which the population of that region encounter. Hence, the sensitivity of streamflow to the climate variability of different Mediterranean watersheds has been evaluated by many authors, who present various tendencies throughout the basin (Milly et al. 2005, Ludwig et al. 2004, Trigo et al. 2004 and Blinda & Thivet 2009).

These studies and many others treated the climate variability in the region from different perspectives. For instance, historical trends of temperature, precipitation and runoff for various regional areas have been evaluated intensively presenting various tendencies throughout the basin. Sahsamanoglou and Makrogiannis (1992), Giorgi (2002), New et al. (2001) and Jacobeit (2000) suggested a positive temperature trend in the western region of the Mediterranean for a variety of time periods in the last century. For other regions, Türkes et al. (2002) and Zhang et al.

(2005) reported an increase in annual temperature trends over southern Turkey and the Middle East area, respectively. For precipitation trends in the 20^{th} century, Norrant and Douguédroit (2006) reported a negative precipitation trend in the Middle East with monthly and seasonal variations. In Greece and vicinity, Hatzianastassiou et al. (2008) reported negative annual precipitation trends, while Giorgi (2002) suggested increasing and decreasing winter precipitation trends in the western and eastern Mediterranean, respectively.

In addition, the runoff trends of many watersheds during the 20^{th} century have been investigated in many Mediterranean regions. The Duero River basin in Spain was found to experience negative runoff trend (Ceballos-Barbancho et al., 2008). The Karkeh River in Iran showed a positive and negative runoff in December and May (Masih et al., 2009). In Turkey, Topaloglu (2006) reported positive and negative runoff trends in the western and northern regions of the country, respectively. Oueslati (2009) suggested a negative trend of annual runoff in Morocco.

From the other hand, lately many authors attempt to connect the Mediterranean's climate variability during the 20^{th} century to the global or continental atmospheric circulations.

For rainfall, Kadioglu et al. (1999) and Türkeş and Erlat (2003) related monthly precipitation in Turkey to El Niño events and the North Atlantic Oscillator phase. Van Oldenborgh et al. (2000) reported a relation between the spring precipitation and El Niño for most Europe and part of Asia. Ulbrich and Christoph (1999) related climate change trend in winter precipitation of the eastern and western Mediterranean to the NAO. Krichak and Alpert (2005) and Krichak et al. (2002) reported a correlation between the East Atlantic–West Russia (EA–WR) and the East Mediterranean precipitation behavior. Gonzalez-Hidalgo et al. (2009), Martin et al. (2004) and Vazquez (2001) correlated the Mediterranean Oscillation Index (MOI), the Eastern Atlantic and the Eurasian pattern with precipitation changed over the Mediterranean part of the Iberian

Peninsula.

For temperature, Feliks et al. (2010) synchronized the Nile River flow variation with the North Atlantic Oscillator (NAO) phases. Similarly, Mann (2002) related the temperature variations in the Middle East to the NAO. Trigo et al. (2004) suggested a negative correlation between NAO and the temperature changes of the western Mediterranean.

For runoff, Price et al. (1998) reported a correlation between seasonal stream flow in the Jordan River and El Niño**.** Cullen and Menocal (2000) related runoff changes of Tigris and Euphrates rivers to the NAO.

In addition to the hydro-climatological trends analysis studies stated above, scientists predicted the future effect of climate change on water resources for different regions on the globe including the Mediterranean area. Lehner et al. (2001) predicted a reduction of the European river flows by up to 30% by 2070. Similarly, Nohra et al. (2006) projected a reduction of annual runoff in the Mediterranean region. Milano (2010) suggested a reduction of surface runoff in the whole Mediterranean basin during the second half of the 21st century. Smith et al. (2000) found a future negative correlation between temperature and runoff of the Tigris and Euphrates rivers. Other authors studied the effect of climate variability on water resources through the employment of various hypothetical climate change scenarios (Shamra, 2000; Michel and Hulme, 2000; Milly et al., 2005; Baltas and Mimikou, 2007; Abdulla and Al-Omari, 2008). Different findings have been reported by these and other authors which reflect the effect of the spatial and temporal characteristics of each studied area on the results and emphasize the necessity of investigating the hydro-climatological features of each area of concern.

Considering the above outlined results, it can be deduced that the hydrological behavior of a watershed would be subject to various spatial responses depending on its location, physical characteristics and size. Hence, any change or variation in climate and its further effect on water resources, negative or positive, has to be studied on the local scale (watershed or basin level). This is needed, first, to examine the existence of such an effect and its degree of implication and, second, to retain a clear vision of the type of effective mitigation measures specifically needed for the watershed under study.

1.3 Study Objectives and Methods

1.3.1 Motivations

The East Mediterranean region, including Lebanon, is most likely to be adversely affected by climate change (IPCC 2007). In particular, the sequences of climate changes on fresh water availability in this specific region, which suffers historically from water shortage, may be significant. In addition, most of the watersheds in the East Mediterranean suffer from lack of hydro-climatological data making the study of climate and hydrology trends a challenge. The Litani Basin, the largest river in Lebanon, is experiencing water quantity reduction in the last couple decades as observed by the basin's population and authorities. The implications of climate change on the Litani Basin's water quantity in the past and future are analyzed in this study. A comprehensive methodology is presented to overcome the lack of the hydro-climatological data of the basin (or any other comparable basin).

1.3.2 General Remarks

The Litani Basin, which is located in Lebanon, east of the Mediterranean Sea, was selected as a case study in an effort to develop a tangible correlation between climate change and its long term hydrology behavior. Indeed, the Litani Basin in many ways resembles most of the Middle Eastern watersheds in its physical features (e.g. the dominance of micro-climates in a relatively small geographic area, and geophysical diversity and biodiversity within a limited area); it also resembles others in its limited resources (e.g. limitation of hydro-climatological data and reliability of available data) and bureaucratic state (e.g. high cost and difficulties in accessing data). Its case study importance is furthered by the importance of its water resources to Lebanon, which, as stated previously, is in a region where water scarcity and/or shortage are problematic. This mid-sized basin is characterized by its diverse micro-climates and physiographical features. It is divided into two regions: the Upper Litani Basin (ULB) with elevations of 800 m and above and the Lower Litani Basin (LLB) with elevations of 800 m and below. The ULB is considered a mountainous area with a sub-arid climate, while the LLB is more of a coastal area with a sub-humid climate. The basin is divided by an artificial lake. Hence, both parts can be illustrated as having distinct climates and physiographical characteristics.

1.3.3 Objectives

The main objective of this study is to reveal the impacts of natural climate variability and climate change on the hydro-climatology of the Litani Basin. Sub-objectives of the study include:

1. Developing a methodology to generate hydro-climatological data for the basin, presently subject to data scarcity.
2. Investigating the historical hydro-climatological watershed performance of the basin through the study of temperature, precipitation and runoff trends of the basin and its sub-basins during the 20th Century, and studying trends based on Mann-Kendall and Sen Slope nonparametric trend analysis.
3. Teleconnecting different global and regional natural climate patterns, such as the North Atlantic Oscillation (NAO); El- Niño Southern Oscillation (ENSO); the Mediterranean Oscillation Index (MOI); and 10 additional indices, with temperature and precipitation

variations of the basin and sub-basins, and investigating the correlation between natural climate patterns and basin hydro-climatological variations linked to statistical correlation.

4. Modeling and calibrating the Litani watershed daily discharge using the Hilslope River Routing (HRR) model based on the novel Pfafstetter methodology for basin codification, adopting both kinematic and diffusion wave solutions for routing.
5. Generating a gamma and mixed exponential distribution precipitation model to synthesize daily precipitation data. Testing the ability of the model (developed for large-sized basins) to simulate mid-sized watersheds.
6. Conducting a hypothetical methodology with the purpose of quantifying the effect of climate change on the watershed streamflow, while modeling the Litani Basin's runoff under different climate conditions and examining the impact of climate change on the watershed's streamflow.

1.3.4 Impact of the Study

Eastern Mediterranean countries, with their historical water resources scarcity, are experiencing severe demographic, social, cultural, economic and environmental changes. Based on statistics from the Eastern Mediterranean Regional Office (EMRO), the population for twenty-two countries in this region has increased from a mere 194 million in 1970 to more than 550 million in 2008, with an annual growth rate of around 3% (EMRO website, WHO 2008). However, moving the water resources communities toward adequate reactions for encountering climate change potentials remains a subject of much controversy This is a burden found even in developed countries (Rayner et al., 2005).

Previous studies conducted on the regional scale (East Mediterranean) which forecast climate change sometimes give contradictory results. This study will attempt to project and apply a wide spectrum of these diverse products on the local scale, illustrating their potential effects on the basin streamflow regime. Consequently, this study aims to address the following specific questions:

- Did the basin's streamflow, precipitation and temperature experience increased or decreased trends during the 20th Century? How did the whole basin and the two sub-basins perform? Did the response change spatially in a mid-sized basin?
- Is there any connection between the basin's hydro-climatological behavior and a selection of global and regional natural climate patterns? What is the response of the whole basin and its two sub-basins?
- How can we generate long-term hydro-climatological data, when this data has not been available?
- How reliable is data from the generated synthetic daily precipitation and runoff?
- Is the HRR model capable of simulating mid-sized catchments?
- What is the hydrological response of the two sub-basins to climate alteration?

1.4 Thesis Organization

This thesis is divided into six chapters. Following this introductory chapter, Chapter 2 demonstrates and investigates the implication of temperature and precipitation trends on the Litani Runoff. It lays out the methodology and procedures used to address and discuss the issues of the basin's hydro-climatological trends for the periods 1900-2008 and 1970-2008. Chapter 3 shows the correlation of both precipitation and temperature of the Litani Basin with thirteen different global and regional teleconnection patterns. Chapter 4 presents the methodology used to generate synthetic daily runoff data and investigates the runoff trends of the Litani Basin.

Chapter 5 reviews the studies relating climate change to water resources variability in the East Mediterranean region, and tests the Litani's hydrology performance under different climate scenarios reflecting possible future climate changes. Chapter 6 lays out the general conclusions and recommendations carried out in this thesis.

The format and the contents of chapters 2, 3, 4, and 5 are essentially the same as the final submission to the journal editors. Consequently, repetition of a few facts was inevitable.

2 Temperature and precipitation trends in Lebanon's largest river: the Litani Basin

Ramadan H.H, Beighley R.E. and Ramamurthy A.S.
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2.1 Abstract

This study deals with the historical hydro-climatological watershed characteristics of the Litani basin located in Lebanon, east of the Mediterranean Sea, during 1900-2008. The basin is divided into 2 distinct sub-basins. The Upper Litani Basin (ULB) is mostly dominated by mountainous geophysical features and the Lower Litani Basin (LLB) is closer to the Mediterranean coast. Monthly and annual temperature and precipitation data were generated from different sources including global gridded data, satellite data and local station data. As long term runoff records were not available, previously generated monthly synthetic runoff data were employed. Temperature and precipitation trends were investigated using the Mann-Kendall and Sen Slope nonparametric trend tests. The mean annual and monthly runoff was subsequently correlated with temperature and precipitation variations using a multiple linear regression approach. The results show that between1900-2008, the whole Litani basin, including both sub-basins, experienced a drying trend without a significant change in temperature. However, within the 1970-2008 period, the whole basin grew notably warmer in all seasons, without being wetter; this climatic pattern was reflected in the LLB but not in the ULB, which was only slightly warmer but also slightly wetter in this period. In addition, the results revealed distinctive seasonal and annual correlations between temperature and precipitation changes and the basin's runoff. However, runoff for both the ULB and the LLB was shown to be more frequently correlated with precipitation than with temperature. Positive correlations were found between runoff and precipitation during winter and wet seasons, while a negative correlation was detected during winter between temperature and runoff variations of the ULB. Hence, continuation of increasing temperature and decreasing precipitation trends may pose a threat to future water-resources in the Litani as a whole, and the ULB in particular.

2.2 Introduction

The Intergovernmental Panel on Climate Change has emphasized the need for investigating climate variability and change impacts on available water resources at regional and local scales. Understanding the variability of hydrological systems at the basin or watershed scales due to climate change is especially important to policymakers and stakeholders needing to make informed decisions to develop long-term, sustainable water resource policies. For example, Bates et al. (2008) stated the incessant need for improved knowledge regarding climate change impacts. They emphasized the need to understand and model the relationship between climate changes and the hydrological cycle at the local scale. The basin (or watershed) scale meets this criterion since many local factors acting on temperature, precipitation and runoff trends (such as the structural and physical basin characteristics) and hence, local rainfall quantities and temperature are not necessarily similar to those acting on a regional (10^4 to 10^7 km^2) or coarser scale (Pfister et al., 2000).

The Mediterranean region ($2.5x10^6$ km^2) is known to have diverse topographic, ecologic and climatic features. The dynamics of the Mediterranean climate are due to a wide range of factors that dominate the overall basin characteristics. However, the importance of local features on climate behavior can be substantial (Lionello et al., 2006). Xoplaki (2002) recognized excessive sub-regional variability of temperature and precipitation trends in many local Mediterranean areas. This was not statistically significant if viewed from the larger, regional scale. Hence, quantifying climate change at the local scale (less than 10^4 km^2) is one of the most critical and uncertain issues when assessing Mediterranean climate variability (Lionello et al., 2006).

The adverse effects of temperature and precipitation changes on hydrology have been shown to be significant. Bates et al. (2008) present a long list of climate change effects on water resources. In particular, they state with high confidence that the projected changes in climate will result in a decrease of water resources in many semi-arid and arid areas such as the Mediterranean basin. Alterations of snow melt seasons, higher evapotranspiration rates and frequent flooding, to name a few, are direct products of air temperature warming that may affect runoff quantity, quality and seasonality (López-Moreno et al., 2009; Kundzewicz et al., 2007; Huntington, 2006; Loukas et al., 2002).

During the last century, trends of temperature and precipitation have been shown to differ in sign and magnitude from region to region around the globe and even within the same region (IPCC, 2007a; 2007b). For the Mediterranean regions, various temperature and precipitation trends have been detected. For instance, Sahsamanoglou and Makrogiannis (1992) considered 39 meteorological stations in different regions of the Mediterranean and concluded that for the period 1950-1988 there was a positive air temperature trend in the western Mediterranean (up to +0.02 ºC/year) and a corresponding negative trend in the eastern Mediterranean (up to -0.02 ºC/year), while a positive trend was found for mean air temperature at the 500 hPa layer over the whole region. Similar findings were detected in the Mediterranean by Giorgi (2002), New et al. (2001) and Jacobeit (2000) for different time periods of the 20th century. However, Türkes et al. (2002) noted an increase in annual, winter and spring mean temperature over the southern regions of Turkey during the 20th century and Zhang et al. (2005) reported significant increasing trends in the annual maximum of daily maximum and minimum temperature for 52 stations in the Middle East from 1950 to 2003.

For precipitation trends, several regions of the Mediterranean basin have been examined. Norrant and Douguédroit (2006) noted a significant decrease in precipitation during winter in the near east area studying 63 station records located throughout the Mediterranean. They found different seasonal or monthly precipitation trends in different countries. Hatzianastassiou et al. (2008)

reported around 9.4% decrease of the mean annual precipitation in Greece and surrounding areas for 26 years (1979-2004). However, Giorgi (2002) reported positive winter precipitation trends for the western Mediterranean land area and a corresponding negative trend for the eastern Mediterranean for the same period. In addition, Jacobeit et al. (2004) noted a slight positive winter precipitation trend for the southeastern basin between 1951 and 2000. These different, even opposite, findings illustrate the effect of the spatial and temporal characteristics of each studied area on the results and emphasizes the necessity of investigating the hydro-climatological features of each area of concern.

In Lebanon, due to the scarcity of reliable data, few studies have investigated the effects of climate change on hydrology. To the best of our knowledge no such study has been conducted on the watershed level. Lebanon will encounter a serious water deficit, especially in the Beqaa Valley, and will be unable to meet its national water demand by 2025 (Bou Zeid and El-Fadel, 2002). The Litani River is one of the most valuable fresh water resources in Lebanon that originates from the Beqaa Valley area. The basin's water is used currently for irrigation and hydropower. The Litani River generates around 10% of Lebanon's power production. It irrigates currently around 5,600 ha of agricultural land and is projected to irrigate more than 54,000 ha in the near future (LRA, 2011). This is in addition to the plan laid out by the Litani River Authority (LRA) to feed the capital Beirut and other rural areas with potable water by building four additional dams along the Litani reaches (LRA, 2011). Hence, any alteration of the Litani River hydrology will have a significant socio-economical effect on Lebanon.

This study presents and applies a methodology that serves two objectives: 1) investigate the temperature and precipitation trends for the Litani Basin under different temporal (1900-2008 and 1970-2008) and spatial (upper, lower and whole Litani basin) ranges and 2) describe correlations between these climate change factors and the basin's runoff.

2.3 Lebanon and the Litani Basin

Lebanon lies in the semi-arid/sub-humid eastern Mediterranean zone. Its weather is characterized by hot and dry extended summers and wet short winters. Lebanon contains a variety of micro-climates dispersed all through the country even with its relatively small area (around 10,450 km^2). While the western slopes with temperate altitudes of Mountain Lebanon and the coast areas witness a sub-humid climate, the central plain and a sub-desert area in the northeast part of the country are considered semi-arid.

Most of the rain falls in Lebanon between December and February, while the dry season occurs between June and August. Despite the actual short rainy season period of the year (80 or 90 days), the average yearly precipitation amount is estimated to be 700 to 1100 mm in the coast zone, 200 to 800 mm in the Beqaa Valley, and close to 2000 mm in the mountains. The yearly precipitation is able to generate an average annual flow of 8,600 million m^3 that feeds 40 major streams and rivers (17 of them are perennial rivers) and more than 2,000 springs.

The Litani River is the largest and longest river in Lebanon, generating around 30% of the total surface water flow of all rivers flowing in the Lebanese territories. It originates in the Beqaa Valley, 10 km west of Baalbeck City, from "Al Oleic" springs in "Hosh Brada" (altitude 1000 m) and flows southward to discharge into the Mediterranean Sea, 7 to 8 km north of the City of Tyre in South Lebanon. The Beqaa plains, where the Upper Litani flows, lie between the foot of the slopes of Lebanon and the Anti-Lebanon Mountains. The total drainage area of the basin is around 2175 km^2 with a channel length of about 170 km and an annual discharge rate of 750 million m^3 (LRA, 2011).

The Litani basin is divided in two parts (Figure 2-1), the Upper Litani Basin (ULB) and the Lower Litani Basin (LLB), and has nine tributaries; the most important tributary is the Ghozail River, which consists of six additional tributaries. The ULB is located between the altitudes of 800 and 2615 m and drains towards Qaraoun Lake. It occupies about 70% of the total Litani Basin. The LLB drains from about 800 m to the Mediterranean. The two sub-basins represent two distinct climatic and physiographical settings as the ULB is mostly dominated by a mountainous area while the LLB is mostly coastal. In addition, this distinct topology raises the possibility of treating the ULB and the LLB as two separate entities with contrasting climate conditions, where the ULB is considered mountainous, and the LLB is almost in a coastal zone. This gives an opportunity for studying and comparing the hydrological responses of climate change of one watershed that is divided into two heterogeneous orographic features, illustrating the significance of local features control. Hence, as the upper basin is dominated by a relatively high elevation area, it is expected to experience higher precipitation and snow rates which affect streamflow sustainability and seasonality, while the coastal lower basin is expected to be more exposed to higher temperature and lower precipitation (Abd-el-Al, 1993). The Litani basin will be studied in 3 different regions: (1) whole basin, (2) upper basin (ULB) and (3) lower basin (LLB).

2.4 Data sources

Temperature and precipitation data for the area under study were obtained from three different sources (global gridded, satellite and local station data), and correlated to assess the quality of the individual sources. Global gridded data are high resolution station data available for almost the whole globe, and have been adopted from the University of Delaware (UD) and the University of East Anglia (CRU TS). Satellite data have been adopted from the Tropical Rainfall Measuring Mission (TRMM) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Due to the scarcity in measured data and bureaucratic access problems, data from two local stations have been chosen based on availability. This includes monthly temperature data from Ksara Obsy Station (located in the Beqaa Valley – Lebanon) and precipitation data from Lebaa Station (South Lebanon – outside Litani river basin borders).

Monthly temperature datasets include: (*a*) gridded temperature during 1900-2006 from University of Delaware (UD) consisting of spatial interpolation (0.5°x0.5° resolution) of up to 12,200 stations spread around the world (Matsuura and Willnott, 2007) ; (*b*) 0.5°x0.5° gridded and aerially averaged temperature during 1901-2002 from University of East Anglia (CRU TS 2.1, Mitchell and Jones, 2005) derived from monthly time series from stations representing 3,000 land regions, (*c*) satellite data (0.05°x0.05° resolution) consisting of land surface temperature from 2000 to present adopted from the Moderate Resolution Imaging Spectroradiometer (MODIS, Seemann et al., 2003) and d) Ksara Obsy station data available for the period 1921-1960.

Monthly precipitation datasets include: (*a*) gridded (0.5°x0.5° resolution) precipitation during 1900-2006 from University of Delaware consisting of spatial interpolation of up to 22,000 worldwide monthly precipitation stations (Matsuura and Willnott, 2007), (*b*) satellite data (0.25°x0.25° resolution) adopted from the Tropical Rainfall Measuring Mission (TRMM, Huffman et al., 2007) covering the latitude band of 50 ° N-S from 1998 to present, (*c*) interpolated gauge based gridded precipitation (0.5°x0.5° resolution) during 1901-2002 from

University of East Anglia (CRU TS, Mitchell and Jones, 2005) and d) Lebaa station precipitation data available for the period 2001-2008.

For runoff, due to the lack of long term measured data, the synthetic data generated by Ramadan et al. (2011b) have been used.

2.5 Methodology

Watershed-scale climate change analysis was conducted using the following steps: 1) long-term monthly surface temperature and precipitation time series from 1900 to 2008 were generated on the basis of monthly data sets from several historical global gridded datasets (CRU TS and UD), satellite data (MODIS and TRMM), and in-situ gauged data (Ksara-Obsy and Lebaa); 2) the data were extended to cover the period between 1900 and 2008; 3) temperature and precipitation trends during 1900-2008 were analyzed using Mann-Kendall and Sen Slope nonparametric statistical methods and 4) temperature and precipitation variations were correlated with runoff of the Litani basin using multiple regression analysis.

2.5.1 Time series generation

The Litani basin was delineated first using ASTER Global Digital Elevation Maps (NASA, 2009). Subsequently, two types of gridded data were generated from the data sources represented in the previous section: a) Basin-wide data produced from satellite and global gridded datasets and b) cell based data. The latter consisted of temperature and precipitation data extracted from the grids where the weather stations (i.e., Ksara Obsy and Lebaa) are located.

For any given gridded dataset (precipitation or temperature) over the Litani watershed, spatial averaged quantities, $\bar{x}$, were approximated by:

$$\bar{x} = \sum_{i=1}^{n}(x_i A_i) \div A \qquad (2\text{-}1)$$

where, x_i and A_i are the data value and area, respectively, at the i^{th} pixel (grid or cell) in the Litani watershed, A is the total watershed area, and n is the number of pixels within the watershed under study. Basin-wide averaging of historical monthly temperature and precipitation time series was performed for each dataset.

Monthly precipitation and temperature time series from 1900-2008 for the Litani watershed were combined. A single data set each of temperature and precipitation was generated. This was done by: 1) calibrating the relationship between each of the UD and CRU TS datasets versus local station data through simple regression; 2) generating two datasets (one for temperature and one for precipitation) by using the monthly mean of each value of the calibrated UD and CRU TS data; and 3) testing the generated data against satellite data (MODIS and TRMM). The Pearson linear correlation was used to test the reliability of the data. Hence, correlations between basin-wide average temperature and precipitation from satellite datasets (MODIS/TRMM) and global gridded datasets (UD and CRU TS) were determined. These correlations are strong with correlation coefficients greater than 0.95 that are statistically significant at 0.01% level (Table 2-1).

In order to illustrate the reliability of the data, correlations between gauged data and their spatially associated grid (pixel or cell) value from the global gridded datasets and satellite datasets were conducted. The Ksara Obsy station was selected as the surface air temperature calibration station. On the basis of the overlay analysis, Ksara Obsy (Figure 2-1) was located within grid no. 81072 of the UD and CRU TS gridded temperature datasets. Correlations of actual surface temperatures at Ksara Obsy station with the surface temperature at grid no. 81072 from UD and CRU TS datasets are extremely strong with correlation coefficients greater than

0.99 and statistically significant at 0.01% level. Labaa Station (Figure 2-1) was selected as the ground precipitation calibration station. It is spatially associated with grid no. 94462 of TRMM datasets. Lebaa was the closest station to the Litani basin for which one could get reliable data. Correlation between actual precipitation and the precipitation at cell no. 94462 of TRMM dataset is strong with a correlation coefficient of 0.93 (R^2=0.87) and statistically significant at 0.01% level.

Correlations between the spatial mean temperature/precipitation in the Litani Basin and those for global gridded and satellite extrapolated datasets are shown in Table 2-2. The correlation coefficients range from 0.995 to 0.998 and from 0.976 to 0.982 for temperature and precipitation, respectively, at 0.01% significance.

IPCC (2007a; 2007b) indicated that the sharpest rise of observed global surface temperatures occurs post 1970. Hence, another set of time series was built in order to study the possible changes of the hydro-climatological performance of the Litani Basin after 1970.

2.5.2 Data extension and testing

As the temperature and precipitation datasets have different temporal durations, a correlation and variance based time series extension method (Matalas and Langbein, 1962) was applied as:

$$y_i = r\frac{\sigma_y}{\sigma_x}(x_i - \bar{x}) + \bar{y} \quad (2\text{-}2)$$

where, r, σ_x, σ_y , $\bar{x}$, and $\bar{y}$ are the correlation, standard deviations, and means for the two time series during the concurrent period. All datasets were extended to cover the period 1900-2008. This method is based on a linear regression function built between two datasets with different time periods and, hence, it is limited to general linear regression assumptions (Kachigan, 1986).

However, since the datasets in this study are highly correlated, the adverse effect on the data quality of a relatively short extrapolated period is small.

2.5.3 Data pre-whitening

One of the problems in detecting and interpreting trends in hydrologic data is the confounding effect of serial dependence. Specifically, if there is a positive serial correlation (persistence) in the time series, then the non-parametric test will suggest a significant trend in a time series, that is, in fact random more often than specified by the significance level (Kulkarni and Van Storch, 1995). For this, Von Storch and Navarra (1995) suggest that the time series should be 'pre-whitened' to eliminate the effect of serial correlation before applying the Mann-Kendall test. The present study incorporates this suggestion, and examines the possible statistically significant trends in the time series ($x_1, x_2, \ldots, x_n$) using the following procedures:

(1) Compute the lag-1 serial correlation coefficient designated by r_1;

(2) If the calculated r_1 is not significant at 5% level, the Mann-Kendall test is applied to original time series to find its trend;

(3) If the calculated r_1 is significant at 5%, prior to application of the Mann–Kendall test, "pre-whitened" time series may be obtained as ($x_2 - r_1x_1, x_3 - r_1x_2, \ldots, x_n - r_1x_{n-1}$).

2.5.4 Temperature and precipitation trend analysis

Following the generation, calibration and testing of the data, the Mann-Kendall test was used to determine the statistical significance of the trends in the time series. The data were tested and "pre-whitened" first from any serial dependence following the Von Storch and Navarra (1995) approach.

Mann-Kendall's statistic S for a time series (D_k, k=1, 2, …, n) is calculated as follows:

$$S = \sum_{j<1} (\text{sgn}(D_i - D_j)) \tag{2-3}$$

where, sgn(x)=1, if $x > 0$; sgn(x) = 0, if $x = 0$; sgn(x) = -1, if $x < 0$. The Z-statistic, from which the p-value is derived, was calculated as follows:

$$Z = \frac{S-1}{[Var(S)]^{1/2}} \text{ if } S > 0 \tag{2-4}$$

$$Z = 0 \text{ if } S = 0 \tag{2-5}$$

$$Z = \frac{S+1}{[Var(S)]^{1/2}} \text{ if } S < 0 \tag{2-6}$$

$$Var(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \tag{2-7}$$

where n is the number of data points, t_p is the number of ties for the p^{th} value, and q is the number of tied values (Kendall, 1975). An increasing trend will have a large positive Z-statistic, while the Z statistic for a decreasing trend will be negative and have a large absolute value. A level of statistical significance α is then selected. A value of $Z_{1-\alpha/2}$ is determined using a standard normal distribution table. If $|Z| > Z_{1-\alpha/2}$, the series is said to display a trend significant to α. This means that there is a probability (at α %) that a trend was falsely identified. By introducing the expected variance of S in the determination of Z, the Mann-Kendall test is able to reject what might appear to be trends over small periods of time. For example, if a 3 year period of time displays a consistent increase in P and the expected variance of S is small enough, then the test will likely reject the presence of a trend in this isolated time series as it is not of great statistical significance to observe such phenomena.

If a linear trend is present in a time series, the true slope (change per unit time) can be estimated by using a simple non-parametric procedure developed by Sen (1968). The slope estimates of time series ($x_1, x_2, \ldots, x_n$) are first computed by:

$$S_s = \frac{x_j - x_k}{j - k}, \text{ for } j = 1, \ldots, n, \; k=1, \ldots, j-1 \tag{2-8}$$

where, S_s is the slope between data points and, x_j and x_k are data values at times j and k ($j > k$) respectively. Upon calculation of slope, Sen's estimator is the given by the median slope.

A specific confidence interval of ranks (α) is found by:

$$C_\alpha = Z_{1-\alpha/2} \times \sqrt{Var(S)} \tag{2-9}$$

Ranks of the lower bound (L) and upper bound (M) of confidence interval are:

$$L = n \times (n-1)/4 - C_\alpha / 2 \tag{2-10}$$

$$M = n \times (n-1)/4 + C_\alpha / 2 + 1 \tag{2-11}$$

The slopes corresponding to L and M are chosen as the lower and upper confidence interval, respectively. The median slope is then defined as statistically different from zero for the selected confidence interval if zero does not lie in the estimated confidence interval.

2.5.5 Correlation of temperature and precipitation with runoff

Finally, in order to detect the implications of climate change on the basin's water resources, we conduct a multiple linear regression (Kleinbaum et al., 1998) analysis on the runoff variations induced by two climate factors, i.e., temperature and precipitation. The multivariate regression equation used has the following form:

$$Q = c + aP + bT \tag{2-12}$$

where Q, P and T are the annual/seasonal/monthly runoff, precipitation and temperature respectively; c is a constant, and a and b are the precipitation and temperature coefficients respectively. This equation was employed to correlate runoff with temperature and precipitation. Annual, seasonal and monthly runoff data were obtained from Ramadan et al. (2011b). As the Litani basin is divided into two distinct sub-basins by the Qaraoun dam, two runoff quantities have been used in this study representing the ULB and LLB outlets.

2.6 Results

Figures (2-2) and (2-3) show the annual mean temperature and annual precipitation respectively for the 1900-2008 period with their 5 year moving average. These figures were developed from the combination of global gridded, satellite and local station data. The difficulty of detecting evident climate trends visually from these figures is apparent. Hence, trends were detected as described in the methodology section and are presented in Tables (2-3) and (2-4) showing the data serial correlation when detected, Sen Slope value which presents the decadal temperature and precipitation variations, and its statistical confidence interval (CI). Based on the Mann-Kendall and Sen slope procedure findings during 1900-2008, the Litani Basin has experienced a significant drying trend, with a decrease in annual precipitation at a rate of ~1.1 mm/decade. The greatest decrease in rainfall occurred in the spring and monsoon (wet) seasons (Table 2-3) with the largest drying trend (6.3 mm/decade) occurring in December. However, annual, seasonal, and monthly mean surface temperature series did not show a significant trend, except for November and winter (Oct – Dec), during which a significant cooling trend at a rate of 0.1 ºC/decade existed. These findings are in general agreement with Giorgi (2002), Jacobeit (2000) and

Sahsamanoglou and Makrogiannis (1992) implying the dominance of the Mediterranean regional climate on the whole Litani weather variability.

According to Table (2-4), there was no significant trend in precipitation in the Litani Basin during 1970-2008, except for the fall season where a positive trend of 0.2 mm/decade was observed. However, surface temperature had a significant warming trend with a rate of 0.2 ºC/decade for annual and dry season (June to September), 0.3 ºC/decade for monsoon (November to March) and summer seasons, and 0.4 ºC/decade during the transitional season (April to May). In fact, the Litani Basin has shown, in general, a similar rise to the Mediterranean region temperature post 1970. However, the seasonal temperature variations of the Mediterranean region differed from those of the Litani. Hence, the analysis has shown that the largest warming trend of the Litani Basin occurs in the month of May during 1970 to 2008 with a warming rate of 0.6 ºC/decade. Similarly, the results illustrated a warming rate of 0.5 ºC/decade in December, a warming rate of 0.4 ºC/decade in August and September and a warming rate of 0.2 ºC/decade in June.

On a smaller scale, analyzing ULB and LLB time series show different trends. Here, precipitation trends were detected and monthly temperature and precipitation changes seemed to differ from the analysis of the whole Litani Basin. Hence, the following were departures from the trends observed in the whole Litani basin: 1) for the period 1900-2008, the LLB showed negative precipitation trends during April, summer and transitional seasons, positive precipitation trends during August and September, and a negative temperature trend during monsoon season. Temperature trends were not detected for the ULB; 2) for the period 1970-2008, the LLB showed positive precipitation trends during August and September and no temperature trends during annual, May, September, December, fall, winter, dry, monsoon and transitional seasons.

The ULB showed a positive temperature trend during October and displayed no precipitation trends.

Comparing the ULB and LLB precipitation and temperature trends between 1900 and 2008 (Table 2-3), the LLB showed an accentuated drying trend with monthly trends. Although both regions had the largest rainfall loss per decade in December, the rate was 7.7 mm of rainfall loss per decade for the LLB, while the ULB showed a loss of 5.7 mm/decade. Meanwhile, a significant cooling temperature trend appeared only in the LLB with a rate of 0.2 °C/decade for November and 0.1 °C/decade in winter and monsoon periods. For the 1970-2008 period, the LLB had the highest positive precipitation trend of 0.7 mm/decade in September and other positive trends during August when rain seldom occurs in Lebanon, and during the fall season (Table 2-4). This is in contrast to the ULB which showed no significant precipitation changes for the post 1970 period. For temperature, the ULB showed warming trends after 1970 during annual, summer, fall, winter, dry, monsoon and transitional seasons in contrast to the cooling trend that was observed during the 1900-2008 period. However, the LLB had fewer significant increasing temperature trends than the ULB after 1970 because significant positive trends were only observed during the summer season, especially in June and August. The ULB and LLB had highest warming values in December and August, respectively.

Finally, the correlation coefficients of the Litani's runoff variations with temperature and precipitation through multiple regression (equation (2-12)) are listed in Table (2-5). In both the ULB and LLB, runoff was more frequently correlated with precipitation than with temperature, particularly post-1970. Hence, changes in precipitation rather than temperature may be more indicative of changes to runoff, making the long-term drying trend (accentuated in the LLB) potentially more consequential to water resources. The regression coefficients between

November and April and for annual, transitional, spring, fall, winter and monsoon periods indicate significant positive correlation between precipitation and runoff for both ULB and LLB and for the two temporal phases (Table 2-5). These findings are consistent with rainfall temporal distribution in Lebanon where most of the rain falls between November and April.

Temperature correlations with runoff have some variations between the ULB and LLB. A negative correlation, when significant, is shown to occur in both ULB and LLB, which could be due to the effect of higher temperature on the evapotranspiration rate and consequently, on runoff reduction. According to Table (2-5), the ULB and the LLB have a significant correlation between temperature and runoff in December and spring season for the period 1900-2008. However, both sub-basins have observed no correlation for the same periods of the year during 1970-2008. For other months and seasons the differences in the response of the ULB and LLB are evident. For example, both sub-basins have significant correlation coefficients during March and April for the period 1900-2008. However, there was no statistical significance in April for the ULB and in March for the LLB for the analysis after 1970. In addition, in contrast to the LLB, the ULB temperature variations have significant correlation with runoff for annual, monsoon and winter seasons during 1900-2008 period.

For the post 1970 period, there was no significant correlation between temperature and annual runoff. However, there were significant negative correlations in the ULB with temperature during January, March, winter and monsoon which might affect the water budget of the ULB if the warming trend continues in the future. Analysis of the LLB runoff indicated different seasonal behavior. Based on the results illustrated in Table (2-5), negative correlations between runoff and temperature were observed during 1970-2008 in April. Furthermore, significant negative correlations were shown in June and September when rain usually does not fall in the Litani's vicinity. This might affect the low flow of LLB if the trend persists.

2.7 Conclusions and summary

Regional studies showed that general hydro-climatological trends of regional areas may help in giving water managers a general spectrum of climate directions. However, in order to define priorities for planning, budgeting and implementing nationwide strategies for water sustainability and management, it is vital to characterize the direct effects at the basin level. In this study, the Litani basin's hydro-climatological response was investigated using time series analysis, trend tests and multiple regression methods. The results illustrate the existence of varied climate patterns and highlight the influence of climate trends on a basin's hydrology. Some results differentiate between the upper and lower basin hydro-climatological response. This underlines the importance of physical characteristics of the area showing that, even for a mid-size watershed, the response differs from one morphological location to another. The results indicate that in the long-term (1900-2008), the dominance of a drying trend over ULB, LLB and the whole basin was evident, especially annually and during winter, spring and monsoon seasons. The rate of precipitation reduction was shown to be even highest over the LLB. However, no significant temperature trends were detected in the Litani Basin or within the sub-basins during this same time period. Conversely, in the short-term (1970-2008), the Litani Basin witnessed a shift to annual and seasonal warming trends, however no precipitation trends were detected. In addition, since runoff was positively correlated with precipitation, especially during the rainy season, and negatively correlated with temperature, the Litani's runoff is likely to decline due to both long-term decreases in precipitation and short-term increases in temperature. The ULB in particular exhibited a temperature increase in the last 40 years and may be at a greater risk of experiencing reduced runoff if such temperature trends persist.

The drier and warmer climate may pose serious implications to the Litani water sustainability. The integration of the results of this study into the basin's water resources management and planning may give the Litani's authorities a better picture of the yearly, seasonal and monthly variations of water quantity due to climate change. This will assist in formulating a more comprehensive water resources planning and management approach through the optimization of the best timing for water storage, use and distribution for both the ULB and LLB.

Natural climate variability and/or anthropogenic contribution might be the reason of long term hydro-climatological fluctuation of the basin. The effect of natural climate variability on the Litani basin is discussed in the chapter 3.

Tables

Table 2-1 Correlation between basin wide global gridded datasets (UD and CRU TS) and satellite datasets (MODIS and TRMM)

MODIS-Temp	UD-Temp	CRUTS-Temp
$r^{\dagger}$	0.991	0.982
$p^{\ddagger}$	<0.01%	<0.01%
TRMM	UD-Prcp	CRUTS-Prcp
$r^{\dagger}$	0.967	0.956
$p^{\ddagger}$	<0.01%	<0.01%

†: Pearson's correlation coefficient; ‡: significance level
UD: University of Delaware
CRU TS: Climate Research Unit Time Series
MODIS: MODerate Resolution Imaging Spectroradiometer
TRMMM: Tropical Rainfall Measuring Mission
Temp: Temperature
Prcp: Precipitation

Table 2-2 Correlation between extrapolated time series with original time series

Temp.	UD-Temp	CRUTS-Temp	MODIS
$r^{\dagger}$	0.998	0.998	0.995
Precip.	UD-Prcp	TRMM	CRUTS-Prcp
$r^{\dagger}$	0.981	0.976	0.982

†: Pearson's correlation coefficient
UD: University of Delaware
CRU TS: Climate Research Unit Time Series
MODIS: MODerate Resolution Imaging Spectroradiometer
TRMMM: Tropical Rainfall Measuring Mission
Temp: Temperature
Prcp: Precipitation

Table 2-3 Summary of temperature and precipitation serial correlation and Sen Slope during 1900-2008 for the Litani Basin

Variables			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Spring	Summer	Fall	Winter	Dry‡	Monsoon‡	Trans‡
Whole Basin	Precipitation	s-corr.†	0.02	0.01	0.09	0.04	0.15	0.13	0.57**	0.38**	0.03	0.15	0.01	0.13	0.21*	0.05	0.03	0.24*	0.16	0.32**	0.25**	0.04
		Sen Slope (mm/10yr)	-4.6**	-5.1*										-6.3**	-1.1**	-3.2**			-2.3**		-3.1**	
		Sen Slope 95% CI	(-8.1, -1.4)	(-8.8, -1.1)										(-10.1, -2.4)	(-1.9, -0.4)	(-5.4, -1.2)			(-4.1, -0.5)		(-4.7, -1.4)	
	Temperature	s-corr.†	0.08	0.02	0.05	0.14	0.17	0.28**	0.38**	0.32**	0.14	0.20*	0.06	0.07	0.39**	0.04	0.29**	0.45**	0.08	0.54**	0.01	0.19*
		Sen Slope (°C/10yr)											-0.1*						-0.1*			
		Sen Slope 95% CI											(-0.2, 0)						(-0.1, 0)			
Upper Basin	Precipitation	s-corr.†	0	0.03	0.1	0.04	0.16	0.14	0.6**	0.42**	0.03	0.16	0.02	0.14	0.19	0.04	0.02	0.25**	0.16	0.31**	0.22*	0.03
		Sen Slope (mm/10yr)	-3.8*	-4.1*										-5.7**	-1.3**	-2.5*			-1.7*		-2.6**	
		Sen Slope 95% CI	(-6.9, -0.5)	(-8.0, -0.5)										(-9.0, -1.8)	(-2.1, -0.5)	(-4.7, -0.6)			(-3.6, -0.1)		(-4.2, -1.0)	
	Temperature	s-corr.†	0.08	0.04	0.02	0.11	0.20*	0.37**	0.42**	0.37**	0.21*	0.20*	0.04	0.04	0.45**	0.07	0.38**	0.51**	0.07	0.59**	0.02	0.21*
		Sen Slope (°C/10yr)																				
		Sen Slope 95% CI																				
Lower Basin	Precipitation	s-corr.†	0.06	0.02	0.08	0.05	0.14	0.17	0.54**	0.33**	0.06	0.12	0	0.11	0.26**	0.12	0.07	0.38**	0.16	0.49**	0.33**	0.07
		Sen Slope (mm/10yr)	-7.2**	-7**		-1.4*				0.007**	0.1*			-7.7**	-1.6**	-5.1**	-0.7*		-3.5**		-4**	-1*
		Sen Slope 95% CI	(-10.8, -3.6)	(-11, -2.9)		(-2.9, -0.1)				(0.003,0.017)	(0, 0.1)			(-12.2, -3.1)	(-2.4, -0.7)	(-7.2, -2.9)	(-1.2, -0.1)		(-5.8, -1.7)		(-5.6, -2.3)	(-1.8, -0.2)
	Temperature	s-corr.†	0.01	0.02	0.07	0.11	0.17	0.17	0.38**	0.33**	0.20*	0.28**	0.18	0.03	0.43**	0.06	0.25**	0.45**	0.23*	0.49**	0.08	0.15
		Sen Slope (°C/10yr)											-0.2**						-0.1**		-0.1*	
		Sen Slope 95% CI											(-0.3, -0.1)						(-0.1, 0)		(-0.1, 0)	

*: Significant at 5% level
**: Significant at 1% level
†: Lag-1 serial correlation coefficient
‡: Seasons: Dry from Jun to Sep; Monsoon from Nov to Mar; Transitional (Trans) from April to May
CI: Confidence Interval
Blank spaces: Slope is not significant

Table 2-4 Summary of temperature and precipitation serial correlation and Sen Slope during 1970-2008 for Litani Basin

Variables			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Spring	Summer	Fall	Winter	Dry‡	Monsoon‡	Trans‡
Whole Basin	Precipitation	s-corr.†	0.17	0.27	0.03	0.17	0.13	0.23	0.68**	0.36*	0.05	0.09	0.15	0.05	0.03	0.03	0.26	0.28	0.11	0.34*	0.12	0.26
		Sen Slope (mm/10yr)																0.2*				
		Sen Slope 95% CI																(0, 0.5)				
	Temperature	s-corr.†	0.01	0.06	0.02	0.22	0.31	0.75**	0.44**	0.40*	0.31	0.29	0.06	0	0.63**	0.12	0.49**	0.63**	0.17	0.73**	0.03	0.16
		Sen Slope (°C/10yr)					0.6**	0.2*		0.4**	0.4**			0.5*	0.2*		0.3**	0.2*	0.4*	0.2*	0.3*	0.4**
		Sen Slope 95% CI					(0.2, 1)	(0, 0.4)		(0.2, 0.7)	(0.2, 0.6)			(0.1, 0.9)	(0, 0.3)		(0.1, 0.6)	(0, 0.4)	(0.1, 0.5)	(0, 0.4)	(0, 0.5)	(0.1, 0.6)
Upper Basin	Precipitation	s-corr.†	0.17	0.27	0	0.18	0.12	0.22	0.68**	0.41*	0.04	0.11	0.1	0.06	0.04	0.05	0.27	0.28	0.09	0.33*	0.13	0.27
		Sen Slope (mm/10yr)																				
		Sen Slope 95% CI																				
	Temperature	s-corr.†	0	0.09	0.1	0.14	0.38*	0.81**	0.47**	0.46**	0.43**	0.31	0.07	0.08	0.67**	0.2	0.62**	0.67**	0.21	0.76**	0.06	0.22
		Sen Slope (°C/10yr)					0.5*	0.2*		0.5**	0.3*	0.5*		0.7**	0.2*		0.4**	0.3**	0.5**	0.2*	0.4**	0.5**
		Sen Slope 95% CI					(0.1, 0.9)	(0, 0.4)		(0.3, 0.8)	(0.1, 0.5)	(0.1, 0.9)		(0.2, 1.1)	(0, 0.4)		(0.1, 0.6)	(0.1, 0.5)	(0.3, 0.7)	(0.1, 0.4)	(0.1, 0.7)	(0.2, 0.7)
Lower Basin	Precipitation	s-corr.†	0.16	0.28	0.09	0.14	0.12	0.31	0.69**	0.28	0.17	0.04	0.26	0.03	0.01	0	0.21	0.48**	0.15	0.58**	0.07	0.22
		Sen Slope (mm/10yr)								0.1**	0.7*							0.4*				
		Sen Slope 95% CI								(0, 0.3)	(0.1, 1.3)							(0.1, 0.8)				
	Temperature	s-corr.†	0.09	0.07	0.14	0.13	0.23	0.44**	0.44**	0.35*	0.33*	0.38*	0.1	0.01	0.54**	0.11	0.27	0.55**	0.35*	0.57**	0	0
		Sen Slope (°C/10yr)						0.2*		0.3*							0.3*					
		Sen Slope 95% CI						(0, 0.4)		(0, 0.5)							(0, 0.5)					

*: Significant at 5% level

**: Significant at 1% level

†: Lag-1 serial correlation coefficient

‡: Seasons: Dry from Jun to Sep; Monsoon from Nov to Mar; Transitional (Trans) from April to May

CI: confidence interval

Blank spaces: Slope is not significant

Table 2-5 Results of multiple linear regression of annual, monthly and seasonal runoff with precipitation and temperature coefficients a and b respectively

	UPPER LITANI BASIN (ULB)						LOWER LITANI BASIN (LLB)					
	1900-2008			1970-2008			1900-2008			1970-2008		
Mon/Season	a	b	R	a	b	R	a	b	R	a	b	R
Jan	**0.06** (0.01)	-0.83 (0.42)	0.53	**0.05** (0.02)	**-1.45** (0.63)	0.49	**0.09** (0.01)	-0.38 (0.4)	0.66	**0.07** (0.02)	-0.92 (0.62)	0.52
Feb	**0.06** (0.01)	-0.34 (0.35)	0.59	**0.08** (0.02)	0.04 (0.51)	0.71	**0.09** (0.01)	-0.19 (0.37)	0.7	**0.08** (0.02)	-0.43 (0.52)	0.74
Mar	**0.03** (0.01)	**-1.4** (0.33)	0.56	**0.04** (0.02)	**-1.5** (0.55)	0.54	**0.07** (0.01)	**-1.11** (0.32)	0.66	**0.08** (0.02)	-1 (0.55)	0.64
Apr	**0.04** (0.01)	**-0.65** (0.26)	0.46	**0.04** (0.02)	-0.5 (0.38)	0.5	**0.05** (0.01)	**-0.84** (0.3)	0.54	**0.05** (0.02)	**-1.36** (0.45)	0.68
May	-0.01(0.02)	0.02 (0.17)	0.08	-0.1 (0.05)	0.22 (0.31)	0.28	-0.01 (0.02)	-0.02 (0.21)	0.04	0 (0.05)	-0.31 (0.31)	0.21
Jun	-0.04 (0.03)	-0.05 (0.06)	0.14	-0.1 (0.01)	-0.1 (0.12)	0.23	-0.04 (0.05)	-0.15 (0.12)	0.14	0.03 (0.06)	**-0.36** (0.17)	0.34
Jul	0 (0.01)	-0.01 (0.01)	0.14	0 (0.01)	0 (0.01)	0.29	-0.07 (0.06)	-0.08 (0.08)	0.18	-0.1 (0.07)	-0.07 (0.1)	0.32
Aug	0 (0)	0 (0)	0.13	0 (0)	0 (0)	0.16	-0.02 (0.02)	-0.09 (0.05)	0.23	0 (0.02)	-0.1 (0.06)	0.36
Sep	0 (0)	0 (0)	0.11	0 (0)	0 (0)	0.12	-0.01 (0.01)	-0.04 (0.03)	0.25	0 (0.01)	**-0.11** (0.04)	0.53
Oct	0 (0)	0 (0)	0.69	0 (0)	0 (0)	0.8	0 (0)	-0.02 (0.02)	0.42	0 (0)	-0.04 (0.03)	0.47
Nov	**0.01** (0)	0.03 (0.04)	0.76	**0.02** (0)	0.02 (0.07)	0.71	**0.02** (0)	-0.02 (0.05)	0.8	**0.01** (0)	-0.01 (0.09)	0.53
Dec	**0.03** (0.01)	**-0.77** (0.27)	0.59	**0.05** (0.01)	-0.7 (0.44)	0.64	**0.05** (0.01)	**-0.59** (0.26)	0.66	**0.06** (0.01)	-0.59 (0.35)	0.71
Annual	**0.09** (0.01)	**-0.36** (0.16)	0.78	**0.1** (0.02)	-0.3 (0.24)	0.72	**0.15** (0.01)	-0.33 (0.23)	0.79	**0.14** (0.02)	-0.46 (0.31)	0.75
Spring	**0.11** (0.01)	**-0.79** (0.25)	0.74	**0.12** (0.02)	-0.6 (0.38)	0.75	**0.13** (0.02)	**-0.74** (0.34)	0.7	**0.15** (0.03)	-0.69 (0.5)	0.75
Summer	-0.03 (0.02)	-0.05 (0.03)	0.2	0 (0.02)	-0.1 (0.04)	0.32	-0.05 (0.05)	-0.17 (0.1)	0.21	0 (0.06)	-0.22 (0.13)	0.33
Fall	**0.01** (0)	0 (0.03)	0.7	**0.01** (0)	0.07 (0.04)	0.72	**0.02** (0)	-0.05 (0.04)	0.71	**0.01** (0)	-0.03 (0.07)	0.34
Winter	**0.1** (0.01)	**-0.68** (0.29)	0.79	**0.12** (0.01)	**-0.97** (0.43)	0.84	**0.12** (0.01)	-0.15 (0.31)	0.8	**0.11** (0.02)	-0.78 (0.5)	0.79
Dry	-0.02 (0.01)	-0.04 (0.02)	0.21	-0.04 (0.02)	-0.1 (0.03)	0.39	-0.07 (0.04)	-0.14 (0.1)	0.26	-0.1 (0.05)	-0.19 (0.12)	0.42
Monsoon	**0.11** (0.01)	**-0.57** (0.18)	0.89	**0.13** (0.01)	**-0.61** (0.26)	0.92	**0.15** (0.01)	-0.03 (0.23)	0.88	**0.14** (0.02)	-0.14 (0.46)	0.81
Trans	**0.09** (0.01)	-0.39 (0.24)	0.55	**0.11** (0.02)	0.27 (0.38)	0.61	**0.1** (0.02)	-0.57 (0.31)	0.53	**0.09** (0.03)	-0.89 (0.51)	0.61

a: Precipitation coefficient; b: Temperature coefficient
Number between brackets is the Standard Error of the coefficient
Seasons: Dry from Jun to Sep; Monsoon from Nov to Mar; Transitional (Trans) from April to May
Bold and underlined numbers represent a & b coefficients with 5% significance
R: Correlation

Figures

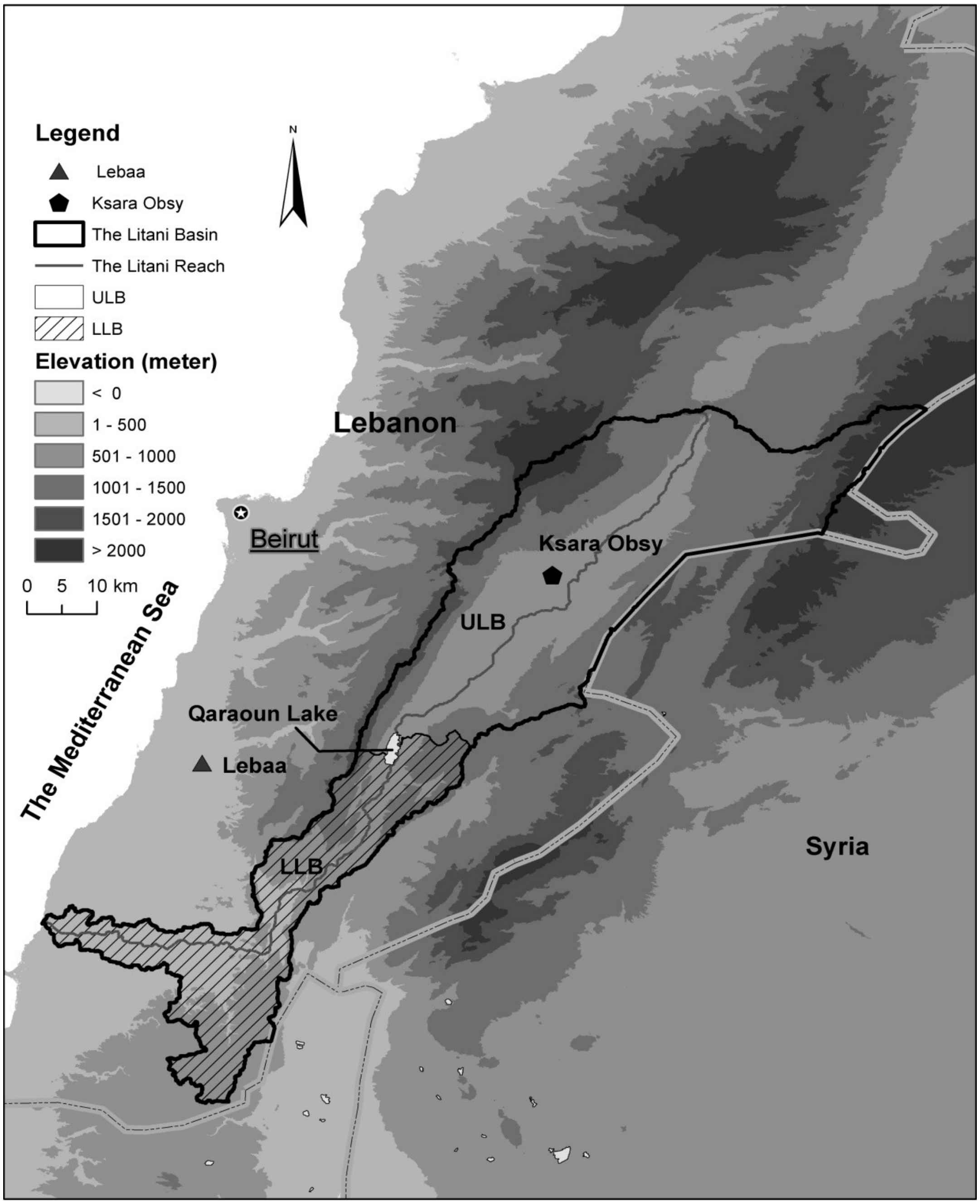

Figure 2-1The Litani watershed in topographical map of Lebanon
ULB: Upper Litani Basin
LLB: Lower Litani Basin
Ksara Obsy and Lebaa: 2 weather stations
Beirut: Capital of Lebanon

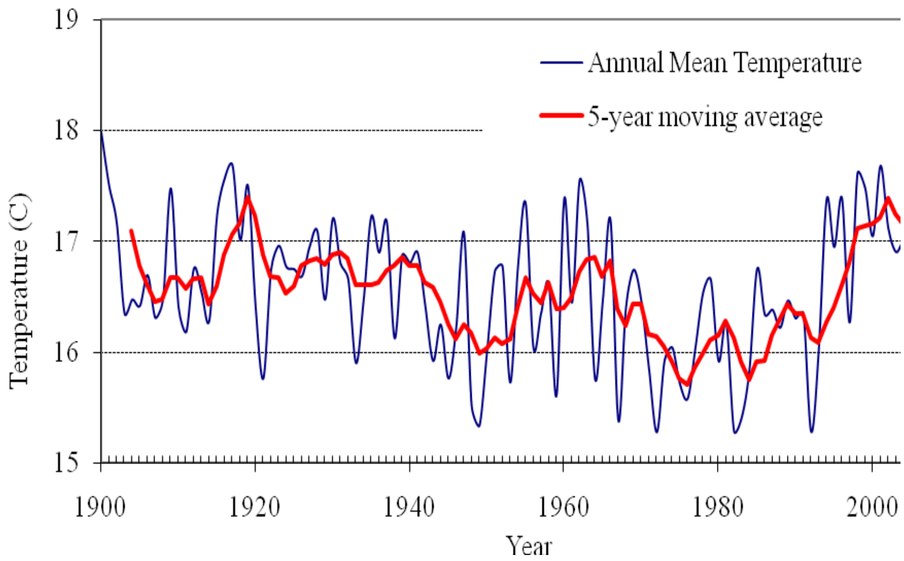

Figure 2-2 Litani Basin's annually averaged temperature time series from 1900 to 2008

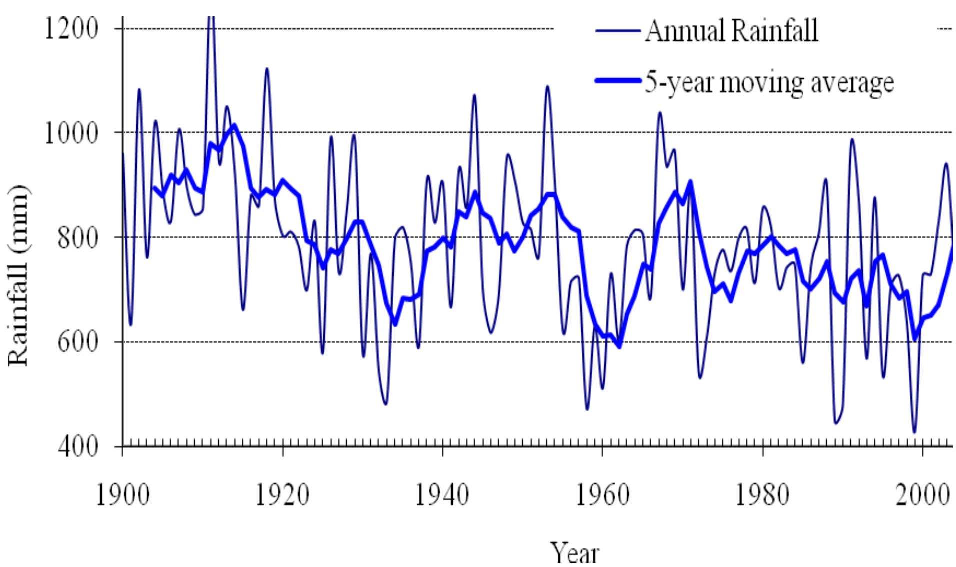

Figure 2-3Litani Basin's annually averaged surface rainfall time series from 1900 to 2008

3 Inter-Annual Temperature and Precipitation Variations over the Litani Basin in Response to Atmospheric Circulation Patterns

Ramadan H.H, Ramamurthy, A.S. and Beighley R.E.
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3.1 Abstract

This study examines the sensitivity of a mid-size basin's temperature and precipitation response to different global and regional climate circulation patterns. The implication of the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), Indian Monsoon and 10 other teleconnection patterns of the Northern Hemisphere are investigated. A methodology to generate a basin-scale, long-term monthly surface temperature and precipitation time series has been established using different statistical tests. The Litani River Basin is the focus of this study. It is located in Lebanon, east of the Mediterranean Basin, which is known to have diverse geophysical and environmental characteristics. It was selected to explore the influence of the diverse physical and topographical features on its hydro-climatological response to global and regional climate patterns. We also examine the opportunity of conducting related studies in areas with limited long-term measured climate and/or hydrological data. Litani's monthly precipitation and temperature data have been collected and statistically extrapolated using remotely sensed data products from satellites and as well as in-situ gauges. Correlations between 13 different teleconnection indices and the basin's precipitation and temperature series are investigated. The study shows that some of the annual and seasonal temperature and precipitation variance can be partially associated with many atmospheric circulation

patterns. This would give the opportunity to relate the natural climate variability with the watershed's hydro-climatology performance and thus differentiate it from other anthropogenic induced climate change outcomes.

3.2 Introduction

The American Meteorological Society's glossary of meteorology defines climate as "the slowly varying aspects of the atmosphere-hydrosphere-land surface system" where all these factors are connected in one way or the other. This connection is described as being complex, inherently random or dominant, but still remains unknown (Huschkle 1959). Generally, a climate phenomena or a climate element change occurring in one location may affect another climate element at a different location.

Climate variability is marked by changes with time of the atmospheric elements such as temperature, precipitation, wind, humidity and atmospheric pressure on different spatial scales. It can be evaluated through long period statistical divergence of the meteorological components. However, the climate system is known to follow a nonlinear behavior accompanied by different levels of complexity, randomness and unstable feedback nature. Meanwhile, climate behavior differs and is based on the associated time and space scales. Hence, the apparent cause and effect explanations of climate variability can be problematic to establish. Time (days to centuries) and space (global to local) scales chosen for climate behavior exhibit variable responses. The Intergovernmental Panel on Climate Change (IPCC 2007b) considers the measure of climate variability similar to the measure of climate change. However, the differentiation between long term natural changes and the changes induced by human interference remain questionable.

As the sustainability of future water resources prompts serious concerns, the Intergovernmental Panel for Climate Change (IPCC 2007a) emphasized the need for studying climate variability at the regional and local scale, especially at the watershed or basin level. Drawing a line between natural and human induced long term climate variability sources is also important to distinguish the effect of natural climate variability characterized by global and regional climate patterns change on watershed regime behavior. For example, changes in precipitation and temperature routine over a region at a scale relevant for decision makers and stakeholders would have significant implications on resource management and water availability, and consequently, on the balance of socio-economical, water and environmental systems. In addition, understanding the variability of local precipitation and temperature associated with the regional and global climate regime would improve climate forecasting and the identification of climate change features (Giorgi 2002).

Long-term atmospheric circulation and variability can be manifested through climate patterns known as "teleconnection patterns". This term refers to natural recurring interannual and interdecadal oscillations and persistent pressure and circulation anomalies over a region, a continent or throughout the globe (Moron et al. 1998). Teleconnection patterns are presented as numerical indices type and employed to determine the strength and implication of the patterns over a specific region or continent during a certain period of the year. Hence, in an effort to standardize these common climate phenomena, earth scientists developed climate index time series that summarize the meteorological behavior of the oceans and atmosphere on a regional as well as a global scale. Steinbach et al. (2003) listed a description of well-known climate indices and some correlations among them. However, many other authors investigated the physical behavior of these teleconnections in various regions of the globe (Wallace and

Gutzler 1981; Barnston and Livezey 1987; Hurrell 1995). Furthermore, numerous research projects and studies have been conducted correlating these indices to many climate variability factors mostly on the global and some regional scale. Glantz et al. (2009) provided an extensive bibliography and a comprehensive review of many indices with yearly and seasonal teleconnections linking some regional weather variations to global climate anomalies.

The purpose of this study is to improve our knowledge of climatology and natural variability of the Litani Basin (Lebanon) in response to annual and seasonal time scales. The basin is located in the East Mediterranean region which currently is subjected to water scarcity. In order to enhance our understanding of the basin response, this contribution will be realized through teleconnecting different global and regional natural climate patterns with the basin's temperature and precipitation anomalies using statistical methods. A statistical correlation approach will be used which allows one to investigate the correlation between natural climate patterns and basin hydro-climatological variations. Teleconnection patterns are considered to be significant components of natural climate variability. Hence, this study will help to acknowledge the possible role of various global and regional climate circulations on a mid- sized local basin's temperature and precipitation which can be eventually linked, in a way or another to the basin's streamflow variations. Consequently, the dry and wet as well as warm and cool seasonal climatic variability of the basin maybe partially associated with the global and regional natural climate circulations. It is believed that the results from this study will assist decision makers acquire a better understanding of the climatological factors affecting the

Litani Basin hydro-climatology performance and, hence, permit one to consider these factors in both the current and future planning and forecasting methods and procedures.

In this study, 13 teleconnection patterns have been chosen to be investigated in correlation with the Litani basin's temperature and precipitation variance (Table 3-1); 10 of them are defined as Northern Hemispheric (NH) pattern by the Climate Prediction Center of the National Weather Services of the United States. The North Atlantic Oscillation (NAO) is based on the difference between the subtropical high in Ponta Delagada- Azores and subpolar low in Stykkisholmur – Iceland, and it is considered to be a measure of the strength of the westerlies (Hurrell 1995). The East Atlantic (EA) consists of a north-south dipole of anomaly centers (Barnston and Livezey 1987) and crosses the entire North Atlantic Ocean and displaced towards the southeast relating to the NAO pattern. It is described by one positive center over the British Isles and two negative centers over central Atlantic and Eastern Europe. The East Atlantic/Western Russia (EA-WR) comprises two anomaly centers located over western Europe and the Caspian Sea in winter and three anomaly centers located over western-northwestern Russia, northwestern Europe and the Portuguese coast during spring and fall seasons. It is referred to as Eurasia-2 (EU2) by Barnston and Livezey (1987). Scandinavia (SCAND) consists of 3 circulation centers, where the main one is located over Scandinavia and a segment of the Arctic Ocean in Siberia. The other two centers are located over Western Europe and Western China (Magnolia). SCAND plays a considerable role on precipitation patterns in Europe and it affects the height anomalies over Scandinavia, Western Russia, the Iberian Peninsula and Northwestern Africa (Barnston and Livezey

1987). Polar/Eurasia (POL) contains one main center over the polar region, and separate centers of opposite sign over Europe and northeastern China (CPC 2011). Hence, it affects the changes of the mid-latitude circulation that arise over a great fraction of Asia and Europe. The West Pacific (WP) pattern consists of a north-south dipole of anomalies. One center is situated over the Kamchatka Peninsula and a wide center of opposite sign covering a section of southeastern Asia and the lower latitudes of the farthest western North Pacific (Wallace and Gutzler 1981).

The spring, summer and fall East Pacific-North Pacific (EP-NP) pattern has three main anomaly centers where its center of action is located over the Pacific Ocean affecting mainly various North American regions (Barnston and Livezey 1987). Pacific/North American (PNA) illustrates the location, direction and potency of a low (trough) and high (ridge) pattern of air pressure on the Northern Pacific Ocean and North America (Barnston and Livezey 1987). The Tropical/Northern Hemisphere (TNH) is apparently a prominent mode during winter (CPC 2011). It contains one primary anomaly center over the Gulf of Alaska and a second anomaly center over Hudson Bay. The Pacific Transition (PT) pattern exists during August-September and has main centers of action located over the intermountain region of the United States and over the Labrador Sea and other weak anomaly centers with opposite signs over the Gulf of Alaska and over the eastern United States (CPC 2011).

The three remaining teleconnection patterns selected for the studies are the following:

The El Niño Southern Oscillation (ENSO) which is regarded as the earth's dominant source of year-to-year climate variations and to have a continental to global hydro-climatological influence (Rasmussen and Wallace 1983); the Indian Monsoon which is considered as a key factor affecting the climate of the eastern and central Mediterranean (Lionello et al. 2006); and one regional teleconnection pattern known as the Mediterranean Oscillation Index MOI-1 defined by Conte et al. (1989) as the normalized pressure difference between Algiers (36.4°N, 3.1°E) and Cairo (30.1°N, 31.4°E) and referenced as (MOAC). The Mediterranean Oscillation Index is described as a teleconnection pattern with opposite pressure and rainfall anomalies between the central-western and Eastern Mediterranean area.

3.3 Teleconnections and the Mediterranean

The Mediterranean is located in a region of great climate interest and challenge, because it is exposed to different climate patterns and includes accentuated orographic variation, complex land topography, and a wide ecological spectrum. These extensive disparities sometimes make the local physio-geographic aspects prevail over the global, continental and regional factors. The Mediterranean is located in the transitional zone between the subtropical high pressure arid zone (North African deserts) and the mid Latitude (North Europe). It is exposed to the South Asian Monsoon in summer and Siberian high pressure system during winter. The Mediterranean climate is controlled by many geo-graphical elements where the small scale process plays an important role (Xoplaki et al. 2000).

In this study, the role of the main northern hemisphere climate patterns, such as North Atlantic Oscillation (NAO) and East Atlantic and West Russia Pattern (EA-WR) are considered. It is shown that these two patterns have an influence on the major inter-annual variability of the atmospheric circulation which is associated with climatological changes in the surface across the Eastern Mediterranean region (Krichak et al. 2002). However, the hydro-climatological correlations with other teleconnection patterns are studied as well to investigate the influence of ENSO, MOAC, the Indian Monsoon and all other Northern Hemisphere teleconnection as defined by Smith et al. (2008).

Relating climate patterns to the regional weather response and its various consequences in the Mediterranean area was the core of much research in the last decade. Ropelewski and Halpert (1987) identify 17 global core regions that appear to have a clear ENSO-precipitation relationship. Hurrell (1995) relates NAO behavior to the regional precipitation and temperature variability over Europe and the Mediterranean. Al-Fenadi (2007) found a correlation between the North Libya Temperature index and ENSO. Kadioglu et al. (1999) investigated the Turkish monthly total precipitation variation between 1931 and 1990. They found that much of the monthly variability is related to El Niño events. Feliks et al. (2010) investigated the synchronization of the NAO with Eastern Mediterranean interannual and interdecadal climate variability including the Nile River flow. They realized the presence of a prominent oscillatory mode with a 7 to 8 yr period in the climatic indices studied synchronized with the NAO.

Mann (2002) documented the domination of the NAO over large scale temperature variations in the Middle East. Meanwhile, an anti-correlation of temperature variability with NAO was recognized over most of the western Mediterranean region (Hurrel 1995; Trigo et al. 2004). Hurrell and Loon (1997) also noted that the moisture conditions over the Mediterranean Basin were related to the NAO indices. Türkeş and Erlat (2003) studied the seasonal and annual precipitation over Turkey and its negative correlation with the NAO.

Ulbrich and Christoph (1999) conducted a couple of simulations showing that the climate change trend in winter precipitation relies significantly on the northward deviation of the storm track coupled with the shift and amplification of the NAO, which generate decreased and increased precipitation in the northwestern and southeastern Mediterranean regions, respectively. Moreover, Cullen and Menocal (2000) related the change in stream flows of Tigris and Euphrates rivers to the NAO indices. They stated that 27% of the change in precipitation is correlated with the NAO.

Other studies were conducted to explore the effect of ENSO on different regions of the Mediterranean. Van Oldenborgh et al. (2000) found a strong connection between warm winter El Niño and higher precipitation in spring for the area covering Southern England to Asia. Price et al. (1998) also showed that La Niña years were coupled with below normal rainfall. However, they found these results intriguing as the indicated statistically significant correlations appear only in the last 25 years. They also revealed a significant correlation between seasonal stream flow in the Jordan River and the Seasonal NINO4 temperatures. Other findings in correlating temperature and precipitation variability in Europe and Africa with ENSO can be found in many other published papers (Giorgi 2002).

The various effects of other atmospheric circulation patterns on the other hand have been investigated in the Mediterranean region. For example, it was shown that the South Asia Monsoon's strength has an effect on the climate of the eastern and central Mediterranean causing significant instability in sea level pressure over the Middle East accompanied with low pressures in summer and high pressures in winter (Lionello et al. 2006). Krichak and Alpert (2005) correlated the positive trend of the East Atlantic–West Russia (EA–WR) teleconnection pattern with the precipitation decline over the East Mediterranean during the last couple of decades of the 20th century. Similarly, Krichak et al. (2002) detected a relation between the East Mediterranean precipitation and the EA-WR teleconnection pattern. Gonzalez-Hidalgo et al. (2009) demonstrated significant effect of the Mediterranean Oscillation Index (MOI) and the precipitation variability over the Mediterranean part of the Iberian Peninsula. For the same region, precipitation variability has been associated with the Eastern Atlantic pattern (Martin et al. 2004) and the Eurasian pattern (Vazquez 2001) as well. Toreti et al. (2010) showed a strong linear correlation between seasonal temperatures over Italy and the Eastern Atlantic (EA) pattern in all seasons except during autumn and a negative correlation between the Scandinavian (SCAND) pattern and summer temperatures. Xoplaki et al. (2000) and Krichak et al. (2002) demonstrated a significant contribution of the EA pattern to the precipitation variations over the East Mediterranean.

3.4 Study Area

The Litani Basin is located in Lebanon (Figure 2-1), east of the Mediterranean Basin. The climate of this region is described in general by short, wet winters and long, dry summers. Lebanon is subject to many continental air masses and depressions such as the Siberian high pressure, Indian Monsoon and Cyprus depression (HMSO 1962). In addition, the diverse orographic array alters the local climate conditions.

Lebanon is positioned between the subtropical aridity of Africa and the subtropical humidity of the eastern Mediterranean area. It is described as a mountainous on the East Mediterranean coast and characterized by a diverse climate despite its small surface area (~10,450 km^2). This is due to the wide topographical variations of the country. Hence, Lebanon can be divided into 3 different climate zones; the coastal strip with dry-hot summers and short rainy winters, the mountains with cooler summers and longer, colder and wetter winters, and the Beqaa Valley which undergoes, generally, a dry sub-arid climate with hot summers and cold winters. Average annual temperature in the coast is approximately 27ºC in summer and 14ºC in winter with a 3ºC decrease per 500 m elevation gain. Most of the rainfall takes place from November to March with an annual average of around 850 mm divided as: 800 mm on the coasts, 1000 mm on the mountains and 400 mm on the Beqaa Valley (NOAA –Lebanon Data Rescue website). The later is located between two high altitude mountains where the west slopes are as high as 3088 m above sea level in the north of Mount Lebanon chain and the east slopes go up to 2814 m in the Anti-Lebanon Mountain chain located at the north east boundaries of the country. The Mount Lebanon chain (west slopes) acts as a barrier between the Mediterranean Sea and the Beqaa Valley. This causes the climate of the interior zone and mainly in the Beqaa Valley to vary from sub-humid in the south to arid in the north within less than 100 km strip. The orographic rainfall in the Mount Lebanon and Anti-Lebanon regions vary drastically in a short distance to reach as much as 1500 mm on the peak of the mountains which are covered by snow most of the year. In summer, however, most of the country is totally dry between June and August with almost zero precipitation.

The Litani Basin is considered the largest source of surface water in Lebanon, originating west of Baalbeck city which is located in the Beqaa Valley at an altitude of 1000 m with a drainage area of about 2,170 km^2. In 1959, the Litani River Authority completed the building of the Albert Naqash dam and the Qaraoun artificial lake at the Qaraoun village region located in the Beqaa Valley at an altitude of 800 m. The lake has the capacity of storing water up to 0.22 km^3. Practically, this lake divided the basin into two separate basins: The Upper Litani Basin (ULB), which is located in the Beqaa plain between the Lebanon and Anti-Lebanon slopes, covers 68.5% of the whole basin drainage area from 800 m altitude and up, and it drains toward the Qaraoun Lake. The Lower Litani Basin (LLB) covers the remaining part and it drains toward the Mediterranean. Hence, ULB is mostly dominated by mountainous features while LLB is mostly coastal falling from 500 m altitude to the sea level in a short distance of around 100 km length. In this study, the Litani Basin is treated first as a one entity and then as two different basins with variable climate features: The ULB is mostly dominated by a sub-arid climate in the flood plains but surrounded with mountain summits that are covered with snow more than 9 months of the year; and the LLB is mostly dominated by a sub-humid coastal climate with a very limited snow cover during winter. The average annual precipitation over the whole basin is around 700mm, where around 550mm fall in the area of river's origin and around 800 mm at the river's mouth. The discharge rate of the basin is approximately 0.5 km^3/yr for the ULB and 0.3 km^3/yr for the LLB.

The consideration of two basins in the studied region will open the possibility of relating the two distinct basins' local weather factor variation, precisely precipitation and temperature, to many synoptic climate patterns. It may demonstrate the possible effect of the local physiographic variety on the response to larger climate factors such as the teleconnection patterns in a relatively small surface area.

The Litani River has a remarkable social, economic and environmental importance to Lebanon, especially to communities living in the neighborhood of the basin. River water used is related to the amount of annual precipitation on the basin vicinity. Portion of the water is invested in hydro-electric power generation and irrigation which makes the annual precipitation in the region crucial to the community's water needs. Hence, the importance of annual rainfall variations in relation to the river water management and to the socio-economical status of the region cannot be more emphasized. However, this river is a subject of serious water deficit due to many socio-economical strains and climate change.

3.5 Data and Methodology

The present study aims to investigate the correlation between the precipitation and temperature variation over the Litani Basin region with different global and regional climate patterns known as teleconnections. The process starts with data collection, preparation and calibration. The geographical data of the Litani Basin area was gathered first by integrating ASTER Global Digital Elevation Map data (NASA, 2009). The lack of reliable long term gauge data that cover the studied area imposes the burden of using quite different available resources. Consequently, monthly satellite data, global reanalysis global grid data and the available limited gauge data for the couple of stations located in the region were used. The reanalysis gridded data consist of spatial interpolation of thousands of stations spread around the world, with 0.5ºx0.5º resolution adopted from 2 sources: University of Delaware data for Temperature and Precipitation, (UD-Temp and UD-prcp) between1900 and 2006) and University of East Anglia (CRU-TS and CRUTS-prcp) between 1901 to 2002 ; Satellite data include: Tropical Rainfall Measuring Mission (TRMM) covering the daily precipitation data between 1998 and 2008 with 0.25º resolution, and the Moderate Resolution Imaging Spectroradiometer for temperature (MODIS-Temp) with 0.05º resolution, (2000-2009); Local measured data include: Ksara Obsy station (1921 to 1960) located in the Beqaa Valley, North-East of Lebanon, for temperature data and Lebaa station (2001 to 2008) located in South Lebanon for gauged precipitation data. Data sources are indicated in Table 3-2.

In this study, various climate pattern indices were selected. The standardized north hemispheric teleconnection indices were chosen based on proximity to the Mediterranean basin and historical attempts studying these phenomena in relation to the Mediterranean climate variability. El Niño - Southern Oscillation (ENSO) index which is the standard SST index of El Niño - Southern Oscillation (ENSO) at Nino 3.4 region: 5ºN~5ºS, 120º-

170ºW (ERSST.v3), and 10 other standardized northern hemisphere teleconnection indices were adapted from NOAA (Smith et al. 2008); the North Atlantic Oscillation (NAO) index was adapted from the data published by the University of East Anglia, UK (Hurrell 1995); the Mediterranean Oscillation Index (MOI) was based on studies of the University of East Anglia UK (Conte et al. 1989). In particular, the correlations with North Atlantic Oscillation (NAO), known as influential to climate pattern in the Mediterranean region and El- Niño Southern Oscillation (ENSO) with its global influence on climate variability were studied for an extended period (1900-2008) as data for both indices were available. The data were divided into two different periods; pre and post 1970, because in the 70s NAO experienced a phase change, i.e., from negative to positive (Appenzelleret al. 2000). Data for NAO were derived from Climate Research Unit (CRU) over the period 1821-2008. For ENSO, data were derived from the National Oceanic and Atmospheric Administration (NOAA) Bivariate ENSO Time Series data source. In addition, the Indian monsoon correlation was investigated as well for the same period to detect evidence of correlation with temperature and precipitation. It was adapted from the Institute of Global Environment and Society (IGES), USA.

The following methodology was employed to combine different reanalysis datasets, satellite data, and meteorological data in order to generate one set of gridded time series of monthly surface temperature and precipitation from 1900 to 2008. The geo-processing of the Litani Basin was achieved through the application of the Geographical Information System (GIS) for watershed delineation which is controlled mainly by the topography of the basin and river network. Subsequently, the gridded datasets of temperature and precipitation were spatially averaged over the basin and reducing the data to a single value varying over time. Two types of extrapolated time series for the period 2000-2008 were generated: a) a cell based time series which consists of extracted data from the grids where the used weather station are located (Ksara-Obsy and Lebaa) and b) a basin wide data averaging of the observations of satellite and the reanalysis of records. Satellite and weather stations data were employed to calibrate the reanalysis of gridded time series. More detailed information regarding the methods used for dataset construction can be found in a related publication (Ramadan et al, 2011a). To investigate the correlation between the climatological factors and the selected climate patterns, the Pearson correlation coefficient, which is defined between two variables X and Y, is applied:

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{(n-1)S_x S_y} \qquad (3\text{-}1)$$

where $\overline{X}$ and $\overline{Y}$ are the means of the variables, S_X and S_Y represents the standard deviations of X and Y variables, respectively.

Confirmatory data analysis procedures require statistical test(s) of significance to be used accordingly. Here, a *t*-test is applied in order to evaluate the significance of the determined correlation coefficients. Hence, the null hypothesis that correlation coefficient (r) = 0 is tested as:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \qquad (3\text{-}2)$$

where r is the Pearson's correlation coefficient, and n is the size of the sample. Based on the calculated standard t value, probability (p) can be found by using the t curve tail area table. If $p < 5\%$ (or 1%), the correlation is considered significant and the null hypothesis is rejected (i.e., there is a significant trend in the data series).

3.6 Results and Discussion

Annual and interannual correlations for temperature and precipitation were examined considering teleconnection indices for the entire Litani Basin as one entity, the ULB and the LLB. The highlighted results represent the significant linear correlations at 1% or 5% level. The absence of such correlation does not mean necessarily a lack of dependence between the indices and the time series. On the contrary, as Pozo-Vasquez et al. (2001) suggested, a non-linear complex relationship may be dominating which merits more attention in future studies.

For the period between 1950 and 2008, the results are presented for the entire Litani Basin (Table 3-3), ULB (Table 3-4) and LLB (Table 3-5). Temperature variability over the entire Litani Basin shows an overall annual negative correlation with NAO index at 1% level. Meanwhile, mean temperature shows to be negatively correlated with NAO in all seasons except in spring. These results are in agreements with Wallace and Gutzler (1981) relating the negative correlation between NAO and temperature variations over the eastern Mediterranean with the intensification of the westerlies (Hurrell 1995). In addition, the high-pressure variance overshadowing the east Mediterranean region, especially in winter, is associated with the NAO. This favors an anticyclone flow of surface winds and directs the advection of cold air coming from southeastern Europe to the northern Red Sea (Felis et al. 2004). However, for the same aforementioned period, no interannual significant linear correlation has been found between precipitation and NAO (Table 3-3) except in summer where precipitation in that area is nearly zero. This does not reveal necessarily the lack of any other type of non-linear correlation.

On the other hand, comparing teleconnections of the ULB versus the LLB (1950-2008) shows some similarities and contrasts. The ULB shows a year round NAO negative temperature correlation, except in spring, which is in contrast to the LLB illustrating a negative correlation in spring and a non significance in summer, dry and transitional seasons. In contrast, the LLB shows a negative NAO summer precipitation correlation. The effect of NAO outside the winter season remains to be questionable (Hurrel 1995).

For the El Niño South Oscillation (ENSO), it is demonstrated that this phenomena that takes place mainly in the Pacific area has a global climatological variation impact (Wallace and Gultzer 1981). The changes of pressure gradient across the Pacific are associated with changes in temperature and precipitation anomalies on the eastern and western Pacific coasts leading to worldwide climate variability (IPCC 2007b). During El Niño, the eastern Pacific warms up affecting the jet streams in the subtropics which become stronger leading to wetter (drier) winter conditions in the east (west). However, Pozo-Vasquez et al. (2001) revealed numerous difficulties to relate El Niño to climate variability in Europe due mainly to the different types and potencies of El Niño episodes leading to various and inconsistent climatological responses. For the Litani Basin, from 1950 to 2008 (Table 3-3) the ENSO index does not show statistically significant relationships with the mean yearly air temperatures except for a negative correlation in spring. However, the mean precipitation in the wet season from November to March is positively correlated with the ENSO index at 1% level. These results are in agreement with the general conclusions of Price et al. (1998), Kadioğlu et al. (1999) and Giorgi (2002) but are controversial when compared with other studies (Türkeş, 1998). This inconsistency is due to the different spatial and temporal data investigated and the statistical analysis methods used. This can be shown in comparing even the different spatial setup of the Litani Basin itself as the spring temperature correlation between 1950 and 2008 (Tables 3-4 and 3-5) vanishes when segregating the ULB and the LLB; while the wet season precipitation correlation shows the same consistency as the whole basin.

The East Atlantic-Western Russia (EA-WR) pattern is shown to have no significant correlation with the Litani precipitation with all various temporal and spatial data used. However, the connection with temperature variation is evident. An annual negative correlation between the Litani's temperature and EA-WR pattern is detected. This is in addition to the seasonal correlation found throughout the year except in spring and transitional seasons. The temperature variability of the Litani Basin seems to be strongly associated with the two anomaly centers of the pattern located over the Caspian Sea and Western Europe. While more intense northern airflow is associated with the positive EA-WR, the negative phase is linked to positive height anomalies over the Caspian Sea and western Russia and negative height anomalies over northwestern Europe (Krichak and Alpert 2005). Thus, the EA-WR pattern is likely to convey amplified anomalous northeasterly or southeasterly circulation connected with temperature variations in the

Eastern Mediterranean area including Lebanon. However, no evidence of its connection with precipitation patterns has been found. The ULB gives similar results but the LLB looses the annual and the fall season correlation. Correlations between winter temperature and EA-WR have been found for other areas in the East Mediterranean as shown by Hasanean (2004) giving additional evidences on the influence of large scale oscillation on a local meteorological scale in mid latitude regions.

The Eastern Atlantic (EA) teleconnection pattern is shown to be negatively correlated with precipitation during spring, winter and transitional seasons for the ULB or the entire basin. These results are in agreement with Hatzaki et al. (2010) who demonstrated a significant correlation between East Mediterranean precipitation and EA pattern during the spring, winter and autumn seasons. However, no significant correlation was found in spring precipitation for the LLB, while a negative correlation for the ULB is evident. This may be associated with the role of the local orographic lifting during spring period when the coastal area starts to warm up. For temperature, a positive correlation was found annually and during the summer, spring, dry and transitional seasons but no correlation was present during winter and wet seasons. However, the LLB alone shows a positive temperature correlation during transitional season.

A negative correlation can be found between fall precipitation and the SCAND pattern which may be attributed to the dry air advection from Asia (Kutiel et al. 1996). This pattern, which is portrayed by a strong anomaly located over the Scandinavian Peninsula, shows negative temperature correlation over the Litani Basin. The strength, phase and seasonality of these correlations appear to be identical in the ULB and the LLB.

The Polar/Eurasia (POL) pattern shows significant positive correlation with annual precipitation anomalies. This is in addition to the correlation illustrated during the fall season. The stronger positive correlation between the POL pattern and precipitation is found during the wet season as this pattern is known to be mostly prominent between December and February. The positive precipitation correlation in the wet season seems to be due to the enhanced circumpolar vertex during the positive phase of the POL pattern. It is apparent that the geophysical conditions in the case of the Litani Basin do not have an effect on the response of the precipitation to the POL pattern. Hence, the precipitation correlations of the ULB and LLB with the POL pattern are considerably similar. Moreover, no significant linear correlation is found with temperature variability.

As stated by the Climate Prediction Center (USA), the positive phase of the East Pacific-North Pacific (EP-NP) pattern is linked with above-average surface temperatures over the eastern North Pacific; below-average temperatures over the central North Pacific and eastern North America; above-average precipitation over north of Hawaii; and below-average precipitation over southwestern Canada. The low and high pressure anomalies associated with this pattern are shown to produce a strong regional circulation in the Mediterranean vicinity (Lionello and Galati 2008). For the Litani Basin, a negative correlation was found between EP-NP pattern and temperature changes during the summer and the dry season. Same results were illustrated for the ULB, while the LLB showed no sensitivity.

The Tropical/Northern Hemisphere pattern (TNH) connection with the Mediterranean meteorological variability has not yet been investigated. For the Litani Basin, no correlation is detected with temperature anomalies. However, negative correlation with precipitation is observed during wet and winter season.

Pacific / North American (PNA) pattern, which is associated with climate variability over North America, shows no linear correlations with precipitation and temperature anomalies over the ULB and/or the LLB. The same results are found for Pacific Transition (PT) and West Pacific (WP) patterns showing no impact on the climatological variation of the area under study. For these last three patterns, no evidence has been found in literature that shows any type of correlation with the East Mediterranean area. In fact, the PNA, WP and PT patterns behavior have not been studied in relation with the Mediterranean area climate variation.

The Litani basin shows a significant correlation of temperature with Mediterranean Oscillation Index – Algiers and Cairo (MOAC) during winter and wet seasons. These results show similarity for each region of the Litani Basin. The strong positive geopotential height anomalies, which prevail over the western central basin of the Mediterranean during wintertime and extend toward Russia, drive cool air to the Eastern Basin dominated by lower height anomalies (Krichak et al. 2000). The results are in agreement with Nastos et al. (2011) who found a statistically significant negative correlation between wintertime temperature and MOAC over Greece for the period 1951-2007 and 1955-2001 respectively. In contrast, Elmallah and Elsharkawy (2011) observed positive correlation with wintertime temperature anomalies over Egypt which confirms the importance of the distinct local characteristics of each zone in the Eastern Mediterranean region.

For precipitation, annual and winter season positive correlation with MOAC has been detected for the whole basin and the LLB, while the ULB shows no statistically significance during winter. Likewise, Gonzalez-Hidalgo et al. (2009) noticed a positive correlation between precipitation and the Mediterranean Oscillation Index over the Iberian Peninsula during the rainy season for the second half of the 20th century.

Studying NAO index associated links between 1900 and 2008, Table 3-6 indicates an extended negative temperature correlation of the entire basin in winter and wet seasons. Comparing pre- to post-1970 for the entire basin as one entity, NAO shows a shift in the temperature negative correlation from spring to summer (CRU data) associated with a post 1970 negative correlation established during the dry season which vanished in the transitional season. Meanwhile, consistent, negative annual and seasonal (fall, winter and wet) temperature correlations prevail.

For precipitation, CRU data shows a positive annual correlation which has been lost for post 1970 and a negative correlation is built on the same time period for the dry season. Looking at a smaller scale, for the ULB (Table 3-7), NAO correlations show a switch of temperature correlation from spring to summer during pro- and post- 1970 respectively, which is similar to the behavior of the entire Litani basin. It reveals a continuous annual, fall, winter and wet association and a drastic change between pre and post 1970 during the dry and transitional seasons. In addition, precipitation correlation changes from annually positive to negative during dry season. For the LLB (Table 3-8), a continuous winter and wet temperature association with NAO is shown with a loss of post-1970 annual, spring and transitional seasons correlations. Similar to the LLB results, in the transitional season the LLB precipitation illustrates the establishment of a positive correlation during post 1970.

Likewise, extending the temporal setup for ENSO (1900-2008) delivers interesting results (Table 3-9). The negative correlation of spring temperature is shown to be consistent with 1950-2008 results just for post 1970 period and a positive correlation is established for the extended period of 1900-2008 during the fall. The positive correlation of precipitation with ENSO during wet period seems to be stronger after 1970 for a different spatial setup. The results also show that the extended period between 1900 and 2008 contains a significant influence of ENSO during winter on the Litani Basin precipitation. These results may be affected by the changes of the frequency, intensity and duration of El Niño events after 1970 as noted by Price et al. (1998), and producing a stronger link between the Pacific and mid-latitude systems.

The Indian Monsoon index seemed to be negatively correlated with temperature in summer and dry season for the 3 different set ups of the Litani basin (Table 3-10). Ziv et al. (2004) pointed out the important role of the South Asian Monsoon in controlling the East Mediterranean summer regime and suggested a mechanism which may explain this phenomenon. He indicated that the strengthening of the Asian Monsoon during summer may cause pressure drops over western Asia and, hence, to increase the northwesterly winds known as the Etesian winds blowing over the region. Consequently, an advective cooling would be triggered in the vicinity of the East Mediterranean causing the summer temperature to decrease. However, the India Monsoon index did not show any significant annual or interannual linear correlation with the precipitation behavior over the studied basins.

3.7 Summary and Conclusions

The annual and interannual precipitation and temperature variations over the Litani Basin have been examined in connection with different global and regional circulation indices. The associated time series for monthly temperature and precipitation were related to annually and seasonally to thirteen teleconnection patterns. Pearson linear correlation coefficients were employed to describe the variance distribution of the series in connection with the selected indices. Based on data availability, twelve indices were used for the period 1950-2008. Two indices were obtained between 1900 and 2008 (NAO and ENSO were inclusive in both groups) and one index covering the period between 1900 and 2000 period (All-India rainfall monsoon).

Data for the study watershed was spatially averaged three ways: (1) entire basin, (2) upper, mountainous basin and (3) lower, coastal basin. Generally, moderate correlation values (i.e., ~0.26 to 0.6) with 1% to 5% significance have been found in select seasons between temperature variation and NAO (negative), EA (positive), EP-NP (negative), EA-WR (negative), SCAND (negative), MOAC (negative) and ENSO (negative). Similarly, significant correlation values (i.e., ~0.26 to 0.4) have been found in select seasons between precipitation and NAO (negative), EA (negative), TNH (negative), POL (positive), MOAC (positive) and ENSO (positive). However, PT, PNA and WP patterns showed no correlation with either measure. Although most of the results from this study were consistent with previous, similar studies of the East Mediterranean area, some findings highlight the uniqueness of the basin's geophysical characteristics and local weather implications. This was specifically exhibited through the response variability of the Upper Litani Basin (ULB) versus the Lower Litani Basin (LLB). The later lost its annual negative temperature correlation with NAO circulation pattern after 1970 and had no significant correlation during the dry season from 1950 to 2008. Similarly, substantial differences were noticed for the response magnitude and direction of the correlation between the ULB and LLB precipitation variations and NAO, especially prior to 1970. However, the LLB was shown to build a positive correlation with ENSO after 1970. For the Indian Monsoon, the LLB showed no sensitivity at any time, while a negative temperature correlation was present for the ULB prior to 1970. Some other teleconnections show various correlations almost throughout the year, such as NAO and EA-WR (with temperature). Other teleconnections showed seasonal correlations such as TNH (winter and wet season with precipitation), POL (fall and wet season with precipitation), MOAC (winter season with precipitation; winter and wet with temperature), ENSO (wet season with precipitation; spring with temperature), EA (spring, winter and transitional seasons with precipitation; spring, summer, dry and transitional with temperature), SCAND (fall season with precipitation; summer with temperature), EP-NP (summer and dry season with temperature), NAO (summer season with precipitation).

In order to study the runoff trend of the Litani Basin and the effect of climate change on its hydrology, a synthetic runoff data is generated due to the lack of measured data. Chapter 4 presents the rainfall data generation, runoff modeling and the generated streamflow trends of the Litani Basin in the 20th century.

Tables

Table 3-1 Summary of the used teleconnection patterns and their locations

Teleconnection Patterns	Abbriviations	Circulation Centers	References
North Atlantic Oscillation	NAO	Ponta Delagada (Azores) and Stykkisholmur (Iceland)	Barnston & Livezey (1987)
East Atlantic	EA	North-South Diapoles across the North Atlantic	Barnston & Livezey (1987)
East Atlantic/Western Russia	EA-WR	Western Europe, Caspian Sea in winter and Russia, northwestern Europe and Portugal in spring and fall	Barnston & Livezey (1987)
Scandinavia	SCAND	Scandinavia, Western Europe and Magnolia	Barnston & Livezey (1987)
Polar/Eurasia	POL	North Pole, Europe and northweastern China	CPC (2011)
West Pacific	WP	Kamchatka (Russia) and another wide center located between southeastern Asia and western North Pacific	Wallace and Gutzler (1981)
East Pacific-North Pacific	EP-NP	Alaska-Western Canada, central north pacific and eastern North America	Barnston & Livezey (1987)
Pacific/North American	PNA	Hawaii, the intermountain region of North America, south of the Aleutian Islands (North Pacific Ocean) and over the southeastern United States	Barnston & Livezey (1987)
Tropical/North Hemisphere	TNH	Gulf of Alaska and Hudson Bay (Canada)	CPC (2011)
Pacific Transition	PT	Intermountain region of the United States, Labrador Sea (North Atlantic), Gulf of Alaska and Eastern US	CPC (2011)
El Nino Southern Oscillation	ENSO	Tropical Pacific Ocean	Rasmussen & Wallace (1983)
India Monsoon	India Monsoon	Indian Ocean especially in the Arabian Sea	Parthasarathy et al. (1995)
Mediterranean Oscillation Index	MOAC	Algiers City (Algiers) and Cairo (Egypt)	Conte et al. (1989)

Table 3-2 Data Sources

Data type	Periods	Resolution	Data source (visited 12/21/2010)	% of coverage
UD-Temp [1]	1900-2006	0.5º	http://climate.geog.udel.edu/	100
CRU TS-Temp [1]	1901-2002	0.5º	http://www.cru.uea.ac.uk/	100
MODIS-Temp [2]	2000-2008	0.05º	http://edcdaac.usgs.gov/modis/	100
UD-Prcp [1]	1900-2006	0.5º	http://climate.geog.udel.edu/	100
TRMM [2]	1998-2008	0.25º	http://disc.sci.gsfc.nasa.gov	100
CRU TS-Prcp [1]	1901-2002	0.25	http://www.cru.uea.ac.uk/	100
HadCRUT3	1850-2008	/	http://www.cru.uea.ac.uk/	Global average
NASA-GISS	1880-2008	/	http://data.giss.nasa.gov/gistemp/	Global average
Station - Ksara Obsy	1921-1960	/	http://data.giss.nasa.gov/gistemp/	33.8N, 35.9E
Station – Lebaa [3]	2001-2008	/	Ministry of Public Work - Lebanon	33.3N, 35.3E
NAO	1950-2008 1821-2008	/	http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml http://www.cru.uea.ac.uk/cru/data/nao/	/
ENSO	1950-2008 1900-2008	/	http://www.cpc.ncep.noaa.gov http://www.esrl.noaa.gov/psd/people/cathy.smith/best/	/
MOI	1958-2007	/	http://www.cru.uea.ac.uk/cru/data/moi/	/
Indian Monsoon	1900-2000	/	http://www.iges.org/india/allindia.html	/
Northern Hemisphere Teleconnection	/	/	ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh	/

Notes: 1 reanalysis datasets; 2 satellite datasets; 3 gauge data

Table 3-3 Correlation between temperature/precipitation and teleconnection indices for the entire Litani Basin (1950-2008)

	Climate Patterns	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO	-0.25	-0.39**	-0.32**	-0.44**	-0.5**	-0.42**	-0.38**	-0.27**
	EA	0.26**	0.43**	-0.16	0.11	-0.02	0.44**	0.33**	0.39**
	WP	-0.20	-0.22	0.16	0.04	-0.08	-0.12	0.13	-0.19
	EP-NP	-0.02	-0.27**	-0.10	-0.07	-0.07	-0.29**	-0.12	-0.04
	PNA	-0.04	0.04	0.00	0.06	-0.01	0.02	0.08	-0.08
	EA-WR	-0.10	-0.43**	-0.35**	-0.59**	-0.51**	-0.48**	-0.32**	-0.09
	SCAND	-0.08	-0.33**	0.05	0.07	0.19	-0.24	-0.17	-0.07
	TNH	N/A	N/A	N/A	-0.14	-0.07	N/A	N/A	N/A
	POL	-0.20	0.03	-0.20	0.02	-0.09	0.15	-0.20	-0.07
	PT	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A
	MOAC	-0.20	0.03	-0.08	-0.52**	-0.48**	-0.15	-0.17	-0.21
	ENSO	-0.28**	0.03	0.01	-0.13	-0.21	0.04	-0.13	-0.18
Precipitation	NAO	-0.04	-0.26*	-0.07	-0.10	-0.16	-0.15	-0.02	0.04
	EA	-0.27*	0.14	0.21	-0.36**	-0.19	0.02	-0.09	-0.31*
	WP	0.16	-0.10	-0.01	-0.10	0.08	-0.14	-0.15	0.10
	EP-NP	-0.09	-0.04	-0.02	0.17	0.22	-0.10	0.07	-0.20
	PNA	0.01	0.15	-0.04	0.09	0.10	0.19	-0.01	0.04
	EA-WR	-0.20	-0.10	-0.07	0.18	0.19	-0.09	0.00	-0.17
	SCAND	0.16	-0.07	-0.29*	0.09	0.19	0.08	-0.01	0.08
	TNH	N/A	N/A	N/A	-0.3*	-0.34**	N/A	N/A	N/A
	POL	0.19	0.06	0.29*	0.21	0.41**	0.13	0.28*	0.10
	PT	N/A	N/A	N/A	N/A	N/A	0.01	N/A	N/A
	MOAC	0.06	-0.12	0.20	0.27*	0.19	-0.25	0.31*	0.06
	ENSO	0.16	0.06	0.24	0.24	0.32*	-0.03	0.17	-0.06

* significant at 5% level, ** significant at 1% level, N/A is not applicable

Spring occurs in the months from Mar. to May, summer is from Jun. to Aug., fall is from Sep. to Nov., winter is from Dec. to Feb, wet-season is from Nov. to Mar., dry-season is from Jun. to Sep., and the transitional (Trans) is Apr. and May.

Table 3-4 Correlation between temperature/precipitation and teleconnection indices for the Upper Litani Basin (1950-2008)

	Climate Patterns	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO	-0.21	-0.41**	-0.28*	-0.41**	-0.43**	-0.41**	-0.32*	-0.28*
	EA	0.27*	0.43**	-0.16	0.16	0.03	0.43**	0.36**	0.38**
	WP	-0.25	-0.24	0.16	0.08	-0.08	-0.14	0.08	-0.24
	EP-NP	-0.03	-0.29*	-0.16	-0.10	-0.09	-0.33*	-0.19	-0.03
	PNA	-0.01	0.07	0.08	0.10	0.01	0.07	0.14	-0.05
	EA-WR	-0.07	-0.41**	-0.41**	-0.57**	-0.47**	-0.48**	-0.32*	-0.04
	SCAND	-0.11	-0.31*	0.00	0.03	0.13	-0.21	-0.22	-0.08
	TNH	N/A	N/A	N/A	-0.10	-0.02	N/A	N/A	N/A
	POL	-0.20	0.07	-0.17	0.01	-0.12	0.18	-0.17	-0.09
	PT	N/A	N/A	N/A	N/A	N/A	0.07	N/A	N/A
	MOAC	-0.20	0.02	-0.10	-0.52**	-0.46**	-0.17	-0.16	-0.24
	ENSO	-0.25	0.03	-0.02	-0.15	-0.21	0.03	-0.14	-0.17
Precipitation	NAO	-0.05	-0.25	-0.08	-0.10	-0.17	-0.15	-0.04	0.04
	EA	-0.27*	0.14	0.21	-0.37**	-0.22	0.01	-0.11	-0.32*
	WP	0.17	-0.10	-0.02	-0.12	0.06	-0.12	-0.14	0.11
	EP-NP	-0.09	-0.05	-0.04	0.17	0.22	-0.10	0.07	-0.19
	PNA	0.02	0.15	-0.04	0.09	0.09	0.19	-0.02	0.06
	EA-WR	-0.19	-0.09	-0.08	0.17	0.18	-0.09	-0.01	-0.18
	SCAND	0.16	-0.07	-0.28*	0.10	0.20	0.09	-0.01	0.08
	TNH	N/A	N/A	N/A	-0.29*	-0.33*	N/A	N/A	N/A
	POL	0.17	0.06	0.29*	0.21	0.41**	0.12	0.28*	0.09
	PT	N/A	N/A	N/A	N/A	N/A	0.02	N/A	N/A
	MOAC	0.08	-0.12	0.18	0.25	0.17	-0.25	0.3*	0.06
	ENSO	0.15	0.04	0.23	0.23	0.31*	-0.04	0.16	-0.05

* significant at 5% level, ** significant at 1% level, N/A is not applicable

Table 3-5 Correlation between temperature/precipitation and teleconnection indices for the Lower Litani Basin (1950-2008)

	Climate Patterns	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO	-0.26*	-0.18	-0.31*	-0.46**	-0.55**	-0.24	-0.32*	-0.17
	EA	0.15	0.24	-0.10	0.00	-0.12	0.24	0.09	0.3*
	WP	0.01	-0.08	0.11	-0.05	-0.08	-0.02	0.18	0.00
	EP-NP	0.02	-0.09	0.07	0.00	0.00	-0.03	0.10	-0.08
	PNA	-0.09	-0.05	-0.16	-0.02	-0.06	-0.15	-0.11	-0.12
	EA-WR	-0.16	-0.29*	-0.09	-0.56**	-0.5**	-0.26*	-0.14	-0.20
	SCAND	0.02	-0.26*	0.12	0.15	0.29*	-0.20	0.04	-0.02
	TNH	N/A	N/A	N/A	-0.22	-0.17	N/A	N/A	N/A
	POL	-0.13	-0.11	-0.20	0.04	-0.01	-0.01	-0.15	-0.02
	PT	N/A	N/A	N/A	N/A	N/A	-0.02	N/A	N/A
	MOAC	-0.18	0.05	-0.05	-0.53**	-0.51**	-0.09	-0.19	-0.14
	ENSO	-0.25	0.04	0.08	-0.08	-0.15	0.05	-0.03	-0.15
Precipitation	NAO	-0.02	-0.29*	-0.03	-0.10	-0.15	-0.19	0.00	0.04
	EA	-0.24	0.22	0.20	-0.35**	-0.14	0.19	-0.03	-0.27*
	WP	0.13	-0.17	0.03	-0.06	0.12	-0.22	-0.15	0.08
	EP-NP	-0.10	-0.07	0.01	0.17	0.22	-0.20	0.06	-0.23
	PNA	-0.01	0.16	-0.03	0.07	0.13	0.22	0.03	-0.01
	EA-WR	-0.22	-0.17	-0.06	0.21	0.23	-0.19	0.03	-0.14
	SCAND	0.17	-0.13	-0.3*	0.06	0.15	0.00	-0.02	0.08
	TNH	N/A	N/A	N/A	-0.32*	-0.36**	N/A	N/A	N/A
	POL	0.23	0.07	0.28*	0.20	0.39**	0.19	0.28*	0.10
	PT	N/A	N/A	N/A	N/A	N/A	-0.02	N/A	N/A
	MOAC	0.01	-0.09	0.21	0.3*	0.23	-0.23	0.32*	0.04
	ENSO	0.16	0.12	0.25	0.25	0.36**	0.05	0.20	-0.06

* significant at 5% level, ** significant at 1% level, N/A is not applicable

Table 3-6 Correlation between NAO and temperature/precipitation for the entire Litani Basin

	Index	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO_1900_1969(1)	-0.35**	-0.16	-0.24*	-0.53**	-0.48**	-0.17	-0.47**	-0.3*
	NAO_1970_2008(1)	-0.03	-0.42**	-0.41*	-0.43**	-0.46**	-0.53**	-0.38*	0.06
	NAO_1900_2008(1)	-0.24*	-0.29**	-0.27**	-0.49**	-0.47**	-0.33**	-0.41**	-0.19*
Precipitation	NAO_1900_1969(1)	0.09	-0.13	0.01	0.02	0.10	-0.07	0.26*	0.07
	NAO_1970_2008(1)	-0.19	-0.23	0.18	-0.11	-0.02	-0.45**	-0.01	-0.08
	NAO_1900_2008(1)	0.01	-0.18	0.05	-0.02	0.03	-0.28**	0.20*	0.04

(1) http://www.cru.uea.ac.uk/cru/data/nao/

* significant at 5% level, ** significant at 1% level

Table 3-7 Correlation between NAO and temperature/precipitation for the Upper Litani Basin

	Index	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO_1900_1969(1)	-0.33**	-0.17	-0.24*	-0.54**	-0.49**	-0.16	-0.45**	-0.3*
	NAO_1970_2008(1)	-0.04	-0.48**	-0.43**	-0.38*	-0.39*	-0.6**	-0.41*	0.01
	NAO_1900_2008(1)	-0.23*	-0.33**	-0.29**	-0.47**	-0.45**	-0.37**	-0.42**	-0.21*
Precipitation	NAO_1900_1969(1)	0.09	-0.13	0.01	-0.01	0.06	-0.08	0.24*	0.06
	NAO_1970_2008(1)	-0.21	-0.23	0.17	-0.13	-0.06	-0.45**	-0.04	-0.09
	NAO_1900_2008(1)	0.00	-0.18	0.05	-0.05	0.00	-0.29**	0.17	0.03

* significant at 5% level, ** significant at 1% level

Table 3-8 Correlation between NAO and temperature/precipitation for the Lower Litani Basin

	Index	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	NAO_1900_1969(1)	-0.38**	-0.12	-0.23	-0.52**	-0.47**	-0.16	-0.49**	-0.31**
	NAO_1970_2008(1)	0.01	-0.03	-0.13	-0.49**	-0.52**	-0.03	-0.05	0.16
	NAO_1900_2008(1)	-0.23*	-0.06	-0.15	-0.49**	-0.48**	-0.07	-0.23*	-0.12
Precipitation	NAO_1900_1969(1)	0.09	-0.15	0.00	0.09	0.17	-0.04	0.29*	0.09
	NAO_1970_2008(1)	-0.16	-0.30	0.19	-0.05	0.05	-0.43**	0.04	-0.06
	NAO_1900_2008(1)	0.02	-0.23*	0.05	0.04	0.09	-0.26**	0.24*	0.07

* significant at 5% level, ** significant at 1% level

Table 3-9 Correlation between temperature/precipitation and ENSO

	Zone	Index	Spring	Summer	Fall	Winter	Wet	Dry	Annual	Tran
Temperature	Entire Basin	ENSO_1900_1969	0.15	-0.18	0.14	0.17	0.14	-0.06	0.12	0.12
		ENSO_1970_2008	-0.39*	-0.03	0.11	-0.18	-0.27	-0.04	-0.21	-0.26
		ENSO_1900_2008	-0.07	-0.10	0.12	0.00	-0.05	-0.05	-0.04	-0.03
	Upper Litani Basin	ENSO_1900_1969	0.15	-0.17	0.14	0.17	0.15	-0.06	0.12	0.13
		ENSO_1970_2008	-0.35*	-0.05	0.00	-0.22	-0.30	-0.06	-0.26	-0.25
		ENSO_1900_2008	-0.06	-0.09	0.07	-0.01	-0.07	-0.05	-0.08	-0.03
	Lower Litani Basin	ENSO_1900_1969	0.13	-0.19	0.16	0.15	0.13	-0.07	0.11	0.11
		ENSO_1970_2008	-0.33*	0.01	0.28	-0.05	-0.13	0.04	0.05	-0.20
		ENSO_1900_2008	-0.07	-0.10	0.2*	0.04	-0.01	-0.03	0.05	-0.04
Precipitation	Entire Basin	ENSO_1900_1969	0.02	0.02	0.09	0.25*	0.25*	0.01	0.07	-0.02
		ENSO_1970_2008	0.22	0.01	0.29	0.29	0.49**	-0.10	0.28	0.01
		ENSO_1900_2008	0.09	0.04	0.15	0.23*	0.31**	-0.04	0.13	-0.02
	Upper Litani Basin	ENSO_1900_1969	0.03	0.00	0.09	0.25*	0.25*	0.01	0.06	-0.02
		ENSO_1970_2008	0.22	0.00	0.26	0.29	0.48**	-0.11	0.27	0.02
		ENSO_1900_2008	0.09	0.02	0.14	0.23*	0.31**	-0.05	0.12	-0.01
	Lower Litani Basin	ENSO_1900_1969	0.01	0.07	0.09	0.25*	0.24*	0.03	0.09	-0.02
		ENSO_1970_2008	0.20	0.10	0.34*	0.28	0.49**	-0.01	0.30	-0.03
		ENSO_1900_2008	0.07	0.11	0.16	0.22*	0.3**	0.03	0.13	-0.04

* significant at 5% level, ** significant at 1% level

Table 3-10 Correlation between India Monsoon index (Jun-Sep)

Zones	Period	Temperature	Precipitation
Entire Basin	1900-1969	-0.25*	-0.08
	1970-2000	-0.03	0.03
	1900-2000	-0.15	-0.04
Upper Litani Basin	1900-1969	-0.26*	-0.10
	1970-2000	-0.03	0.03
	1900-2000	-0.16	-0.04
Lower Litani Basin	1900-1969	-0.22	0.02
	1970-2000	-0.03	-0.01
	1900-2000	-0.13	0.00

* significant at 5% level, ** significant at 1% level

4 Modeling Streamflow Trends for a Watershed with Limited Data: A case on the Litani Basin, Lebanon

Ramadan H.H, Beighley R.E. and Ramamurthy A.S.

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4.1 Abstract

Streamflow variability in the upper and lower Litani Basin was modelled due to the lack of long-term measured runoff data. To simulate runoff and streamflow, daily rainfall was derived using a stochastic rainfall generation model and monthly rainfall data. Two distinct synthetic rainfall models were developed based on a two-part probabilistic distribution approach. The rainfall occurrence was described by a Markov Chain Process, while the rainfall distribution on wet days was represented by two different distributions (i.e., Gamma and Mixed Exponential distributions). Both distributions yielded similar results. The rainfall data were then processed using Water Balance and Routing models to generate daily and monthly streamflow. Compared with measured data, the model results were generally reasonable (e.g., mean errors ranging from 0.1 to 0.8 at select locations). Finally, the simulated monthly streamflow were used to investigate discharge trends in the Litani Basin during the 20th century using the Mann-Kendal and Sen Slope nonparametric trend detection methods. A significant drying trend of the basin was detected reaching a streamflow reduction of 0.8m^3/s and 0.7m^3/s per decade in January for upper and lower basin respectively.

4.2 Introduction

Water resources availability, sustainability and management in the Mediterranean basin and its vicinity have been the subject of many historical, political and scientific disputes. The East Mediterranean region is distinctively suffering from water stress due to population growth and lack of effective water management systems. The implications of climate change in water resources sustainability may pose additional challenges to stakeholders and water managers in the region (Koutsoyannis et al., 2009; IPCC 2007a). In addition to the shortage of studies and deficiency of scientific data, the Intergovernmental Panel on Climate Change (IPCC 2007a, Cudennec et al., 2009) predicted that the Eastern Mediterranean countries will face serious adverse effects of the potential global climate change, and asked for immediate plans of action and related supporting studies to facilitate appeasing such impacts. Lebanon is one of the countries expected to face the most severe potential water shortage in the area, where a 60% reduction of water resources per capita is anticipated by the year 2050 (Angelakis and Kosmas 1998).

In the last two decades, the detection of hydrologic trends has been the focus of numerous studies for different regions (Rimbu et al., 2002; Yue et al., 2003; George 2007; Kim and Jain, 2010). Meanwhile, the streamflow variability in different watersheds located throughout the Mediterranean region has been evaluated by many authors. For instance, Ceballos-Barbancho et al. (2008) studied trends of streamflow, precipitation and temperature for the Duero River basin in Spain for the period 1957–2003 and concluded that a strong correlation existed between streamflow and precipitation with a decreasing runoff trend. Topaloglu (2006) showed a significant decreasing runoff trend in western Turkey, while noticing that some other basins draining to the Black Sea experienced significant increasing runoff trends. Cullen et al. (2002), in a study of five Middle Eastern Rivers (1938-1984), concluded that there is a streamflow connection to rainfall variability for the December to March period. For six different watersheds in Morocco, Oueslati (2009) found a decreasing trend of annual runoff between 1960 and 1987 denoting the longest drought over the period 1980-1987. For the Karkeh River in Iran (1961-2001), Masih et al. (2009) recently recorded an increase in streamflow trend during December and a decrease during May for five different stations distributed in the basin.

Angelakis and Kosmas (1998) identified a drastic change in the availability of future water resources for the Mediterranean region due to projected population growth and renewable water resources availability. They stated reduction per capita in 2050 of 60% of water resources in Lebanon; 50% in Egypt, Algeria, Tunesia and Morrocco; 40% in Turkey; and 25% in Libya and Syria. On top of these complexities is the outlook of the climate variability and long-term climate change that will inflict unknown new conditions on the region. Because of the climate, prevalent water shortage may attain dramatic proportions in certain dry years. In some Mediterranean countries, water shortage has already become a permanent problem as a result of the continuous deficit in the demand-supply balance. Other countries are close to declaring a water crisis.

In Lebanon, according to the Ministry of Environment (Khawlie, 1999), even with the apparent ample resource of water, the country will still experience a potential water deficit. This is due to the interference of human activities that include groundwater exploitation, land use alteration, water pollution and climate change impacts (Hreiche et al., 2007). Hence every effort should be made to sustain the renewable water resources available, starting with those of most value to the Lebanese economy and development.

The streamflow of the Litani Basin, located in the Eastern Mediterranean region is one of the most robust sources of fresh water in Lebanon. This waterbody was used during the 20th century for agriculture and hydro-power production but decision makers continue to discuss the possibilities of using it more effectively. Studying the streamflow behaviour of the watershed will assist decision makers, stakeholders and legislators prioritizing their next actions. However, lack of historical runoff data poses a burden to the completion of this mission.

The present study has two objectives. The first is to generate daily discharge data for the Litani Basin, using a deterministic water balance and routing model (Beighley et al., 2009). Given that the application of this model requires daily precipitation data which were not available during the study period, the stochastic gamma distribution and the mixed exponential precipitation generation models were developed to generate the required precipitation forcings. This development adds another feature to the water balance and routing model, making it useful for all catchments lacking precipitation data. The second objective is to investigate the streamflow trends in the upper and lower Litani Basin. Using the monthly synthetic streamflow for the 1900-2008 period, a statistical nonparametric methodology (Ramadan et al., 2011b) was implemented to detect the runoff variations of the basin throughout the last century.

4.3 The study area

The Litani River (Figure 2-1) is considered to be one of the most important watercourses in Lebanon draining about one-fifth of the Lebanese territory. This river originates from the Beqaa plains and discharges into the Mediterranean Sea north of Tyre City in South Lebanon. The Litani is often regarded as the key to Lebanon's future socio-economic development, described by the eminent Lebanese hydrologist, Ibrahim Abd-el-Al as a "gift of Lebanon, just as the Nile is the gift of Egypt" (Abd-el-Al, 1993). The Litani is often regarded as the key to Lebanon's future socio-economic development. This fresh water resource is used mainly for hydropower generation and irrigation. Three power plants are built on the vicinity of the river to generate around 190 Mega Watt of power (10% of Lebanon's total power production). In addition, the use of the Litani River for irrigation is projected to increase from around 5,000 hectare to more than 21,000 hectare in the near future. This will irrigate a part of the Beqaa Valley in East Lebanon and another part of South Lebanon's agricultural land.

In this study, the Litani Basin drainage area was delineated using the ASTER Global Digital Elevation Map data (NASA, 2009). The resulting land area is approximately 2,180 km^2, which agrees with the values stated in the literature. Table 4-1 provides a summary of the basin's spatial characteristics.

After the building of the Albert Naqash dam, known as the Qaraoun dam, in 1959, the Litani basin was divided into an upper and a lower basin where the former discharges to the Qaraoun Lake and the later drains into the Mediterranean sea. The estimated annual average capacity of the Litani River is around $770x10^6$ m^3. It is employed to generate hydroelectric power and irrigate the upper and lower reaches of the Litani. Potentially, part of water will also be supplied to Beirut, Lebanon's capital.

4.4 Data sources and methodology

Long term discharge data are crucial for the investigation of trends in water resources sustainability of any basin. For the Litani Basin in the 20th century, such data are either incomplete or not available due to civil war and other logistical constraints. The only daily time series data found within the Litani River Authority's (LRA) database are the daily discharges for 15 gauges located along the river reach and main tributaries between 1971-1974 and 1999-2008. However, even for these time periods, data were not complete. Further, the availability of the daily precipitation data on the Litani Basin are limited.

Therefore, to investigate the water sustainability of the Litani Basin, we took the following approach: 1) generate monthly precipitation data for the Litani Basin form different available sources such as global gridded precipitation records, satellite and gauge data, 2) build a long term, synthetic daily precipitation series by implementing a statistical methodology to generate daily values from the generated monthly precipitation data, 3) use the daily rainfall in a Rainfall-Runoff model, including calibration and validation, to generate a long term daily discharge series, 4) investigate the long term discharge trends using nonparametric statistical methods.

To model the daily synthetic precipitation series, the following monthly precipitation datasets were used: (a) gridded 0.5º resolution precipitation for the period 1900-2006 from University of Delaware (UD) (Matsuura and Willnott, 2007), (b) gridded 0.25º resolution tropical rainfall measuring mission rainfall (TRMM) for the period 1998-present (Huffman et al., 2007), and (c) gridded 0.5º resolution precipitation for the period 1901-2002 from University of East Anglia (CRU TS- Mitchell and Jones, 2005). UD and CRU TS data were calibrated against a local weather station data (Lebaa station) through a simple regression and then validated against TRMM satellite data using Pearson linear correlation method. Consequently, a single precipitation dataset was generated by using the mean of each value of the calibrated UD and CRUTS data. Detailed procedures for data collection, calibration and validation are provided in Ramadan et al. (2011a).

To build the daily discharge data series, we used the Hillslope River Routing (HRR) model (Beighley et al 2009). The HRR model applies the Pfafstetter sub-basin framework (Pfafstetter, 1989), which has recently been used as a standardized discretization approach. The HRR model has only been tested for large scale basins such as the Amazon (Beighley et al., 2009) and Congo (Beighley et al., 2011), making this study its first application to a mid-size basin.

To generate the daily discharge series, the challenge of limited precipitation data had to be overcome. Consequently, to investigate the water sustainability of the Litani Basin or any other basin with a similar lack of long term hydrological data for any period of time, the following steps were needed.

4.4.1 Stochastic rainfall modelling

A wide range of models have been used in the past two decades in the generation of synthetic rainfall data. These models rely on rainfall occurrence, i.e. possibility of a rainy day and rainfall magnitude, i.e. expected amount of rain per day. However, the common limitation of these models is their dependence on several years of historical daily precipitation data in order to estimate the model parameters prior to generating the missing data. This makes these models impractical for areas where measured daily data are not available.

Among others, Geng et al. (1988) presented a simpler approach requiring only monthly rainfall data to generate daily precipitation statistics. They present a daily precipitation generator derived from available monthly data that uses the Markov first order two-state chain methodology illustrating the probability of wet days occurrence in a given period (month) and a Gamma model describing the daily amount of rain. Despite the fact that higher order Markov chain models have been considered by several authors (Coe and Stern, 1982; Wilks, 1999), the first order Markov chain was suggested as an effective and yet simple approach that describes the daily precipitation occurrence and has been widely implemented with success (Caskey, 1963; Hopkins and Robillard, 1964; Geng et al., 1986; Schuol and Abbospour 2007). The first order Markov chain is a stochastic process, where the probability of transition from one state to another depends solely on the immediate previous state.

To generate a daily rainfall distribution, two transformation factors must be estimated: the transformation factor from a wet day to a wet day, $p_{w|w}$, and the transformation factor from a dry day to a wet day, $p_{w|d}$. The probability of a wet day, p_w, could be estimated by:

$$p_w = p_{w|d} \times p_d + p_{w|w} \times p_w^{'} \tag{4-1}$$

where, p_w is the probability of wet for the current day, p_d is the probability of dry for the previous day and $p_w^{'}$ is the probability of wet for the previous day. Because rainfall is a random phenomenon, the following assumptions are made:

$$p_w^{'} = p_w \tag{4-2}$$

$$p_d = 1 - p_w \tag{4-3}$$

Based on rainfall gauged data at the Lebaa station, the transformation factor of a wet day after a dry day is significantly correlated with the frequency of a wet day (Figure 4-1). The best fit equation for this case is:

$$p_{w|d} = 0.87 p_w \tag{4-4}$$

Combining with equations (4-1), (4-2), (4-3) and (4-4), the transformation factor of a wet day after a wet day is then estimated as:

$$p_{w|w} = 0.13 + 0.87 p_w \tag{4-5}$$

The Gamma distribution is widely used for modelling monthly, seasonal and nonzero rainfall variations (Geng et al. 1986; Schuol and Abbaspour, 2007). This method is considered site-specific as the calculated parameters of the gamma distribution can be computed from the known average amount of precipitation per wet day in a monthly time interval, following the estimation of the wet days per month as explained above.

The daily rainfall random variable (x) is considered gamma-distributed with shape factor α and scale factor β. Its probability density function is given by Eq. (6).

$$f(x;\alpha;\beta) = x^{\alpha-1}\frac{e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \tag{4-6}$$

where, $\Gamma(\alpha)$ is a gamma function and is defined by the following finite integral:

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1}e^{-x}dx \tag{4-7}$$

for $\alpha > 0$;

For a given time series of n data points x_i with a gamma distribution, its scale factor β, and shape factor α, are calculated by:

$$\beta = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 / \bar{x} \tag{4-8}$$

$$\alpha = \bar{x}/\beta = n\bar{x}^2 / \sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{4-9}$$

which require daily precipitation records.

In the case that the daily precipitation records are not available, as in our case, Geng et al (1986) suggested a linear relation between the average amounts of rain per wet day measured on a monthly basis. However, one could build a new nonlinear relation that better fit the data by fitting the best curve for the relation between the Gamma scale factor β and the average rain amount per day using available gauged data (Figure 4-2). From the nonlinear best fit, the scale factor could be estimated by the averaged rainfall per rain day:

$$\beta = 0.60 R_w^{1.40} \quad (4\text{-}10)$$

$$R_w = R / f(R) \quad (4\text{-}11)$$

Here, R_w is the rainfall per wet day, R is monthly rainfall and $f(R)$ is the monthly rainfall frequency, respectively. R and $f(R)$ could be found directly from the data archives. Based on equations (4-1) – (4-11) and the monthly rainfall and frequency archive data, the daily rainfall time series could be generated by following the model processing logic illustrated in Figure 4-3.

In addition to the Gamma distribution, we employed the mixed exponential distribution. This widely used distribution is considered most accurate for the simulation of daily precipitation data (Hussain, 2008). The results of both distributions were compared in order to detect the best fit of the daily precipitation amount. The density function of the three-parameter mixed exponential distribution is given by:

$$f(x) = \frac{P}{\beta_1} \exp\left[\frac{-x}{\beta_1}\right] + \frac{1-P}{\beta_2} \exp\left[\frac{-x}{\beta_2}\right] \text{ for } x>0,\ 0<P<1,\ 0<\beta_1<\beta_2 \quad (4\text{-}12)$$

where β_1 and β_2 are the mean of the two exponential distributions and P is a weighting factor. The parameters were computed using the maximum likelihood method. The results of both distributions were compared through the traditional goodness of fit procedure (Chi square method).

4.4.2 Modelling daily runoff data

The response of the hydrology of a fluvial transport network to different conditions of rainfall and temperature is described through modelling. Numerous hydrologic models are available covering different terrestrial modelling scales from continental to medium and small watersheds. New developments in watershed modelling in the last decade rely on the assimilation with spatial simulation programs such as Geographic Information System (GIS) models. These models offer an opportunity for incorporating the details of land features in various scales and resolutions with the hydrologic physical elements and present a simple yet reliable sound scientific structure for different aspects of water resources engineering and management. However, these models still have limitations such as their limited division of basins or sub-watersheds and unsuitable scaling and grid based framework, to name a few.

Beighley et al. (2009) presented a physically-based semi-distributed hydrology model which estimates daily to hourly discharge by integrating a topographically based framework attributing land surface features with water balance dynamics, in an attempt to provide more realistic description of the basin hydraulic characteristics. The Hillslope River Routing (HRR) model has been tested successfully over an extensive range of spatial scales (<1000 to 4.7M km^2) and has proven the ability to characterize the basin in adequate spatial and temporal details through the employment of a continuous-time simulation platform.

The hydrologic process of the basin is modelled using a framework based on the topography of the land surface and a routing system that is able to generate realistic floodplain and river channel hydraulic characteristics (Beighley et al. 2009, Verdin et al, 2006). A topographic method is used to subdivide the basin into irregular computational grid (Pfafstetter, 1989, Verdin and Verdin, 1999).

The Pfafstetter delineation and codification methodology for river systems, developed by Otto Pfafstetter (1989), has a simple self-replicating numbering system that has the potential for global applicability (Vogt et al., 2007). The economy of the number of digits used for topographic units and the topological information which these digits present, in addition to the flexibility in data storage and processing, make this system advantageous. This hierarchal system proved to work in regions where topographic conditions change rapidly over short distances, as in the case of the Litani basin area, where a flexible-irregular grid system is used. As it is designed to work for many resolutions, the delineated watershed can be illustrated by different levels of classification. In this study, the Digital Elevation Model (DEM) of the Litani basin was approximated by the second version of the 3-arcsec (~90-m) DEM developed from ASTER Global Digital Elevation Map data (NASA, 2009). Pfafstetter code (Verdin and Verdin 1999) is applied to each watershed according to the total drainage area located upstream of the watershed's outlet, and its location within the overall drainage system. Working from the mouth of the basin and moving upstream, Pfafstetter divided the watershed into 3 categories: basins, interbasins, and internal basins. Here a Pfafstetter basin is an area that drains by a tributary and hence does not receive drainage from any other drainage area, a Pfafstetter interbasin is a part of the main stem located between 2 tributaries, and hence receives flow from upstream watersheds, and an internal basin (or closed basin) is a drainage area that does not drain to another watershed or waterbody.

Figure 4-4 shows the watershed delineation at level 2. In the Pfafstetter coding system, level 1 corresponds to the coarser scale of watersheds while higher levels (levels 2, 3, 4, etc.) embody finer decomposition of the area into smaller watersheds. For level 1, each Pfafstetter unit is divided into 4 basins (assigned numbers 2, 4, 6 and 8 – from downstream to upstream) and 5 basins (assigned numbers 1, 3, 5, 7 and 9 – from downstream to upstream). For every subsequent level (2, 3…etc), each unit is further divided into another 9 units successively. A closed basin is assigned the number zero. Basins maybe subdivided until tributaries can no longer be found. This recursive process generates a set of independent drainage areas exchanging surface water through the stream network nodes and the numbering system can be used to locate the topological location of the drainage units along the stream network. The system is designed to cover the area range from the globe to small watersheds. Hence, for the Litani basin, level 2 seems to be adequate for showing different drainage area characteristics.

Using the code developed by the Spatial Hydro Research Laboratory (San Diego State University) and downloading the above reference datasets, the following processing sequence was performed:

Pfafstetter Basin Generation: The Pfafstetter Basin at level 2 was generated by Pfafstetter Code with a threshold area of ~9000 m^2 (10 cells size of 90m SRTM DEM). The DEM was used to define flow directions, ground slopes and the resulting drainage network (Moglen and Beighley, 2000).

Pfafstetter Units Splitting: All Pfafstetter units were split along its longest flowpath (for headwater sub-basins) or along the main channel (for inter-basins).

Split Pfafstetter Units were overlayed with precipitation grids: Generated spatially average monthly precipitation series for each Pfafstetter unit from TRMM (0.25 degree), CRU TS and UD (0.5 degree) precipitation grids.

After subdividing the watershed in irregular computational grids following the Pfafstetter approach, the given rectangular gridded precipitation data were remapped to the irregular grid system. For this purpose, an area weighted averaging method was used wherein each data value was spatially averaged according to the drainage unit area (Eq. 13):

$$\overline{X} = \frac{\sum_{i=1}^{n} (X_i A_i)}{A_{unit}} \qquad (4\text{-}13)$$

where $\overline{X}$ is the computed average, X_i is the data value in pixel i within the model unit, A_i is the area of pixel i within the model unit, n is the number of unique data regions in the model unit, and A_{unit} is the total area of the model unit.

Each sub-basin drainage area was then approximated as an open-book system connected from upstream and downstream and consisting of a channel reach surrounded by a single plane (i.e., hillslope) on each side. Each irregular grid was then transformed and approximated to 4 different rectangular units illustrating the following: a channel reach segment, a floodplain and a total of 2 hillslopes each discharging laterally from one side to the channel/floodplain. Computation of the hydrologic cycle components were divided into two Models: 1) vertical water balance and 2) hydraulic routing.

The main purpose of water balance modelling was to evaluate and assess water availability and sustainability. Conceptually, the water budget model was used based on the concept of mass conservation and presented in mm/day as shown by Beighley et al. (2009):

$$\Delta S_c + \Delta S_u = P - E_s - E_c - E_T - Q_s - D \qquad (4\text{-}14)$$

where ΔS_c is the variation in canopy water storage; ΔS_u is the variation in the rooting zone water storage; P is precipitation; E_s is soil evaporation; E_c is canopy evaporation; E_T is transpiration; Q_s is water available for surface runoff; and D is the water transferred to the lower soil layer.

For routing, one dimensional kinematic and diffusion wave methodologies are both used (Mahmood and Yevjevich, 1975, Ponce, 1989). The kinematic wave method is used for the upland surfaces and sub-surfaces runoff and for tributary channels while the diffusion wave (Maskingum-Cunge) method is assigned for the interbasin and floodplains runoff. A comprehensive explanation of the functionality and parameterization of the model can be found in Beighley et al. (2009). Computational procedure is based on the physical laws governing the flow of shallow water in a one dimensional stream, in particular the conservation of mass (continuity), and momentum principles (St-Venant’s equations), and Manning's equation (resistance to flow) in order to calculate flood wave movement. Manning roughness coefficient was assumed to be uniformly distributed over each sub-basin. The values of n were calculated through a trial and error process to provide a good fit to the hydrograph of the measured data. As a result, n values were estimated equal to 0.03 and 0.05 for the ULB and LLB, respectively.

Subsurface runoff (q_{ss}) is calculated combining Darcy's law and Dupuit approximation. Hence, the continuity equation of the subsurface flow returns to:

$$\frac{\partial q_{ss}}{\partial x} + \frac{\partial h^*}{\partial t} = D(t) \tag{4-15}$$

where h^* is the effective depth of the flow and D(t) is the rate of the vertically percolating water.

Similarly, the overland (surface) flow q_s is:

$$\frac{\partial q_s}{\partial x} + \frac{\partial y}{\partial t} = Q_s(t) \tag{4-16}$$

where q_s is the surface flow rate per unit width, y is the notional mean depth of flow and Q_s (t) is the rate of excess water transported to the soil surface.

Relationships required for estimating channel width as a function of upstream drainage area in the Litani basin were generated using a correlation between measured channel widths and their corresponding drainage area (Leopold and Maddock 1953). Based on the runoff available data and the Litani's channel width variability, the best fit relation is:

$$B = 2.58 A_d^{\ 0.2} \tag{4-17}$$

where B (m) is the channel width and A_d (km^2) is the corresponding drainage area.

After generating and calibrating the runoff data with available runoff measurements (1998-2008), a non-parametric statistical approach was used in order to investigate the runoff trend of the Basin during the last century. The Mann-Kendal test (Kendal, 1975) was employed to test the significance of the runoff trends. Once a linear trend was detected, the Sen Slope method (Sen, 1968) was applied to estimate the true slope of runoff change per unit time. More details of this methodology applied to the Litani Basin can be found in Ramadan et al. (2011a).

4.5 Results

Pearson's linear correlation and chi-square goodness-of-fit tests were used first to determine the difference between simulated discharges which are generated based on mixed exponential and gamma rainfall distributions. The results presented in Fig 4-5 and 4-7 show that no significant difference was found. The Pearson correlations between the simulated runoffs of both methods are 0.99 and 1 for the Upper Litani Basin (ULB) and the Lower Litani Basin (LLB), respectively. It is the same for the Chi-square P values that hit 100% for both basins. Hence, no difference is found in using the two methods to generate rainfall for the basins under study.

The Pearson correlation was used as well to evaluate the performance of the model by comparing the simulated results between the measured data between 1999 and 2009. The rainfall stochastic models give approximately similar streamflow results for both gamma and mixed exponential distributions (Tables 4-2 and 4-3). The Pearson correlation of the gamma distribution and mixed exponential for the daily time step ULB are 0.76 and 0.75 respectively and 0.64 for the LLB. Monthly time step simulation yields stronger correlation reaching 0.85 (gamma) and 0.84 (mixed exponential) for the ULB and 0.72 for the LLB. For the 1999-2009 simulation time period, the conservation of water mass reaches 98.8% (gamma) and 99.4% (mixed exponential) for the ULB while the LLB showsd significant differences in water balance (e.g., 32%). This is primarily due to the Qaraoun lake maintenance performed in 2002-2003 period causing an extreme discharge downstream and, consequently, impacting the water budget results of the LLB.

Another method was additionally employed to appraise the quality of the simulated runoff results. Moriasi et al. (2007) suggested evaluation guidelines to compare the accuracy of the runoff modelled values with the measured data. Three quantitative statistics were used: Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and ratio of the root mean square error to the standard deviation of measured data (RSR).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right] \quad (4\text{-}18)$$

where Y_i^{obs} is the i^th^ observation of the measured runoff, Y_i^{sim} is the i^th^ observation of the modelled runoff, Y_i^{mean} is the mean of the measured runoff, and n is the total number of observations.

$$PBIAS = \frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n} Y_i^{obs}} \quad (4\text{-}19)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = 1 - \left[\frac{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2}} \right] \quad (4\text{-}20)$$

where RMSE is the root mean square error and $STDEV_{obs}$ is the observation standard deviation.

A simulation model performance is described as satisfactory if NSE > 0.50 and RSR < 0.70, and if PBIAS ±25% for streamflow.

Tables 4-2 and 4-3 show the results of the outlet of ULB and LLB located at Joub Jannine and Qanmieh areas, respectively. Based on Moriasi et al. (2007) criteria, the ULB results indicate a satisfactory performance for both distributions, whether applied to the daily or the monthly time series. However, the LLB results do not reflect satisfactory performance. This is due to the presence of outliers in the measured data that are linked to the random maintenance of the Qaraoun Lake. The major maintenance outlier for the LLB data appears during 2002-2003 period. Upon removal of this period from the data, the response significantly improves. For example, the Pearson correlation increases to 81% and the monthly NSE, PBIAS and RSR values comply with Moriasi et al.'s (2007) criteria. For the simulated daily discharges, removing the outlier from the data notably improves the results (NSE increases and RSR decreases), though does not bring it to meet the used criteria, except for PBIAS.

Figures 4-5 and 4-6 show the results of the calibrated (1999-2004) and validated (2005-2009) modelled versus measured data for the ULB and LLB, respectively. For the two basins, gamma and mixed exponential models simulate satisfactorily the annual water budget for a maximum error of 1.2% after removing the impacted data period (Tables 4-2 and 4-3). Similarly, in the monthly time scale, the model reasonably reproduces the monthly streamflow for both basins once the outliers are eliminated.

After generating daily rainfall data, hence making it possible to model the runoff data between 1900 and 2008, the trends for the upper and lower basin runoffs were analyzed separately using Mann Kendall and Sen Slope nonparametric statistical approaches. As shown in Table 4-4, the simulated runoff reveals a drying trend in the period 1900-2008, and a peak loss in January (0.8 and 0.7 m^3/s per decade for the ULB and LLB, respectively). Other significant losses are seen in February and during the spring season. No trend is apparent in the fall season, while a negative trend is seen in the ULB alone in the summer and dry seasons affecting the low flow rate of this sub-basin. The ULB and LLB demonstrate different responses in May, June, summer, dry and transitional seasons reflecting the unique geophysical and geospatial characteristics of each sub-basin. It is known that precipitation and runoff are highly correlated. Hence, these results are in agreement with the precipitation trends analysis presented by Ramadan et al. (2011a) that shows generally a decreasing rainfall trend between 1900 and 2008, especially in winter and wet seasons.

4.6 Summary and Conclusions

The aim of this study is to simulate the runoff of the Litani Basin to evaluate its variability during the 20th century. As the monthly precipitation is the only available data type, a stochastic model is used to generate the required daily precipitation. This model consists of two parts: the first part simulates the wet versus the dry days per month, and the second part distributes the monthly precipitation among the wet days using Gamma and Mixed Exponential distribution models. Both simulated distributions give comparable daily rainfall results for the basins in comparison.

Water balance and routing models are employed to simulate the Litani's streamflow. The basin is divided into two independent sub-basins, ULB and LLB. Monthly and daily modelled streamflow for both basins show significant correlation with measured data. Correlation ranged between 0.65 and 0.85 with a maximum mass difference of 1.2%. According to the Moriasi et al. (2007) runoff simulation performance criteria, the daily and monthly modelled results for ULB show good agreement with the measured data (e.g. $0.54<NSE<0.7$, $-1.15<PBIAS<-0.54$, $0.55<RSR<0.68$). However, the LLB runoff results show weak association with the measured data due to the presence of a few outliers. Upon removal of one major outlier, the LLB demonstrates good agreement with the monthly measured data (NSE= 0.62, 0.64; PBIAS= -0.75, 0.09; RSR= 0.62, 0.6). Finally, the runoff trends of the ULB and LLB are examined using a nonparametric statistical approach. The results show that the streamflow of both basins experience a drying trend between 1900 and 2008 within a reduction range of 0.1 to 0.8 m^3/s per decade.

The Litani basin is one of few remaining perennial basins in Lebanon. Hence, its runoff decrease would have serious implications on the water use and management of the basin and, consequently, on the total water budget of Lebanon. Different factors may have contributed to the surface water loss in the last century. These include climate change, land use alteration and non-regulated groundwater pumping to name a few. Linking these factors to the basin's hydrology will aid in identifying the causes of the Litani's streamflow reduction.

After the generation of the long runoff, the impact of climate change on the Litani streamflow will be examined by implementing a set of hypothetical climate variation scenarios. The procedure and the results are discussed in Chapter 5.

Tables

Table 4-1 GIS generated Litani basin land surface features

	Area (km^2)	Land slope (%)	Main channel slope	flow length (km)
Total	2180	17.7	1.32%	182
Upper Basin	1540	16.0	1.47%	106
Lower Basin	641	21.8	1.11%	75.5

Table 4-2 Model performance evaluation for a daily time step

Location	Method	Correlation	Mass Diff	NSE	PBIAS	RSR
ULB (Joub Jannine)	Gamma	0.76	1.2%	0.56	-1.15	0.67
	MED	0.75	0.6%	0.54	-0.54	0.68
LLB (Qasmiye)	Gamma	0.64	-31%	0.32	30.89	0.82
	MED	0.64	-32%	0.32	31.39	0.83
LLB (Qasmiye†) (No data during 09/02-8/03)	Gamma	0.65	1%	0.41	-0.93	0.77
	MED	0.66	0%	0.43	-0.10	0.76

†: No data during water year of 2002/2003 (9/1/2002-8/31/2003) – outlier

Table 4-3 Model performance evaluation for a monthly time step

Location	Method	Correlation	Mass Diff	NSE	PBIAS	RSR
ULB (Joub Jannine)	Gamma	0.85	1.2%	0.70	-1.12	0.55
	MED	0.84	0.6%	0.69	-0.56	0.56
LLB (Qasmiye)	Gamma	0.72	-31%	0.41	31.00	0.77
	MED	0.72	-32%	0.41	31.51	0.77
LLB (Qasmiye†) (No data during 09/02-8/03)	Gamma	0.80	0.7%	0.62	-0.75	0.62
	MED	0.81	-0.1%	0.64	0.09	0.60

†: No data during water year of 2002/2003 (9/1/2002-8/31/2003) – outlier

Table 4-4 Runoff Sen Slope trends for the Upper and Lower Litani Basin between 1900 and 2008

Months/Seasons	Runoff - Sen slope *ULB*+ *(m³/s/10yr)*	Runoff - Sen slope *LLB*+ *(m³/s/10yr)*
Jan	-0.8**	-0.7**
Feb	-0.7**	-0.6**
Mar		
Apr		
May	-0.2*	
Jun	-0.1*	
Jul		
Aug		
Sep		
Oct		
Nov		
Dec	-0.3*	-0.2*
Annual	-0.2**	-0.2**
Spring	-0.6**	-0.6**
Summer	-0.2*	
Fall		
Winter	-0.1*	-0.1*
Dry‡	-0.1*	
Wet‡	-0.4**	-0.4**
Trans.‡	-0.2*	

+ ULB: Upper Litani Basin, LLB: Lower Litani Basin
*5% significance
**1% significance
Dry from Jun to Sep; Transitional (Trans) from April to May; Wet from Nov to Mar.

Figures

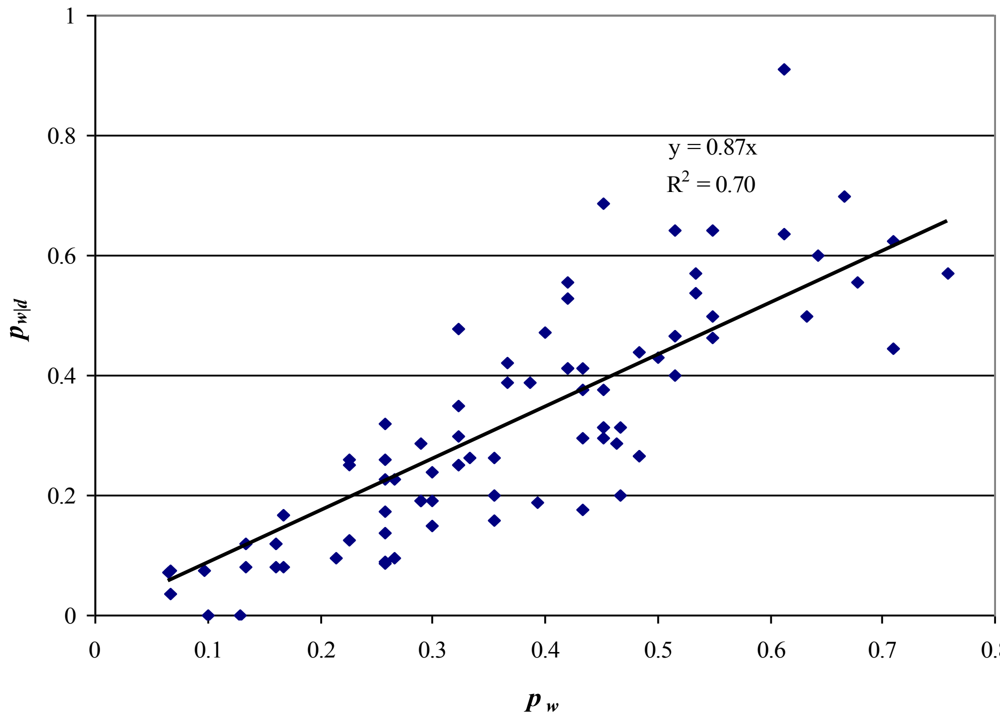

Figure 4-1 Relationship between the probability of wet after a dry day and the probability of wet

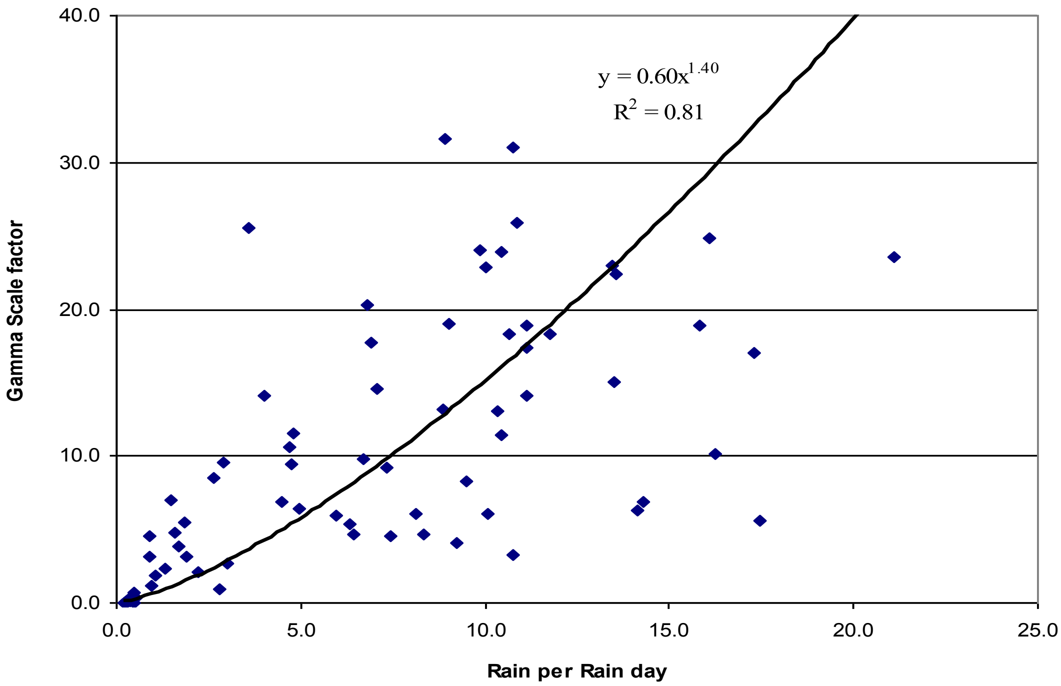

Figure 4-2 Relationship between gamma scale factor and average rainfall per wet day

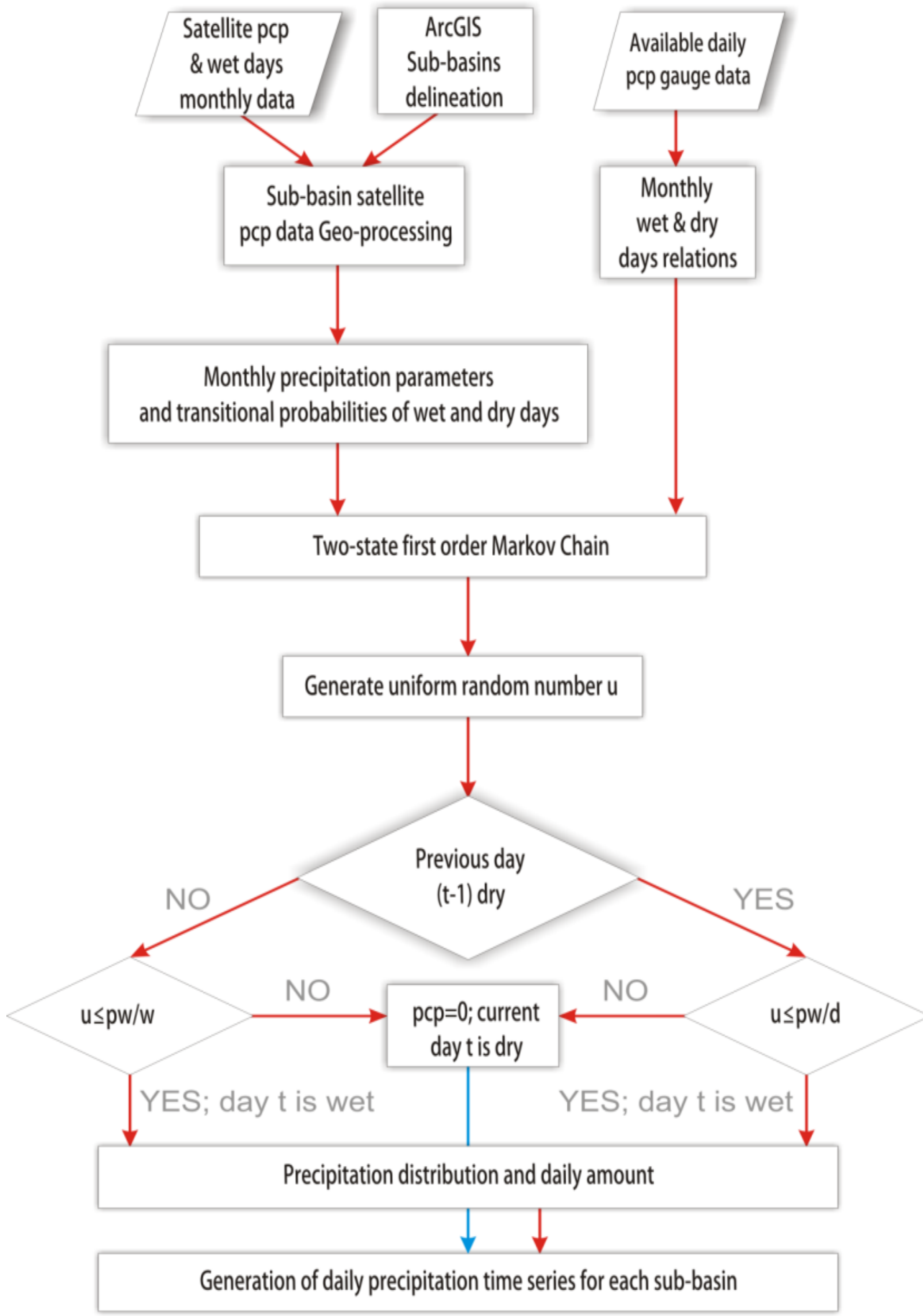

Figure 4-3 Flow chart for daily rainfall generation

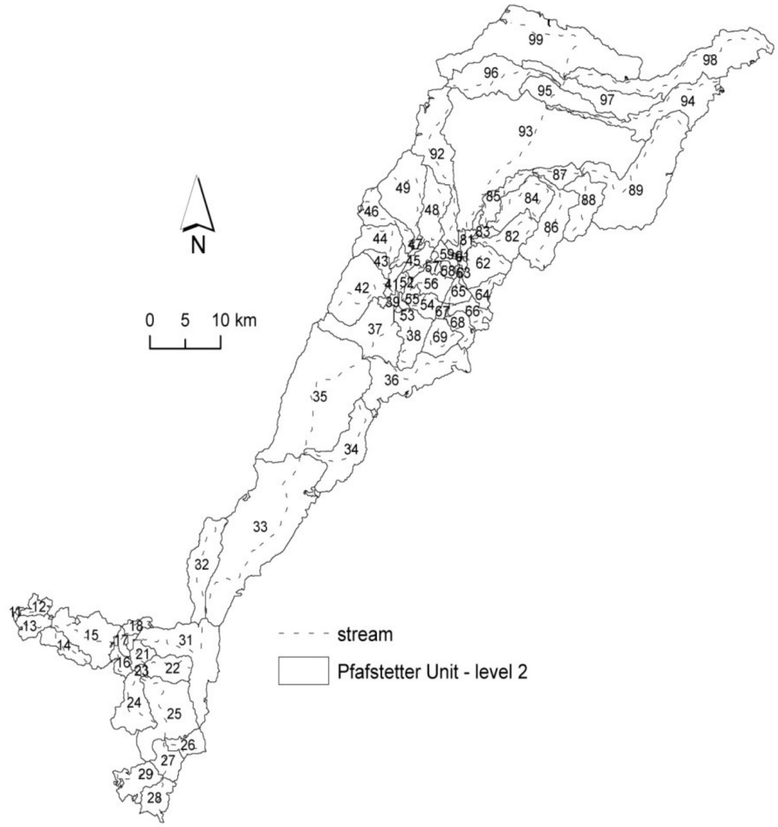

Figure 4-4 Pfafstetter level 2 – the Litani watershed

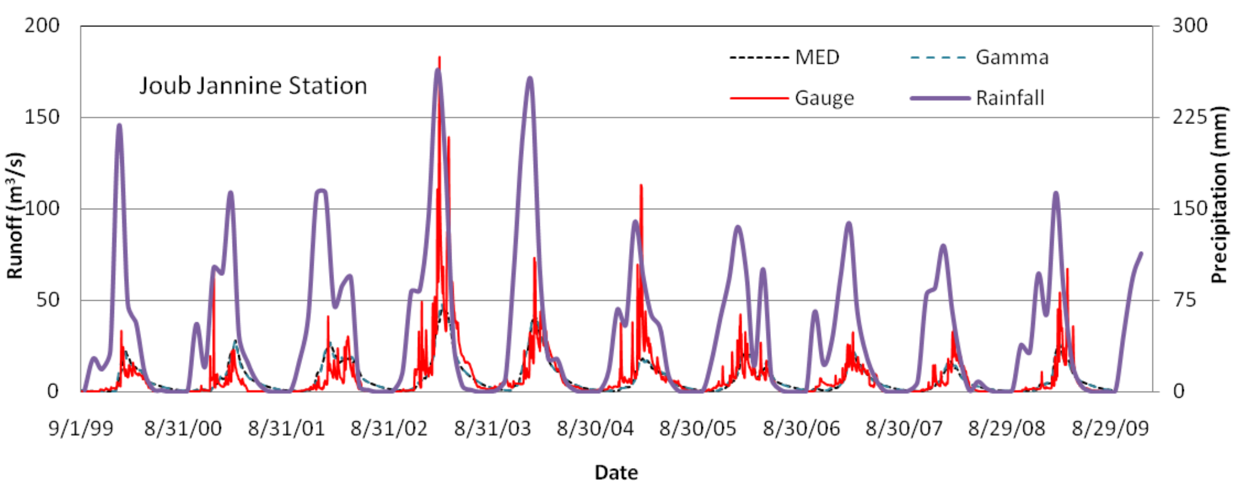

Figure 4-5 ULB precipitation (modelled) and runoff (measured and modelled) between 1999 and 2009

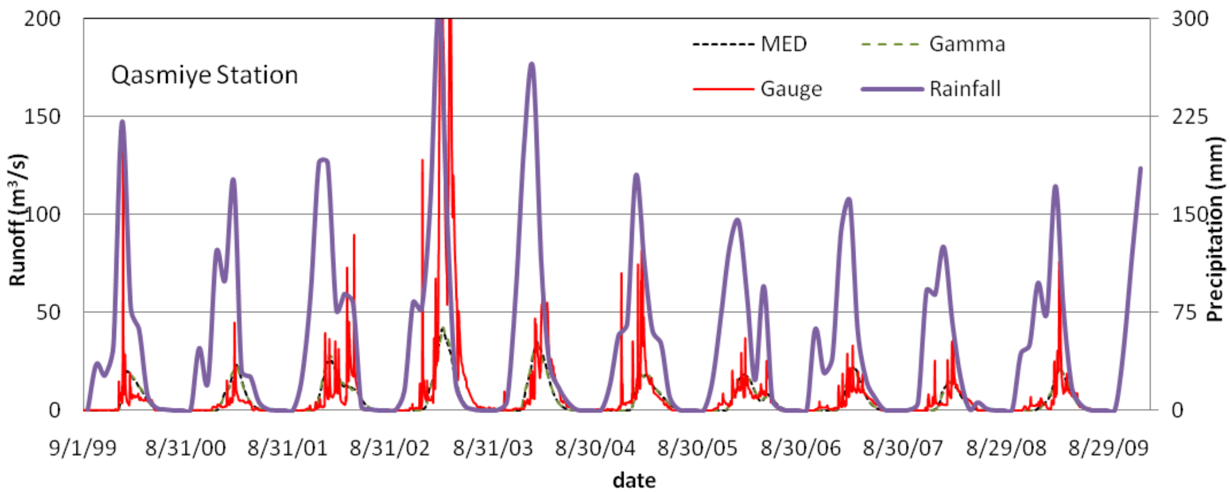

Figure 4-6 LLB precipitation (modelled) and runoff (measured and modelled) between 1999 and 2009

5 Sensitivity Analysis of Climate Change Impact on the Hydrology of the Litani Basin in Lebanon

Ramadan H.H, Ramamurthy A.S. and Beighley R.E.

(***International Journal of Environment and Pollution – 2nd Review under progress, 01/12***)

5.1 Abstract

The belief that climate in the 21st century will be most likely different from what we experienced in the 20th century has been overlooked in terms of water resources vulnerability in most of the East Mediterranean countries including Lebanon. In this study, the effects of climate change on the surface water of the largest watershed in Lebanon, the Litani Basin, were examined. The basin is divided into 2 distinct sub-basins, each dominated by unique physiographical and micro-climatic features. A series of 82 hypothetical scenarios were imposed on each of the sub-basins' precipitation and temperature data. Based on this, an integrated hydrological model was developed while conserving the climate variables. A sensitivity analysis examined the relative changes of runoff from the historical baseline (1961 to 1999) for 82 different combinations of precipitation and temperature changes. The analysis suggested a reduction of runoff for a temperature increase, especially in the upper Litani. However, a 1% decrease of monthly precipitation yielded about 2% of runoff reduction for both sub-basins. The combination of temperature increase and precipitation reduction produced the largest reduction of the basin's runoff. Furthermore, to present a sense of the severity of climate change to the basin, a Climate Change Water Impact Index (I_{CCWI}) was developed. It detected the degree of the temporal and spatial sensitivity of the basin's runoff to climate

modification. This index enabled the computation of the temporal implication of different climate change scenarios on each sub-basin's runoff. I_{CCWI} values indicated that the lower basin is more sensitive to climate changes than the upper basin. They also indicated that the runoff during transitional and fall seasons are more sensitive to precipitation and temperature variations than during the wet season.

5.2 Introduction

Climate change induced by human emissions of green-house gases can be inferred by various changes in temperature and precipitation values and patterns (IPCC, 2007b). This may lead to an altered atmosphere-earth balance and to a direct and perhaps a severe impact on our natural environment and, consequently, on all life on earth. The impact of climate change on water resources has gained particular interest due to its relevance to human life (Abu Ziad and Biswas, 1991; Arnell, 1999; Oki and Kanae, 2006; Kundzewicz, et al. 2007; Bates, 2008; Praskievicz and Chang, 2009; Pittock and Connell, 2010). Accommodating the effects of climate change on fresh surface water in particular is of utmost importance. Streamflows are the first human resource of renewable water and its sustainability is vital to our life, aquatic ecosystems and food chain. Warmer climate, for instance, may cause an increase in evapotranspiration, reduce the runoff water availability and impose more stress on the soil moisture.

The relation between observed changes in climate and the hydrological cycle on the basin scale has been a subject of intensive studies in the last two decades. These studies revealed that the European countries are likely to experience a decrease in river flows of 10-30% by 2070 due to climate change (Lehner et al., 2001). In addition, it is predicted that the end of the twenty-first century is likely to witness an increase in the annual mean precipitation, and runoff in high latitudes in the northern hemisphere, southern and eastern Asia, and central Africa. On the contrary, a decrease in the annual precipitation and runoff is projected to the Mediterranean region, southern Africa, southern North

America and Central America (Nohara et al., 2006). Arnell and Liu (2001) suggested that smaller watersheds maybe more sensitive to climate change than others.

Hypothetical climate change scenarios have been employed in many regions around the world to conduct sensitivity analysis studies (Lettenmaier & Gan, 1990; Bobba et al., 1999, Shamra, 2000; Baltas and Mimikou, 2007). McCabe and Hay (1995) tested nine hypothetical scenarios on East River streamflow reflecting changes in mean seasonal and annual temperatures of -4°C, 0°C, and +4°C and changes in precipitation of -20%, 0%, and +20%. Xu (2000) examined the impact of 1-3ºC temperature change combined with a change of 0%, 10% and 20% in precipitation on 25 catchments' streamflow in the center of Sweden. Wang et al (2003) applied their hypothetical approach to investigate the changes for the Huaihe Basin in China. Blake et al. (2007) generated hypothetical scenarios of climate change using General Circulation Model (GCM) outputs to investigate New York City's water supply sensitivity.

The Eastern Mediterranean countries with their historical water resource scarcity are experiencing significant demographic, social, cultural, economic and environmental changes. Lebanon, in particular, is likely to suffer from a severe water stress in the not-too-far future (Angelakis and Kosmas, 1998). Here, a 60% reduction in water resources per capita is anticipated by the year 2050. The Litani Basin generates around 30% of the total surface water of the nation. Therefore, investigation of the effect of climate change on the streamflow regime of this watershed in Lebanon is necessary and needed.

The objective of this study is to test the sensitivity of the Litani basin subject to a possible climate change. We intend to generate an understanding of the relative changes in the runoff values subject to different temperature and precipitation variations. Because the basin is divided into two sub-basins by a dam and dominated by two different microclimate characteristics (semi-arid mountainous versus semi-humid costal), the runoff sensitivity to climate change of each sub-basin is analyzed separately. At the outset, different hypothetical climate change scenarios are applied to the climate data and new datasets are modeled for each scenario. Climate change scenarios are portrayed as precipitation and temperature deviations. Second, the Hillslope River Routing (HRR) hydrology model is applied to generate and analyze the streamflow of the Litani Basin under each climate change scenario. Subsequently, the Climate Change Water Impact Index (I_{CCWI}) is introduced to assess the sensitivity of each sub-basin's streamflow toward climate change. Furthermore, the streamflow of the ULB and the LLB was examined by employing the potential temperature and precipitation changes in Lebanon at the end of the 21st century suggested by Önol and Semazzi (2009).

5.3 Climate Change implications on water resources in the Mediterranean and Lebanon

The Mediterranean region is considered vulnerable to climate change effects on water resources. Lionello et al., (2006) stressed the need for accurate information "at regional scale" related to the impacts of potential climate change on the Mediterranean area which suffers chronically from water shortage. In particular, the East Mediterranean region, known for having a historical susceptibility to water scarcity, would encounter additional challenges preserving and restoring the sustainability of fresh water due to downsides of climate change. Numerous related studies treated the Mediterranean area as a single region which makes their results biased from the local perspective due to the vast diversity of the Mediterranean region's ecosystems, regional climate and orographic features. Hence, many authors found variable responses to climate change and variations in climate structures in different regions of the Mediterranean (New et al., 2001; Hansen et al., 2001; Giorgi, 2002 and Ramadan et al., 2011a). Moreover, studies covering the Mediterranean region climate change impacts mostly focused on the west basin while relatively few investigations have been conducted on the east basin.

Predicting the future impacts of climate change, and based on the latest assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007a), most of the Middle East area is expected to become hotter and drier. Cullen et al., (2002) considered that increased greenhouse gases may promote North Atlantic Oscillator’s upward trend, resulting in potential reduction of precipitation and winter river flow in the Middle East. Alpert and Silverman (2003) found a negative precipitation trend over the Mediterranean including the east basin between 1958 and 1998. However, high sub-regional variability of precipitation trends has been noted with a significant decrease in the eastern Mediterranean and a general decrease of 20% of the winter precipitation starting from the mid 20th century (Türkeş et al., 2002; Xoplaki, 2002 and Mariotti et al., 2002). Giorgi (2006) and IPCC (2007a) predicted that the warming climate in the Mediterranean region as a whole to exceed the global average and to be accompanied by a large reduction in precipitation. Gao and Giorgi (2008) projected a 10%-50% decrease in winter precipitation over part of the East Mediterranean area (Greece and southern Turkey) and a 5-6°C increase in summer temperature (Balkans and western turkey).

However, climate change scenarios employed by the IPPC (2007) predicted that, over most of the Arab region, the annual average temperature will increase by 0.5-1°C, 1-1.5°C and 2.5-3.0°C by the year 2030, 2070 and 2100, respectively. . Some other scenarios predicted even higher temperature changes. For rainfall, IPCC (2007a) predicted a decrease of 10-20% for the northern Arabian Peninsula, and an increase of 10-30% in the southwest part of Saudi Arabia, United Arab Emirates and Oman.

Few studies have been conducted in the Middle East area to investigate the impact of climate change on streamflow behavior, including a potential of flooding and a reduction/increase in high and low flows. Arnell (1999) concluded that the Middle East (around the Mediterranean) will encounter exacerbated water resources stress due to climate change. Milly et al., (2005), using 12 different climate models, showed a negative runoff trend for the period 1900-1970 and projected a 10-30% decrease of runoff in the Middle East region by 2050. Smith et al. (2000) studied the Euphrates River and found a ~42% drop and ~50% raise in streamflow with a corresponding decrease/increase of 25% of rainfall, a ~60% drop and ~43% raise of annual runoff for respective 5°C imposed decrease/ increase in temperature with similar sensitivity recorded for the Upper Tigris, Greater Zab and other rivers in the area. Abdulla and Al-Omari (2008) reported a 70% reduction of Zarqa River's annual runoff, for a 4°C temperature increase combined with 20% rainfall reduction. Similarly, Fujihara et al., (2008) foresaw a 52-61% decrease in annual runoff in the 2070s of the Seyhan River basin in Turkey. Milano (2010) noted as well the likeliness of severe and unavoidable decrease of runoff trends in the Southern and Eastern basin.

For Lebanon, where the water sector is already encountering many challenges, fewer studies can be found. Michel and Hulme (2000), in attempt to estimate the climate change on a country-by-country basis, reported a 0.5°C warming trend in the 20th century (1901-1998) in Lebanon. They employed a coarse horizontal grid model (2.5° latitude by 3.75° longitude) and a future scenario in which greenhouse gas concentrations increase by approximately 1% per year and, hence, projected for Lebanon a warming of 4.3 -4.8°C at the end of the 21st century (2080s). Hreiche et al. (2007) noted significant effects of a 2°C warming on the flow characteristics of a Lebanese watershed affected by snow cover. He concluded an early peak flow and drought occurrences which could cause a serious alteration of water resource management system. Önol and Semazzi (2009) conducted a regional seasonal modeling study for 21 countries located in the East Mediterranean. They reported for Lebanon a continuous range of positive average temperature change trends and a widespread of negative and positive seasonal precipitation trend. Similarly, Ragab and Prudhomme (2002) suggested a future temperature increase in 2050 between 1.5 and 3ºC. Based on these results, it could be concluded that Lebanon will experience a warming trend throughout the year with a reduction in winter precipitation partially compensated during autumn. Non significant precipitation related results were found during summer and spring. In fact, most of the precipitation in Lebanon falls in winter and autumn seasons. However, they pointed out the need for higher resolution models in order to produce better results. Lately, Ramadan et al. (2011a) revealed the presence of a drying trend over the Litani Basin for the period 1900-2008 which was accentuated after 1970. However, they reported different hydro-climatological seasonal behaviors of the ULB versus the LLB. In addition, general observations from the local people agreed upon the systematic loss of the seasonal snow cover and yearly average precipitation (Ramadan, 2009). For example, Abboud (2007) noted a continuous decrease of water quantity in the last 10 years for the Qaraoun Lake in the Upper Litani Basin (ULB). Similarly, Nasrallah (2009) pointed out that the average amount of annual rain data (~ 800 mm) in all parts of Lebanon dropped to 350 mm in 2009, resulting in the lower storage of the Qaraoun Lake witnessed in the last 50 years.

5.4 Study Area

Lebanon (Figure 2-1) consists of a north-south Eastern Mediterranean narrow coastal strip and two parallel mountain chains within an elevation range of 800 to 3000 m separated by the Beqaa plains. The weather of this relatively small country (10,540 km^2) varies from semi-arid (Beqaa valley) to sub-humid (coasts) with a short wet and cold season versus an extended dry season. Most rainfall occurs in the winter months with a yearly average rainfall of 700 to1100 mm in the coastal zone, 200 to 800 mm in the Beqaa Valley, and up to 2000 mm in the mountains. The annual average temperatures range from 13 °C to 27 °C on the coast, 0 °C to 18 °C in the mountains and 5 °C to 26

°C in the Beqaa Valley. The annual surface runoff in Lebanon is approximately 4.1 km^3 and the groundwater recharge is about 3.2 km^3 (Frenken, 2009).

The Litani River is the longest River in Lebanon (~182 km) and provides around 750 MCM of water per year. The Litani Basin (Figure 2-1) occupies around 20% of the Lebanese territory and it is the largest in size of all basins in Lebanon (~2175 km^2). The Litani River's runoff is mainly used for hydropower generation and agricultural irrigation. In 1960, the basin was divided into 2 separate sub-basins after building the Alfred Naqash dam with the artificial Qaraoun Lake. The dam divides the basin into the Upper Litani Basin (ULB) and the Lower Litani Basin (LLB). Both basins present distinct geophysical characters. The ULB is located in a semi-arid area mostly occupied by mountainous areas (elevation: 800-2600 m) and drains completely in the Qaraoun Lake. The LLB is located in a mostly semi-humid area closer to the coast (elevation 0~800 m) and drains in the Mediterranean Sea.

5.5 Methodology and data sources

In this study, the simulation and analysis of the ULB and LLB streamflow under 82 different hypothetical climate scenarios are examined. A new index termed as the Climate change water impact index (I_{CCWI}) that describes the changes of the runoff due to temperature and precipitation deviations is introduced.

5.5.1 Data Sources

Due to lack of hydro climatological records, data were collected for a 41-year period (1961-1999) from different sources. Precipitation and temperature records were derived from different gridded, satellite and weather station data (Table 1). The processes of gathering, calibrating and generating the datasets were explained in Ramadan et al. (2011a). For runoff, synthetic data were developed for the Litani Basin following the procedure described by Ramadan et al. (2011b) as measured data for the designated period were not available.

5.5.2 Climate Scenarios

A scenario is a tool to help in raising awareness about the potential changes and alternative states of the future and their influence on developmental and human life. An "inquiry-driven scenario analysis" (Alcamo, 2008) is established, based on a variety of possible visions to the future of climate parameters (e.g. temperature and precipitation) in the area. This approach assumes structural continuity of the socio-ecological systems and does not portray discontinuity and shock. Although hypothetical, these scenarios are intended to represent the degree of changes that might be anticipated for the ULB and LLB streamflow under different climate set ups. The scenarios are in the vicinity of the IPCC (2007a) forecasts for the East Mediterranean area. However, they are only intended to test the sensitivity of the flows in the Litani River to potential climate change.

The period of 1961-1999 is used as a baseline or the "business as usual" case. Different incremental climate scenarios are applied to the monthly temperature and precipitation baseline datasets (Table 2). The responses of the Litani Basin's streamflow under temperature and precipitation changes are examined. Temperature and precipitation changes are applied separately and simultaneously leading to a total of 81 combinations. Furthermore, the streamflow of the ULB and the LLB are examined by employing the findings of the seasonal potential temperature and precipitation changes in the 21st century suggested by Önol and Semazzi (2009). The seasonal scenario consists of temperature increases of 2.8°C in winter, 3.3°C in spring, 3.1°C in summer and 4.1°C in autumn, a precipitation reduction of 28.7% in winter and a precipitation increase of 58.6% in autumn. Temperature and precipitation datasets for each scenario are used as input data to the Hydrology model.

5.5.3 Hydrology model

The Hillslope River Routing (HRR) model (Beighley et al., 2009) is applied to simulate the ULB and LLB hydrological response to each of the hypothetical scenarios. This physically-based semi-distributed hydrology model is integrated with the Geography Information System (GIS) program. It simulates daily to hourly discharge connecting the water balance dynamics with land surface features. It consists of a water balance and routing models. The water budget model is used based on the concept of mass conservation such as:

Storage = Input – Output + Sources (or minus sinks) (5-1)

The routing model is one dimensional and employs the kinematic wave method for upland, hillslope areas and subsurface runoff, and first order tributary channels, and the

Muskingum-Cunge (MC) diffusion wave routing method for interbasin channels and floodplains (Maidment, 1992). The computational procedure is based on the solution of the governing equation of shallow water in a one dimensional flow, that is, continuity and St-Venant's equations. Hence, the channel discharge Q_{sb} is given by:

$$\frac{\partial Q_{sb}}{\partial x}+\frac{\partial A_{sb}}{\partial t}=q_s+q_{ss}=q_l \tag{5-2}$$

where A_{sb} is the channel flow cross section; q_s is the surface discharge water per unit width; q_{ss} is the subsurface flow; q_l is lateral flow; x is the downstream coordinate and t is time.

The combination of momentum conservation and Manning's equation (resistance to flow) is employed as:

$$S_f=\frac{n^2v^2}{R^{4/3}}-\frac{\partial y}{\partial x}-\frac{v}{g}\frac{\partial v}{\partial x}-\frac{1}{g}\frac{\partial v}{\partial t} \tag{5-3}$$

Where, n is the manning roughness, v is the mean velocity; R is the hydraulic radius; S_o is the channel bed slop, y is the flow depth, and g is the gravity acceleration. The procedure of simulating the runoff of the Litani Basin based on synthetic rainfall data using HRR model is described in Ramadan et al. (2011b).

5.5.4 Sensitivity analysis

In this study, the sensitivity analysis attempts to determine the impact of climate change hypothetical scenarios on the runoff of the Litani River. Hence, the consequences of likely changes of temperature and/or precipitation on runoff in the ULB and LLB are examined. Fifteen runs of the HRR model are conducted for each scenario and their mean runoff values are considered. Monthly, seasonal and annual simulated stream flows of each scenario are compared with those of the baseline period (1961-1999). The positive and negative deviations from the basic period are presented as a percentage from the baseline.

In addition, the Climate Change Water Impact Index (I_{CCWI}) is developed. It can weigh the sensitivity of any element of the water budget equation to all applied scenarios collectively. It describes the effect of changes of climate state on a selected hydrological element. In this study, the sensitivity of the runoff to climate change is examined. Hence, I_{CCWI} communicates the state of the baseline runoff and the runoff response to climate alteration. It quantifies the impact of the 82 temperature and/or precipitation changes simultaneously on the mean monthly, seasonally and yearly runoff for both the ULB and LLB. It is defined as:

$$I_{CCWI} = \sqrt{\frac{1}{\mathrm{m \times n}} \sum_{\mathrm{i=1}}^{\mathrm{m}} \sum_{\mathrm{j=1}}^{\mathrm{n}} \left(\frac{U_{i,j}}{U_b} * 100 - 100\right)^2} \tag{5-4}$$

where, $U_{i,j}$ is the water budget's element (e.g. runoff) for the i^{th} precipitation and j^{th} temperature scenario, U_b is the element's baseline value, *m* and n are the total number of modeled precipitation and temperature scenarios, respectively. The I_{CCWI} is a non-dimensional value representing the mean percentage change between the element starting value (e.g. baseline value) and the element new values of the n scenarios. The higher the I_{CCWI}, the more sensitive is the water budget's element to the precipitation and/or temperature changes. Using this index, the temporal and spatial sensitivity of the basin's runoff can be assessed and the most/least sensitive month or season to climate change can be evaluated.

5.6 Results and Discussion

For the baseline period (1961-1999), the yearly total precipitation of the ULB (LLB) varied from 438 mm in 1999 (404 mm in 1999) to 1050 mm in 1967 (992 mm in 1967) with an average value of 753 mm (709 mm) and a standard deviation of 145 mm (154 mm). The wettest and driest recorded months were January and July, respectively for both sub-basins. The average monthly temperature of the ULB (LLB) fluctuated between 4.7°C (10.7°C) and 23°C (26.8°C). The coolest and warmest months were January and August, respectively, for both sub-basins. Accordingly, the LLB was subjected to a relatively drier and warmer climate than the ULB during the baseline period.

Table 3 illustrates the results of the sensitivity experiments. The ULB seems to be relatively more sensitive to temperature changes than the LLB. The results suggest a minor runoff reduction (increase) due to warming (cooling) climate. For instance, a warming of 1°C may yield a 0.3% and 0.05% of yearly runoff reduction in the ULB and LLB, respectively, while a cooling of 1°C may increase the yearly runoff by 0.3% in the ULB and 0.06% in the LLB. The annual runoff reduction maybe mainly attributed to surface water reduction between December and May (Figure 5-1). The decreasing tendency of the simulated runoff is associated with the evapotranspiration increase that is projected to occur with the rising temperature. On the other hand, reduction or increase of precipitation implies a similar runoff trend (e.g. higher precipitation induces higher runoff). Both sub-basins show significant sensitivity to precipitation variations (Figure 5-2). For instance, a 5% reduction of precipitation produces a yearly runoff reduction of 9% in the ULB and 11% in the LLB. Therefore, the combination of the warming and drying climate tendency in the East Mediterranean region, as suggested by the IPCC (2007a) may have a significantly negative impact on the Litani Basin's water balance.

When temperature increase and precipitation decrease are combined, the results indicate a more significant impact on the Litani's runoff. For example, the combination of 1°C temperature increase and 1% precipitation decrease implies a runoff reduction of 2% in the ULB and 2.5% in the LLB. However, for 2°C temperature increase and 10% precipitation decrease, the runoff is drastically reduced by 18% in the ULB and 22% in the LLB. The results become more drastic when the extreme conditions are considered, i.e. +4°C temperature increase and 20% precipitation decrease. In this case, the ULB and the LLB may suffer a surface water decrease of 35% and 41%, respectively.

It can be deduced that for the same climate change scenario, the runoff response varies spatially and temporally across the basin. The ULB maintained relatively higher temperature variances during the baseline period, and hence, projected higher sensitivity to temperature change than the LLB. In contrast, the LLB experienced higher precipitation variance, and hence, demonstrated higher sensitivity to precipitation variability than the ULB. In addition, early occurrence of the peak flow is noticed for warming and drying scenarios.

Similarly, the runoff variations of the river are reported in Figure 5-3 after imposing the seasonal climate change scenario (Önol and Semazzi's, 2009). The results indicate a runoff increase during the fall season and a runoff decrease in the remaining of the year which is mainly due to the precipitation decrease in winter. The peak runoff seems to flatten out significantly for both sub-basins and the runoff peak appears slightly earlier than the baseline runoff. However, the most noticeable outcome of the seasonal scenario is the annual runoff decline in the ULB and LLB by ~25% and ~35%, respectively. This is mainly associated with the wet season runoff loss of ~27% and ~35% in the ULB and LLB, respectively.

Furthermore, the Climate Change Water Impact Index (I_{CCWI}) was employed to examine the temporal and spatial sensitivity of the basin under the 82 different scenarios. Table 4 highlights the I_{CCWI} for the ULB and LLB during different months and seasons. The results suggest that the LLB is generally more sensitive to climate change, as it holds higher I_{CCWI} for all months and seasons than those of the ULB. The most sensitive months to climate change, i.e., months with the highest I_{CCRI}, are November for both sub-basins. September and October are the least sensitive months to climate change for the ULB and LLB, respectively. Likewise, for both sub-basins, Table 4 indicates that the transitional and fall seasons influence precipitation and temperature changes far more than the wet and winter seasons.

5.7 Summary and conclusions

This study utilizes a watershed model and incremental climate change scenarios for projecting the potential effects of climate change at the sub-basin level. In particular, the Litani Basin in Lebanon which is separated into 2 independent sub-basins, was selected for the study. The analysis incorporates an assessment of the impact of 82 climate change outcomes on the Litani Basin's runoff. Monthly precipitation and temperature were altered in order to evaluate the sub-basins' runoff sensitivity to climate change. The modeled results show that the combined changes in temperature and precipitation are likely to affect both the timing and quantity of Litani's streamflow. The runoff magnitude has the tendency to be reduced with a temperature increase and a precipitation decrease. However, the precipitation variation has a heavier weight on the basin's runoff behavior.

The results reveal as well the significant effect of the forecasted climate change in Lebanon on the watershed's surface water. One imposed climate change on the basin's hydrology produced 25% and 35% runoff losses for the upper and the lower basin, respectively. Moreover, by the application of the Climate change water Impact index (I_{CCWI}), it was revealed that the ULB and the LLB runoff hold different levels of sensitivity toward precipitation and temperature variations. The I_{CCWI} of the LLB demonstrate more pronounced sensitivity to climate change than the ULB.

Changes in precipitation distribution and temperature alteration are likely to modify the runoff distribution of the Basin in addition to the decline of surface water availability. This may cause unpredictable consequences on water usage and sustainability.

Transforming these findings into more conformable impacts will be the task of future work.

Tables

Table 5-1 Data Sources

Source	Details	Goal	Remarks
Ramadan et al., 2011b	Collect gridded, satellite and gauged records	Generate single sets of temperature and precipitation data	Data was extended and generated for the Litani Basin covering 1900-2008 period
Ramadan et al., 2011c	Modeled daily and monthly runoff data	Generate long term daily and monthly runoff data	Data was generated for the Litani Basin covering 1900-2008 period
Matsuura and Willmott, (2007) - University of Delware, UD	Monthly temperature and precipitation gridded data	Producing high-resolution historical climate data over spatially extensive regions	Gridded with 0.5º resolution, covering 1900-2006 period
Mitchell and Jones (2005) University of East Anglia, CRU TS	Monthly temperature and precipitation data	Producing archived temperature and precipitation gridded data provided by weather stations around the world	Gridded with 0.5º resolution covering 1901-2002 period
Seemann et al. (2003) - MODIS	Satellite temperature data	Atmospheric data to predict global change accurately	0.05º resolution and started in 2000
Huffman et al. (2007) -TRMM	Satellite precipitation data	Rainfall measurements around the tropics and subtropics	0.25º resolution and started in 1998
Lebaa Station	Guaged precipitation data	Daily measured data	Located in South Lebanon covering 2001-2008 period
Ksara Obsy	Guaged temperature data	Monthly measured data	Located in the Beqaa Valley covering 1921-2006

Table 5-2 Precipitation and temperature scenarios

Precipitation Scenarios	1	2	3	4	5	6	7	8	9
	-20%	-10%	-5%	-1%	Baseline	1%	5%	10%	20%
Temperature Scenarios	A	B	C	D	E	F	G	H	I
	-4C	-3C	-2C	-1C	Baseline	1C	2C	3C	4C

Table 5-3 ULB & LLB annual runoff deviations from baseline under proposed scenarios

Precipitation Scenario	1	2	3	4	5	6	7	8	9
ULB	-33.7%	-17.4%	-8.7%	-1.8%	0.0%	1.8%	9.0%	19.2%	39.7%
LLB	-40.7%	-21.6%	-11.3%	-1.9%	0.0%	2.2%	12.5%	24.1%	51.1%
Temperature Scenario	A	B	C	D	E	F	G	H	I
ULB	0.8%	0.7%	0.8%	0.2%	0.0%	-0.4%	-0.9%	-1.8%	-2.0%
LLB	0.21%	0.13%	0.10%	0.00%	0.00%	-0.04%	-0.26%	-0.32%	-0.34%

Table 5-4 Annual, Seasonal and Monthly Climate Change Water Impact Index

Month/Season	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Spring	Summer	Fall	Winter	Wet*	Dry*	Trans*
ULB	21	22	22	23	23	22	21	19	17	19	28	21	22	22	21	23	21	21	21	23
LLB	27	27	27	28	29	28	28	27	26	21	32	27	27	28	28	28	26	26	28	28

***Wet: from Nov to Mar; Dry: from Jun to Sep; Transitional (Trans): from April to May**

Figures

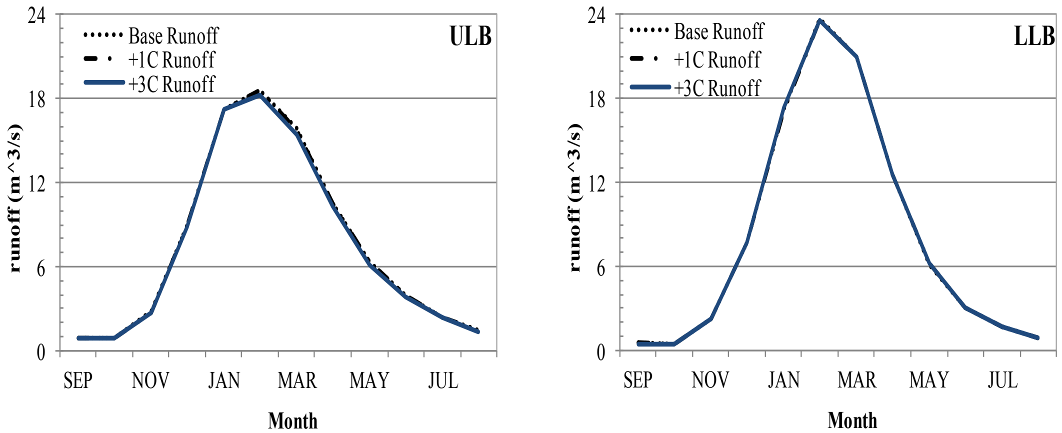

Figure 5-1 ULB & LLB monthly variation the Runoff under scenarios F and H

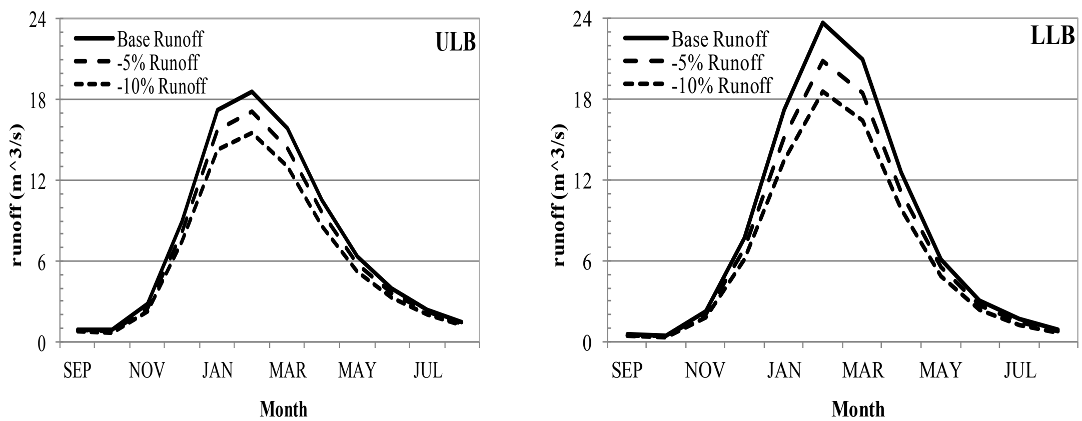

Figure 5-2 ULB & LLB monthly variation of the Runoff under scenarios 2 & 3

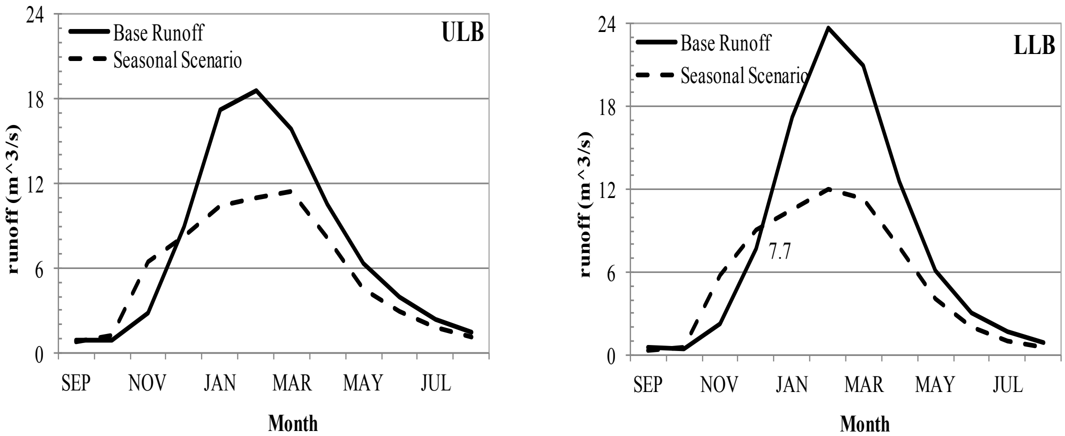

Figure 5-3 ULB & LLB monthly variation of the Runoff under the seasonal scenario

6 Conclusions and recommendations

6.1 Uncertainty Analysis

Since part of the modeling is developed using statistical analysis and as such some uncertainties are associated with the results presented. The following is a summary of the uncertainty elements and related observations associated with the temperature, precipitation, and runoff estimates. For this purpose the uncertainty is defined as the standard error for a normal probability distribution.

(1) Temperature uncertainty (Table 6-1): The uncertainty on temperature includes the following components:

a. Measurement uncertainty: U_m. This uncertainty addresses the accuracy of measured data collected at the Litanti Watershed. This uncertainty is about 0.2°C (Folland et al., 2001), which is 1.2% of long-term mean temperature in the Litani Watershed (16.6ºC);

b. Correlation uncertainty: U_c. Gridded reanalysis data were adjusted to the Litani Watershed on the basis of a linear regression between gridded reanalysis data (CRUTS) and measured air surface temperature from Ksara Obsy station. This uncertainty is calculated through a Monte-Carlo based approach by randomly selecting half of comparable data to develop a linear model and estimate the back prediction error using this linear model with another half of the comparable data. The uncertainty of 1.2% is estimated.

c. Spatial variability due to scale mismatch: U_s. This uncertainty addresses the spatial variability due to gridded temperature data scaled down to the Litani Watershed or the Pfafstetter unit for runoff modeling. As a result of this scale-down approach, the generated data could not capture the spatial variations of the modeling unit which have a smaller scale than the original scale. In this study, we selected the main cell (Grid #81072) of CRUTS dataset in the Litani Watershed. Its long-term (1901-2009) annual mean temperature and the values of its surrounding 8 cells were used to determine the spatial variability (Figure 1). The standard deviation of the surrounding cells are calculated as:

$$\sigma_s = [\sum_{i=1}^{n}(E_p - E_i)^2/n]^{1/2} \qquad (6.1)$$

Where, E_p is the long-term annual mean temperature of grid cell 81072, and E_i is the long-term annual mean temperature for the i^{th} surround cell, which varies from 1 to 8. The spatial variability is defined as:

$$U_s = \frac{\sigma_s}{E_p} \times (1 - \sqrt{\frac{scale_{pfaf}}{scale_{Grid}}}) \qquad (6.2)$$

Where, $scale_{grid}$ is the cell size of gridded CRUTS data (0.5 degree), $scale_{pfaf}$ is the average scale of Pfafstetter unit (0.053 degree) which have averaged area of 0.0028 square degree. The uncertainty of 11.9% is estimated.

d. Total temperature uncertainty could be estimated by

$$U_T = \sqrt{{U_m}^2 + {U_c}^2 + {U_s}^2} \quad (6.3)$$

The total temperature uncertainty is 12.0% at Pfafstetter unit. For basin-wide averaging temperature, the uncertainty decreases to 1.6% since the Litani Watershed has the same scale with CRUTS reanalysis dataset.

(2) Precipitation uncertainty (Table 6-1): The uncertainty in Precipitation data includes the following component:

a. Measurement uncertainty (system error): 0.1 mm for the daily rainfall reading (from Labaa Station data). This system error for annual precipitation will be 0.1 mm times the number of wet day. From the gridded CRUTS data, the long-term averaging wet frequency is 81 days per year. The system error for annual precipitation should be approximated as 8.1 mm, which is about 1.0% of the long-term annual precipitation (783 mm).

b. Correlation error: Gridded reanalysis data were adjusted to the Litani Watershed on the basis of a linear regression between gridded reanalysis data (CRUTS v3.1) and measured precipitation from Lebaa station. The same Monte-Carlo based approach was used to estimate correlation error. The uncertainty of 9.8% is estimated.

c. Spatial variability: Down scale approach was used to generate rainfall for each Pfafstetter. The Pfafstetter unit is smaller than the cell-size of CRUTS gridded reanalysis data. Hence, the generated rainfall could not capture the spatial variability within the reanalysis gridded cell (as seen by the arid north of the basin versus the wetter south of the basin). The uncertainty could be estimated using CRUTS rainfall data with equations 6.1 and 6.2. The uncertainty of 8.2% is estimated.

d. Total precipitation uncertainty: U_P=12.8% at Pfastetter scale. For basin-wide averaging precipitation, the value decreases to 9.9%.

(3) Runoff uncertainty (Table 6-2):

a. Standard Error (SE) is an accuracy metric commonly used for uncertainty analysis between measured and model data. In this study, the standard error is defined as:

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n-2}} \tag{6.4}$$

where y_i is the i^{th} measured runoff from a hydrology station, $\hat{y}_i$ is the modeled runoff, and n is comparable data pairs during measured period.

b. For the long-term mean runoff, its uncertainty could be estimated by:

$$U_{Mean} = SE \times \sqrt{\frac{1}{n} + \frac{(\bar{\bar{\hat{y}}} - \bar{\hat{y}})^2}{ssyy}} = SE \times \sqrt{\frac{1}{n} + \frac{(\bar{\bar{\hat{y}}} - \bar{\hat{y}})^2}{\sum(\hat{y}_i - \bar{\hat{y}})^2}} \tag{6.5}$$

Where, $\bar{\hat{y}}$ is the mean modeled runoff during the measured period and $\bar{\bar{\hat{y}}}$ is the long-term mean modeled runoff (01/01/1901-12/31/2009). On the basis of measured runoff at Joub Jannine hydrology station for the Upper Litani Basin (ULB) and Qasmiye hydrology station for the Lower Litani Basin (LLB) during the period of 09/01/1999 - 08/31/2009, the uncertainty for the mean modeled runoff at the upper station and lower stations are 7% and 14% respectively. The higher uncertainty of the lower basin is mainly due to the non-recorded maintenance of the Qaroun Lake as stated in Chapter 4.

(4) The uncertainty of the developed synthetic rainfall is mostly due to the highly varied topography and its effect on the prevailing westerlies that result in orgraphic rainfall. Consequently, this would cause some uncertainty in the runoff distribution. This is in addition to the modeling uncertainty as shown above.

(5) An additional uncertainty maybe suggested due to the conversion of monthly to daily data which may affect the daily distribution and intensity of the rain and, consequently, on the daily runoff hydrograph.

(6) The uncertainty of the results shown above shall be considered prior to make any related decision to the basin's planning and management.

6.2 Conclusions

The objective of this study was to correlate climate change and streamflow variability of a mid-size watershed for areas lacking hydro-climatological data. The case of the Litani Basin located in Lebanon, east of the Mediterranean Sea, was selected. The basin is divided into 2 physiographically distinct sub-basins separated by the Qaraoun dam. The Upper Litani Basin (ULB) is mostly mountainous and the Lower Litani Basin (LLB) is mostly coastal.

Climate change and streamflow variability of the Litani Basin were examined from different perspectives. Local climatological data availability were one of the major challenges that this study faced. This was overcome through the collection of monthly temperature and precipitation data from different sources which include the available gridded data, satellite data and few local stations limited data. These records were calibrated and blended. Consequently, a unique data set for temperature and precipitation was generated for the period 1900-2008. Another data related challenge was the lack of long term measured streamflow data as the only available runoff records were for the 1999-2008 period. Alternatively, the long term streamflow data were generated through simulation using HRR model. HRR is a semi-distributed physical hydrology model using Pfafstetter hydrologic coding, water balance and routing modeling. This model, however, requires daily precipitation as input data which were not available as well. Hence, daily precipitation data was modeled using gamma and mixed exponential distribution. These synthetic data were then employed to simulate the runoff of the Litani Basin. The generated runoff data were calibrated and validated against the available measured runoff data and the performance of the HRR model was evaluated.

The generated data were employed in the following directions:

1. A trend analysis was conducted to study the temperature, precipitation and runoff variations of the Litani Basin as a whole, the LLB and ULB. The analysis covered 1900-2008 and 1970-2008 periods using the Mann-Kendell and Sen Slope non-parametric statistical methods.

2. Statistical correlations between temperature and precipitation variations with 13 different global and regional teleconnection circulation patterns were produced using the Pearson's correlation approach.
3. A sensitivity analysis was carried out to examine the effects of climate change on the Litani's simulated streamflow. 82 hypothetical temperature and precipitation change scenarios were generated. A new index termed as the Climate change water impact index (I_{CCWI}) is introduced and applied.

   The findings and recommendations can be summarize as the following:

   - For the period 1900-2008, the dominance of the drying trends over ULB, LLB and the whole basin is evident, especially during annually and winter, spring and monsoon seasons
   - Long-term (1900-2008) precipitation has decreased over the whole basin. However short-term (1970-2008) precipitation has not shown notable increase or decrease in the last 40 years. Conversely, temperature has not changed significantly over the long term, but in the short-term has increased significantly across the basin in the last 40 years.
   - Because runoff is positively correlated with precipitation and negatively correlated with temp, runoff should be declining due to both factors and in both long- and short-term. The ULB in particular (i.e. more so than the LLB) seems to be experiencing increased temperature since 1970, and may be at greater risk of reduced runoff if such temp trends persist.

- Temperature was less frequently correlated with runoff than was precipitation. Runoff from both ULB and LLB was more sensitive to (more frequently correlated with) precipitation than to temperature.
- Temperature in selected seasons is correlated with NAO (negative), EA (positive), EP-NP (negative), EA-WR (negative), SCAND (negative), MOAC (negative) and ENSO (negative).
- Precipitation in selected seasons is correlated with NAO (negative), EA (negative), TNH (negative), POL (positive), MOAC (positive) and ENSO (positive).
- No correlation was observed with PT, PNA and WP patterns.
- ULB and LLB showed different responses to many teleconnection patterns highlighting the uniqueness of the basin's geophysical characteristics and local weather implications.
- The LLB showed no sensitivity at any time to India Monsoon, while a negative temperature correlation was present for the ULB prior to 1970.
- Daily rain can be generated using both Gamma and Mixed Exponential distribution with similar results.
- HRR program can simulate the runoff of mid-sized basins with satisfactory results.
- Runoff of the Litani basin showed decreased trends. Water quantity of the perennial river maybe at risk.

- The Litani Basin streamflow is more sensitive to precipitation changes than temperature changes. However, the ULB showed some level of sensitivity toward temperature changes.
- The most serious scenario that may affect the basin's streamflow rate is a combination of temperature increase and precipitation decrease.
- The Climate change Water Impact Index (I_{CCWI}) revealed that the LLB's runoff is more sensitive to the projected climate change than the ULB. However, from temporal perspective, I_{CCWI} showed that the runoff rates during November and transitional season are the most sensitive periods to climate change throughout the year.
- Examining the trend of yearly, seasonal and monthly maximum and minimum temperature and precipitation variations in the last century and their potential changes would be beneficial instead of using average values. This would produce more details on the climate change trends of the area. However, the availability and accessibility to the data in the region remains a serious burden to researchers.
- Future studies may focus on the application of the IPPC generated scenarios over the Litani Basin and simulate its streamflow change through a hydrology model accordingly. Regional Circulation Models (RCM) with the high resolution maybe employed.
- As the land use has been altered in many locations in the basin during the last 50 years (deforestation, urban area expansion, range and agricultural land

reduction…etc), the effect of the combination of climate and land use change on the Litani's flow would be worth studying.

- Studying the effects of the Litani's streamflow potential changes on the basin's water management system is recommended. This would present a different perspective on the seasonal and monthly availability of fresh water and, hence, on the potential water distribution planning.

Tables

Table 6-1 Temperature and precipitation uncertainty for the Litani Basin

Uncertainty Item	Category	Value
Temperature	Measurement Error	1.0%
	Correlation	1.2%
	Spatial variability	11.9%
	Uncertainty (for Pfafstetter Unit)	**12.0%**
	Uncertainty (for the Litani Basin Mean)	**1.6%**
Precipitation	Measurement Error	1.00%
	Correlation	9.8%
	Spatial variability	8.2%
	Uncertainty (for Pfafstetter Unit)	**12.8%**
	Uncertainty (for the Litani Basin Mean)	**9.9%**

Table 6-2 Uncertainty for the modeled daily runoff for the ULB and LLB

Items	ULB	LLB
SE (m^3/s)	6.70	9.61
Mean runoff in m^3/s during 1999-2009	7.36	7.62
Mean runoff in m^3/s during 1901-2009	8.70	6.30
data pairs in month	120	120
Ssyy	10732	21140
Mean runoff uncertainty (m^3/s)	0.62	0.88
Mean runoff uncertainty (%)	**7%**	**14%**

Figures

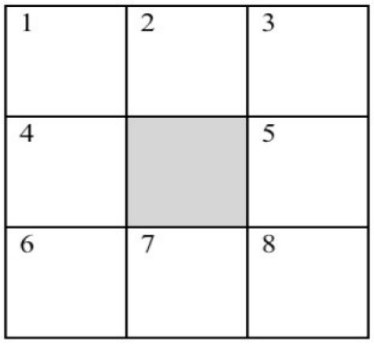

Figure 6-1 3x3 grid layout with anchor cell in the centre (Grid # 81072) and eight surrounding neighbor cells

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Appendix A

Figure A-1. Elevation Map of the Mediterranean Region

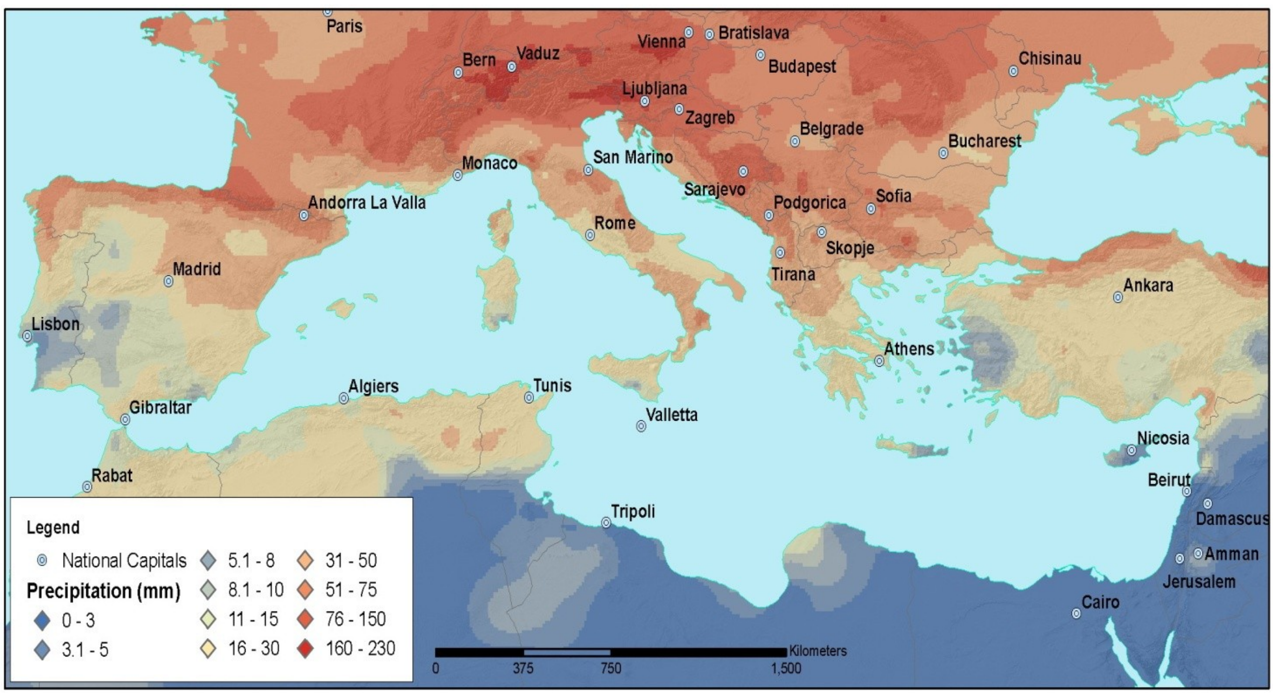

Figure A-2. Mediterranean Region - Average Precipitation - Dry Season 2008

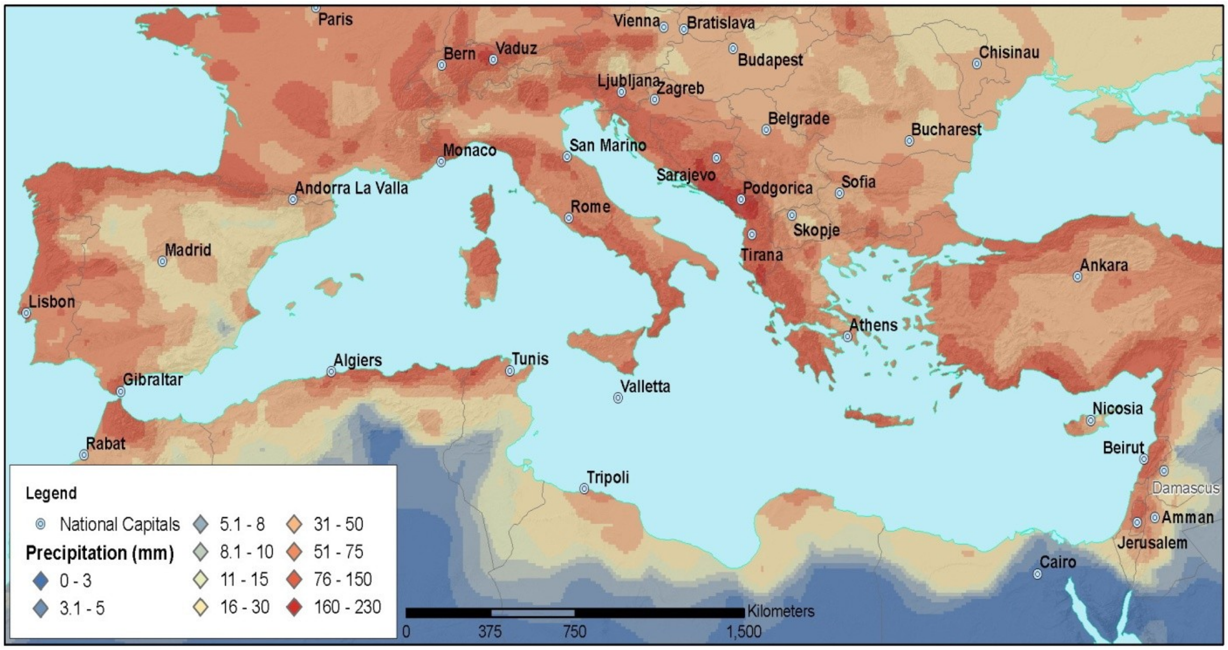

Figure A-3. Mediterranean Region - Average Precipitation - Wet Season 2008

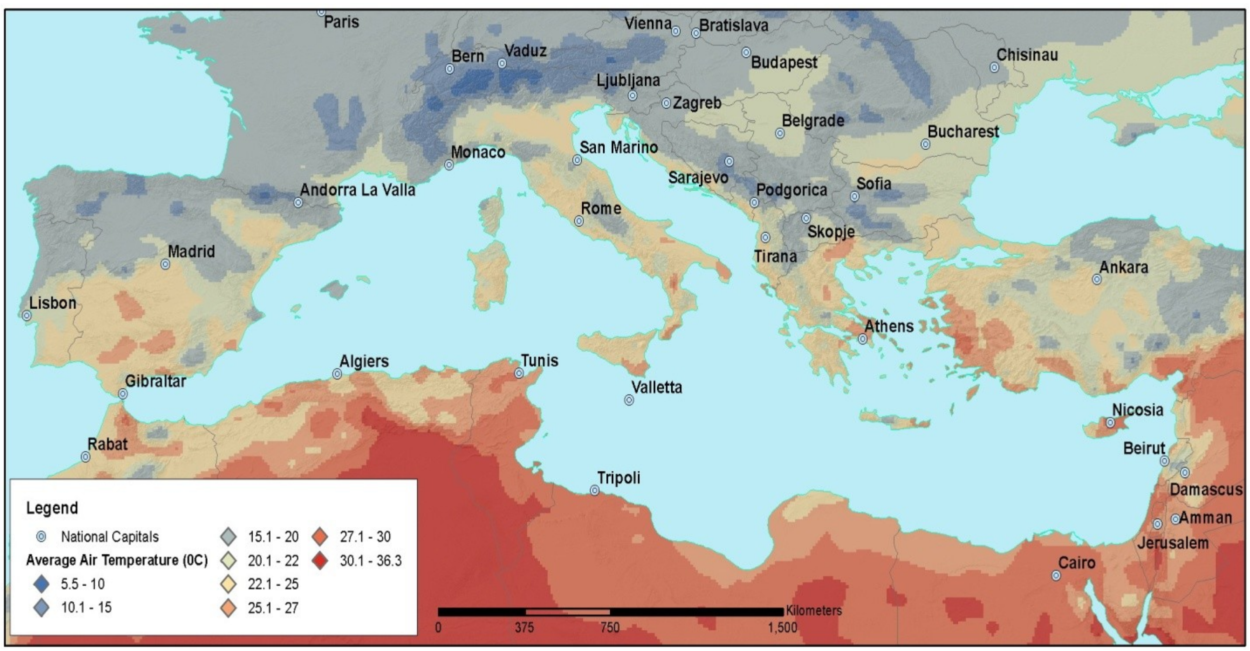

Figure A-4. Mediterranean Region - Average Air Temperature- Dry Season 2008

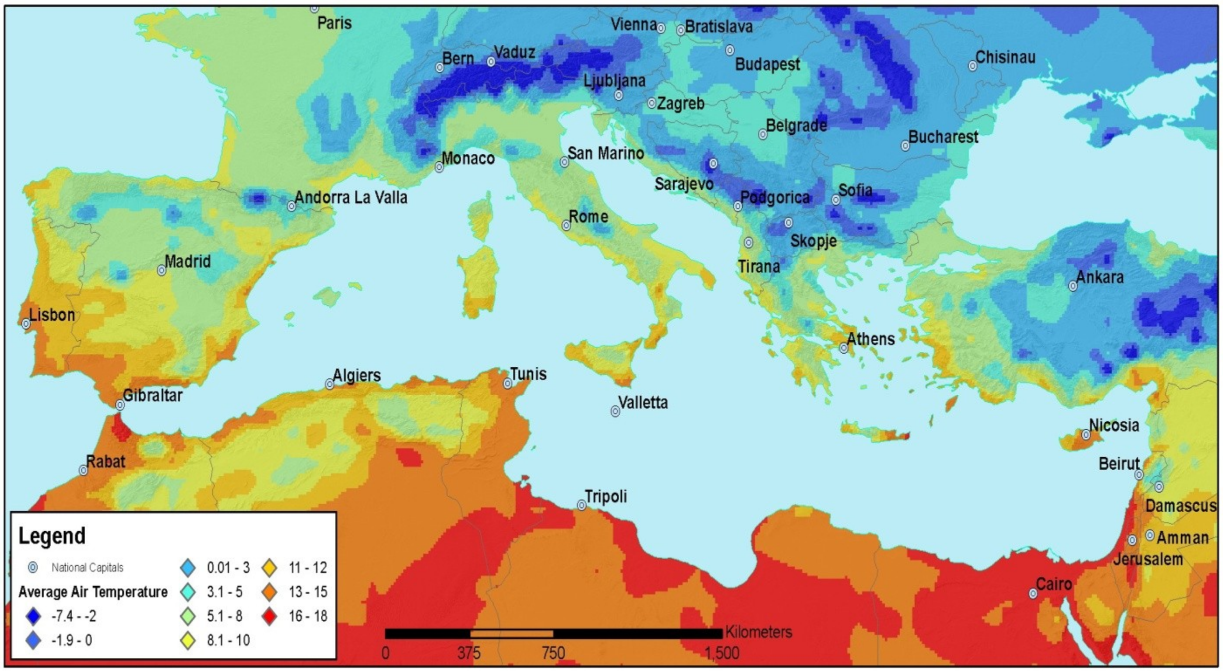

Figure A-5. Mediterranean Region - Average Air Temperature- Wet Season 2008

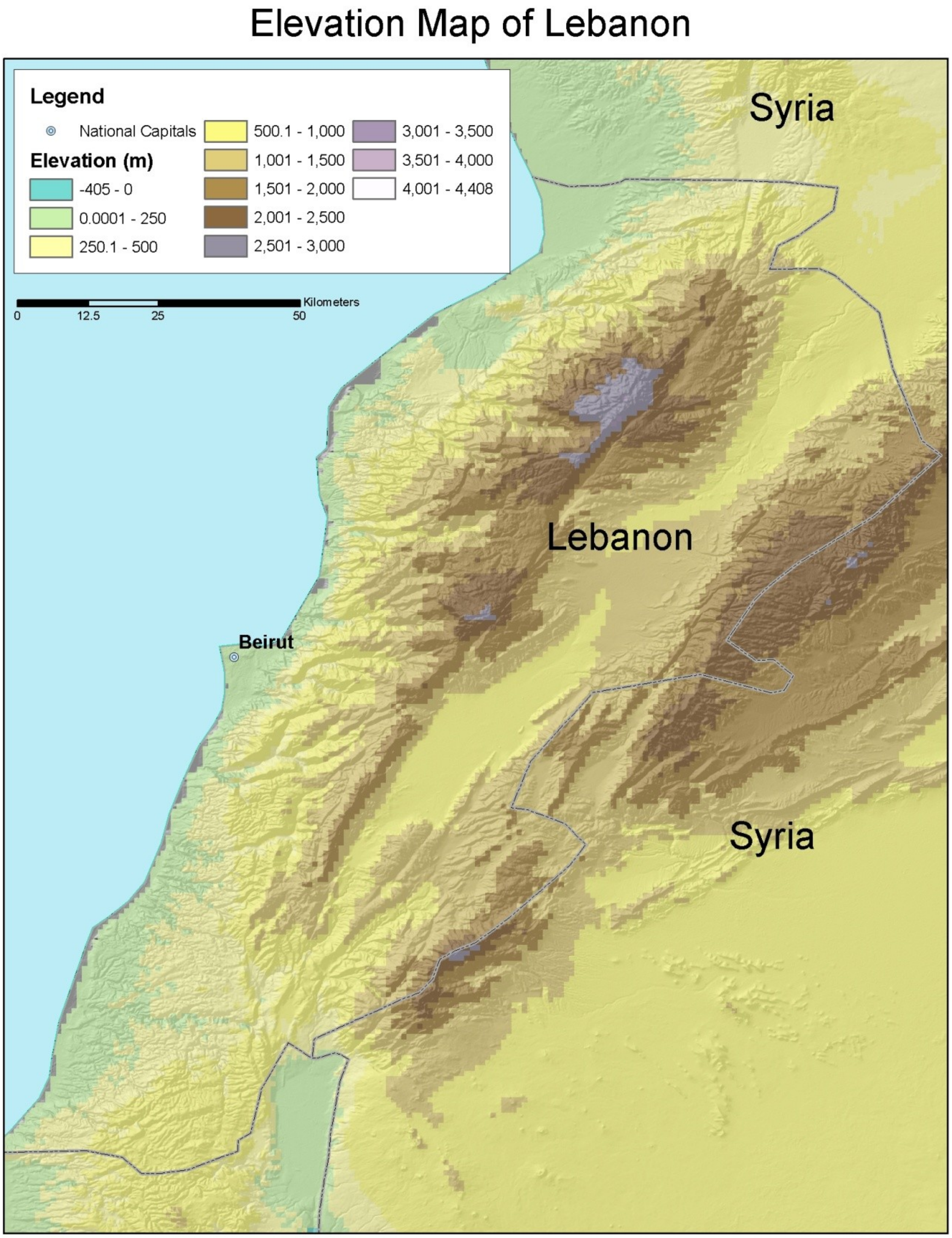

Figure A-6. Lebanon – Elevation Map

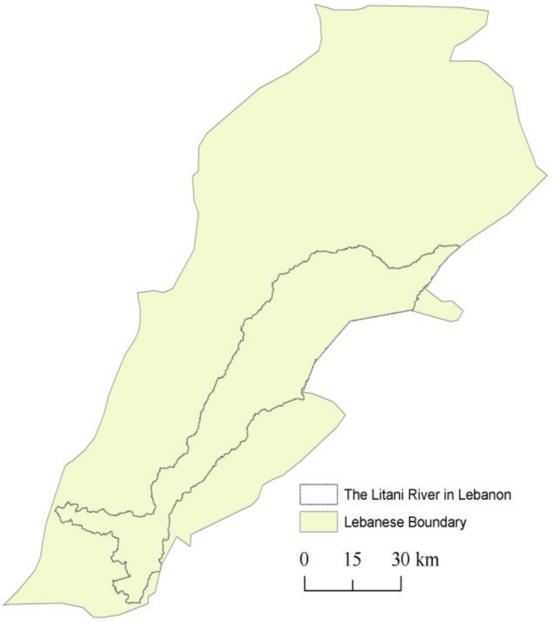

Figure A-7. Location of the Litani Watershed in Lebanon

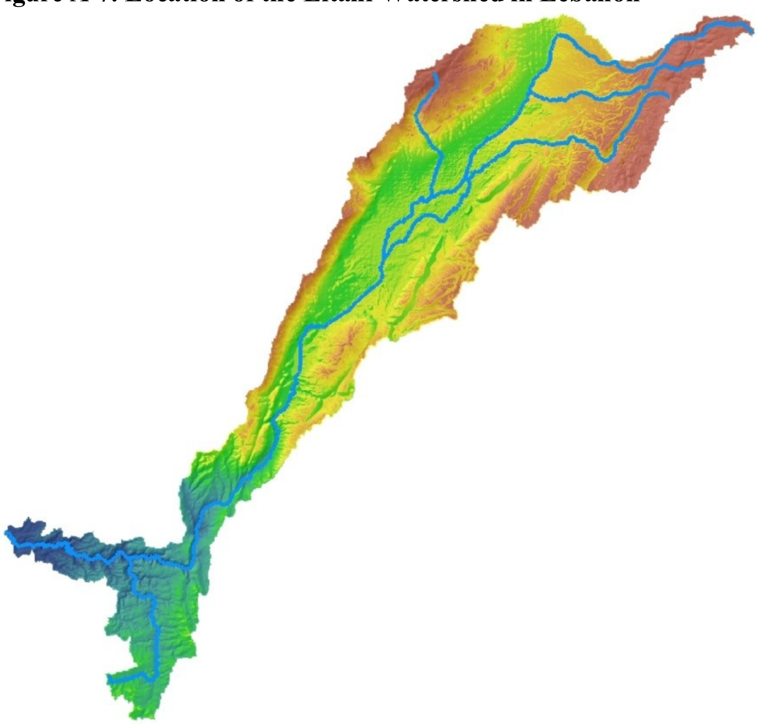

Figure A-8. The Litani watershed main stems

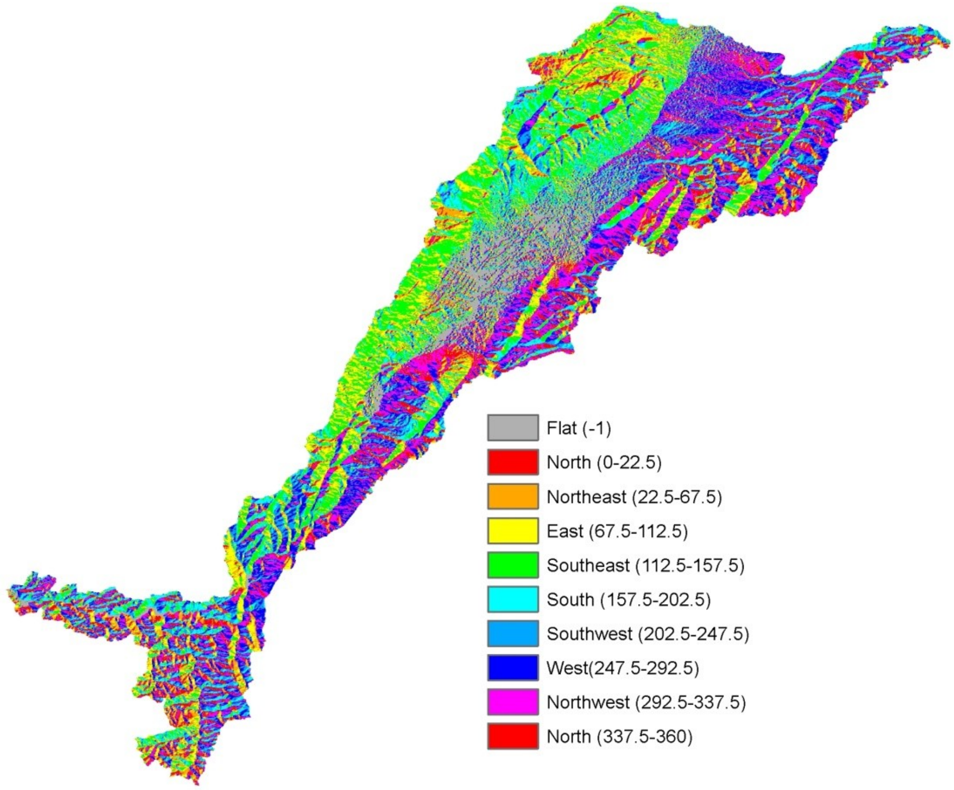

Figure A-9. Slope aspect map of the Litani Watershed