Water Allocation Optimisation of the Litani River Basin

Litani Water Resources System Modelling

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Challenge the future

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by

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Preface

'You don't learn to walk by following rules. You learn by doing, and by falling over' - Richard Branson

Months of hard work, tears and frustration are over. A feeling of being proud and a finished thesis report is what is left. This thesis report was written in order to finish my study Water Management, Civil Engineering at the University of Technology in Delft. During my thesis, I enjoyed the combination of my Bachelor in Technology, Policy and Management and my current Masters. For me, the topic was really challenging. It was the first time of doing a research on my own and I had to learn many new Python-skills. It was not always easy, but now we are here, at the end of my graduation project, at the end of my TU Delft career. While the process was tough at odd times, I really enjoyed the purpose of the study: improve the water allocation of Lebanon. A real on-going case with high needs since water becomes more and more a scarce good, not only in Lebanon.

I believe that my contribution is a useful one, since water scarcity is increasing. The number of regions that has to deal with water scarcity is increasing and therefore measures have to be taken. Of course, there is no guarantee that a measure that works in this area also will works in another water scarce area. However, the model can be adapted in order to determine what kind of measures have to be taken. Moreover, I have contributed in the documentation about the *Python* library I used: *Scipy.minimize*. Of which, the documentation is very limited.

I would like to thank my thesis committee: Dr. S. Pande, Prof. dr. Ir. P van de Zaag, Dr. ir. E. Abraham and Dr. ir. L.M. Hermans. Saket Pande for always being available for help and answering questions, but also for keeping me on the right track. Edo Abraham for all my (stupid) Python related question. Furthermore, I would like to thank Pieter van de Zaag for all the knowledge he shared about Lebanon and water allocation models. Leon Hermans for helping me out in the end of my thesis. Besides my thesis committee, I also would like to thank Jonna van Opstal and Gonzalo Espinoza Devalos. They shared a lot of information and knowledge about this area with me. Without this information, the results of my thesis would never be that good as they are right know.

Getting Pfeiffer-disease during my master thesis made the process a difficult one. Luckily my friends, roommates of 4.93 and group mates of the Ladysmith project group where there to learn me to take the rest when needed and to join me for coffee/tea/cookie breaks. A special thanks to two of my room mates: Anna and Vera, which have listened for hours to my struggles, but always got me positive again. Last, but not least, there was the endless love of my family and Lars. They always supported me, even during the times when I was really frustrated and hated everything and everyone. It feels great when people are convinced you are doing great, even when you ask the most stupid questions.

Now it is the time to finish a phase of my life. A phase which I really enjoyed. Doing study-projects with friends, being active in committees, getting inspired by a lot of teachers and professors and all other activities. One thing has been really important for me during this phase: coxing. I will never forget all the experiences, friends and opportunities I got there. Now, it is time for a new phase, with hopefully a lot of new opportunities as well.

B.A. Schep
Delft, April 2018

Executive Summary

A water crisis is looming for Lebanon. Economic growth, natural population growth and the inflow of refugees from Syria cause an increased water demand in Lebanon. In the meanwhile, the precipitation rates of Lebanon are decreasing. An important water source of Lebanon is the Litani river, which is totally located within the borders of Lebanon. The water of this river is used for agricultural purposes, production of hydropower and supply of domestic water. At the moment, domestic water supply is only a small user of the water of the Litani river. However, water supply from the Litani river to the capital of Lebanon, Beirut is proposed. The Litani already nearly dries up each year and therefore the water allocation of the Litani river has to be optimised. This research aims to optimise the water allocation of Lebanon, in order to protect the country against the looming water crisis. Since the Litani is the most important river of Lebanon, the research focuses only on this basin: the Litani River Basin (LRB).

Optimal water allocation is achieved when the social benefits gained from the deviation of water are at a maximum. The social benefits are described by three principles: economic efficiency, social equity and sustainability. Since the Litani river is an important source for the Lebanese economy, the economic efficiency principle is assumed to be the most important principle in optimising the water allocation. This means that the optimal water allocation is achieved when the profits from the deviation of water are maximised. In order to optimise the water allocation in the LRB, the current water allocation is needed. In this research project, first the current water allocation will be described. Afterwards, scenarios will be applied to see what the effect is on the current water allocation. The research ends with the implementation of measures in order to see their effect on the water allocation.

The current water allocation is based on hydrological data of the area and the assumption that in the current water allocation everyone tries to maximise the total income of the LRB. The maximum profit can be determined by using the following equation:

$$\text{profit} = \alpha \sum_{i=1}^{60} (P_{c,i} * Ya(t)_{c,i}) + (1-\alpha) \sum_{t=1}^{12} (c_{hydro} * Q_{hydro} * P_{hydro}) + \sum_{t=1}^{12} Q_{domestic} * P_{domestic}$$

The water of the Litani river is used by three different sectors, which are represented in the formula: agriculture, energy and supply of domestic water. In most of these sectors, water does not directly generate a profit. For example the agricultural sector: yields are increased by the availability of water and these yields will be sold. Formulas of the Food and Agricultural Organisation (FAO) are used in order to determine the actual yields (Y_a). The actual yield depends on reference evapotranspiration (ET_{ref}), actual evapotranspiration (ET_a) and crop characteristics. α is added to the equation in order to model the current situation. α describes the current power of the agricultural sector. This value is based on the current amount of water flowing to this sector and the profits that are generated within this sector. The value of this objective function is limited by the hydrological conditions of the area. The current power of the agricultural sector is 0.445. Therefore, the power of the hydropower sector is 0.555. When water is used for the production of hydropower, it can be used for other purposes afterwards. A part of the water that is used for the production of hydropower is used for the supply of domestic water afterwards, therefore the domestic water sector is not included in the objective function.

In the current water allocation 71.7% of the water is used in the agricultural sector. The other 28.3% is used to produce hydropower. Of this water 23.4% is afterwards supplied as domestic water to the inhabitants of the LRB. The agricultural water use is mainly high in the subbasins with a high marginal value. If one extra unit of water is flowing to these subbasins, the increase in the profits will be significant. The model is based on the assumption that all individuals try to maximise the total income of the Litani River Basin and therefore the water will be used in the subbasins with the highest marginal value.

Two scenarios are applied to see the effect on the current water allocation: a water supply to Beirut and a flow to the downstream subbasins. Water supply to Beirut is a proposed solution in order to provide the inhabitants of Beirut with enough domestic water. The water that will be supplied to Beirut,

first will be used to produce hydropower. Therefore, the minimum flow to the hydropower stations will be 93 million m^3/year. In order to reach this amount of water, less water will be used for agriculture. This causes a decrease in the profits generated within the area. Furthermore, the Qaraoun Lake is over-exploited. In the end of the season in which hydropower is produced, the Qaraoun Lake is almost empty. In the first years, 93 million m^3/year can be delivered to Beirut. However, the Lake has to be over-exploited to reach this amount and therefore the water could not be supplied in the last years. The demand of Beirut is too high to be supplied by the LRB.
The supply of water to the downstream basins will only take place during the dry months. In the current water allocation the water level is high during these months, since the water is not used for the production of hydropower in these months. During the dry period, the demand of the agriculture in the downstream subbasins is high. During these months 10% of the water stored in the Qaraoun Lake will flow downstream. The profit will remain more or less constant, however the flow to the hydropower stations will decrease. The amount flowing from the Qaraoun Lake to the downstream subbasins is small compared to the area of the downstream subbasins and therefore the effect will not be significant.

Measures are proposed to see how the water allocation could be optimised. Replacing water sensitive crops by water insensitive crops is the best way to optimise the water allocation within the LRB. There are two reasons why this measure is the most effective one. The first reason has to do with the yield response factor. Water insensitive crops have a lower yield response factor and therefore the decrease in yield will be less significant when a water-deficit occurs. Furthermore, the water insensitive seasonal crops are groundnut and tobacco. These crops are profitable crops and this will positively affect the water allocation within the LRB as well.

The other principles of optimising the water allocation are social equity and sustainability. It is difficult to give a conclusion about the sustainability, since the exact water levels in the Litani are unknown. However, the system is not sustainable when it has to supply water to Beirut. In order to reach this demand, the water of the lake has to be over-exploited. A conclusion can be drawn about the social equity principle, agricultural water is available within the entire LRB and the agricultural profits generated per hectare are equally divided over the area. Since there is enough water available for the inhabitants of the LRB and agricultural water is available over the entire basin, the water allocation is optimal according to the social equity principle. However, when Beirut is included in this social equity principle, the water allocation will be optimal when water is supplied to Beirut as well.

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α	Power of the agricultural sector	-
β	Runoff coefficient	-
η_{irr}	Efficiency of irrigation system	-
γ	Part of Q_{rest} that is used in the agricultural sector	-
λ	Lagrangian multiplier	-
$\mathcal{L}$	Lagrangian expression	-
π_A	Agricultural profit	USD/year
π_H	Hydropower profit	USD/year
θ_{agri}	Profit function of agricultural sector	-
θ_{hydro}	Profit function of hydropower production	-
A	Total area	ha
a_c	Ratio of a subbasin covered by a crop	-
a_{irr}	Ratio of a subbasin equipped for irrigation	-
c	Indication of the crop type	-
c_{hydro}	Conversion rate of water flow to energy produced by hydropower plant	-
ET_a	Actual evapotranspiration	mm/month
ET_{max}	Maximum evapotranspiration	mm/month
ET_m	Modelled evapotranspiration	mm/month
ET_o	Observed evapotranspiration	mm/month
ET_{ref}	Reference evapotranspiration	mm/month
i	Indication of the month	month
j	Indication of the subbasin number	-
k_b	Bare soil evapotranspiration coefficient	-
k_c	Crop coefficient	-
K_{sat}	Saturated hydraulic conductivity	mm/month
k_y	Yield response factor	-
P	Precipitation	mm/month
P_c	Price for a certain crop	USD/tonne
p_c	Soil moisture depletion factor of a crop	-
$P_{domestic}$	Price for domestic water	USD/m^3
P_{hydro}	Price for hydropower	USD/kWh
P_{pc}	Production costs of agricultural products	USD/ha

Q_{agri}	Water used in the agricultural sector	mm/year
$Q_{domestic}$	Water used for domestic water supply	m^3/month
$Q_{hydro,max}$	Maximum flow to the hydropower stations	m^3/month
Q_{hydro}	Water used for hydropower	m^3/month
Q_{irr}	Water used for irrigation	mm/month
Q_{rest}	Undefined component of the water balance	mm/year
RAW	Readily available soil water	mm
S	Storage in a subbasin	mm
S_{FC}	Field capacity	mm
S_{GLUE}	Least absolute error	-
S_{WP}	Wilting point	mm
TAW	Total available soil water	mm
Y_a	Actual yield	tonne
Y_{max}	Maximum yield	tonne/ha/year

Glossary

agent	An individual or group of individuals who are acting in a certain problem. Each agent has its own states and rules of behaviour and therefore will affect the problem in its own way.
basin	An area corresponding to a certain river. In a basin, all the precipitation will accumulate in the same river.
evaporation	The process of transferring water from a liquid state into a gaseous state.
evapotranspiration	The sum of different components of evaporation. The different components of the collective all have a different source of its water: soil, open water, wet surfaces, plants or snow/ice (Lawrence et al., 2007).
Marginal value	The marginal value of water in each sector is the profit that can be generated in the sector by the use of one unit of water. The calculated values are the economic value, when the maximal use is not yet achieved. The social values of the water use are not included.
stakeholder	A person of party with an interest in a certain problem.
subbasin	A part of a basin. In this smaller part, all precipitation will accumulate in a tributary of a river which will flow into the main river.
transpiration	The process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapor and is released to the atmosphere.
water allocation	The deviation of water over the different water-users in the area. This deviation is over time and space.

Acronyms

ABM	Agent Based Modelling.
CPR	Common Pool Resources.
DEM	Digital Elevation Map.
FAO	Food and Agricultural Organisation of the United Nations.
GDP	Gross Domestic Product.
GLDAS	Global Land Data Assimilation Systems.
GLUE	Generalised Likelihood Uncertainty Estimation.
LLB	Lower Litani Basin.
LRA	Litani River Authority.
LRB	Litani River Basin.
MCA	Multi-Criteria Analysis.
MCP	Marginal Cost Pricing.
PCR-GLOBWB	PCRaster Global Water Balance.
RAW	Readily Available soil Water.
SLSQP	Sequential Least SQuares Programming.
TAW	Total Available soil Water.
ULB	Upper Litani Basin.

1

Introduction

'While some believe that Lebanon houses the city where Jesus turned water into wine, most of the country's residents today no doubt wish that the government could miraculously do the opposite.' - Matt Nash, 2014

In 2014, Lebanon reached a new record. The precipitation in the country has never been that low before (Espinoza-Dávalos and Bastiaanssen, 2017). Annual rainfall levels are decreasing, while water consumption is increasing due to economical development, natural population growth and the high inflow of refugees from Syria. In Lebanon, a water crisis is looming. One may speak of a water crisis, when the demand for freshwater exceeds its supply (Saleh, 2014). The looming water crisis is not only caused by the lack of availability of water; lack of a good governance structure and poor resource management are also contributing (IHE Delft, 2017).

For this research project, the basin of the most import river of Lebanon is researched, the Litani River Basin (LRB). This basin drains its water into the Litani river, Lebanon's major source of fresh water. Water of this river is used for irrigation of crop lands, production of hydropower and supply of domestic/industrial water. In general, water used for the production of hydropower is not competing with other sectors. However, in the case of the LRB, a part of the water is pumped into a tunnel (Awali tunnel) and pumped out of the basin (Litani River Authority, 2012a; Rahaman and Varis, 2005; Ramadan, 2012). This water cannot be used anymore in the LRB and so competes with other sectors in the LRB. While the supply of water is decreasing, the demands are increasing. Domestic water supply from the LRB to the capital of Lebanon, Beirut, is proposed and irrigation projects are started in order to increase the yields produced by farmers (Food and Agricultural organization of the United Nations , 2008). Such a complex system requires good management to protect the area from a water crisis. Since the Litani already dries up each year, changes in management are needed. The Litani River Authority (LRA) is responsible for the allocation of water in the LRB.

In this chapter literature related to the research topic is discussed. The literature review leads to a research objective including its relevance and research questions. This chapter concludes with an outline of the rest of the report.

1.1. Literature Review

Each year the Litani river nearly dries up, which is an indication of inefficient water allocation. To protect Lebanon from a water crisis, the water allocation has to be optimised. Based on this statement, the question will arise about what an optimal water allocation is and how this optimal water allocation can be found. In the past, research is executed about optimal water allocation and how to find this optimal water allocation (Dinar et al., 1997; Tandi, nd). In this section, theories and methods defined by others are discussed. The theories and methods are explained, critical notes are defined and it is discussed how they are used in order to find an answer to the research question of this thesis project.

1.1.1. Optimal Water Allocation

Optimisation of water allocation in the LRB is already mentioned several times in this report, but what is an optimal water allocation? Optimisation is about finding an alternative with the highest achievable performance under the given constraints (Dinar et al., 1997). The desired factors have to be maximised, while the undesired aspects have to be minimised. According to Dinar et al. (1997), optimal water allocation maximises the social benefits gained from the deviation of water. The social benefits are described according to the following principles (Dinar et al., 1997):

- **Economic efficiency**
  Economic efficiency is the situation in which it is impossible to generate a larger total welfare from the available resources. In this case, it is about optimal water allocation, so the total profits generated from water should be as high as possible for a country. To achieve this goal, the marginal benefit from the use of water should be equal for agricultural purposes, hydropower production and domestic water supply.
- **Social equity**
  The concept social equity is about fairness regarding to several principles. For example, every individual of a community should have equal access to community resources and opportunities. For this specific case, everyone has to have a fair opportunity to access the water of the Litani. This is not only valid to the different users of water (agricultural, hydropower and domestic water supply), it is also valid to farmers situated upstream and downstream of the Qaraoun Lake.
- **Sustainability**
  According to the dictionary, sustainability is about the fact that goods and services should not be produced in such a way that the resources cannot be replaced and that the environment is damaged. If this is applied to the water allocation problem of the LRB, the environment is also considered to be a user of the Litani. For the sustainability principle, the benefits for humans and the ecological system are taken into account (Tandi, nd).

The first principle of the principles mentioned above, economic efficiency, is the most clear principle of social benefits. However, an important distinction has to be made between profits for the LRB and profits for the entire country. Since there is not enough information available about the water use outside of the LRB, economic efficiency is only about the profits generated from water in the LRB. The other two principles, social equity and sustainability, are less clear and less objective. First of all, what is a fair opportunity in the principle social equity? It might be fair that upstream farmers get more water compared to the downstream farmers, since the precipitation levels are lower in this area. Then the question raises, what should be the difference between upstream farmers and downstream farmers? Also the third principle, sustainability, is uncertain. Are the benefits for the ecological system equal to the benefits for human, or should there be a difference and what should be the difference in that case? The Litani river is an important source for the Gross Domestic Product (GDP) of Lebanon, since 10% of the energy supply in Lebanon is generated by the hydropower stations in the LRB. The profits generated in the agricultural sector are 6% of the total GDP. The economic principle is therefore the most relevant principle of social benefits. Furthermore, it is also the most clear and defined principle and therefore assumed to be the most important principle of social benefits in optimal water allocation. The other two principles, will be discussed but are not taken into account in the model used to find the optimal water allocation.

1.1.2. Common Pool Resources

The water of the Litani river is a Common Pool Resources (CPR), which means that exclusion is difficult and the yield is substractable (Becker and Ostrom, 1995; Ostrom and Gardner, 1993). Water used by one sector cannot be used by another sector, the same holds for the users within a sector. Water used by an upstream farmer cannot be used by a downstream farmer. Both properties, difficulty of exclusion and substractability, have to be applicable for a resource in order to make it a CPR. When a resource is difficult to exclude, but not substractable it is called a public good. If a resource is substractable, but easy to exclude it is called a private good. The two properties can be explained by the following definitions:

- **Difficulty of exclusion**
  It is difficult to limit the use of the source, this can be for several reasons. A reason could be the high costs of parcelling or fencing the resource or the costs of designing and enforcing property rights exclude access to the resource (Ostrom and Gardner, 1993).

- **Subtractability**
  If one takes a certain amount of a particular resource, this amount is not available anymore for somebody else (Ostrom and Gardner, 1993). For example, a fish caught by someone, cannot be caught by anybody else, so the fish is subtractable.

According to Ostrom and Gardner (1993): 'The logic of the individually rational utility seeker may not coincide with the logic of the community.' This makes CPR prone to a "tragedy of the commons", in which the individual and group interest are in conflict (Becker and Ostrom, 1995). This note is important for the optimisation of the water allocation in the LRB. The group interest, the interest of all inhabitants and organisations in the LRB, is to divide the water over time and space in such a way that the profits are maximised. An individual farmer might be aware of this group interest, but his or her interest will be to maximise its own income. This individual farmer might take some extra water, in order to increase its income. This temptation to cheat, is a property of the "tragedy of the commons" (Ostrom and Gardner, 1993; Villamayor-Tomas et al., 2014). Not only farmers are involved in this situation, but also other water using sectors. Most probably, this farmer is not the only one cheating a little bit, his neighbour and the other sectors will do this as well. In that case, there is a risk of having too little available water for the farmers downstream or for the other water demanding sectors. To control this tragedy of the commons, control by an external authority is needed (Ostrom and Gardner, 1993). This external authority should decide on collective actions, be the owner of the CPR and provide technical knowledge. Another imposed solution to regulate CPR, is privatise the common good (Becker and Ostrom, 1995).

This "tragedy of the commons" is important to keep into mind by the optimisation of the water allocation in the LRB. The profits that could be generated in the optimal situation might be unreachable by the fact that people are trying to maximise their own income. This will especially occur when the profits are at a maximum, when water is mainly used in the downstream subbasins. In that case, the risk of cheating by upstream water users will be high and therefore the chance of reaching this turnover will be small. In other words, optimal water allocation is not only about maximising the profits generated from water, but also about decreasing the chance of cheating.

1.1.3. Hydroeconomic Modelling

'Humans have changed the way the world works. Now they have to change the way they think about it, too.' - The Economist, 2011

Scientists, including hydrologists, have ignored the human factor for a long time. In traditional hydrological models, human activities are prescribed as external forcing. A new science is developed in order to get a better understanding of coupled human-water systems: socio-hydrology. According to this science, humans and their actions are part of the water cycle dynamics (Sivapalan et al., 2012). One specific kind of study about coupled human-water systems is hydroeconomics (Pande and Sivapalan, 2016). Hydroeconomics is a tool for discovering new strategies in order to improve the value generated from water. In a hydroeconomic model, the water allocation is driven or evaluated by the economic value it generates (Brouwer and Hofkes, 2008; Harou et al., 2009). As mentioned in Subsection 1.1.1, economic efficiency is the most important principle of water allocation optimisation for the LRB-case. A hydroeconomic model consists of the components of a water balance, water-related infrastructure and its locations and cost/benefits that can be generated (Harou et al., 2009).

In economic models, market prices are used to determine the costs and benefits. However, in most places in the world there is a lack of good functioning water markets and therefore these cannot be used to determine prices. Water valuation is needed in order to determine the economic value of water. Several methods are available to valuate water, for example by the determination of the Lagrangian multiplier. The Lagrangian multiplier uses the components of the water balance and its constraints (Pande et al., 2011).

Hydroeconomic models allocate the water according to the values that can be generated and the hydrological constraints. However, as mentioned in Subsection 1.1.2, individual water users might cheat in order to improve its own income. These individual actions are not taken into account in a hydroeconomic model and therefore the optimal water allocation that is found might be impossible to achieve.

1.2. Objective and Research question

In order to protect Lebanon against a water crisis, the aim of this study is to optimise the water allocation of the LRB. The looming water crisis for Lebanon is not only about the quantity of water, but also about the quality of water. However, water quality is not included in this research project. In order to reach this research objective the following research question has to be answered:

'What is the current water allocation within the Litani River Basin, and which actions could improve this water allocation?'

Hydroeconomic models are already used more often in order to improve the water allocation of an area. However, most of these models are about one specific type of water. For example, optimising the water allocation within the agricultural sector. In this research project, the different water using sectors are combined, taking into account the current power deviation. It might be optimal to flow almost all the water to a certain sector, however a significant change in the water use per sector will receive a lot of political stress. This political stress will reduce the effectiveness of the optimal water allocation. In this model the political power deviation is taken into account. This political power describes the current deviation of water and within this power deviation, the water allocation will be optimised. Applying this value makes the optimal water allocation an achievable allocatin.
Besides this scientific relevance, the project has also a practical relevance. A looming water crisis is not only a problem of Lebanon, but also of other countries in the Middle East and Northern Africa (ANP, 2017; Sustainable Development Department Middle East and North Africa Region, 2010). This makes this research project an interesting project. The knowledge about optimal water allocation gained in this project could be used for other countries in this area as well. Not only the results, but also the modelling principles used to get the results are applicable for other basins. The current situation will be modelled in *Python*. Afterwards, scenarios and potential measures are implemented in order to see the effect on the water allocation. Based on these results, measures could be recommended in order to optimise the water allocation. In order to obtain an answer to the main research question, the following sub-questions will be answered.

1. *What is the current water allocation based on the current water balance? What are the differences between the 'actual' water allocation and the modelled water allocation?*
   The modelled current water allocation is based on the water balance of the years 2010 - 2016 of Lebanon (Espinoza-Dávalos and Bastiaanssen, 2017). Water allocation is about the distribution of water over time and space. Based on the hydrological processes in the LRB and the assumption that all individuals together try to maximise the social benefits gained from the deviation of water, the current water allocation is defined. This modelled water allocation is compared with the 'actual' water allocation based on the data of Espinoza-Dávalos and Bastiaanssen (2017). Differences between the 'actual' water allocation and the modelled water allocation can be caused for two reasons: lack of knowledge about the optimal water allocation or the presence of system boundaries. Comparing the results of both water allocation could help to find a reason for the differences.

2. *What is the effect on the water allocation, if water is also allocated to Beirut?*
   A water supply from the LRB to Beirut is proposed. How will the water allocation change, when less water is available for the agricultural sector and production of hydropower. Is it desirable that water of the Litani river is used in Beirut or not?

3. *What is the effect on the water allocation, if water is allocated from Qaraoun Lake to the downstream subbasins?*
   At the moment, the water from Qaraoun Lake to the downstream basins is negligible and therefore excluded from the current water allocation. However, 'Canal 800' is constructed in order to use water from Qaraoun Lake to irrigate the land in the downstream basins. What will be the effect on the water allocation, when water is supplied to the downstream subbasins?

4. *What measures can be taken in order to optimise water allocation?*
   The scenarios of the previous research questions are applied in the current water allocation, but are there possibilities to improve the water allocation within the area? Measures will be proposed and tested n order to see their effectiveness.

1.3. How to read this document?

A short introduction of the study area is already given in this section, some more information about the study area and the water users is given in Chapter 2. Based on this information and the data, the current water allocation is modelled. The methodology used to answer the research question is described in Chapter 3. The principles of the model of the current water allocation are described in Chapter 4. In Chapter 5, the differences between the actual water allocation and the modelled water allocation are described. Afterwards, two scenarios are applied to this current water allocation in order to see the effect on the water allocation. Firstly, domestic water is also supplied to Beirut. The effect on the water allocation is described in Chapter 6. Secondly, during the dry months water flows from Qaraoun Lake to the downstream subbasins in order to increase the agricultural water availability in the downstream subbasins. These effects on the water allocation are described in Chapter 7. The second part of the research question is about optimising the water allocation by the implementation of measures. In Chapter 8, measures and their effect on the water allocation are described. In the end, the results are discussed in Chapter 9. An answer to the research question and sub-questions will be given in Chapter 10. This chapter also includes the recommendations.

2

The Actual Situation of the Litani River Basin

An improvement of the water allocation is needed in order to prevent Lebanon from a water crisis. In this section, some more details are given about the actual situation regarding to water in Lebanon/Litani River Basin (LRB) and how the water allocation is managed currently. In the last subsection, details are given about the expected changes which influence the likeliness of a water crisis in Lebanon.

2.1. The Litani River

Litani river is the largest river in Lebanon in length (with a reach of 170 km) and width and that is why it is an important water source for the entire country (Litani River Authority, 2017b). The river is entirely located within the borders of Lebanon. Litani river drains water from the central Bekaa Valley, via the south Bekaa Valley, to the Mediterranean Sea (Amery, 1993). So, from the northeast of the country to the southwest. An outline of the Litani river within the LRB is given in Figure 2.1. The Litani river has sixteen tributaries in total. These tributaries are quite small with an average reach of ten kilometres. The river is a rain-fed river, this means that the discharge depends on the rainfall in the LRB. As can be seen in Figure 2.3, the precipitation is decreasing in Lebanon and therefore the discharge in the Litani river will decrease as well. Among other places the discharge is measured in Joub Janine, a city in the Bekaa Valley approximately ten kilometres upstream of the artificial Qaraoun Lake. The discharge and rainfall of 2010 at this place are given in Figure 2.4. The average yearly discharge over the last ten years measured at this location is 268 million $m^3/year$ (International Resources Group, 2011). Since most of the rainfall occurs in winter (December - May), the discharge of the river is much higher in these months compared to the summer months June, July, August and September. During these summer months the rainfall is close to zero, while the water demand for agricultural purposes will be high in the dry months.

The area which drains its water into the Litani river is called the Litani River Basin (LRB) and has a total surface area of approximately 2150 km^2. Since the construction of the largest artificial lake of Lebanon, the Qaraoun Lake, in the 1960s, the basin can be subdivided into two parts: Upper Litani Basin (ULB) and Lower Litani Basin (LLB). The ULB is the area upstream of Qaraoun Lake, the area downstream of the lake is called the LLB. With a surface area of 1500 km^2, the ULB is the largest of the two subbasins in which most of human activities are concentrated (Litani River Authority, 2011). A zoomed figure of the LRB is given in Figure 2.2, in which the Qaraoun Lake with its dam, El Wauroun Dam, is given.

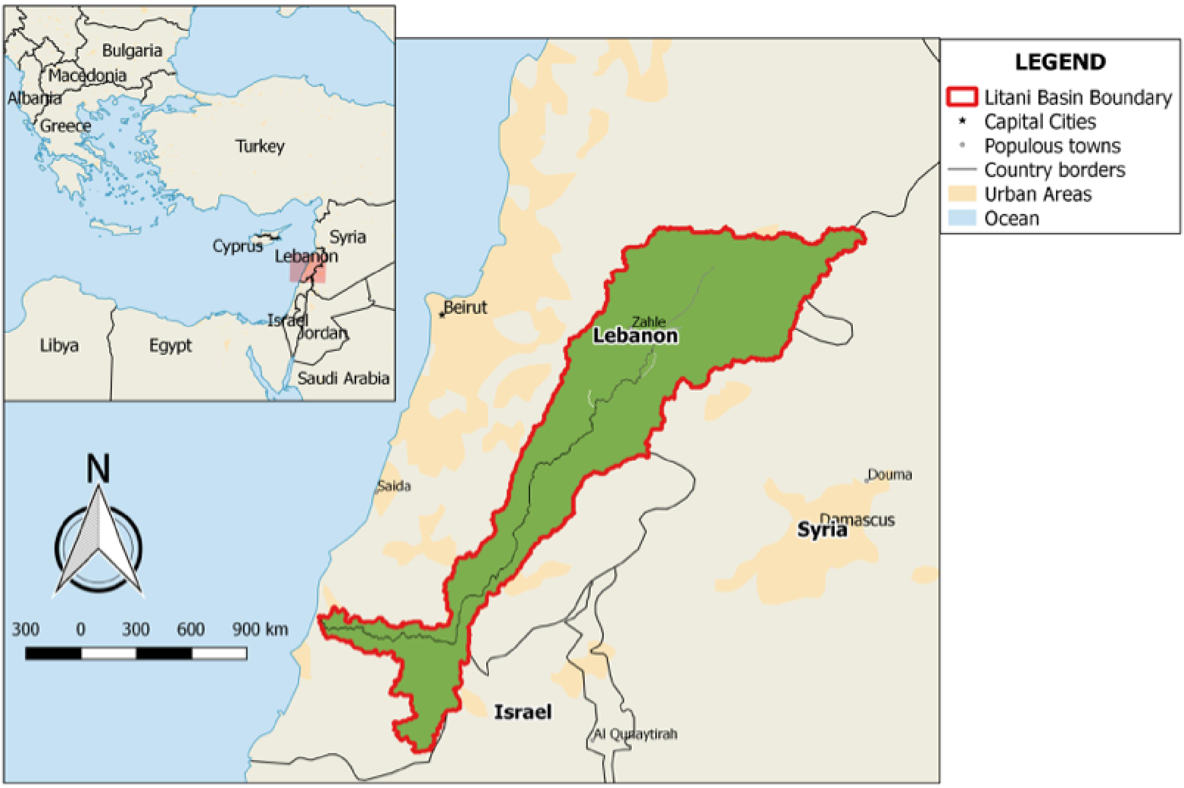


Figure 2.1: The topography of the Litani River Basin, which is located within Lebanon, Middle East. The Litani drains into the Mediterranean See, in the south of Lebanon.

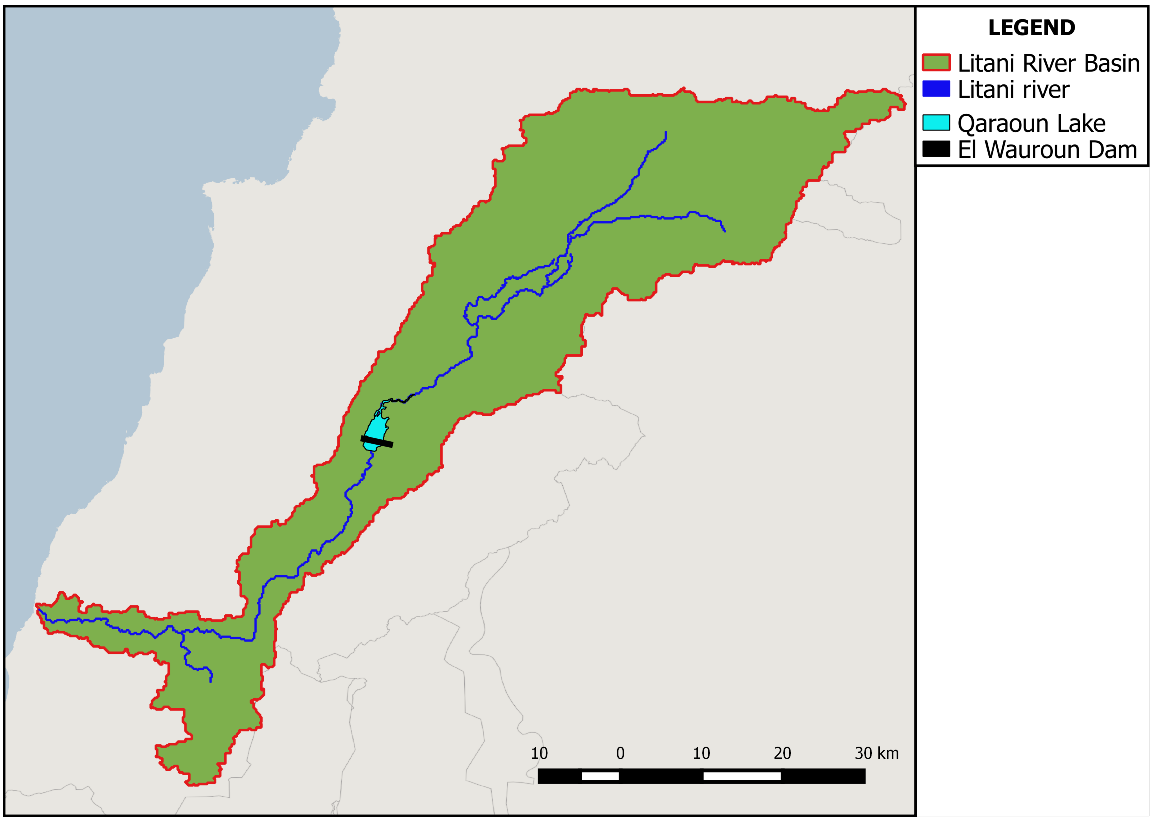


Figure 2.2: A more detailed overview of the Litani River Basin, in which the Qaraoun Lake and El Wauroun Dam are indicated. The lake is the boundary between the ULB and LLB.

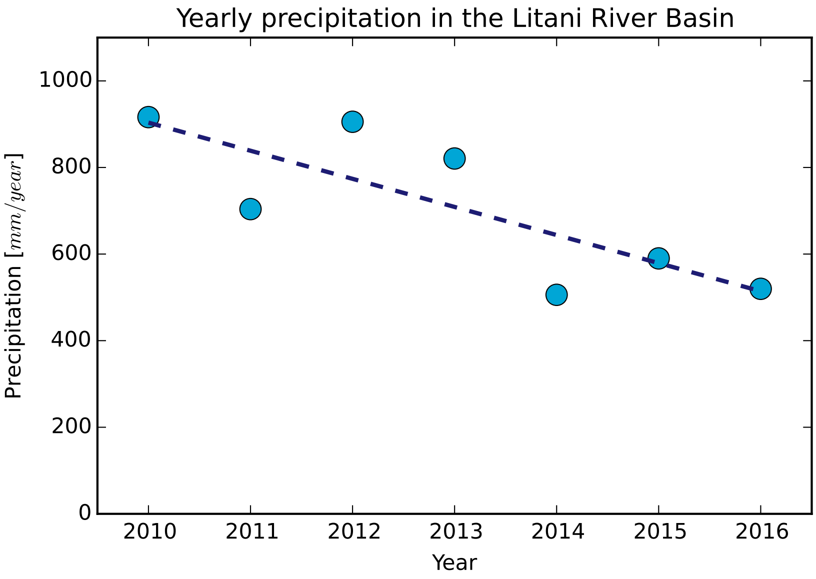


Figure 2.3: The average yearly precipitation over the entire LRB for the years 2010-2016. The precipitation is based on the data of Espinoza-Dávalos and Bastiaanssen (2017). As can be seen, the lowest value of precipitation is achieved in 2014. A decrease in precipitation is shown by the trend line. However, to litlle years are included to give an actual trend, but it gives an idea.

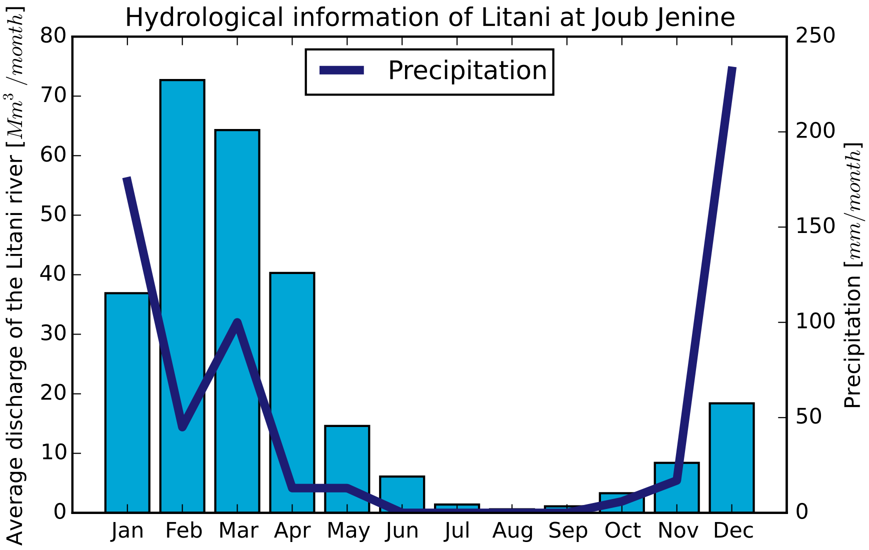


Figure 2.4: Discharge and precipitation measured at Joub Janine in 2010 (International Resources Group, 2011). During the summer season, the precipitation levels are low and therefore the discharge levels as well.

Water of the Litani river is used for several purposes: irrigation of crops, the production of hydropower and supply of domestic water. A significant user of the water in the LRB is the agricultural sector. The agricultural water use consists of two parts. In the first place, the roots of the crops take the water they need from the groundwater. In order to increase the produced yields, farmers will apply extra water, irrigation. Irrigation is the addition of controlled amounts of water to plants in order to increase the yields of a farmer. If the amount of available groundwater is limited, farmers will irrigate their crops. Approximately 51% of the agricultural area in the LRB is equipped for irrigation (FAO and Aquastat, 2017). Irrigation is mainly needed during the dry season, when the groundwater table is lowering due to the fact that water is used while the supply is small. Since the 1960s, water of the Litani river is also used for the production of hydropower. Water is stored in Qaraoun Lake. The El Wauroun Dam is constructed in the middle of the lake in order to produce hydropower in three power stations: Markaba, Awai and Joon (Litani River Authority, 2017c). In general, water used for the production of hydropower can be used for other purposes afterwards. This is caused by the fact that water is not converted to energy, but the energy of falling water is used to generate energy. A part of the water is used for the supply of domestic water. This is about 25 million m^3/year, in order to supply domestic water to the 375,000 inhabitants of the LRB. The rest of the water is pumped out of the basin and therefore cannot be used for any purpose in the LRB. An overview of the average amounts of water used by the several sectors is given in Table 2.1.

Table 2.1: The water demands of the LRB per sector. A part of the water used for the production of hydropower is used for domestic and industrial water supply in the LRB. Therefore, this amount is not needed to add in the total sum of water demands of the LRB.

Sector of water demand	**Average water demand**	**Percentage of total water demand**
Irrigation	284 million $m^3/year$	51%
Hydropower production	275 million $m^3/year$	49%
Domestic/Industrial water supply	25 million $m^3/year$	9% of water used for hydropower production
Total	*559 million* $m^3/year$	*100%*

2.2. Litani River Authority

In 1954, the LRA was established in order to manage the water allocation to the different stakeholders which are mentioned in Section 2.1. The LRA is a public institution, with administrative and financial autonomy. The main task of the authority is to initiate irrigation, drinking water and electricity projects. Their other tasks are to establish a transport network between power stations and the users of power and to invest in technical and administrative projects according to water allocation in the LRB. Since 1996, the LRA has been given some extra tasks (Litani River Authority (2017a)):

- Responsibility for the planning and structure of new irrigation schemes.
- Monitoring the surface flow across the entire country.
- Monitoring the water quality in the LRB.

Based on the aim of the LRA to manage the water allocation, it can be argued that the LRA is responsible for the operations of the three categories of water users of the LRB. This task is a growing challenge since it is expected that the water supply is decreasing while the water demands are increasing. An improved water allocation is needed in order to prevent a water crisis from occurring. One measure in order to improve the water allocation is already taken by the LRA. During the summer months, when the demands of the agricultural sector are high, there is no hydropower produced. Even after the implementation of this measure, the river dries out during summer.

In other words, the LRA is responsible for the water governance. Water governance is ”the practice of coordination and decision making between different actors around contested water distributions” (Zwarteveen, 2017). There are three streams which are important in water governance (Rogers and Hall, 2003): Distribution of water(rights), voice, authority and knowledge. There is not a single way for the LRA to achieve effective water governance. However, several approaches will help to improve the effectiveness (Rogers and Hall, 2003):

- **Open and transparent**
  Everyone should understand what is going on and everyone should get access to information used to make decisions.
- **Inclusive and communicative**
  Actors should be involved in the process of decision-making.
- **Coherent and integrative**
  Policies and its actions must be coherent.
- **Equitable and ethical**
  The advantages and disadvantages should be equally divided between and among the various interest groups.

By taking future decisions about improving the water allocation, the LRA has to take into account these approaches in order to succeed.

2.3. Expected Changes of Water Demands

The Litani river nearly dries up each year and expected changes in the water availability will increase the pressure on the water source. The problem of the looming water crisis in Lebanon has two sides: a growing demand and a decreasing supply. Decreasing water supply is caused by climate change. An effect of the changing climate is a decrease in precipitation. Since the river is a rain-fed river, the flow of the river will decrease. The increasing water demands are more complex, since there are several factors influencing water demands. The changes that might occur and so increase the water demand will be discussed in the next paragraphs. A summary of the factors increasing the water demand and its amounts are given in Table 2.2. The increased demand of water of the Litani influences the need of an improved water allocation in the LRB.

2.3.1. Domestic Water Supply to Beirut

Managing Beirut's water supply has always been a challenge, but since there are more than a million Syrian refugees in Lebanon, this has become even more challenging. Several options will be considered in order to solve this problem, for example the usage of new technologies, a decrease of the leakage of water or the usage of new supply areas. One of the proposed new supply areas is the LRB. The extra water demand will be about 93 million $m^3/year$. Since the water is not used for the hydropower generation, but only pumped out of the basin, this water can potentially be used for the supply of domestic water to Beirut.

2.3.2. Irrigation Canals: Canal 800 and Canal 900

Irrigation is needed in times when the groundwater availability is limited in order to increase the yields of a field and so its profits. 'Canal 800' and 'Canal 900' are two projects to increase the irrigation potential of Lebanon. Both canals are man-made channels diverted from the Litani river downstream of the El Wauroun dam. 'Canal 800' has to irrigate 15,000 ha in the LLB, for which an amount of 20 million $m^3/year$ is needed. 'Canal 900' has to irrigate an area of 19,000 ha upstream of the Qaraoun lake (ULB) during the dry months. The demand for this area will be around 30 million $m^3/year$.

Table 2.2: Overview of the potential water demand increases of the LRB

Initiative	**Average water demand**	**Percentage of current water demand**
Water supply to Beirut	93 million $m^3/year$	16.6%
Canal 800	20 million $m^3/year$	3.6%
Canal 900	30 million $m^3/year$	5.4%
Maximum increase	*143 million* $m^3/year$	*25.6%*

3

Methodology of Optimising the Water Allocation of the Litani River Basin

The aim of this study is to optimise the water allocation of the LRB. The method used in order to optimise this water allocation is described in this chapter. Besides the method, the used data sets and program is described.

3.1. Method

In order to answer the research question, a model is used. The method consists of three important steps which are represented in Figure 3.1 and shortly described in this section. In order to optimise the current water allocation, first the current water allocation has to be defined. This current water allocation is based on data of Espinoza-Dávalos and Bastiaanssen (2017) and literature findings. The modelled water allocation will be compared with the model of Espinoza-Dávalos and Bastiaanssen (2017), which is defined as the actual water allocation. Afterwards, scenarios will be applied in order to see the effect on the current water allocation. In the first scenario water will be supplied to Beirut and in the second one, water from the Qaraoun Lake is supplied to the downstream basins. In the last phase, measures are implemented in order to see the effect on the water allocation. Based on the implementation of these measures, the LRA can be advised about the optimisation of the water allocation in the LRB.

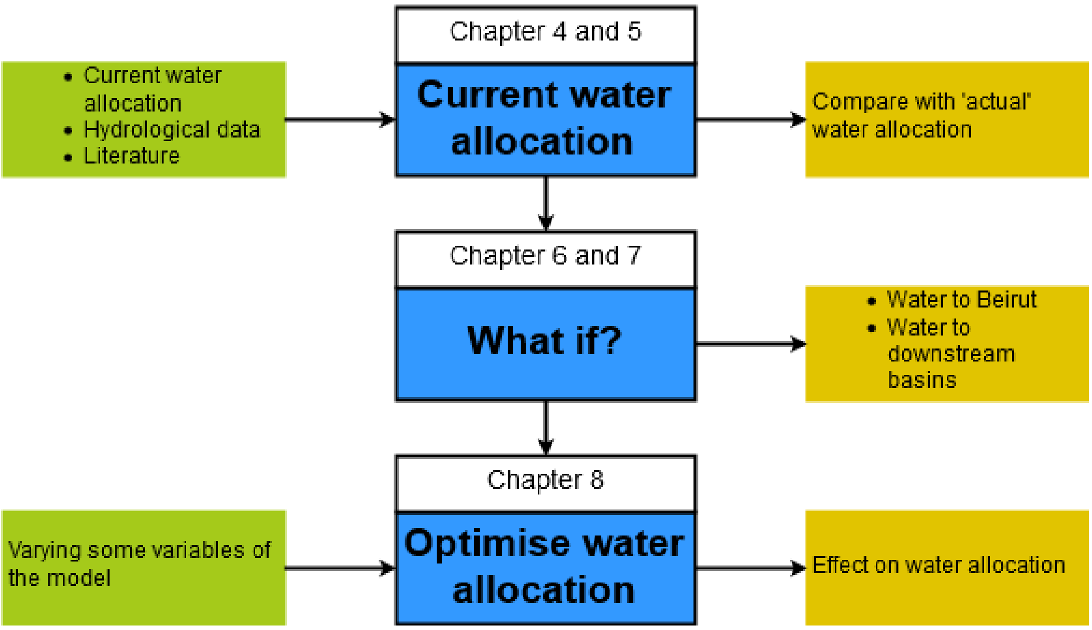


Figure 3.1: The structure of the methodology used in order to find an answer to the research question.

3.2. Data sets

Several data sets are used to develop the model and so the optimisation of the water allocation in Lebanon. The used data sets are listed in Table 3.1. The hydrological data sets have a monthly time step. The Digital Elevation Map (DEM) and land-use data set are derived at one moment.

Table 3.1: Overview of the used data sets, their source, year of data and resolution.

Data sets	**Source**	**Year**	**Spatial resolution**
DEM spatial	GMTED2010 (Danielson and Gesch, 2011)	2010	0.002 °
Precipitation	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010-2016	0.011 °
Evapotranspiration	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010-2016	0.011°
Reference evapotranspiration	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010-2016	0.011°
Soil water index - First day of month	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010	0.011°
Soil water index - Last day of month	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2016	0.011 °
Soil water index - Monthly mean	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010-2016	0.011 °
Root depth	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2016	0.002 °
Runoff coefficients	IHE (Espinoza-Dávalos and Bastiaanssen, 2017)	2010-2016	0.011 °
Soil field capacity	IGBP-DIS (Global Soil Data Task, 2000)	2013	0.083 °
Land-use	CNRS (National Council for Scientific Research, 2017)	2017	not applicable
Soil map	FAO (FAO, 2007)	2007	not applicable

3.3. Sequential Least SQuares Programming

Python is used to find the current water allocation and to optimise the water allocation. Within *Python* several libraries are available to solve problems. This problem is solved by using the *SciPy.optimize* library. This library consist of multiple optimization algorithms (Jones et al., 01), useful to solve an optimisation problem. The Sequential Least SQuares Programming (SLSQP) algorithm is used. This algorithm is the only one within the library that is able to deal with equality and in-equality constraints at the same time (Antoniou and Lu, 2007). A constraint is a boundary to the solution of the model. Not each combination of values is a potential outcome to the model and therefore constraints are added in order to make it a realistic model. The constraints applying to this situation are described in Section 4.4 and Section 4.5. In an equality constraint, a function is equal to a certain value and for an inequality constraint a function is smaller or larger than a certain value (Antoniou and Lu, 2007). SLSQP is only able to deal with inequality constraints in which a formula is larger than a certain value. If the formula is smaller than a certain value, the constraint has to be multiplied by -1.

In the *SciPy.optimize* library an objective function is minimized. This means that the variables are chosen in such a way that the value of the objective function is as low as possible. However, maximisation of an objective function is also possible within the library. Therefore, the objective function and its outcome has to be multiplied with -1.

3.4. Subdivision into Subbasins

In order to increase the detail of the model, the LRB is subdivided into 60 subbasins. The hydrological conditions are varying over the LRB. For example, the precipitation levels are higher in the north of the LRB and citrus crops are only cultivated in the south (Espinoza-Dávalos and Bastiaanssen, 2017). In order to take these differences into account, a distributed model is used. A disadvantage of using a distributed model is the risk of equifinality, which means that their might be more combinations of variables that lead to an acceptable result (Hrachowitz, 2017). In such a situation, a set of results might be accepted as being 'true', while it is not. One of the advantages of using a distributed model is about the conclusions. Regional conclusions can be drawn and regional advice can be given (Hrachowitz, 2017). A measure that would work in a dry area, might potentially not work in a wet area.

The LRB is subdivided into 60 subbasins. This subdivision is based on flow accumulation, which is achieved by using a DEM (Danielson and Gesch, 2011). Water will always flow the lowest point, so for each grid cell it is determined in which direction water will flow. The subbasins of Figure 3.2 are based on a flow accumulation of 1000 grids. Where water of 1000 grids is accumulated is assumed to be part of the river. The area which accumulate in this point, forms a subbasin. Each subbasin is like an agent, it has its own states and rules of behaviour. These rules of behaviour are described in Section 4.4. A subbasin is represented by a conceptual storage reservoir, which is filled by its inflows and emptied by its outflows. The main components which are influencing the storage volume in a subbasin are described in Figure 3.3. The inflows of a subbasin are precipitation and runoff from upstream subbasin(s). Evaporation and runoff to a downstream subbasin are emptying the storage reservoir. Besides these natural processes, the storage reservoir is emptied by human processes. Humans take water out to use it for the production of hydropower or to increase the produced yields by using water for irrigation.

Figure 3.2: The LRB delineated in 60 subbasins and its water streams.

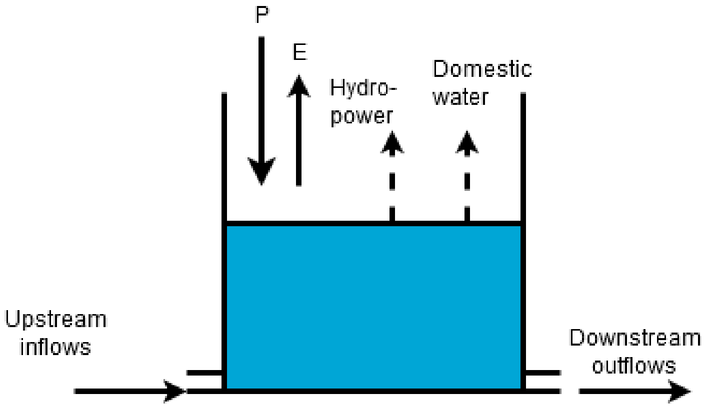


Figure 3.3: Overview of the hydrological processes occurring in the LRB. The bucket is a representation of a subbasins which is filled by the runoff of upstream subbasins and precipitation and emptied by human processes, soil evaporation and runoff to downstream subbasins. The P in the figure represent precipitation and E evapotranspiration.

4

Model of Current Situation

The aim of this study is to optimise the water allocation of the LRB. Optimal water allocation is about maximising the social benefits gained from the deviation of water. These social benefits are described by three principles (Dinar et al., 1997). Since the Litani river is an important river for the Lebanese economy, the economic efficiency principle is assumed to be the most important principle of social benefits. Therefore the water allocation of the LRB will be improved based on increased values gained from the deviation of water. In a hydroeconomic model, a hydrological model is combined with the costs and benefits that can be generated (Harou et al., 2009). The water allocation will be optimised, using a hydroeconomic model. A model of the current situation is needed in order to optimise this water allocation. The model of the current situation is described in this chapter. Changes will be applied to this model in order to optimise the water allocation. Those changes will be described in Chapter 6, Chapter 7 and Chapter 8.

4.1. Hydroeconomic Model

A hydroeconomic model consists of the components of a water balance, water-related infrastructure and its locations and the costs/benefits that can be generated (Harou et al., 2009). The goal of the model is to maximise the profits generated from the deviation of water. The profit that can be generated within the basin is limited by the water balance and the structure of the water-related infrastructure. The main characteristics of the structure of the water-related infrastructure will be described in the next paragraph. Afterwards the potential profit function will be described.

The water of the Litani river is used within three sectors: agriculture, hydropower production and domestic supply. Crops are growing in the subbasins of which the outline can be find in Section 3.4. Which types of crops are growing and how these crops are divided over the area is described in Section 4.6. It is relevant to distinguish different crop types, since the profits that can be generated and the water that is needed differ per crop type. An artificial lake, Qaraoun Lake, is located within the LRB. The water of this lake is used for the production of hydropower. When water is used for the production of hydropower, it can be used for other purposes afterwards. A part of the water, currently 25 million m^3/year (Litani River Authority, 2017c), will be used for the supply of domestic water. Where the other part of the water is used for is unknown.

The water of the LRB will not directly be sold. Water is used in the agricultural sector in order to increase the yields. These yields are sold and so agricultural profits are generated. When water is used to produce hydropower, the power will be sold to the households in order to generate profits and the same holds for the domestic water. The objective of the hydroeconomic model is to maximise the profits generated within the LRB. This objective function can be described as followed:

$$\begin{aligned} \underset{S,Q_{irr},Q_{hydro},Q_{domestic}}{\text{maximise}} \quad & \textbf{profit} \\ \text{subject to} \quad & \textit{hydrological constraints} \end{aligned} \tag{4.1}$$

in which:

$$\text{profit} = \alpha \sum_{j=1}^{60} (P_{c,i} Ya(t)_{c,i}) + (1-\alpha) \sum_{t=1}^{84} (c_{hydro} Q_{hydro} P_{hydro}) + \sum_{t=1}^{84} Q_{domestic} P_{domestic}$$

$$Ya(t)_{c,i} = (-k_{y,c} Y_{max,c} (1 - \frac{\sum_{t=1}^{84} ET_a}{\sum_{t=1}^{84} ET_{max,c}}) + Y_{max,c}) A^j a_c^j \tag{4.2}$$

S	=	Storage in a subbasin	[mm]
Q_{irr}	=	Water used for irrigation	[mm/month]
Q_{hydro}	=	Water used for hydropower	[m^3/month]
$Q_{domestic}$	=	Water used for domestic water supply	[m^3/month]
α	=	Power of the agricultural sector	[-]
P_c	=	Price for a certain crop	[USD/tonne]
Y_a	=	Actual yield	[tonne]
c_{hydro}	=	Conversion rate m^3 to kWh (Appendix A)	[-]
P_{hydro}	=	Price for hydropower (Appendix A)	[USD/kWh]
$P_{domestic}$	=	Price for domestic water (Appendix A)	[USD/m^3]
$k_{y,c}$	=	Yield response factor (Appendix A)	[-]
$Y_{max,c}$	=	Maximum yield of a certain crop (Appendix A)	[tonne/ha]
ET_a	=	Actual evapotranspiration	[mm/month]
$ET_{max,c}$	=	Maximum evapotranspiration of a certain crop (Appendix A)	[mm/month]
A	=	Total area	[ha]
a_c	=	Ratio of a subbasin covered by a crop	[-]
i	=	Month	[$month$]
j	=	Subbasin number	[$-$]
c	=	Crop type	[$-$]

The profit generated in the agricultural sector depends on the yield per crop type that is cultivated. The yield function is based on Doorenbos and Kassam (1979). Each crop type has its own yield response factor and maximum yield. The characteristics are described in Appendix A. In the hydropower sector the flow through the hydropower stations will be converted to power and this power will be sold to households. The conversion from a flow to power and the prices that will be paid by the households are also described in Appendix A. Just like the price that is paid by households for receiving domestic water. The objective function is limited by the hydrological constraints, which are described in Section 4.4 and Section 4.5.

In the first place, the hydroeconomic model is used to model the current water allocation. Therefore the current deviation of water has to be included. α is added to the objective function to represent the current deviation. Characteristics and the determination of α are described in Section 4.3. The objective function Equation 4.1 in combination with α is used to model the current water allocation. This is based on the assumption that everyone in the current water allocation tries to maximise its income and therefore the current water allocation maximises the total income of the LRB, limited by the hydrological conditions.

The model consists of 60 subbasins and monthly data is available of seven years (2010 - 2016). Each year consists of twelve months and therefore 84 months of data for each subbasin is available. This is why the profits are summed from t=1 to t=84.

4.2. Water Valuation

In order to maximise the profits generated from the deviation of water in the LRB, it is interesting to know how valuable the water is. The value of water can be determined by using marginal values. A marginal value is the profit that can be generated with one unit of water. Water has not only an economic value, but also a social value (Harou et al., 2009; Tilmant et al., 2008; Young, 2010). Water used for the first life needs is much more valuable compared to the water used for luxury purposes. In this section the value of water used for agricultural purposes is determined and the value of water used for the production of hydropower and afterwards for the supply of domestic water. The values of water are important to know in an economic optimisation of the water allocation, since water has to be reallocated to a higher-valued use in order to increase the profits from the deviation of water. Since there is a lack of good functioning water markets, other methods are used to valuate water, for example with the use of Lagrangian multiplier (Pande et al., 2011).

4.2.1. Agricultural Water Valuation

The agricultural water valuation is determined by the use of the Lagrangian multiplier. This Lagragian multiplier represents the economic value of water, but the social value is not included (Griffin and Hsu, 1993). More research is needed in order to include this social value. The Lagrangian multiplier of agricultural water within the LRB represents the amount of profit that can be generated within each subbasin, when a subbasin gets one unit of water. Since the areas of the subbasins differ, the profits are divided by the area in order to get the value per hectare. The Lagrangian multiplier is determined by using the following set of equations (KhanAcademy):

$$\mathcal{L}(ET_a, \lambda) = f(ET_a) + \lambda(g(ET_a) - P_{pc}) \tag{4.3}$$

$\mathcal{L}$ = Lagrangian expression [-]
f = Profit function [USD/year]
g = Hydrological constraints Section 4.4 [-]
λ = Lagrangian multiplier [-]
P_{pc} = Production costs of agricultural products Appendix B [USD/year]

$$\begin{aligned} f(ET_a) &= (a^j_{irr} Y_{max,c} - ((1 - a^j_{irr})(k_{y,c} Y_{max,c}(1 - \frac{\sum_{i=1}^{84} ET^j_{a,i}}{ET_{max,c}} + Y_{max,c}) A^j a^j_c \\ g(ET_a) &= \sum_{i=1}^{12} S^j_i + ET^j_{a,j} + \frac{1}{\eta_{irr}} a^j_{irr} + ET_{max,c} - P^j_i + ((1 - a^j_c) ET^j_{ref,i} k_b) \\ \lambda &= \frac{\sum_c -(1 - a^j_{irr}) k_{y,c} Ymax,c(1 - \frac{a^j_c}{ETmax,c}) + Ymax,cA^j a^j_c - P_{pc,c} A^j a^j_c}{A^j} \end{aligned} \tag{4.4}$$

a_{irr} = Ratio of a subbasin equipped for irrigation [-]
η_{irr} = Efficiency of irrigation system [-]
ET_{ref} = Reference evapotranspiration [mm/month]
k_b = Bare soil evapotranspiration coefficient [-]

The profits in the agricultural sector are generated by selling the cultivated crops. Therefore the value of water in the agricultural sector depends on the amount of crops growing in a subbasin and the type of crops. One crop might be more valuable than another and therefore influences the value of the Lagrangian multiplier.

The Lagrangian multiplier is determined per subbasin, the results in percentages are represented in Figure 4.1. The dark-red subbasins have the highest marginal value. If one unit of water will flow to these subbasins, the highest profit can be generated, up to 140,000 USD/ha. The white subbasins have the lowest marginal value per unit of area, around 450 USD/ha. It seems that their are less 'white' subbasins compared to the 'dark-red' subbasins, however the number of basins is the same. The subbasins with a low marginal value per unit of area turned out to be the small subbasins. In order to improve the water allocation, a high percentage of water has to flow to the dark-red subbasins, while less water should to the 'white' subbasins. As can be seen in the figure, the dark-red subbasins are divided over the entire LRB. This means that it is important that water is flowing through the entire LRB and therefore good management is needed.

The marginal value in this project is defined as the money that can be generated by selling the products produced with the water. In this case, the money is earned by selling the purchased crops. Furthermore, this marginal value is only valid until the maximum water demand is achieved. If the maximum water demand is achieved, the value of water in the sector will decrease or be equal to zero. The high marginal values in the agricultural sector are mainly caused by the profitable crops: olives, tobacco and groundnuts. The selling prices of these products are high, while the crop are water-insensitive as well. Therefore, the drop in yield will be limited when there is a water deficit.

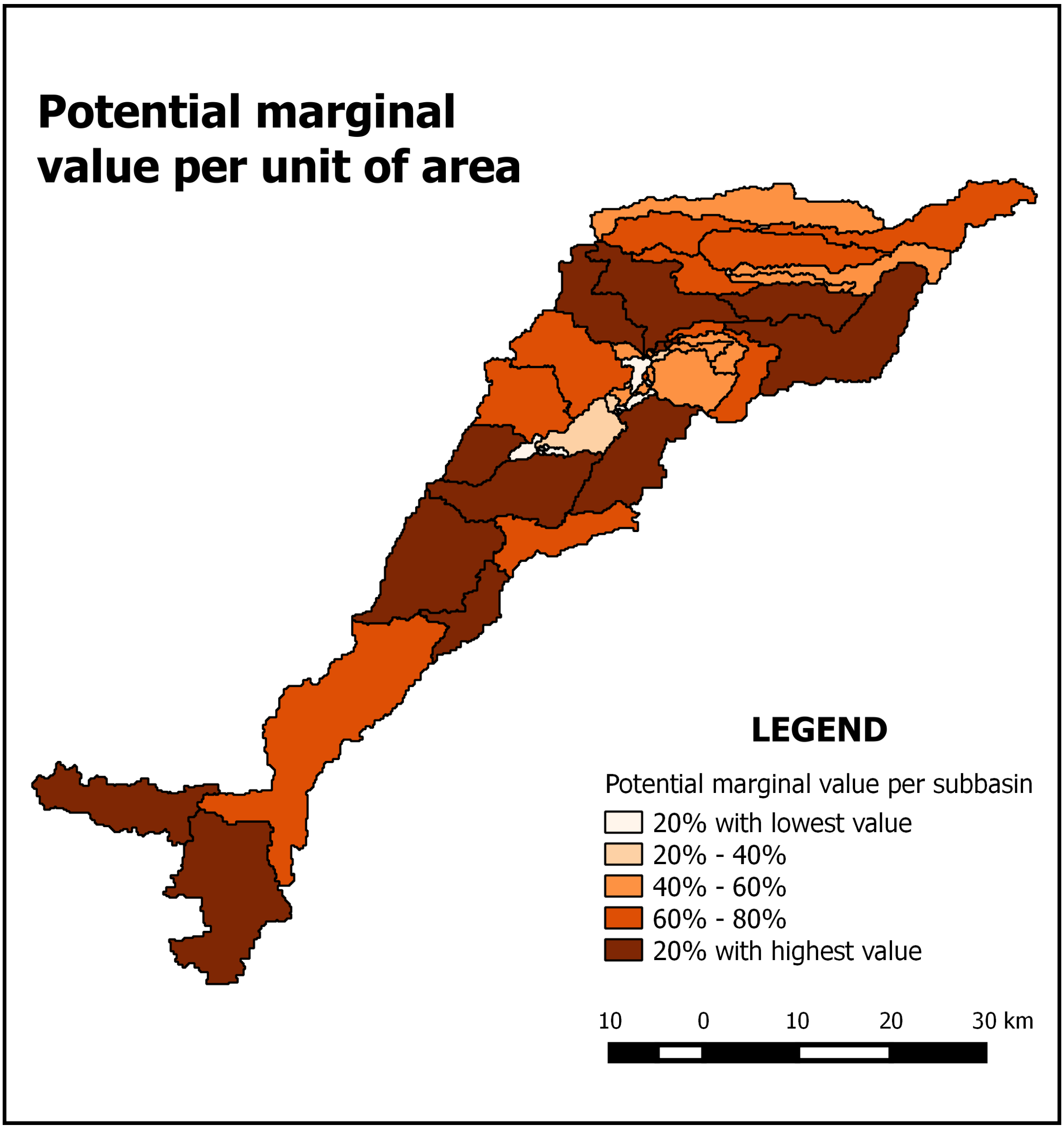


Figure 4.1: The marginal value per hectare of agricultural water in each subbassin of the LRA. These values are determined by using the Lagrangian multiplier, land use data (CNRS) and prices of seeds and trees (see Appendix B). The dark-red coloured subbasins can generate a higher profit by getting one unit of water compared to the light-red subbasins. The legend is divided into five equal parts, each with representation of 20% of the data points.

4.2.2. Water Valuation of Water used for Hydropower Production and Domestic Supply

The determination of the economic value of the water used for hydropower production and domestic supply is easier to determine. In order to determine the economic value, the marginal value is calculated. For these sectors, there is no information found about the production cost and so only the turnovers are taken into account. This makes it more difficult to compare it with the water valuation of the agricultural sector. However it gives an indication of the values.

In order to determine the water values, the profits functions as described in Appendix A have to be used. Marginal values are the values that are achieved when one extra unit of water is applied to an area. Based on this profit function the value of water within the domestic water sector is 0.2 USD/m^3 (FAO and Aquastat, 2017) and the value of water within the hydropower production sector is 566.3 USD/m^3 (Lebanon Electricity Tariffs, 2017). The value that can be created with one unit of water in the hydropower production sector is comparable with the agricultural water value. However, costs are included within the agricultural water value and not in the hydropower water value. Therefore, it can be argued that the valuation of water is lower for water used for the production of hydropower and especially the water used for the supply of domestic water.

At the moment, only economical values of water are compared with each other. The values might change when all social benefits are taken into account. For example, supply of domestic water is a first life need and therefore the social value might be high. This might compensate the low economical value. However, extra research has to be done in order to determine this value.

4.3. Determination of Power of involved Sectors

As described in Section 4.2, the economic value of water in the agricultural sector is much higher compared to the value of water in the hydropower and domestic sector. If the water allocation of the LRB is optimised, the water will flow to the agricultural sector until the maximum yields are achieved. However, in order to optimise the current water allocation, firstly the current water allocation has to be modelled. Therefore an extra variable is added to the the profit function, α. This value represents the current power of the agricultural sector. Since the water in the LRB can be used by either the agricultural sector or the hydropower sector, the power of the hydropower sector will be 1-α. The value of α is based on the current distribution of water, therefore the following equation is used:

$$\begin{gathered} \alpha\pi_A(Q_{agri}) + (1-\alpha)\pi_H(Q_{hydro}) \\ Q_{agri} = \gamma Q_{rest} \\ Q_{hydro} = (1-\gamma)Q_{rest} \end{gathered} \tag{4.5}$$

π_A	=	Agricultural profit	[USD/year]
π_H	=	Hydropower profit	[USD/year]
Q_{rest}	=	Undefined component of the water balance	[mm/year]
Q_{agri}	=	Water used in the agricultural sector	[mm/year]
γ	=	Part of Q_{rest} that is used in the agricultural sector	[-]

The Generalised Likelihood Uncertainty Estimation (GLUE)-method is used in order to determine the value of γ. The GLUE methodology makes use of a random parameter generation. These parameters will be between 0 and 1, since the water used in the agricultural sector can be either small, or large an so close to the rest flow. Based on the current water balance of the LRB and a random parameter, a value of ET_m is determined. Q_{agri} is represented by a part of the ET_m and therefore used. The different values for γ will give different values for ET_m.

The values for γ will be tested by using a likelihood measure. Different likelihood measures are available, for example: Nash-Sutcliffe Efficiency, coefficient of determination, index of agreement and modified forms of these (Krause et al., 2005). The likelihood measure least absolute error (S) is used for the determination of γ. This method tries to find the parameters in which the model is the closest to the set of measured data. The equation corresponding to the absolute error likelihood measure is as followed:

$$S_{GLUE} = \sum_{i=1}^{n} |ET_o - ET_m| \tag{4.6}$$

S_{GLUE}	= Least absolute error	[-]
ET_o	= Observed evapotranspiration	[mm/month]
ET_m	= Modelled evapotranspiration	[mm/month]

100,000 values are tested for γ. The parameter which has the lowest value for S is the best guess of the part of the rest flow that will be used in the agricultural sector and therefore the γ-value that will be used to determine the power of each sector in the LRB. The γ-value with the lowest value for S is the best guess, since the difference between the observed and modelled evapotranspiration is the smallest in that case. The results are given in Figure 4.2. Based on these results, the value of γ is estimated to be 0.175 which has a S-value of 0.034 $mm/year$, and an error of 0.09%.

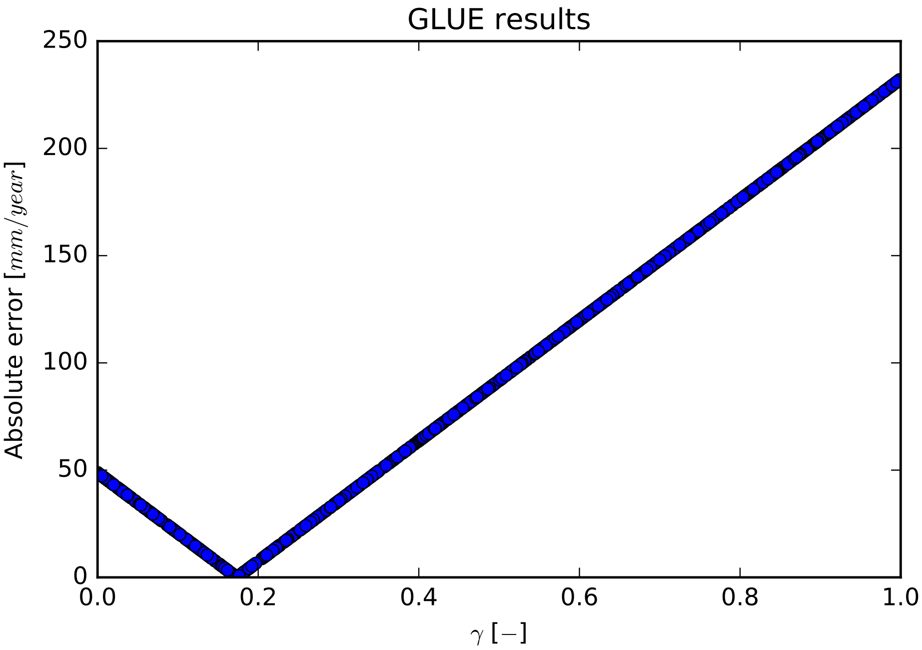


Figure 4.2: The results of the GLUE-method, the values of γ and its corresponding absolute error.

Example 4.1: Generalised Likelihood Uncertainty Estimation

The value for γ is determined based on the water uses in the basin. In order to reduce the run time of the model, the water balance of the entire LRB is used in order to determine γ. Precipitation, domestic water supply, change in storage and observed evapotranspiration are known. The water balance will be:

$$\frac{\Delta S}{\Delta T} + P - Q_{domestic} = Q_{hydro} + Q_{agri} \tag{4.7}$$

Q_{agri}will be equal to a certain part of the "rest" flow, this part is γ. This is described by the following equation:

$$\frac{\Delta S}{\Delta T} + P - Q_{domestic} = \gamma Q_{rest} + (1-\gamma)Q_{rest} \tag{4.8}$$

Different values of γ are used in order to determine the value of Q_{agri}, the value with the smallest error between Q_{agri} and the observed evapotranspiration is the power of the agricultural sector.

The generated profit in a sector depends on the amount of water is flowing to the sector. The more water flowing to a sector, the higher the generated profit can be. The value of α will be determined based on observed profits. Combining Equation 4.9 and Equation 4.10 will result in a value for α which represents the power of the agricultural sector in the current water allocation in the LRB.

$$\begin{aligned} \pi_A^o &= \alpha \theta_{agri} \gamma Q_{rest} \\ \alpha\gamma &= \frac{\pi_A^o}{\theta_{agri} Q_{rest}} \end{aligned} \tag{4.9}$$

$$\begin{aligned} \pi_H^o &= (1-\alpha)\theta_{hydro}(1-\gamma)Q_{rest} \\ (1-\alpha)(1-\gamma) &= \frac{\pi_H^o}{\theta_{hydro} Q_{rest}} \end{aligned} \tag{4.10}$$

θ_{agri} = Profit function of agricultural sector [-]
θ_{hydro} = Profit function of hydropower production [-]

θ_{hydro} is described in Appendix A. The profits generated in the agricultural sector depends on the crop factors which are also described in Appendix A. At the moment, yearly an amount of 275 million m^3 of water is used for the production of hydropower (Table 2.1) (Litani River Authority, 2017c). The profit that will be generated with this amount of water is the observed profit in the hydropower production and therefore will be used in Equation 4.10. In Example 3.2, the calculation is described in detail. The current power of the agricultural sector and therefore the value of α is 0.445.

The power of the agricultural sector and the hydropower production sector is assumed to be constant over the seven years of the model. The power of the agricultural 0.445 is the average of the period of seven years of which data is available. The value of α depends on the water flowing to the basins and the profits functions of the sectors. According to the literature ((Litani River Authority, 2017a)), the amount of water flowing to the hydropower stations is more or less stable around the 275 million m^3/year (Litani River Authority, 2017c) and since the energy prices remain more or less constant as well the variables regarding hydropower production will remain constant. However, the precipitation is decreasing over the years (Figure 2.3) and therefore the water availability will decrease as well. If the water availability decreases and the hydropower production remains constant, the value of α will decrease. For the determination of α in the current situation, the water balance of seven years is used and therefore the average α over the seven years is determined. Since the precipitation was already decreasing in the years 2010 - 2016 (Espinoza-Dávalos and Bastiaanssen, 2017), the real α of the earlier years might be higher, while it might be lower in the later years. In models about the future water allocation within the LRB, most probably a lower value of α has to be used.

Calculation 4.1: Determination of α

The observed profit in the LRB is based on the observed flow and the profit function.

$$\begin{aligned} \pi_h^o &= (0.0537Q_{hydro} + 15,361) * 0.036 \\ Q_{hydro} &= 275,000,000 \\ \pi_h^o &= 532,196.316 \end{aligned} \tag{4.11}$$

These values can be combined in Equation 4.10. In which Q_{rest} is 601,136,304.9 $m^3/year$ (Espinoza-Dávalos and Bastiaanssen, 2017).

$$\begin{aligned} (1-\alpha)(1-0.175) &= \frac{532,196.316}{1,162,683.021} \\ (1-\alpha) &= 0.555 \\ \alpha &= 0.445 \end{aligned} \tag{4.12}$$

4.4. Hydrological Constraints of the Subbasins

The profits that can be generated from the deviation of water are limited by the hydrological characteristics of the area. Not each combination of variables is possible within the model. The profit function consists of two parts, the profits generated from the deviation of water in the subbasins and the profits generated from the deviation of water from the Qaraoun Lake. In this section, the limits to the profit generated in the subbasins are described. The limits to the profit generated in Qaraoun Lake are described in Section 4.5. In each subsection, a constraint, characteristics corresponding to the constraint and when applicable the underlying assumptions are described.

4.4.1. Soil Water Storage Constraint

In reality, water is stored within the soil of the subbasins, the Litani river and the Qaraoun Lake. However, in this model the Litani river is not separately modelled. It is assumed that the water of the river is part of the basins and therefore the soil water storage.

The amount of water that can be stored in the soil depends on the soil type, structure, texture and content of organic matter (de Oliveira et al., 2015). The five dominant soil types of the LRB are: Eutric Cambisols/Chromic Luvisols, Calcic Cambisols, Calcic Xerosols, Chromic Luvisols and Chromic Vertisols. An overview of these soils is given in Figure 4.3. The amount of water that can be stored in the soil is called field capacity. The field capacity of each subbasin is based on the data of Espinoza-Dávalos and Bastiaanssen (2017) and varies between 388 mm and 424 mm. However, this soil characteristics do not include the water of the Litani river which is included in the model. Therefore it is assumed that the field capacity, including the Litani river is three times as large.

The minimum level of water in the soil is called the wilting point. The exact definition of wilting point is the level of water stored in the soil when the hydraulic head becomes negative. This wilting point does also depend on the soil structure, texture and organic content in the soil. Furthermore it depends on the temperature (de Oliveira et al., 2015). The wilting point of each subbasin is also based on data of Espinoza-Dávalos and Bastiaanssen (2017) and varies between 138.59 mm and 220.04 mm.

This limits of the soil water storage can be summarised in the following equation corresponding the storage constraint:

$$S_{WP}^{j} \leq S_{i}^{j} \leq S_{FC}^{j} \tag{4.13}$$

S_{WP} = Wilting point $[mm]$
S_{FC} = Field capacity $[mm]$

Table 4.1: Dominant soil types within the Litani River Basin and their texture

Soil type	**Soil texture**
Calcic Cambisols	No clay, fine texture (Encyclopædia Britannica, 2011)
Calcic Xerosols	Dessert soil with low levels of organic content (FAO, 1974)
Chromic Luvisols	Clay and many nutrients (Encyclopædia Britannica, 2016)
Chromic Vertisols	Clay with a good structure (FAO, 1974)
Eutric Cambisols/ Chromic Luvisols	Combination of Luvisols and Cambisols (FAO, 1974)

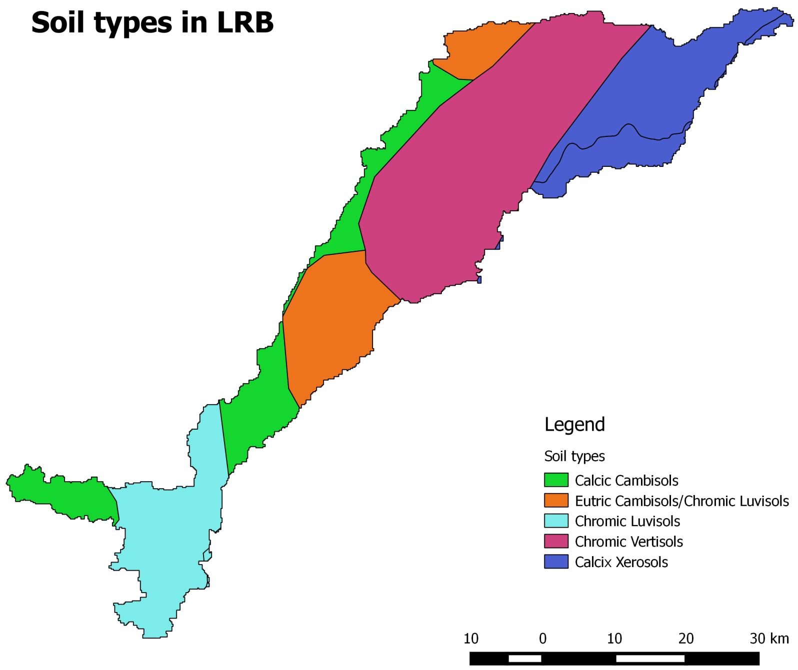


Figure 4.3: Soil map of the LRB (FAO-classification).

4.4.2. Physical Constraint

The physical constraint is based on two important characteristics of a water balance. In the first place, the storage of a certain month in a certain basin depends on the storage of that basin in the previous month. Water cannot be lost or gained from month to month. The storage of a basin in the first month (January 2010) is based on the soil water index of the first day of the month and the root depth (Espinoza-Dávalos and Bastiaanssen, 2017). In the second place, the water use cannot exceed the water availability. The equation of the physical constraint is described as followed:

$$S_i^j = \begin{cases} S_0^j - ETa_1^j - (1 - a_c^j)ET_{ref,i}^j k_b + P_1^j - \frac{1}{\eta_{irr}} Q_{irr,i}^j + \beta^{j-1} S_1^{j-1} - \beta^j S_1^j & \text{if } i = 1 \\ S_{i-1}^j - ETa_i^j - (1 - a_c^j)ET_{ref,i}^j k_b + P_i^j - \frac{1}{\eta_{irr}} Q_{irr,i}^j + \beta^{j-1} S_i^{j-1} - \beta^j S_i^j & \text{if } i > 1 \end{cases} \tag{4.14}$$

P = Precipitation $[mm/month]$
β = Runoff coefficient $[-]$

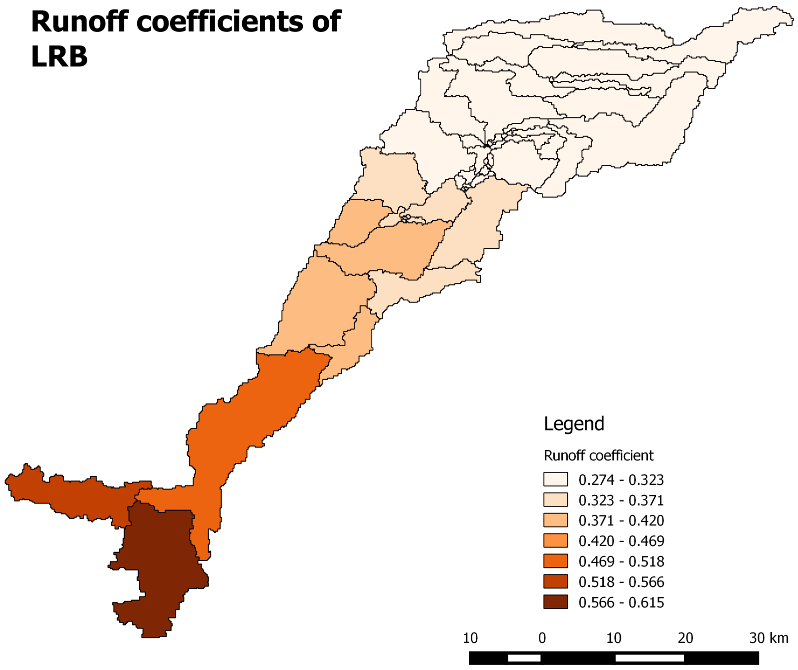
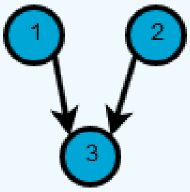


Figure 4.4: Runoff coefficients of subbasins based on GLDAS and PCR-GLOBWB land-surface models.

Each subbasin has its own value for the runoff coefficient. The runoff coefficient of a subbasin depends on the soil characteristics, vegetation characteristics and the height differences in a subbasin. This information can be combined in a land-surface model. For the determination of the runoff coefficients in the LRB, Global Land Data Assimilation Systems (GLDAS) and PCRaster Global Water Balance (PCR-GLOBWB) are used by Espinoza-Dávalos and Bastiaanssen (2017). The outcome of these models is represented in Figure 4.4. β is the part of the water stored in a subbasin that will flow to the next subbasin. To which subbasin the water will flow is determined by the outline of the Litani river. The river is not separately modelled, but the water of the river is part of the storage in the subbasins. Subbasins which are connected to each other by the Litani river will be connected to each other in the model as well. The runoff coefficients and directions are the connection of the subbasins in the model and therefore the core of the physical constraint. An overview of which subbasins are connected to each other is given in the directed graph of Appendix C. In the model, the subbasins are connected to each other by the use of a connectivity matrix. When there is a connection between one point and another point a value is inserted, this value can be one or equal to a runoff coefficient multiplied by minus 1. Consecutive months and subbasins are connected to each other. In Example 3.3 the connectivity matrix is explained in more detail.

Both evapotranspiration and water used for irrigation are used in the physical constraint. The actual evapotranspiration is the water that is directly taken from the soil by the roots of a crop, the flow of irrigation is applied in areas equipped for irrigation. The largest part of the area equipped for irrigation within the LRB is equipped for surface irrigation. This means that a certain amount of water is applied on the surface of the crop lands. A part of this water will evaporate and therefore not be used by the crops. Therefore, the efficiency of the irrigation systems have to be added to the constraint. The efficiency of the irrigation system is the part of the applied water that is used by the crop. This value is around 50% in Lebanon (FAO and Aquastat, 2017).

Example 4.2: Connectivity Matrix



This example is based on an area with three subbasins and a year that consists of three seasons. Subbasin 1 and 2 are not connected with each other, but a part of the water of these subbasins will flow to subbasin 3. The part of the subbasins that will flow to the next subbasin is called the runoff coefficient. Subbasin 1 has a runoff coefficient of 0.437, subbasin 2 of 0.561 and subbasin 3 of 0.321. The water that flows out of subbasin 3, will flow into the sea. Based on the knowledge of Equation 4.14, the connectivity matrix can be defined. The storage of a certain season in a certain basin depends on the storage of the previous season, the runoff of the previous season and optionally the runoff of the upstream basin in the previous season.

$$\begin{bmatrix} S_1^1 \\ S_2^1 \\ S_3^1 \\ S_1^2 \\ S_2^2 \\ S_3^2 \\ S_1^3 \\ S_2^3 \\ S_3^3 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1-0.437 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-0.437 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-0.561 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-0.561 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.437 & 0 & 0 & 0.561 & 0 & 0 & 1-0.321 & 0 & 0 \\ 0 & 0.437 & 0 & 0 & 0.561 & 0 & 0 & 1-0.321 & 0 \end{bmatrix}$$

4.4.3. Transpiration Constraint

Evapotranspiration is a collective term for different kinds of evaporation. The two most important types of evaporation within the subbasins of the LRB are soil evaporation and the evaporation of the crops: transpiration. This constraint is about the last kind of evapotranspiration.

The wilting point can also be defined as the minimal point of soil moisture the plants require not to wilt. The less water available in the soil, the stronger the bounds between the soil particles and the water particles will become. Therefore it becomes more difficult to extract water from the soil. At the wilting point, the strength between the soil particles and the water particles is so large that the roots of a crop are not able to extract the water in order to transport it through the crop. The water that can be extracted by the roots of a crop is called Total Available soil Water (TAW) (FAO). Not all this available water can be extracted by the roots of a crop. The strength of the roots differ per crop type and therefore the fraction of the TAW that can be extracted as well. p_c is the fraction of the total available water storage that can be depleted from the root zone by a certain crop (FAO). An overview of the p_c values per crop type is given in Table 4.2. In each subbasin grows more than one crop type is growing. Based on the crop cover a weighted average p_c value is determined for each subbasin. The Readily Available soil Water (RAW) is the lower boundary of the transpiration in a subbasin.

The upper boundary of transpiration is defined by the maximum evapotranspiration. The maximum evapotranspiration is the amount of water needed by a crop in order to produce the maximum yield. The maximum evapotranspiration depends on the reference evapotranspiration in the area and the crop characteristics. The reference evapotranspiration represents the evaporative demand of the air (Doorenbos and Kassam, 1979). The crop coefficient (k_c) is used to relate the reference evapotranspiration with the water requirements of a crop in order to fully grow (Doorenbos and Kassam, 1979). The crop coefficient differs per crop type and per stage of the growing period. The value can be either smaller, equal or larger than 1. The crop coefficients are summarised per month in Appendix A.

$$ET_{max} = k_c ET_{ref} \tag{4.15}$$

k_c = Crop coefficient [-]

The limits of the transpiration occurring in a certain basin can be described with the following set of equations:

$$\begin{aligned} TAW_i^j &= max(0, S_i^j - S_{WP}^j) \\ RAW_i^j &= TAW_i^j * p_c \\ ETa_i^j &= min(ET_{max,i}^j, RAW_i^j) \end{aligned} \tag{4.16}$$

TAW	=	Total available soil water	[mm]
RAW	=	Readily available soil water	[mm]
p_c	=	Soil moisture depletion factor of a crop	[-]

Table 4.2: Groups of values of depletion factor p_c and the division of the dominant crop types of the LRB in those groups (FAO).

Group 1	**Group 2**	**Group 3**	**Group 4**
p= 0.35	p=0.475	p=0.6	p=0.7
Potato	Banana Grape	Citrus Groundnut Wheat	Olive Maize Tobacco

4.4.4. Irrigation Constraint

The maximum yields are achieved when the evapotranspiration is equal to the maximum evapotranspiration (Doorenbos and Kassam, 1979). In this case, the total water requirements of a crop are satisfied. In order to increase the yields, a farmer can apply extra water to its field. This extra application of water is called irrigation. The Litani river nearly dries out during the summer period, the period in which most crops have a high water demand. Therefore, two irrigation projects have been executed by the LRA, Canal 900 and 'Canal 800'. Both canals get their water from Qaraoun Lake. 'Canal 800' brings the water to the south of the LRB in order to irrigate this area and 'Canal 900' brings the water back upstream in order to irrigate this area (Litani River Authority, 2017c). However, in this model it is assumed that the irrigation water is taken from the soil water in a subbasin. This assumption is based on the assumption that the irrigation scheme is functioning well in the LRB and therefore water that can be used for irrigation is available to a certain extent in all subbasins. However, the quality of the water in the canals and the lake is bad (Amery, 2002). This assumption might therefore be too optimistic.
According to FAO and Aquastat (2017), 51% of the crop lands in Lebanon are irrigated. It is assumed that this percentage also applies for the LRB. The percentage of area equipped for irrigation differs over the subbasins. A detailed explanation about the percentages of area equipped for irrigation per subbasin is described in Appendix A. The percentages of area equipped for irrigation are higher in the areas in which the precipitation is lower and the areas with a low percentage of rain-fed crops. The rain-fed crops are fruit trees and olive trees. The precipitation is low in the south of the Bekaa Valley. 51.2% of the total LRB is equipped for irrigation.
Maximum yields are achieved when the evapotranspiration is equal to the maximum evapotranspiration. Therefore, it is useless to apply more water than ET_{max}. Therefore the irrigation constraint is represented by the following equation:

$$Q_{irr,i}^j \leq a_{irr}^j (ET_{max,i}^j - ET_{a,i}^j) \tag{4.17}$$

4.5. Hydrological Constraints of the Qaraoun Lake

In the first place, water in the Qaraoun Lake is used for the production of hydropower. A part of this water is used for the supply of domestic water to the inhabitants of the LRB. The supply of domestic water is assumed to be fixed and therefore there are no constraints applicable to this part of the profit function. The water used for the production of hydropower is limited, for example by the capacity of the hydropower stations. In each subsection, a constraint, characteristics corresponding to the constraint and when applicable the underlying assumptions are described.

4.5.1. Storage in Qaraoun Lake Constraint

The total volume of the Qaraoun Lake is 220 million m^3 (Litani River Authority, 2017c). This will be the maximum storage within the lake and of course, the storage will be always larger than zero. This can be described by this equation:

$$0 \leq S_i^{61} \leq 220{,}000{,}000 \tag{4.18}$$

4.5.2. Physical Constraint

The principles of the physical constraints are already discussed in Subsection 4.4.2. The physical constraint of Qaraoun Lake differs from the physical constraint of the subbasins for two reasons. In the first place, the water is not used for the production of crops, but it is used for the production of hydropower and supply of domestic water. Furthermore, the actual evapotranspiration will not be limited in a lake and therefore the evapotranspiration will be equal to the reference evapotranspiration. In the model, an extra subbasin is added to represent the Qaraoun Lake, "subbasin 61". The equation corresponding the physical constraint of the Qaraoun Lake is as followed:

$$S_i^{61} = \begin{cases} S_0^{61} - min(ET_{ref,1}^{61}, S_1^{61}) - Q_{hydro,1}^{61} + P_1^{61} + 0.5\beta^3 S_1^3 & \text{if } i = 1 \\ S_{i-1}^{61} - min(ET_{ref,i}^{61}, S_i^{61}) - Q_{hydro,i}^{61} + P_i^{61} + 0.5\beta^3 S_i^3 & \text{if } 1 \leq i \leq 4, 9 \leq i \leq 12 \\ S_{i-1}^{61} - min(ET_{ref,i}^{61}, S_i^{61}) + P_i^{61} + 0.5\beta^3 S_i^3 & \text{if } 5 \leq i \leq 9 \end{cases} \tag{4.19}$$

Qaraoun Lake is located within subbasin 3. Half of the runoff of subbasin 3 will flow to the lake, while the other half will flow to the downstream subbasin. During the dry months: June, July, August and September, water will not be used for the production of hydropower.

4.5.3. Hydropower Production Constraint

The amount of water that can be used for the production of hydropower follows from the water balance. A crop cannot use more water than the amount of water available in the lake. The maximum amount of water that can be used is determined by the capacity of the hydropower stations ($Q_{hydro,max}$). After the use of water for the production of hydropower, it can be used for other purposes. A part of this water is used for the supply of domestic water to the inhabitants of the LRB. Yearly, an amount of 25 million m^3 has to be supplied to these inhabitants. This flow is assumed to be the minimal monthly flow to the hydropower stations.

One of the measures taken by the LRA is about the months in which water is flowing to the hydropower stations. Only in the 'wet' months, water will flow to the power stations. From June till September, the dry months, there is no flow to the hydropower stations. Therefore, there will be no production of power and no supply of domestic water in these months. The domestic demand is a continuous demand and therefore the water has to be stored somewhere in the basin in order to deliver a continues supply of domestic water.

Furthermore, it is assumed that it is difficult to take all the water from the Qaraoun Lake. Water is pumped from the Lake to the hydropower stations. It will be difficult to pump the very last drop out of the lake to the hydropower stations. This all can be summarised in the following equations:

$$Q_{hydro,i} = S_i^{61} + P_i^{61} - ET_{ref,i}^{61} + 0.5\beta^3 S_i^3 \tag{4.20}$$

$$Q_{hydro,i} \leq \begin{cases} 3{,}125{,}000 & \text{if } S_i^{61} \leq 2{,}200{,}000 \\ S_i^{61} & \text{if } 2{,}200{,}000 \leq S_i^{61} \leq Q_{hydro,max} \\ Q_{hydro,max} & \text{if } S_i^{61} \geq Q_{hydro,max} \end{cases} \tag{4.21}$$

$Q_{hydro,max}$ = Maximum flow to the hydropower stations $[m^3$/month]

4.6. Crop Areas within the Litani River Basin

Most of the important parts of the model are described in this section. As mentioned in Section 4.2, agriculture is important for the total profit generated from the deviation of water in the LRB. An important variable within this agriculture is the crops that growing in this area. In this section, more information will be given on the yields cultivated and the crops growing in this area.

The crops growing in the LRB are based on data of National Council for Scientific Research (2017). An overview of the crop types can be found in Figure 4.5. Within the area, two categories of crops can be distinguished, permanent crops and seasonal crops. Permanent crops are growing during the entire year and mostly for more than one year. Seasonal crops are only growing during a certain period of the year and are cultivated at the end of the year. If the crop is cultivated, the ground become bare soil. During these months, the ground will be prepared again in order to grow the crop in the next year again. The permanent crops are well defined by National Council for Scientific Research (2017). The area covered with seasonal crops is only defined as being covered with field crops. Therefore, data of FAO and Aquastat (2017) is used to define these crop types. According to FAO and Aquastat (2017), the dominant field crops in Lebanon are: groundnut, maize, potato, tobacco and wheat. Therefore it is assumed that 20% of the area covered with field crops is covered by each of these dominant field crops. In conclusion, 20% of the area covered with field crops is covered by groundnuts, 20% by maize, 20% by potatoes, 20% by tobacco and the last 20% by wheat.

The crop cover might change over the years. The crop cover of National Council for Scientific Research (2017) is defined in 2017. The data used in the model is from 2010 - 2016 (Espinoza-Dávalos and Bastiaanssen, 2017). Therefore, the crop data does not correspond with the hydrological data. However, most probably, the permanent crops will not change that much over the years. Field crops, which is the largest amount of crops in the LRB might change over the years. 25% of the agricultural in Lebanon is commercial agriculture (Karam and Karaa, 2000). Crops cultivated within the agricultural sector will not change that much over the years. Crops cultivated in the non-commercial sector might change over the years. In conclusion, 75% of the field crops might change year-to-year. However, the field crops are not specified within the data and therefore an assumption about the crop covers is made. Therefore, changes in field crops within the non-commercial sector do not matter for the model.

Different crops are growing within the LRB. Each crop type has its own characteristics and has its own potential profit. The characteristics are described in Appendix A. The potential profits, based on the selling price and the maximum yield of olives, grapes, groundnuts and citrus is high. However, whether this profits are achieved or not depends on the water deficit and the sensitivity of a crop to this water deficit. The water deficit is the difference between the actual evapotranspiration and the water demand of a crop (the maximum evapotranspiration). The water sensitivity of a crop (k_y) is an indicator of the sensitivity of a crop to water deficit. If the water sensitivity is larger than 1, water deficit will result in a significant drop of the yield compared to maximum yield. If the value is smaller than 1, this drop will be less significant (Doorenbos and Kassam, 1979). For example, citrus is a water sensitive crop and therefore a water deficit will result in a significant drop of the achieved profits. This follows from the following equation:

$$(1-\frac{Y_a}{Y_{max}}) = k_y(1-\frac{ET_a}{ET_{max}}) \tag{4.22}$$

k_y <1 Water insensitive crops
$k_y \geq 1$ Water sensitive crops

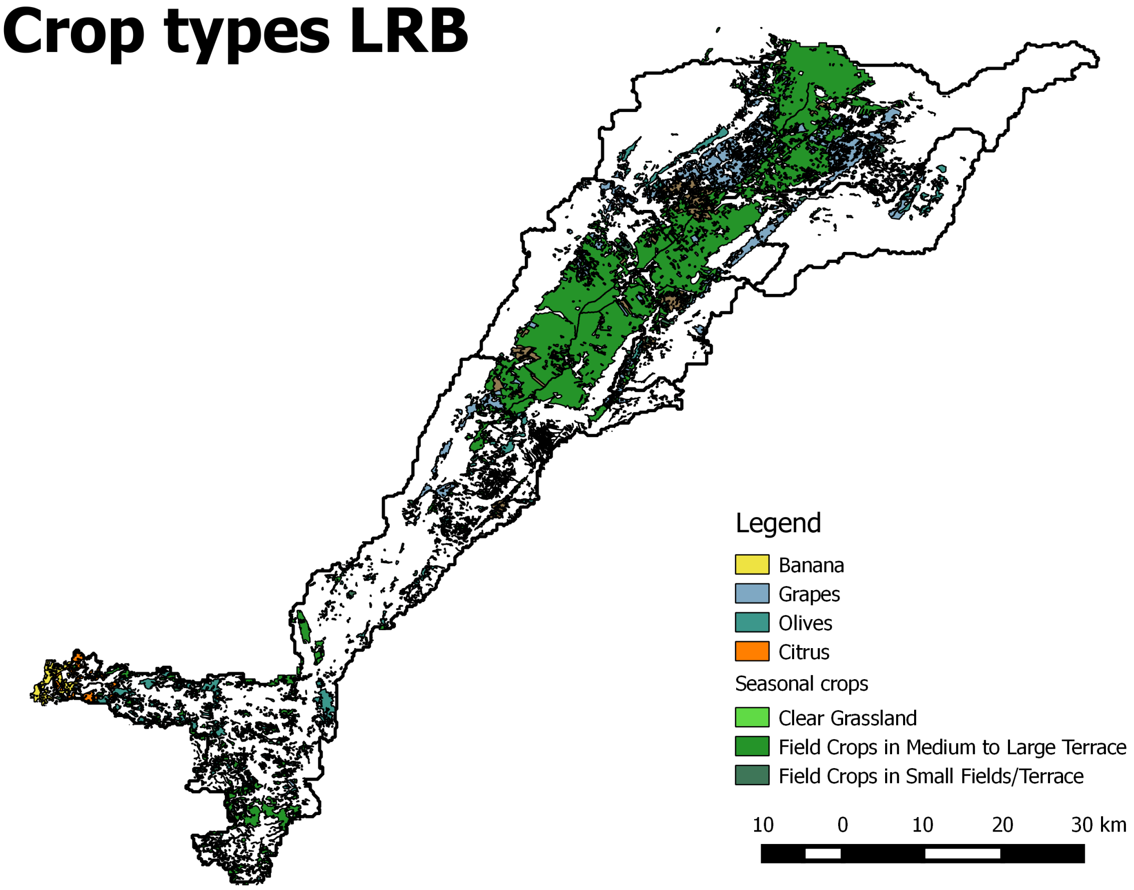


Figure 4.5: Crop types in the Litani River Basin (National Council for Scientific Research, 2017).

5

The Current Water Allocation

In order to optimise the water allocation within the LRB, first the current water allocation has to be defined. In this chapter, the current water allocation is described in order to answer the first research question: *What is the current water allocation based on the current water balance? What are the differences between the 'actual' water allocation and the modelled water allocation?* In the next chapters, several scenarios will be applied and measures implemented. The effects on the water allocation of these scenarios and measures will be compared with the water allocation as described in this chapter.

5.1. Comparison of the Model Results and the Data of Unesco-IHE

A model is used in order to optimise the water allocation within the LRB. This model is based on data provided by Unesco-IHE (Espinoza-Dávalos and Bastiaanssen, 2017). To verify the model, the results of the model are compared with the data of Espinoza-Dávalos and Bastiaanssen (2017). In Figure 5.1, the average soil water storage over the entire LRB is compared. The patterns of the storage are comparable with each other. In other words, the model is a good representation of the soil water storage within the basin.

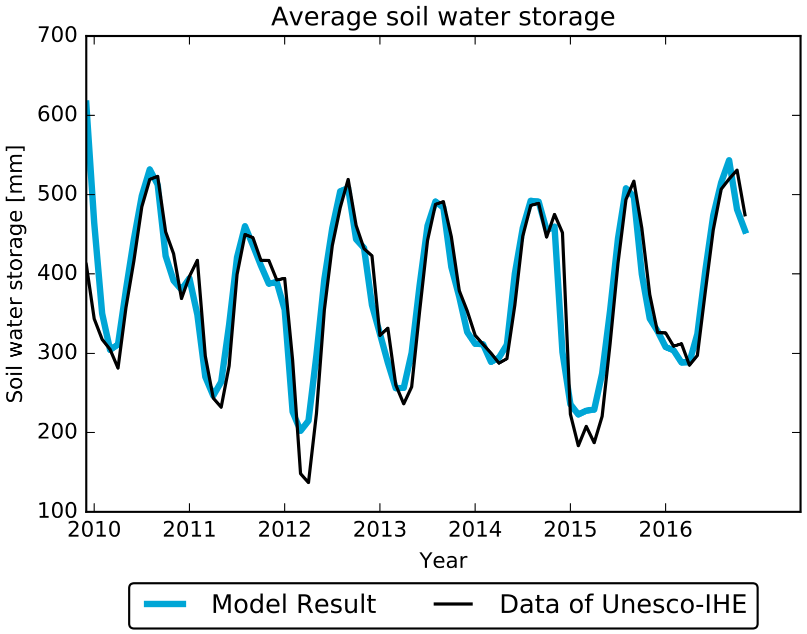


Figure 5.1: A plot of the average monthly storage over the entire LRB. The model is based on data of Espinoza-Dávalos and Bastiaanssen (2017). The data of Unesco-IHE contains storage data as well, this data is represented by the black line within the plot.

In order to verify the results of the model, the profits generated according to the model are compared with the agricultural GDP of Lebanon. Over the years 2010 to 2016, the average yearly GDP of Lebanon was 43.71 billion USD (Worldbank, 2018). The average agricultural GDP over these years was 5.6% of the total GDP (tra, 2018). However, this agricultural GDP is generated within the entire country. If it is assumed that the contribution to the GDP is equally divided over the country, the agricultural GDP of the LRB would be 503 million USD/year. In Table 5.1, the profits according to the model are summarised. The agricultural profit according to the model is higher than this agricultural GDP of the LRB. However, import costs are taken into account in the calculation of the GDP, while these are not taken into account in the model. Assumed that the import costs are also equally divided over the area, the average yearly import costs of the LRB would be 343 million USD. Including this information, the modelled agricultural GDP of the LRB would be 552 million USD/year. The modelled and actual GDP have the same order of magnitude. Therefore, it is assumed that the model can be used for the optimalisation of the water allocation of the LRB. Reasons for a difference between the modelled and actual GDP could be:

- The agriculture within the LRB is more profitable compared to the average.
- The import costs of the LRB are higher compared to the average import costs of the agricultural sector.
- The percentage of area used for agriculture is higher in the LRB, compared to the rest of the country.
- The purchaze prices of the products cultivated within the LRB are estimated too high.
- The seasonal crops are divided differently over the area compared to the assumed deviation.
- The model is based on the assumption that currently every individual tries to maximize the total income of the LRB based on the hydrological conditions. If this is not case, the modelled profits might be higher compared to the actual profits.

Table 5.1: The approximate yearly profits generated from the deviation of water within the LRB.

Sector	**Profit [USD/year]**
Agriculture	895 Million
Hydropower production	0.2 Million
Domestic Supply	5 Million
Total	900.2 Million

5.2. Water Allocation between the Sectors

Water allocation is about the deviation of water. Allocation consists of several dimensions: the deviation between the sectors, over the area and over the time. The last two dimensions are discussed in the Section 5.3. In this section, the deviation of water between the sectors is discussed.

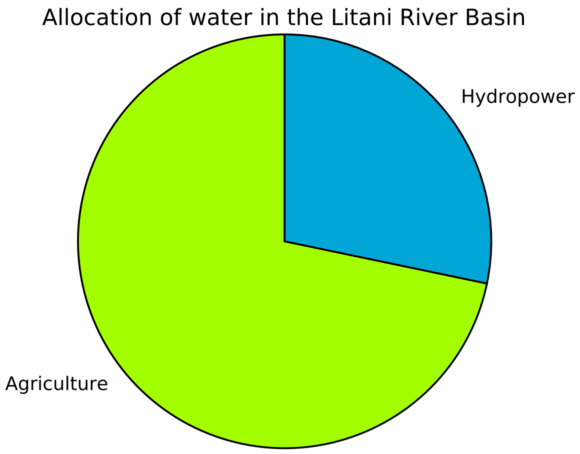


Figure 5.2: This pie chart represents the allocation of water within the Litani River Basin. According to the model, 71.7% of the water is used in the agricultural sector. 28.3% of the used water in the Litani River Basin flows from the Qaraoun Lake to the hydropower stations. Afterwards, 23.4% of this water is used for the supply of domestic water. This plot is based on the model results.

In Figure 5.2, the allocation of water over the sectors is represented. The largest part of the water is used by the agricultural sector, 71.7%. This is equal to an amount of almost 271 million m^3/year. The other part, 28.3%, will flow from Qaraoun Lake to the hydropower stations. This water will be used for the production of hydropower. A part of this water is afterwards used for the supply of domestic water to the inhabitants of the LRB. 23.4% of the water that flows to the hydropower stations is used for the supply of domestic water, equal to 25 million m^3 a year. The yearly profits that are generated from the deviation of these amounts of water is summarised in Table 5.1.

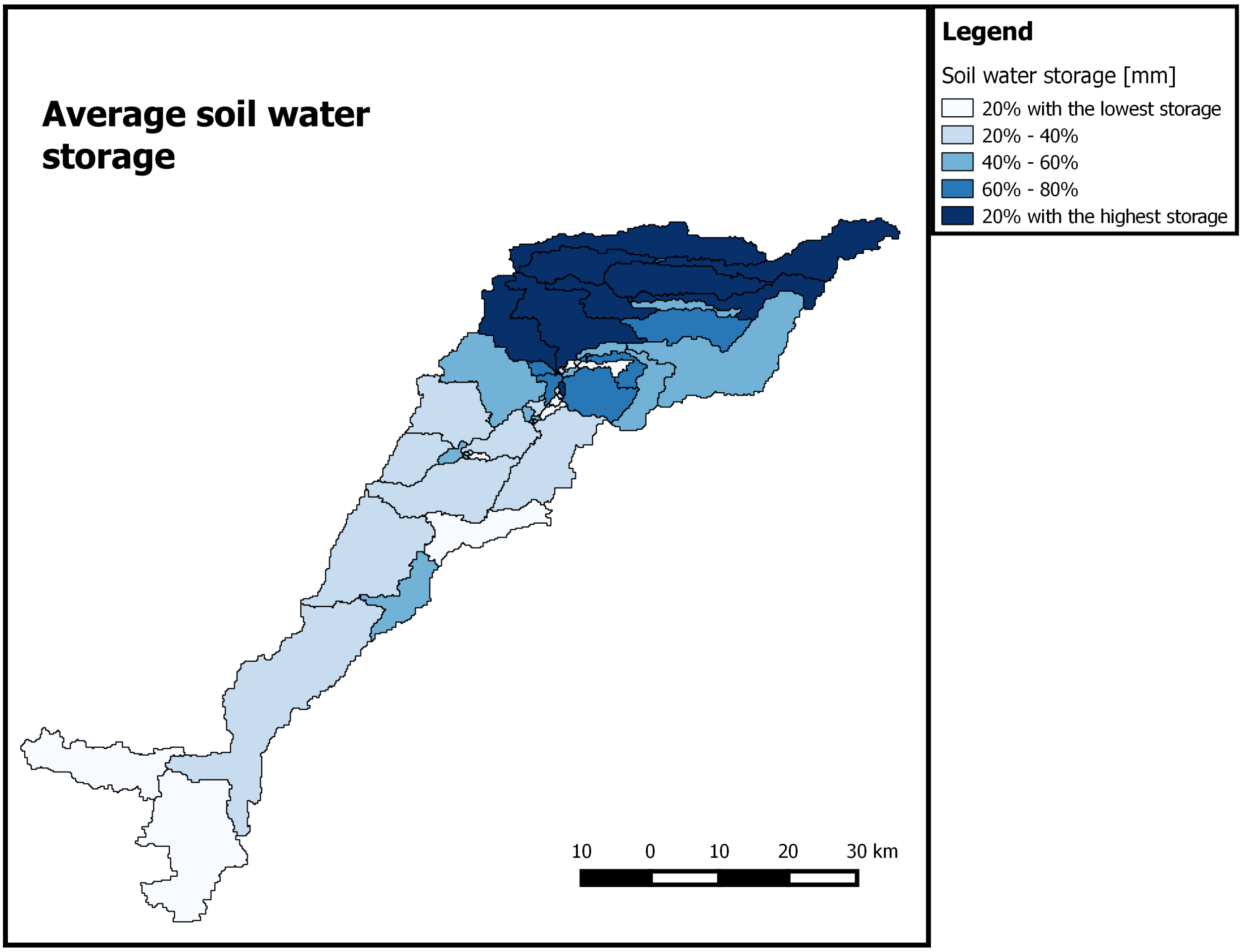


Figure 5.3: The average soil water storage of each subbasin. This average is the average over all subbasins and over all months. In the wet months, the average soil water storage will be higher and in the dry months it will be lower. This plot is based on the model results.

5.3. Water Allocation within the Agricultural Sector

Based on the previous section it can be argued that the agricultural sector is important in the optimalisation of the water allocation in the LRB, since the water is most valuable in this sector. Therefore, the spatial and temporal dimension of the water allocation are discussed in this section.

5.3.1. Spatial Allocation of Water

The water use within the agricultural sector is the water transported through a crop in order to transport the nutrients through the crop. The transport mechanism of the water through the crop is evapotranspiration. The evapotranspiration depends on the soil water storage and the soil depletion factor of the crops growing in the area. In Figure 5.3 an overview is given of the average soil water storage in each subbasin. The lowest value is 200 millimeter, while the highest value is around 850 millimeter. As can be seen in the figure, the highest soil water storage can be found in the north, while the values decrease to the south. In the north of the LRB, the precipitation and the field capacity is higher. Therefore the water availability will be higher.

Since agricultural water use is important for the economy, a good measure to compare the modelled agricultural water use with the agricultural water use of Espinoza-Dávalos and Bastiaanssen (2017) is a comparison of the evapotranspiration. For each subbasin, the modelled evapotranspiration is compared with the evapotranspiration based on the data of Espinoza-Dávalos and Bastiaanssen (2017). The agricultural water use is defined as the sum of the water taken out of the soil by the roots of a crop and the applied irrigation. The plots of this comparison can be found in Appendix D. For some of the subbasins, the evapotranspiration is comparable, for other the modelled evapotranspiration is higher while for a last category the evapotranspiration of Espinoza-Dávalos and Bastiaanssen (2017) is higher. There could be several reasons for a difference between the modelled evapotranspiration and the evapotranspiration of Espinoza-Dávalos and Bastiaanssen (2017):

- The model is based on the assumption that everyone tries to maximise the total income based on the hydrological constraints. However, this might indicate that the individual farmers tries to cheat and optimise their own income instead of the income of the entire basin.
- An error in one of the models
- Another assumption of the model is an optimal working irrigation system. Irrigation water is important for the transpiration of crops. If the irrigation system is not working optimal, the evapotranspiration might be overestimated for some of the subbasins.

Modelled evapotranspiration lower than 'actual' evapotranspiration

In Figure 5.4, an overview of the evapotranspiration within subbasin 55 can be found. Subbasin 55 is a small subbasin in the LRB. The subbasin is located in the middle-west of the LRB. The peaks of the actual evapotranspiration are twice as large the peaks of the modelled evapotranspiration. The entire subbasin is covered with crops, 79% of the subbasin is covered by olive crops and the rest of the subbasin by seasonal crops. Even if all the seasonal crops are maize plants, the crop with the highest maximum evapotranspiration, the evapotranspiration of Espinoza-Dávalos and Bastiaanssen (2017) is higher compared to the maximum evapotranspiration in this subbasin. A reason for this observation could be that a part of the evapotranspiration of a surrounding subbasin is measured within the boundaries of this subbasin. Another reason is already explained in Section 4.2, subbasin 55 is a white subbasin in Figure 4.1. This means that the marginal value of this subbasin is low and therefore it is better to use the water in other basins.

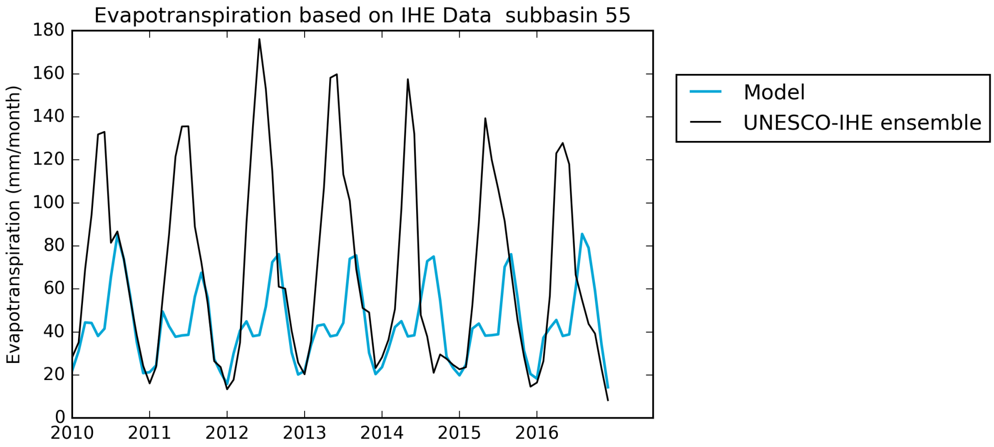


Figure 5.4: Evapotranspiration result of the model and the evapotranspiration of the data of Espinoza-Dávalos and Bastiaanssen (2017) in subbasin 55.

Modelled evapotranspiration higher than 'actual' evapotranspiration

In Figure 5.5, an overview of the evapotranspiration within subbasin 36 can be found. Subbasin 36 is a subbasin in the northeast of the LRB. The peaks of the modelled evapotranspiration are approximately 1.5 times higher compared to the peaks of the actual evapotranspiration. Only a small part of this subbasin is covered with crops (4%), the rest of the area is assumed to be bare soil. The evapotranspiration coefficient of bare soil in 0.35, since the peak of the reference evapotranspiration is about 250 mm/month, the modelled evapotranspiration will be 87.5 mm/month in the summer months. However, the evapotranspiration of Espinoza-Dávalos and Bastiaanssen (2017) is lower. Most probably it means that this area is not entirely bare, but also paved. This will result in a lower evapotranspiration.

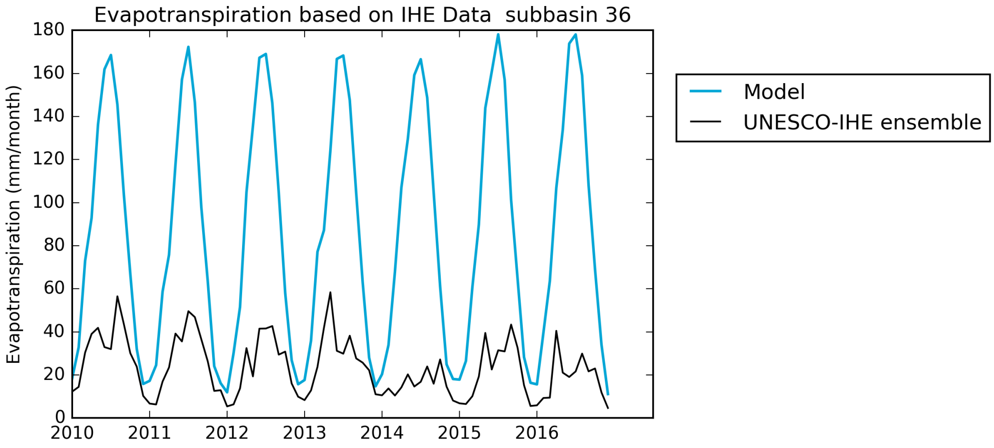


Figure 5.5: Evapotranspiration result of the model and the evapotranspiration of the data of Espinoza-Dávalos and Bastiaanssen (2017) in subbasin 36.

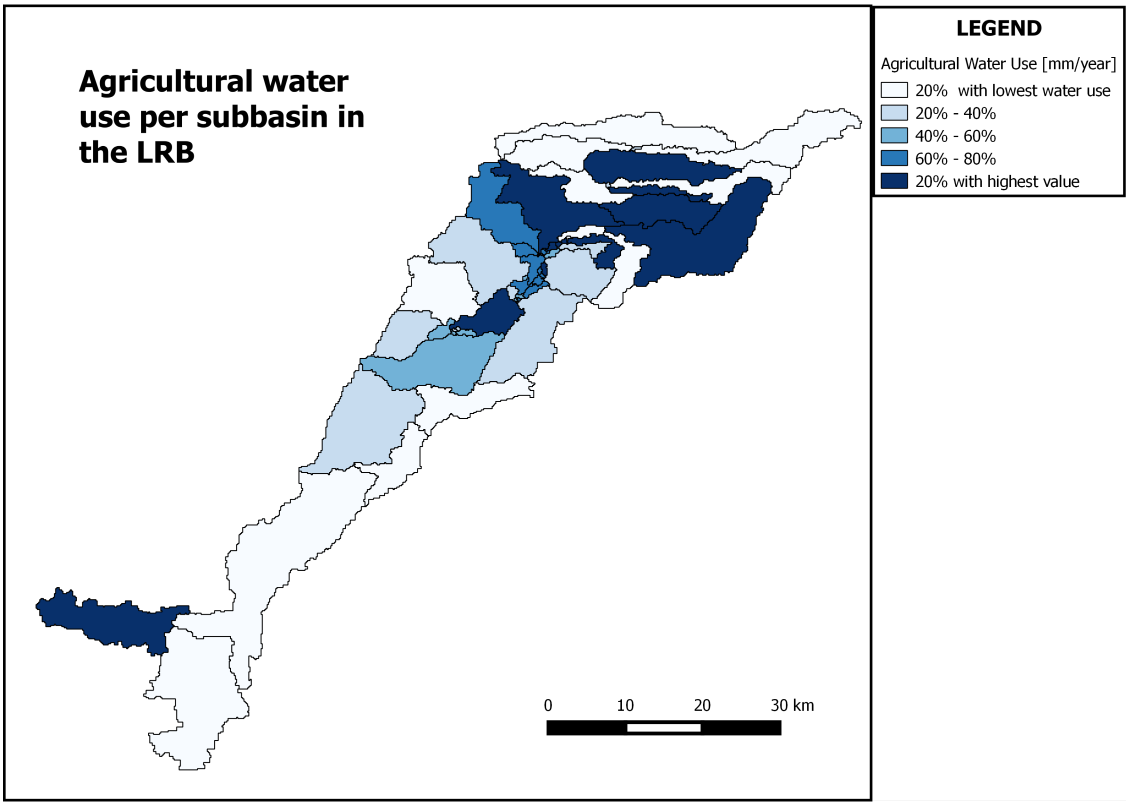


Figure 5.6: Overview of the agricultural water use in each subbasin of the LRA. The subbasins with the darkest colour use the most water, while the white subbasins uses the least agricultural water. The legend is divided into five equal parts, each with a representation of 20% of the data points. The lowest values of the agricultural water use are about 10 mm/year, while the highest values are almost 600 mm/year. This plot is based on the model results.

As already mentioned, the agricultural water use depends on the water availability in a subbasin and the soil depletion factor of the crops growing in the subbasin. In Figure 5.6, an overview of the agricultural water use is given. This is the spatial allocation of the water. The agricultural water use consists of two components: the evapotranspiration which is already discussed in the previous part of this section and the water applied via irrigation. The water applied via irrigation will transpire as well, but is not limited by the soil depletion factor and therefore is considered to be a different component of the agricultural water use. If Figure 5.6 is compared with Figure 4.1 it can be seen that a few of the subbasins with the highest marginal value also have the highest agricultural water use. This model is based on the assumption that all the individuals try to maximise the income of the LRB. If the marginal value of a subbasin is high, the water might be used in order to increase the profits. If the marginal value of a subbasin is low, the water will flow to the next subbasin in order to create a higher value in that

subbasin. This mainly influences the 'natural' transpiration, since the part of the area equipped for irrigation is a fixed value per subbasin.
In Figure 5.7 an overview of the transpiration is given; the total evapotranspiration minus the water applied for irrigation, the 'natural' transpiration. This transpiration is high in the north of the LRB, since the water availability is high in these areas as well (Figure 5.3). Again, there is a strip in the north of the LRB with high values for the transpiration. In this subbasins, the marginal value is high and therefore the water available will be used in order to increase the profits generated within the LRB. A remarkable subbasin is the subbasin the one most downstream of the Litani river. The agricultural water use in this subbasin is high, while the subbasin is coloured white in Figure 5.7. This white colour implies that the water taken from the root zone is low, while the irrigation is high. This subbasin is an exception, in the rest of the LRB the colour-structure of the total agricultural water use and the 'natural transpiration' is comparable. Since the marginal value is high of this subbasin, water will be collected in order to irrigate this land.

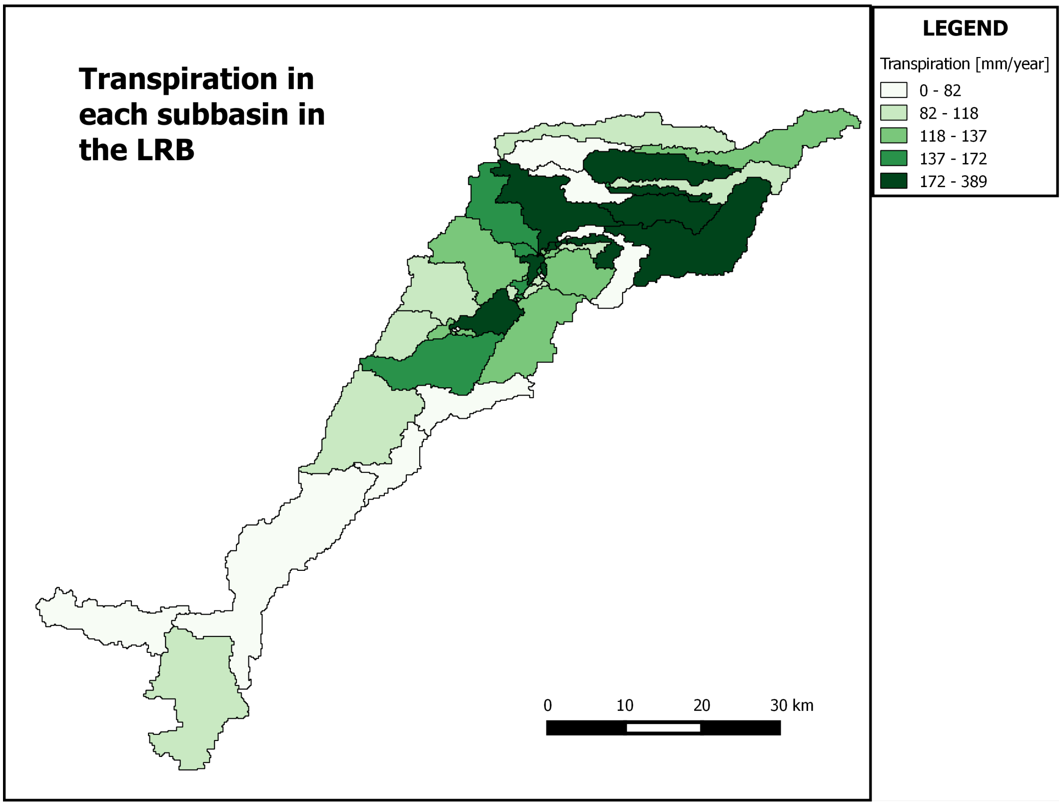


Figure 5.7: Overview of the 'natural' transpiration of the crops. The subbasins with the darkest colour have the highest value of the 'natural' transpiration'. The 'natural' transpiration is defined to be the water that is taken from the soil and transpired by the crops. This plot is based on the model results.

In Figure 5.9, the modelled agricultural water use is compared with the agricultural water use based on the data of Espinoza-Dávalos and Bastiaanssen (2017). The subbasins coloured red have a lower modelled agricultural water use that provided in the data of Espinoza-Dávalos and Bastiaanssen (2017), in the white subbasins this is more or less equal and in the green subbasins the agricultural water use is higher in the model. Mainly the subbasins in which the marginal value is low (Figure 4.1), the modelled agricultural water use is lower compared to the data of Espinoza-Dávalos and Bastiaanssen (2017). Again, the most downstream subbasin is a remarkable one. In the modelled agricultural water use, the water use of this subbasin is already high and in the data provided it is even higher. This subbasin has a low soil water storage and this makes the result even more remarkable. 15% of this subbasin is covered with olive trees. The soil depletion factor of olives is high and the selling price of olives is high as well. So, even if the soil water storage is low, the olive trees are able to take a significant part of it. Furthermore, this crop need water during the entire year, like bananas. Both crops are growing in this subbasin, therefore the agricultural water use is divided over the entire year. In some other basins it is only divided over the months in which the seasonal crops are growing.

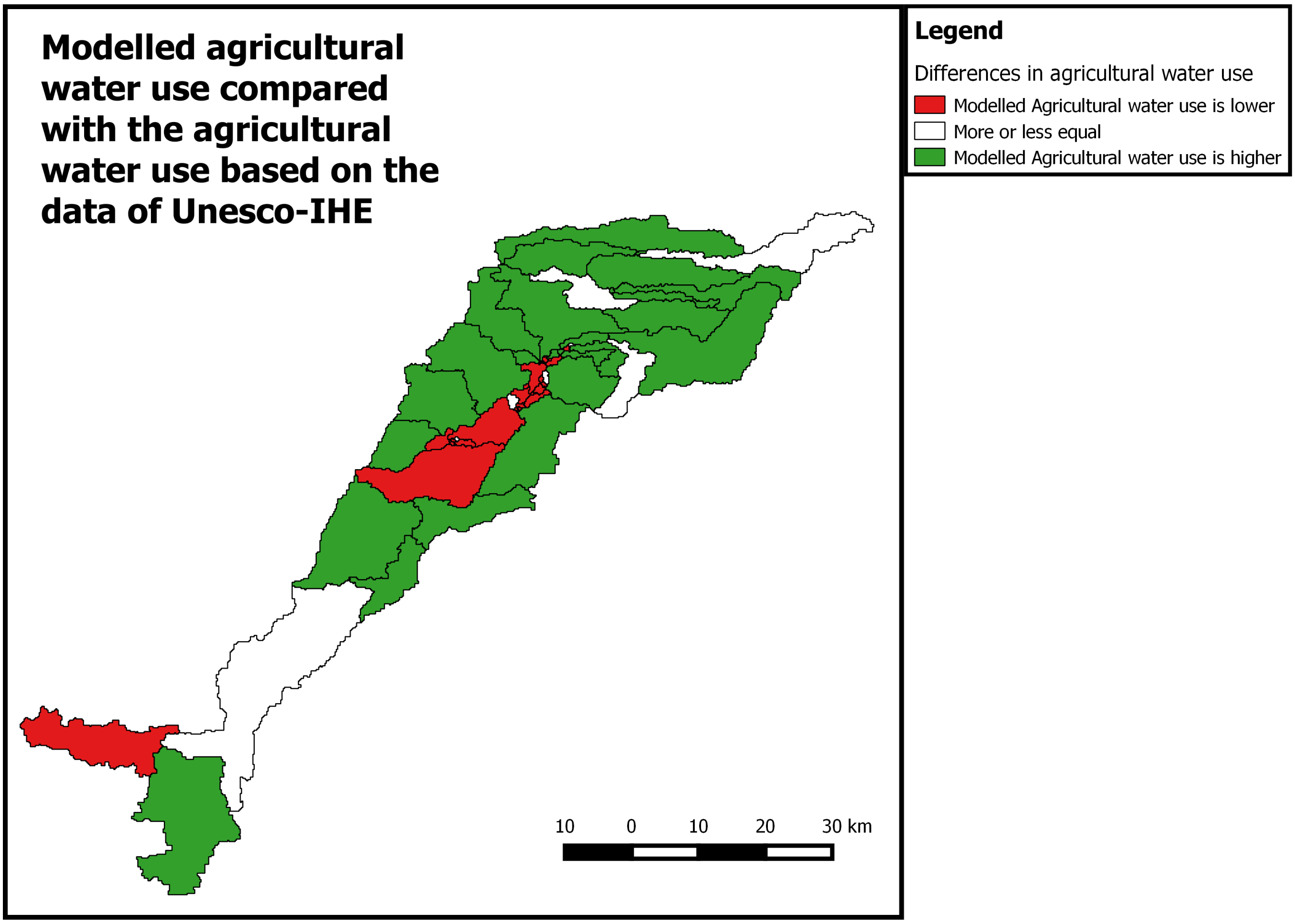


Figure 5.8: This figure represents the differences in agricultural water use between the model and the data provided by Espinoza-Dávalos and Bastiaanssen (2017). The subbasins which are coloured red have a lower agricultural water use in the model, the green ones have a higher agricultural water use. In the white subbasins the agricultural water use is more or less equal. This plot is based on the model results.

Since optimising the water allocation is not only about economic efficiency, but for example also about social equity, the profits per hectare generated in each subbasin are compared with each other. The plot is given in Figure 5.9. The profits generated per hectare are more or less equally divided over the area, except for three subbasins: subbasin 31,subbasin 32 and subbasin 55. Subbasin 31 is not representative since the area of this subbasin is equal to one grid cell, which is entirely covered by crops. Subbasin 32 and 55 are covered for a significant part with olive trees (62.2% and 79%respectively). The selling price of olives is the highest and therefore the profit generated per hectare is high in these subbasins. Subbasin 32 and 52 are the only subbasins with high percentages of the area covered with olive trees.

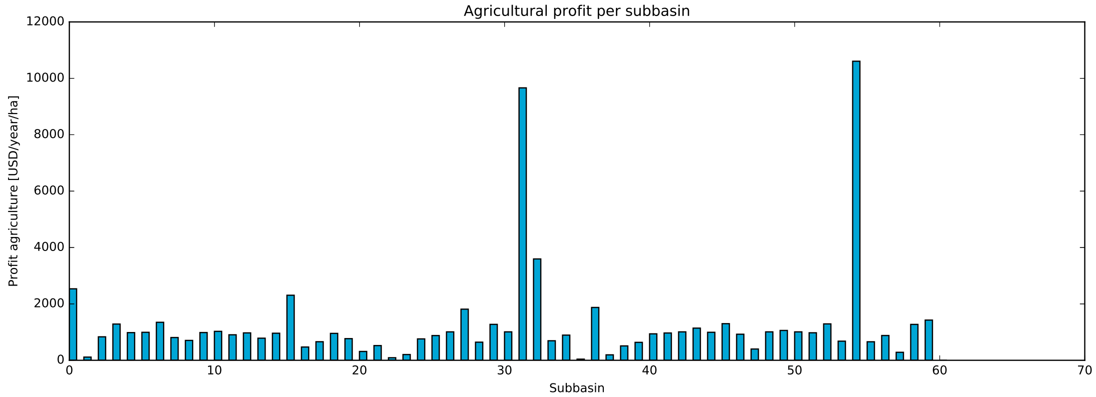


Figure 5.9: The agricultural profits generated per hectare in each of the subbasins of the LRB. This bar plot is based on the model results.

5.3.2. Temporal Allocation of Water

The allocation of water is also about the deviation of water over time. In Figure 5.10 and Figure 5.11, the spatial deviation of water is described. In both plots, the water used in the agricultural sector is high in the months May - September. In these months the water demand of the air is high and therefore the water used in the agricultural sector will be high as well. There are some differences, for example the agricultural water use based on the data of Espinoza-Dávalos and Bastiaanssen (2017) is the highest in the month May. The water demand of the air is the highest in July. This difference could be caused by the assumption made in the model. In the model, it is assumed that the yield response factor is stable of the growing period. However, in reality, the yield response factor is varying over the growing period. For example, it will be high in the vegetative phase. If the vegetative phase takes place in May, farmers might apply water to their crop in this month. However, in the model the yield response factor is assumed to be stable and therefore the farmers will apply water to their crops when the water demand of the air is high.

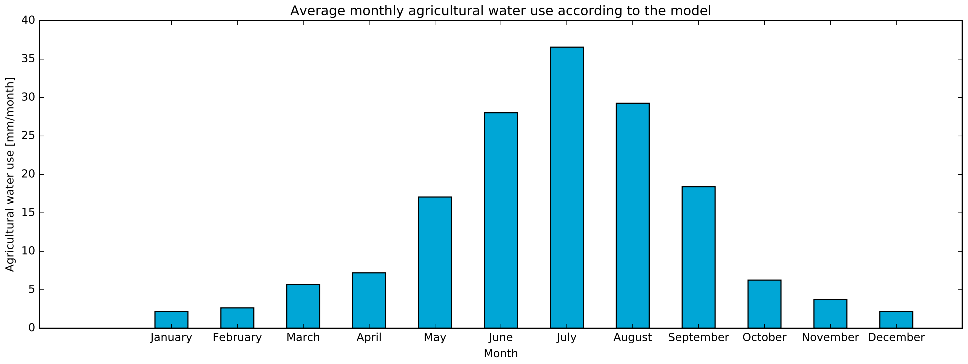


Figure 5.10: The average monthly agricultural water use of the model.

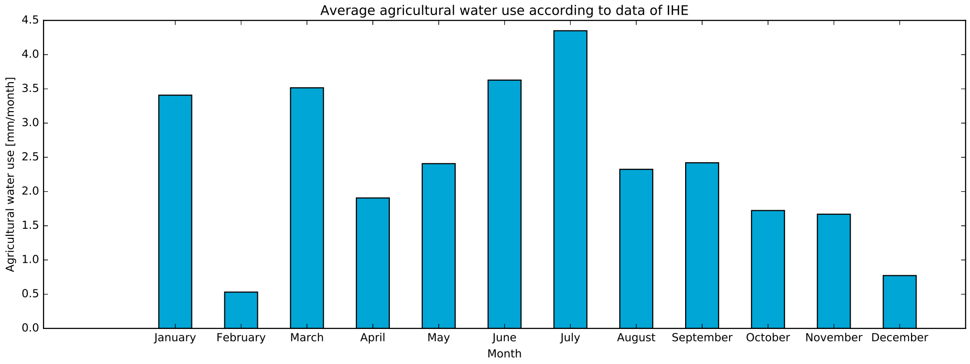


Figure 5.11: The average monthly agricultural water use of the data of Espinoza-Dávalos and Bastiaanssen (2017).

5.4. Current Water Productivity

The water productivity of a crop is the profit that can be generated with the application of 1 m^3 of water. The principle is comparable with the determination of the marginal value, however here the values are determined for each crop type. If just one cubic meter of water is applied, the water productivity will be negative for the water sensitive crops. Therefore the water productivity is defined as the profit that can be generated with the application of one extra unit of water.

If a water-deficit occurs the yield drop of water insensitive crops will be limited. The other way around this also implies that the application of one extra drop will have a limited effect on the profit. The yield response factor of olives is small, so the application of one cubic meter of water has almost no effect. However, the marginal value is 10^6 times higher compared to the values of this graph. This is caused by the high selling prices of olives and the low maximum evapotranspiration. The other water insensitive crops are grapes, groundnuts and tobacco.

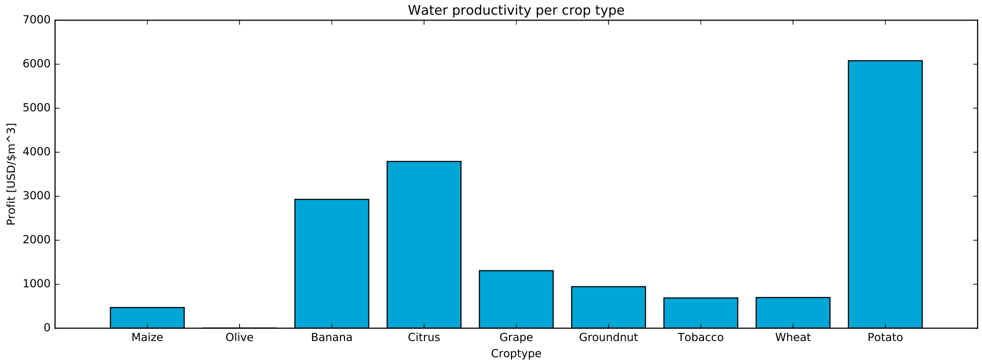


Figure 5.12: The profit that can be generated when one extra cubic meters of water is applied to the crop. This bar plot is based on the model results.

6

Water allocated to Beirut

It has always been difficult to provide enough drinking water for all the inhabitants of Beirut. Since the population of Beirut is growing, it has even become more difficult during the past years. Therefore, a supply from the Litani to Beirut is proposed. In this chapter, the implementation of water supply to Beirut in the model is discussed and the effects on the water allocation within the LRB are described. Based on this information, the second research question could be answered: *'What is the effect on the water allocation, if water is also allocated to Beirut?'*.

6.1. Implementation of water allocated to Beirut

The proposed domestic supply of water to Beirut is assumed to be 93 million m^3/year. It is useless to use the water only for the supply of domestic water. It is better to use water which is used for the production of hydropower for the supply of domestic water. In that case, the water is used for two purposes instead of only one and therefore the value of the water will be higher. Production of hydropower takes only place eight months a year. The proposed supply to Beirut is an extra domestic supply in addition the current supply. Therefore, the minimum monthly flow to the hydropower stations have to be 14.25 million m^3. In conclusion, the hydropower production constraint as described in Chapter 2 is influenced by allocation water to Beirut as well. The equation corresponding the constraint will become:

$$Q_{hydro,i} \leq \begin{cases} 14,250,000 & \text{if } S_i^{61} \leq 2{,}200{,}000 \\ S_i^{61} & \text{if } 2{,}200{,}000 \leq S_i^{61} \leq Q_{hydro,max} \\ Q_{hydro,max} & \text{if } S_i^{61} \geq Q_{hydro,max} \end{cases} \tag{6.1}$$

6.2. Effect on the Current Water Allocation

If the domestic demand of Beirut is supplied from the LRB to Beirut, the profits generated from the deviation of water will decrease by 1.3%. The water used for the production of hydropower and the supply of domestic water are increased, but the water used in the agricultural sector will decrease. Since the agricultural sector in the more profitable sector, the total profits generated will decrease. In Figure 6.1, an overview of the flow from Qaraoun Lake to the hydropower stations is given. The minimal flow the hydropower stations should be 14.25 million m^3 in order to supply enough water to Beirut. As can be seen in the plot, this amount will be achieved during the first years, until 2014. However, the lake is over-exploited if this amount is taken out monthly. In 2015, the minimal flow is not achieved in all the months. In the first months of 2016, the water flowing to the hydropower stations is really high. In the years before, it was sometimes possible to produce more hydropower. However, water had to be saved in order to achieve the minimal flow during the entire wet period. The wet period starts in October and ends in May. For the last year, 2016, not the entire wet period is taken into account and therefore no water has to be saved in the first months of the wet period.

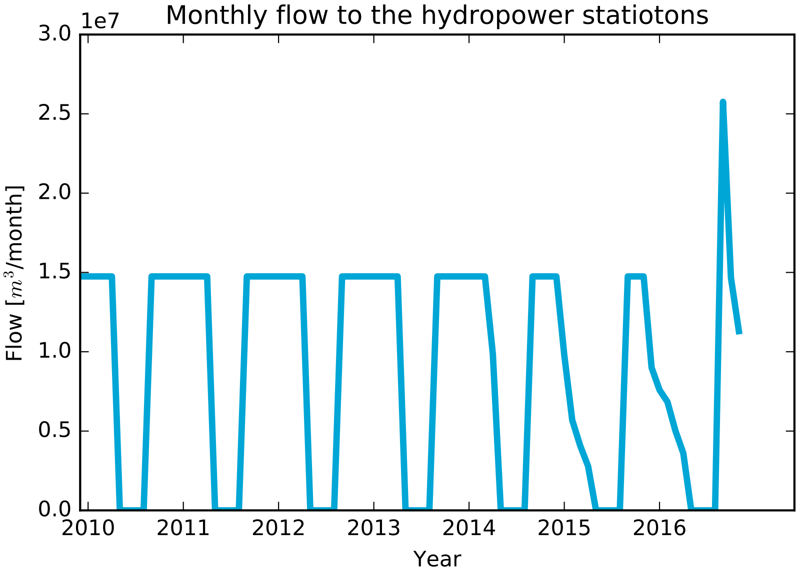


Figure 6.1: A plot of the flow from Qaraoun Lake to the hydropower stations in order to produce hydropower and supply water to the inhabitants of Beirut. This plot is based on the model results.

Allocating water to Beirut will also affect the agricultural water use. More water has to be available within the Qaraoun Lake and therefore less water can be used by the crops. In Figure 6.2, an overview is given of the modelled decrease of agricultural water use due to the allocation of water to Beirut. The effect in the small subbasins around the Litani river and the most downstream subbasin is the most significant. Especially the marginal value of this subbasin is high and therefore will have a contribution in the decrease of the profits.

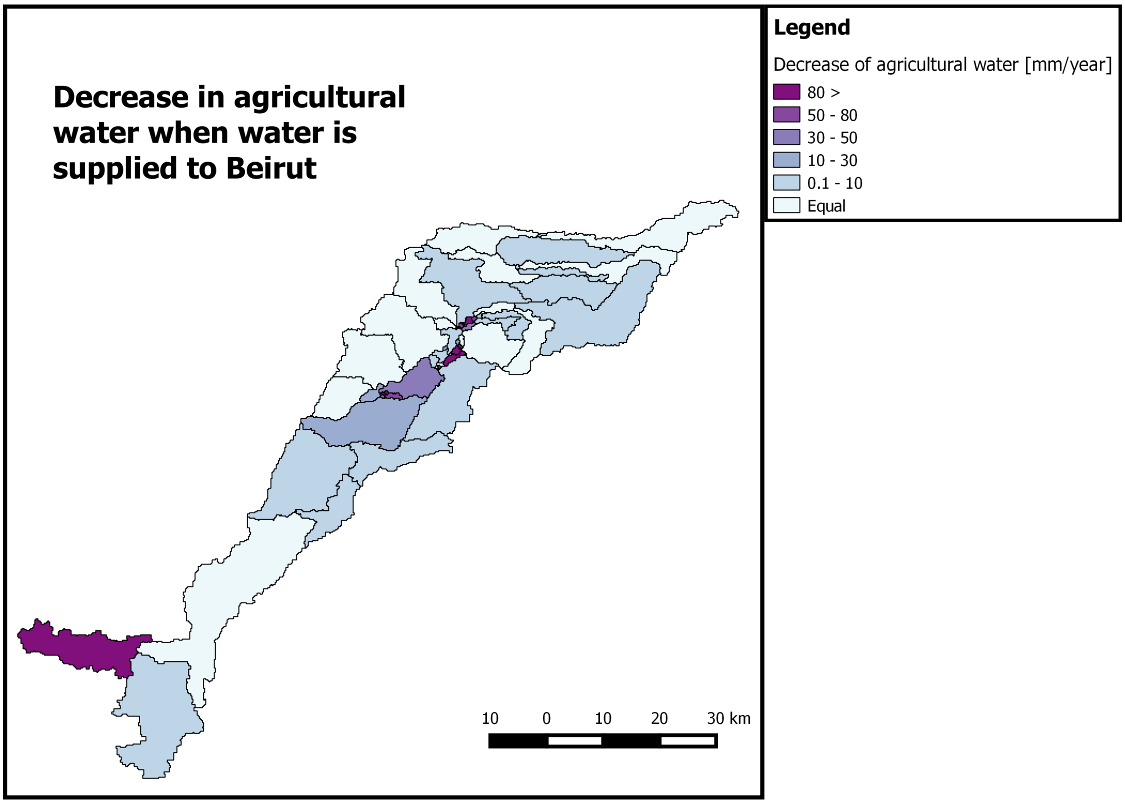


Figure 6.2: An overview of the decrease of agricultural water per subbasin when water from Lake Qaraoun is supplied to Beirut. This plot is based on the model results.

7

Water allocated from Lake Qaraoun to Downstream Subbasins

Based on findings in literature, it is assumed that there is no water flowing from Qaraoun Lake to the downstream subbasins. However, what would be the effect on the water allocation when water if flowing to the downstream subbasins? In order to answer the third research question: *'What is the effect on the water allocation, if water is allocated from Qaraoun Lake to the downstream subbasins?'* the implementation of this scenario is discussed in this chapter. Afterwards, the effects on the current water allocation as described in Chapter 5 are described.

7.1. Water allocated to Downstream Subbasins within the Model

Water allocation to the downstream subbasins is only possible when there is enough water available within the Qaraoun Lake. As can be seen in Figure 7.1, the storage within the lake are higher during the summer months. During the summer months, the water demand of crops is high and therefore it could be useful to allocated water from Lake Qaraoun to the downstream subbasins.

In order to see the effect of water allocation to the downstream subbasins, 10% of the water stored in Qaraoun Lake is allocated to the downstream subbasins. This flow will only be there during the months in which the water is not used for the production of hydropower. So, from June - September. This water will flow to the subbasin 2, the subbasin directly downstream of the Qaraoun Lake. This scenario will influence the sustainability constraints of subbasin 2 and the Qaraoun Lake.

The water availability of Qaraoun Lake will decrease, since a part of the water is used during the dry months. In these months 10% of the storage will flow to subbasin 2. Therefore, the sustainability constraint will become:

$$S_i^{61} = \begin{cases} S_0^{61} - min(ET_{ref,1}^{61}, S_1^{61}) - Q_{hydro,1}^{61} + P_1^{61} + 0.5\beta^3 S_1^3 & \text{if } i = 1 \\ S_{i-1}^{61} - min(ET_{ref,i}^{61}, S_i^{61}) - Q_{hydro,i}^{61} + P_i^{61} + 0.5\beta^3 S_i^3 & \text{if } 1 \leq i \leq 4, 9 \leq i \leq 12 \\ S_{i-1}^{61} - min(ET_{ref,i}^{61}, S_i^{61}) - 0.1 S_i^{61} + P_i^{61} + 0.5\beta^3 S_i^3 & \text{if } 5 \leq i \leq 9 \end{cases} \tag{7.1}$$

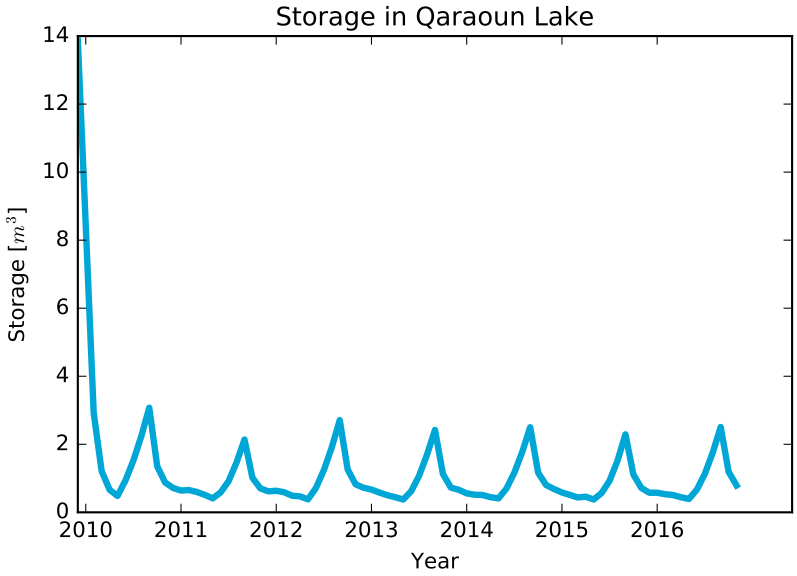


Figure 7.1: The variation of the storage within the Qaraoun Lake over the time in the current water allocation. Currently, the storage is higher in the dry period of the year in which no hydropower is produced. This plot is based on the model results.

7.2. Effect on the Current Water Allocation

When there is flow from Qaraoun Lake to the downstream subbasins the profit will increase with 0.02%. This change lies within the uncertainty of the model and therefore the difference can be neglected. Since the storage within the lake will decrease, the flow to the hydropower stations will decrease by 1.3%. There is a small increase in the water used by the downstream subbasins. As can be see in Figure 7.1, the maximum storage in the Lake is around 3 million m^3. If 10% of this water is supplied to the downstream subbasins, monthly 0.3 million m^3 will flow to the downstream basins. This amount has to be divided over the downstream subbasins. Only considering that the water will be divided over the subbasin directly downstream of the subbasin, this is 1 mm a month, of which a part will be evaporated. Since this increase is almost not observable, this scenario is not effective. More water has to be supplied to the downstream subbasins in order to observe the effect, however this will cause problems within the lake.

8

Improvement of the Current Water Allocation

It is expected that the water availability will decrease morein the coming years. In order to protect the LRB from a water crisis occurring, in this chapter suggestions are given in order to improve the water allocation within the LRB and answering the fourth research question: *What measures can be taken in order to optimise water allocation?*. The suggested measures are discussed in general, afterwards it is described how this measures is implemented in the model and in the end the effect on the current water allocation is described.

The measures which are suggested in this chapter are suggestions in order to improve the current water allocation, therefore the value of α will remain the same. Since it is assumed that the power of either the agricultural sector and the hydropower sector will remain equal. From one day to the other, is is not feasible to make significant changes in the water flowing to a certain sector. The power of the sector will remain the same, but suggestions will be given in order to use the water more efficiently.

8.1. Change to less Water Sensitive Crops

If water deficit occurs by a sensitive crop, the impact will be significant, while the impact is limited for water insensitive crops. The change from water sensitive crops to water insensitive crops will decrease the dependency of water of the area. In order to economic optimisation of water allocation, it is only useful to replace the seasonal crops. Perennial crops will have a yearly yield, but can be used year after year. Changing the water sensitive perennial crops to water insensitive perennial crops will have high investment cost and thus negatively effect the profits generated from water.

There are three types of water sensitive seasonal crops in the LRB; maize, potato and wheat. Groundnut and tobacco are the water insensitive seasonal crops and so they should replace the water sensitive crops (Doorenbos and Kassam, 1979). The potential profit ($Y_{max,c} * P_c$) of potatoes is significant higher than the potential profit per hectare of the water insensitive crops (4-7 times higher) (Doorenbos and Kassam, 1979; FAO, 2017; Indexmundi, 2017). Therefore, this crop is not replaced by a water insensitive crop. Only the crops maize and wheat will be replaced. For each subbasin 50% of the summed area of maize and wheat will be replaced by groundnut crops and the other 50% will be replaced by potato crops. In Table 8.1 a new overview of the seasonal crops can be found.

Table 8.1: New areas covered with seasonal crops

Seasonal crop type	Type	Area covered
Maize	Water sensitive	0
Potato	Water sensitive	$0.2a_{seasonal}$
Wheat	Water sensitive	0
Groundnut	Water insensitive	$0.4a_{seasonal}$
Tobacco	Water insensitive	$0.4a_{seasonal}$

The change from water sensitive crops to water insensitive crops will increase the total profits generated from the deviation of water by 4.3%. Not only caused by the fact that the water sensitive crops are replaced by water insensitive crops, but also by the fact that the less profitable crops are replaced by more profitable crop types. The same amount of water will flow to the hydropower stations and will be used within the agricultural sector. However, the profits that can be generated within the agricultural sector increases. The spatial allocation of water over the subbasins will remain constant as well. The largest part of the LRB is covered with seasonal crops, the same adaptations are applied in the area covered with seasonal crops. Therefore, higher profits can be generated with the same amount of water.

8.2. Change to a more efficient Irrigation System

At the moment, the most common used irrigation system of the LRB is surface irrigation. An inefficient system of irrigation, since fields are flooded and so they get more water then needed. The evapotranspiration rate of Lebanon is high (≈68%) and thus a lot of the irrigated water will evaporated. In the current situation the irrigation efficiency is about 50% (FAO and Aquastat, 2017).
A more efficient irrigation method is a drip (or trickle) irrigation system. At the moment, approximately 32% of the LRB is equipped with this kind of irrigation system. In a drip irrigation system, one drop at the time is dripping through small emitters (Folnovic, 2017). The efficiency of this system ranges from 85 up to 90%. The high efficiency is achieved by two factors:

- The water is applied drop by drop and soaks into the soil before it can be evaporated. When the entire field is irrigated with a high amount at the same time, not all the water can soak in the soil immediately and so will partly evaporated.
- The water is applied at the crop root zone, so at the place where the water is needed. In this way, water will be used by the roots and have little chance to flow to another location where it is not efficiently used.

It is not realistic to replace all the irrigation systems with a few years. Therefore, the efficiency of 90% will not be realistic for the LRB within a few years. Therefore, the irrigation efficiency is increased to 75% in the model.

Figure 8.1: An example of drip irrigation (Folnovic, 2017), in which the land is irrigated drop by drop. This will reduce the evapotranspiration and therefore increase the efficiency of irrigation.

The effect of increasing the efficiency of the irrigation systems is negligible. The changes could not be observed and therefore it can be concluded that increasing the efficiency is not the solution in order to prevent Lebanon from a water crisis occurring. This result is remarkable results, as also discussed in Chapter 9.

8.3. Change to another type of Sustainable Energy

Water of the Litani river is used to produce energy for the entire country, but there are also other resources of sustainable energy available. When water of the LRB is used for domestic water supply to Beirut, this water has to flow through the hydropower stations. If energy is produced by using other sustainable sources, the flow to the hydropower stations is equal to the domestic water needs. Since the flow to the hydropower stations will decrease, the profits generated from the deviation of water within this sector will decrease as well. This decreases the power of the hydropower sector, and therefore the value of α will increase. If the new flow to the hydropower station will be equal to the domestic water supply, the new value of α will become 0.958 (Equation 4.10). In the model, Q_{hydro} is

set equal to 3.125 million m^3/month and α to 0.958 in order to see the effect of this measure on the optimal water allocation.
An increase in α will result in an increase of the profits. Until a certain level, they are linearly correlated. When the value of α increases, more water will be used by the agricultural sector and therefore the profits will increase as well. However, at a certain level, applying more water to the agricultural sector will not results in higher yields or the yield increase will be limited.

8.4. Increase the Water Productivity

Water productivity is about the amount of product that can be produced by using one drop of water (Halsema and Linden, 2012). An increase in the water productivity means that a higher amount of a certain product is produced by using the same drop of water, or in other words: *'more crop per drop'*. Since water in the LRB is used by three sectors, there are three areas which can contribute to the water productivity of the area.

1. **Using greenhouses to produce crops**
   Producing crops in a greenhouse instead of the field can positively affect the crop yield. It is more easy to control the climate and reduce water consumption (Von Zabeltitz, 1997). In a controlled climate system it is more easy to regulate temperature, incoming light and available water to the crops. Since it is better controlled, less water will be evaporated without being productive or flow to another area.
2. **Increasing the efficiency of the hydropower station**
   Water is used in a hydropower station to produce power. The more efficient the system is, the less water is needed for the production of power. This water can be used for other purposes.
3. **Increasing the efficiency of drink-water treatment plants**
   For domestic water it holds the same as water used for the production of hydropower. The more efficient the system, the less water is needed in order to produce the same amount of domestic water.

The options mentioned above are not implemented in the model in order to see the effect on the water allocation. Is is assumed that the water allocation remains the same, however the sectors will use their water more efficient in order to increase the profits within the sector. Since the water is economically most valuable in the agricultural sector, option 1, using greenhouses to produce crops will be the one which results in the highest increase of profits. There is no information available about the current efficiency of the hydropower stations and the efficiency of the drink-water treatments plants. Therefore it is difficult to argue the effect of these implementations.

8.5. Water Pricing

Pricing of goods is used in order to match demand of a good and its supply. When an economy is perfectly competitive, prices will adjust in such a way the demand and supply meet each other all the time (Hanke and Davis, 1973; MacEwan et al., 2006). An economy where the supply meets the demand is an efficient economy, since the income is maximised. When an economy is not in a perfect competition, pricing policies can be used. Since water become more and more scarce, a pricing policy is needed in order to maintain the sustainability of the water resources itself (Rogers et al., 2002). Increasing the prices of water will affect the water availability as followed:

- demand for water will be reduced;
- supply of water will be increased;
- allocation of water between sector will be facilitated;
- marginal efficiency will be improved due to increased revenues;
- sustainability of water use will be increased;
- per unit of water, cost of water to poor people will be reduced.

Water tariffs normally consist of two parts: variable costs and fixed costs (Rogers et al., 2002). The fixed costs are the same for all households, industries or farms. It includes the cost of being connected. The variable costs depends on the usage of water. Most of the time, block tariffs are used for these variable costs. Until a certain level of water usage, the price will be at the same level. If the individual usage rises above this level, the price will increase (Rogers et al., 2002). Since the costs are not included in the current model, this measure is not implemented in the model. Only the advantages and disadvantages will be discussed in this section.
One of the main advantages of a water market is that it most probably will affect the water use

efficiency in the region. Users of water will use their water more efficiently and therefore, less water will be lost. Increasing the efficiency is not the only reason for the introduction of a water market. Another advantage is that water will be allocated to the sectors or areas which generate most money out of it (Savenije, 2002). Sectors that generate more money out of the deviation of water, and therefore are good for the water allocation, will have more money available to buy and use the water. This argument mainly holds for the economic efficiency principle of optimising the water allocation. The gaps between rich farmers and poor farmers will increase and this is against the social equity principle of optimising the water allocation. Richer farmers will have money available to buy more water and therefore increase their yields and get more money as well. Another problem of a water market has to deal with the possibility to trade water (Savenije, 2002). Water will flow downstream and the availability depends over the time and is difficult to forecast. The water has to be used when and where it is available. A last disadvantage of a water market is the fact that water has different values (Savenije, 2002). Water is used for several purposes, and for all these purposes water will have a different value. When a water market is introduced, water price of water have to be applied. However, the profit generated by one cubic meter of domestic water is really limited. The price of water could be therefore only very small, which is negligible in the agricultural sector. Applying this water price in the agricultural sector would not have the positive affect of a water market.

9
Discussion

The results obtained in this research need some important qualifications. Assumptions and simplifications were made in order to get the results. Furthermore, the model is mainly about economic efficiency in which only the financial profits generated from the deviation of water are taken into account. The limits of the model might influence the optimal water allocation or the choice for a certain measure. The assumptions and limits of this model are discussed in this chapter. At the end of the chapter, some suggestions for future research are described.

9.1. Assumptions in the Model

During the research, several assumptions were made. These assumptions can cause a difference between the model results and the actual results. In this section, the main assumptions are summarised including their impacts.

Initial soil moisture - The initial soil moisture is based on the soil water index - first day of the month and root depth (Espinoza-Dávalos and Bastiaanssen, 2017). The soil water index is measured at a certain depth, most often at ten centimeters depth. It is assumed that this soil moisture index holds for the entire depth. However, in practice the soil moisture content will increase over the depth until a certain level. The profile depends on the soil type as can be seen in Figure 9.1 (Bogaard, 2017). At the surface, the soil moisture content will be lower and therefore the initial soil moisture might be overestimated. However, the unsaturated zone is deeper than the root zone (Bogaard, 2017). This difference might compensate the overestimation. Since, exact details about the unsaturated zone are unknown, the exact error of the initial soil moisture content is unknown.

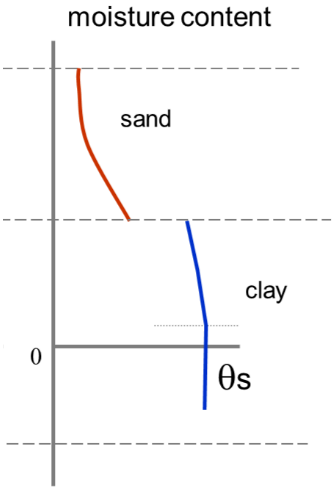


Figure 9.1: Moisture content profile in the unsaturated zone (Bogaard, 2017).

Connectivity matrix - Which subbasins are connected to each other is represented by a connectivity matrix. Whether there is a link between subbasins or not is based on the geography of the river. It is assumed that water will flow via the Litani river. Therefore, the subbasins that are connected to each other by the Litani river are connected in the connectivity matrix. However, via groundwater flow stored water can also flow from one to another subbasin. In that case, extra subbasins might be connected to each other. The total water availability in the LRB will remains the same, the water availability of downstream subbasins might be influenced. It is difficult to determine how it affects the water availability in each individual subbasin, for the one the water availability might be higher, while the water availability in another subbasin might be lower or the same.
The weight of an edge in the connectivity matrix is based on the runoff coefficients, which are determined by the models GLDAS and PCR-GLOBWB. The values are determined based on the characteristics of the subbasin. The river flow of the Litani river is part of the subbasin storage in the model. The runoff of a river differs from the runoff of a subbasin. Therefore, the weights of the edges in the connectivity matrix might be underestimated. If the weights are underestimated, the water availability in the upstream basins might be lower, while the downstream basins might have a higher water availability compared to the model.

Yield response factors - The yield response factor (k_y) qualifies the effect of water stress (Doorenbos and Kassam, 1979). Each crop has its own yield response factor. This factor not only depends on the crop type, but also on the growing stage of a crop. A deficit in evapotranspiration will mainly affect the yield in the yield formation phase. In the model, constant yield response factors are used. The yield response factor of bananas, grapes and olives is constant. However, the yield response factor of citrus, groundnuts, maize, potatoes, tobacco and wheat vary over the growing period. The effect of this assumption on the results will depend on the timing of the evapotranspiration deficit. If the evapotranspiration deficit occurs in the vegetative phase, the actual yields will be underestimated. The yield response factor is lower in the vegetative phase and therefore the effect on actual yield is smaller. If the evapotranspiration deficit occurs in the yield formation phase or flowering phase, the actual yields will be overestimated. In these phases, a water shortage will have a higher impact on the actual yield. Most of the crops have a higher yield response factor in the months June, July and August, the months with low precipitation levels. Farmers will irrigate in these months to reduce the yield losses.

Seasonal crops - The landcover data set used for the optimisation problem, only consists of data about seasonal crops. These seasonal crops are not specified. In Lebanon, five seasonal crop types are dominant: groundnut, maize, potato, tobacco and wheat (FAO and Aquastat, 2017). These crop types differ in crop coefficient, maximum yield, selling prices, maximum evapotranspiration and water sensitivity (FAO, 1974). Therefore a distinction has to be made between those seasonal crops. It is assumed that the five seasonal crop types are equally divided over the subbasins. In conclusion, 20% of the area covered with seasonal crops in a certain basin is covered by groundnuts, 20% by maize, etc. This assumption might influence the profits generated from water and the water availability for other crops. For example, maize and potato have a high potential evapotranspiration. If a subbasin is covered for less than 40% of the field crop area with those crops, this area needs less water and so more water is available for other subbasins. It is difficult to determine how the crops are actually divided over the area. Therefore, no conclusion can be drawn about the effect of this assumption.

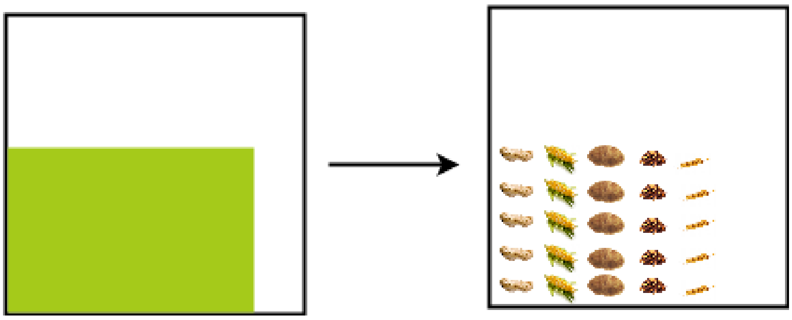


Figure 9.2: The green area in the left square represents the area covered with seasonal crops in a certain subbasin. 20% of this green area is covered with groundnuts, 20% with maize, etc.

Crops are not changing over the years - The crop data used in order to determine the profits in the agricultural sector is based on data of National Council for Scientific Research (2017). This map is generated in 2017, while the hydrological data used in the model is from 2010 - 2016. In conclusion, the crop maps does not match the hydrological data. Permanent crops will remain on a field for several years and therefore those areas will not change that much. Furthermore, 25% of the agriculture in Lebanon is commercial agriculture. The crops cultivated by the commercial farms will remain more or less constant. Commercial farms are specialised in a certain crop type and therefore they will not change their crops year to year. The other 75% of the agriculture in Lebanon is familiar agriculture. The crops cultivated by these farmers is variable. However, since there is already an assumption made about the seasonal crops, this potential changes does not matter. In conclusion, the assumption that the crop map of 2017 could be used in combination with the hydrological data of 2010- 2016 does not have significant effects on the model results.

Soil water storage - The field capacity of the soil indicates the maximum amount of water that can be stored in it. However, in the model, the Litani river is assumed to be part of the soil water storage. In other words, the Litani river is not separately modelled but the water of it is part of the groundwater flow. Therefore it is assumed that the maximum amount of water that can be stored is three times as large as the field capacity. Since, during the wet months, the flow of the river is significant larger compared to the soil water storage. Since there is no information available about the flow of the Litani river, the assumption that the river is part of the subbasins is made. If water is flowing through a river the evapotranspiration will be equal to the reference evapotranspiration, while when it is stored within the soil it will be 35% of the reference evapotranspiration. Therefore, more water will be available during the months in which the reference evapotranspiration is high. Furthermore, the effect of modelling the Litani river as being part of the soil water storage, will increase the soil water storage. Therefore, more water will be available for the non-irrigated crop lands and their actual yields might be higher. In conclusion, based on this assumption, the water availability within the model is higher compared to reality, especially for the non-irrigated crop lands.

Transpiration - The evaporation of a crop depends on the soil water content and the soil moisture depletion factor of a crop. Each crop has its own soil moisture depletion factor (p_c). However, in the model average p_c-values are determined for each subbasin, based on their crop cover. This assumption is made in order to simplify the model. However, as a result of this assumption, crops with a lower p_c compared to the average, will get more water than they are actually able to take from the soil. Crops with a higher p_c compared to the average, will get less water. If the evapotranspiration per crop type is taken, based on a p_c-value per crop type, an extra decision variable is added to the model. In such a model, the model has to determine to which crop the water will flow. However, the soil water storage is stable over a subbasin as well. Differentiation has to be applied to this soil water storage as well to get this crop specific transpiration. Furthermore, decreasing the decision variables in the model will reduce the complexity and therefore the run-time.

Production costs not included - One of the principles of optimal water allocation is economic efficiency. Therefore, total profits are compared in order to determine what the best measure is to take. Only the turnovers are compared, since the production costs are not taken into account. Taking into account the production costs could change the allocation of water over the sectors. If there are differences between the sectors in the production costs per unit of water, it might be more efficient to use more water for the sector with the lower production costs.
However, for the determination of the Lagrangian multiplier the agricultural costs have been taken into account. To determine the agricultural costs, only the prices of the trees or seeds are considered. Average prices and seeds and trees per hectare are used for this Lagrangian multiplier. Permanent crops will stay in the field for more than one year, their average lifespan is taken and it is assumed that the costs are the same for each year of their life. In the actual case, permanent crops have high investment costs and the costs will not be equal for each year. Furthermore, the prices of seeds and trees will fluctuate based on supply and demand. Therefore, the marginal costs will differ per year. Since average costs are taken we can argue that average marginal values are produced as well.

Agricultural irrigation - Only a part of the agricultural area is equipped for irrigation. The percentage of agricultural area equipped for irrigation is based on the data of the Food and Agricultural Organisation of the United Nations (FAO) and information gathered in meetings with local inhabitants (executed by Unesco-IHE). Based on this information, four categories of irrigation percentages are determined in

such away that 51% of the total agricultural land is equipped for irrigation (FAO and Aquastat, 2017). These categories of irrigation are based on the average precipitation in an area and the area covered with fruit and olive trees. The subbasins with comparable characteristics are assumed to have the same percentage of area equipped for irrigation. Since, the information about irrigation is limited, this is the best way to determine the percentage equipped for irrigation in each basin. However, this might cause differences between the modelled evapotranspiration and the actual evapotranspiration for specific subbasins. Over the entire basin, the irrigation percentage is 51%. For one basin the irrigation percentage might be overestimated, while it is underestimated for the other one. Irrigation is used to apply the amount of water a crop needs and therefore increase the yield. If a higher percentage of irrigation is applied in a subbasin with crops with a high water demand, the profits will increase. If an overestimation of irrigation is applied in a subbasin with crops with a low water demand, the total profits will decrease. More details about the agricultural irrigation are given in Appendix A.
Furthermore, it is assumed that the water used for irrigation comes from the groundwater. In reality, the water is pumped from Qaraoun Lake to Canal 800 or Canal 900 and transported to the North or South in order to be used for irrigation by the farmers. The assumption made is only plausible when the irrigation scheme of the LRB works well. Only when the irrigation scheme works well, water for irrigation will be available for all farmers, like in the model. However, in reality the quality of the water flowing through the canals has a bad quality and therefore water is not available for all farmers within the basin.

Bare soils - The area of the LRB is not entirely covered with crops. In the model, the area which is not covered by crops is assumed to be bare soil with an evapotranspiration coefficient of 0.35 (Doorenbos and Kassam, 1979). Not the entire area which is not covered by crops will be bare soil, but a part of the area will be covered by farms, buildings or industries as well. Those areas have a lower coefficient, since water will runoff and so not evaporate. If the water evaporated in non-crop areas is smaller, more water will be available for the supply of domestic water, production of hydropower or agriculture. In other words, less water is lost and therefore the actual turnovers will be higher.

Stable runoff coefficients - The runoff coefficients of each subbasin are determined based on two models: GLDAS and PCR-GLOBWB. These models combine several characteristics of the area in a runoff coefficient. Runoff coefficients depend on soil characteristics, vegetation characteristics and elevation. Soil characteristics and elevation will be more or less constant over time. Vegetation characteristics will differ over the months and between years. For example the greenness of the vegetation: due to extreme high temperatures the vegetation might be less green compared to other years and therefore influences the runoff coefficient. However, an average value for the runoff coefficients is taken. The characteristics of one month might have a higher impact on the water availability than the impact of another month. For example, the months with a high precipitation level, will have more water available and therefore are more important for the determination of the runoff coefficient. The greener the vegetation, the more water they will hold and the lower the runoff coefficient will be. So, in reality, the runoff coefficients might be higher compared to the coefficients used in the model. This will increase the water availability in the downstream basins, since more water will flow to these basin. Since the marginal value in these areas is high, the profits in the optimised water allocation are underestimated.

Gamma (γ) - The bare-soil evapotranspiration is determined by the water availability and reference evapotranspiration. The rest of the water available within the LRB can be used for the production of hydropower or for the irrigation of agricultural crops. One part of the water, the value of γ, is used for the irrigation of the crops. The other part, 1-γ, is used for the production of hydropower. This distribution of water is not based on the optimal case, but on the current situation. The value of γ is used to determine the value of α. Which is added to the the objective function in order to model the current situation. If α is not included in the objective function, all the water available within the basin will flow to the most profitable sector. As described in Section 4.3, the value of γ is determined by using the GLUE-method. The current water balance of the LRB is used in the GLUE-method. Hydrological parameters of 2010-2016 are available, which are used to determine the "rest" water. This "rest" water will be divided over the two sectors in such a way that the difference between the observed evapotranspiration and the modelled evapotranspiration of Espinoza-Dávalos and Bastiaanssen (2017) is as small as possible. The value of γ is based on the sum of the water balance of the seven available years. It would be better to increase the details of γ, for example by determining a value for each month. However, the value of Espinoza-Dávalos and Bastiaanssen (2017) are also based on a model and so are not the "real" values. It is unknown what the differences and the directions of these differences are between the values of Espinoza-Dávalos and Bastiaanssen (2017) and the "real" values. If the values of evapotranspiration are sometimes too high and the other times too low, it is better to use the average values. If the values are always too high or too low, a value per month would be better. Since the direction of the error is unknown, the effect of an average γ on the model is also unknown.

Alpha (α) - The value of α follows, among other things, from the value of γ. As discussed in the previous point of discussion, it would be better to increase the detail of γ and use different values for it. This would also affect the value of α. The current value of α is an average of the seven years of which hydrological data is available. The water used for hydropower is more or less equal over the years. However, the precipitation is decreasing. If the precipitation decreases, the water availability within the LRB will decrease as well. Since the water used for the production of hydropower remains equal, the water that can be used by the agricultural sector will decrease and therefore the turnovers generated in this sector as well. Based on this information, it can be argued that the value of α is decreasing over the years and might further decreasing in the years after.

Water used for hydropower - Hydropower in Lebanon is produced in three hydropower stations: Markaba, Awali and Joun. These hydropower stations operate in a cascade hydropower system. This means that water used by a hydropower station can be used by the following one as well (Bou-Fakhreddine et al., 2016). The Awali plant, the second plant, has the highest capacity of the three hydropower stations. In order to produce its maximum power of 108 MW , 34 m^3/s of water is needed. In the model it is assumed that this amount of water originates from Qaraoun Lake. However, as can be seen in Figure 9.3, water can also originate from Laka Anan. In conclusion, the amount of water used for the production of hydropower and the profits generated out of it might be lower.

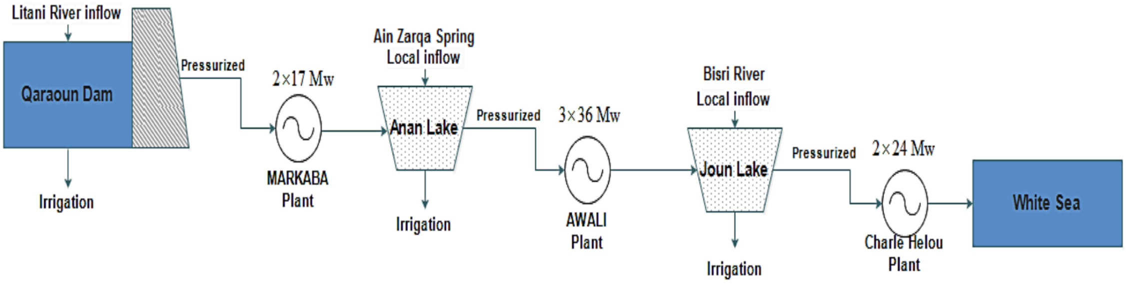


Figure 9.3: A representation of the cascade hydropower system in Lebanon. The hydropower plants are coupled to each other, water used in the one plant can be used in the plants after as well (Bou-Fakhreddine et al., 2016).

Water supply to Beirut - The water that could be supplied to Beirut is firstly used for the production of hydropower. At the moment, this amount of water is also used for the production of hydropower. A part of this water will be used to supply to the inhabitants of the LRB and where the other part is used for is unknown. Most probably, this water will not just flow into the sea, but it will be used for a certain purpose. The suggestion proposed in Chapter 6 could be impossible, when the water has already a certain purpose. In that case, extra water has to be taken out of the Qaraoun Dam in order to increase the flow flowing through the hydropower stations and afterwards can be used for the supply of domestic water to Beirut. The hydropower stations are able to deal with this amount of water, however there will be not enough water available in the basin to supply this amount of water.

9.2. Proposed Measures

Some measures are proposed in order to improve the water allocation of the LRB. For some of these measures, some important notes have to be made. These notions are discussed in this section.

Increase efficiency of irrigation system - Different definitions are used for irrigation efficiency. The most applied definition is: *'the fraction of beneficially used water of the total amount of water that is applied'* (Halsema and Linden, 2012). However, the spatial and time scale is important in this definition. Water that might be assumed as a loss for one farmer, could be a gain for another farmer (Halsema and Linden, 2012; Lankford, 2012). Water applied by an irrigation system could evaporate, but water can also infiltrate to the groundwater table or runoff to other fields. The boundaries of an irrigation system are not equal to the boundaries of a water system (Lankford, 2012). For example, when water runs off to another field of another farmer. This water is assumed to be a loss of the owner of the irrigation system, but a gain for the farmer who lives downstream of this farmer. When drip irrigation is used by a farmer in the LRB, this might increase the irrigation efficiency of the particular farmer, but it does not mean that it also increases the irrigation efficiency of the total area.

Effectiveness of increasing the irrigation efficiency - As described in Chapter 8, the changes within the water allocation are not observed by increasing the efficiency of the irrigation systems. As described in the previous note, in reality this could be the case. However, in the model it is assumed that the water that will not be used by the crops will evaporate. Since less irrigation water will be evaporated, the agricultural water use and therefore also the profits generated within the agricultural sector should increase.

Water pumped out of LRB after production of hydropower - Water used for the production of hydropower is flowing out of the LRB and into another basin in Lebanon. Where this water is used for is unknown, but for sure it has its purposes in that basin as well. One of the measures that is suggested in Chapter 8, is to change to another type of sustainable energy. When this measure is applied, water of the LRB will stay in the basin and could be used for agriculture. However, the water cannot be used in the other basin and so could possibly negatively affect the profits generated from water in Lebanon. This measure is only a useful measure for optimising the water allocation of the LRB and maybe not for Lebanon entirely. Most probably, the LRA cannot implement this measure since it affect other stakeholders. A model in which both basins are included should be generated in order to determine whether this measure is a good measure or not.

Change to another type of sustainable energy - Hydropower could for example be replaced by solar energy or wind energy. The model used for the optimisation of the water allocation in the LRB is only about increasing the profits generated from water. It does not take into account the investment costs of wind turbines or solar panels. These investment costs will be high and take a while before they are earned back. The investment costs of the El Wauroun Dam has been high in the past as well, so it might be better to earn as much money as possible by using this dam.

Produce more water insensitive crops - The measure in which water sensitive crops are replaced by water insensitive crops works well in this area. Not only because of the fact that the drop in yield will be less if water-deficit occurs, but also because of the fact that these crops are more profitable. However, when there is more produced there is a risk of crop diseases and a decreasing market price. Therefore, the solution might be less effective as showed by the model, since these factors are not taken into account.

9.3. Recommendations for Future Research

Future research regarding this topic would be of great help in improving the water allocation of the LRB. Research topics that would be helpful are discussed in this section.

Land cover and irrigation details - Currently, only limited data about land cover and irrigation is available. Future research in which this data is improved could improve the results obtained by the optimisation function. For example, the seasonal crops are not split into the specific crops and therefore assumptions have to be made. The land cover maps should be improved in such a way that all crops of the LRB are represented in it. Satellite-data could also be used in order to determine where irrigation is applied and where not.

Costs of each water using sector - The current model is only about turn-overs generated from the deviation of water. However, the model and optimisation will be even better when the costs are included as well. At the moment, it is difficult to find complemte information about the costs. Information is available of some of the cost components. Since one sector is more complete than other, the costs are not taken into account at the moment. If more details about the costs are collected, the costs can be taken into account as well.

Include the dimensions of the Qaraoun Lake - Water is stored in the Qaraoun Lake in order to produce hydropower. A minimum water level at the El Wauroun Dam is needed in order to produce this hydropower. At the moment, the dimensions of the lake are not taken into account and it is assumed that the water level is sufficient in the months September - April. However, changes in the water availability might influence the period in which the water level is high enough. Including the dimensions of the Qaraoun Lake would give a better insight in the water level and thus the possibility to produce hydropower.

Determine social values of water - The optimisation of the water allocation in this study is based on economic values of water. However, water allocation optimisation is about maximising the social benefits gained from the deviation of water. These social benefits are more than the economic profits. It would be interesting to include the social value of water in the model in order to see how the effect on the optimal water allocation. The social value of domestic water is higher than the social value of agricultural water, which is the other way around in economic values.

Potential scenarios - A trend analysis of Lebanon and comparable areas will help to define in which direction important parameters will move. For example, the population of the LRB. Will it increase or decrease? And what are the expected rates of growth or decrease. Based on a better insight in the future of Lebanon and the LRB, better suggestions for improvement can be done.

Include Litani river in the model - In this model, the water of the Litani river is part of the soil water storage. It would be interesting to adapt the model in such a way that the Litani is separately modelled. This could help in getting insights about when there is water flowing through the river and when the river is dried out.

Measurements of hydrological conditions within the LRB - The model defined in this project is based on data originating from a model. No measurements of hydrological data are available in order to calibrate the model with. Therefore it would be really useful to do measurements. This makes calibration of the model possible and based on a calibrated model, a better advice could be made to the LRA. Based on the actual measurements, the actual situation can be compared with the situation in which all the inhabitant of the LRB try to maximise the total income of the LRB. Differences between this actual situation and the optimised situation could help the area preventing from a water crisis.

10

Conclusion and Recommendations

A water crisis is looming for Lebanon, since water availability is decreasing and the water demands are increasing. In order to protect Lebanon for this water crisis occurring, the water allocation of the Litani River Basin is optimised in this research. An answer to the research question is found by using four sub-questions. It is important to note that some assumptions, described in Chapter 9, are made in order to get this answer. These sub-questions are answered in this chapter in order to conclude with the answer to the research question:

'What is the optimal water allocation for the Litani River Basin, and which actions could improve this water allocation?'

1. What is the current water allocation based on the current water balance? What are the differences between the 'actual' water allocation and the modelled water allocation?

In the model it is assumed that the inhabitants of the LRB try to maximise the total income of the LRB. Based on this assumption and the hydrological conditions of the area, the current water allocation is modelled. For modelling this current water allocation the power of the agricultural sector and the hydropower sector are taken into account. Currently, the hydropower sector have more power.

In the current water allocation, 71.7% of the water is used by the agricultural sector. The other part, 28.3%, is used to produce hydropower. The water used for the production of hydropower can be used for other purposes afterwards. Of the amount of water used for the production of hydropower, 23.4% is used for the supply of domestic water to the inhabitants of the LRB.

Water allocation is not only about dividing the water over the sectors, but also over the area and time. The spatial deviation of water is compared with data provided by Espinoza-Dávalos and Bastiaanssen (2017). The total amounts are comparable, however the values differ from subbasin to subbasin. In some subbasins, the modelled agricultural water use is higher while in other the use is lower. Since, it is assumed that the inhabitants are trying to maximise the total income of the area, the model is assumed to be the representation of the current water allocation. In this water allocation, the agricultural water flows to the subbasins with the highest marginal value. In other words, the water will be used in the subbasins in which the highest value can be reached with using the water.

The last dimension of water allocation is the temporal dimension. In the current water allocation, the water use is high when the water demand of the area is high as well, so during the dry, warm months.

2. What is the effect on the water allocation, if water is also allocated to Beirut?

Since it become increasingly difficult to provide enough domestic water for Beirut, a water supply from the Litani river to Beirut is proposed. Water used for the production of hydropower can be supplied to Beirut afterwards. The yearly demand of Beirut is 93 million m^3. In order to increase the flow to the hydropower stations, more water has to flow to the Qaraoun Lake and therefore less water can be used in the subbasins for agricultural purposes. The agricultural sector is more profitable and therefore the total generated profits will decrease. In the first years, enough water is stored in Qaraoun Lake to supply domestic water to Beirut. However, as a result of this increase water demand of the hydropower stations, the lake will be almost empty at the end of the wet season. In the dry season, the increase in water level is only limited. It becomes more and more difficult to supply enough water to Beirut. In the last modelled years, not enough water can be supplied to Beirut.

In the first years, enough water can be supplied to Beirut. So, potentially a part of the water demand of Beirut can be supplied by the Litani river. However, the water is flowing to the hydropower stations nowadays as well. Most probably, this water will be used afterwards for a certain purpose. However, this purpose is unknown. Therefore it is also unknown if the water just can be taken, or if the demand of Beirut should be above the current flow to the hydropower stations.

3. What is the effect on the water allocation, if water is allocated from Qaraoun Lake to the downstream basins?
In the current water allocation, the water levels in Qaraoun Lake are higher in the dry season. During these months, the water of the lake is not used for the production of hydropower. During these months, the water demand of the crops is high and water from the lake to the downstream subbasins could increase the profits in this area. However, the effect is negligible. The storage of the lake is limited and therefore only a small amount of water will flow to the downstream basins. If only the subbasin direct downstream of the Qaraoun Lake is considered, only 1 mm/month will flow to the subbasin. A part of this water will be evaporated.

4. What measures can be taken in order to optimise the water allocation?
The best measure that could be taken in order to optimise the water allocation of the LRB is to replace water sensitive crops by water insensitive crops. For water insensitive crops, the drop in yield will be less if a water deficit occurs. This is not the only reason that the measure is effective, another reason is that the water insensitive crops in this area are profitable crops. The selling prices of the products are higher than the selling prices of the water sensitive crops. However a drop in market prices due to an increase supply is not taken into account.
The water allocation is not changed by implementing this measure, since all the wheat and maize crops are replaced. In the model, an assumption is made about the deviation of the seasonal crops. Since the deviation of the seasonal crops is assumed to be the same for the entire LRB, the spatial allocation of water will not change.

In the optimal water allocation, the largest part of the water will be used in the agricultural sector. It is assumed that everyone tries to maximise the total income derived from the deviation of water. Therefore the water has to flow to the money. The agricultural sector is more profitable compared to the hydropower sector and the domestic sector and therefore this sector will use most of the water. Within the agricultural sector, the water flows to the areas with the highest marginal value. However, this all is assumed based on the fact that everyone tries to maximise the income. An individual farmers might cheat on this goal in order to increase its own profits. This could also be a reason for the differences between the model and the data of Espinoza-Dávalos and Bastiaanssen (2017). If all the individual farmers just cheat a little bit, the impact will be significant. Control is needed by an external party like the LRA. Irrigation water could be controlled, but it is more difficult to control the groundwater. The LRA could advise the farmers cultivating water sensitive crops to change to to a water insensitive crop. In that case, the farmer will become less depended of the water available and the urge to cheat might decrease.

For the Lebanese economy it would be better if another solution is found in order to supply enough water to Beirut. Based on the current hydrological conditions it is already difficult to supply the entire demand of Beirut. Since, it is expected that the water availability will decrease in the coming years, it will become even more difficult in the years after to supply enough water to Beirut. However, a part of the demand of Beirut could be supplied by the LRB. If water is supplied to Beirut, the power of the hydrological sector will increase. This means a decrease in the power of the agricultural sector (if the other variables remain the same) and therefore an decrease in the profits generated within the LRB. According to the economic efficiency principle the water allocation will be less optimal, but optimising the water allocation is described by more principles. The other two principles of optimal water allocation are the sustainability principle and the social equity principle. Since the water levels of the Litani river are not included, it is difficult to review the sustainability principle. Although emptying the Qaraoun Lake is not according to this sustainability principle. The social equity principle is about the fact that all sectors and individuals should have equal access to water. The agricultural water is equally divided over the area and therefore according to the principle of social equity. There is also enough domestic water available for the inhabitants of the LRB. However, when the entire country is taken into account for the review of the optimal water allocation, the water allocation will be more optimal when water is supplied to Beirut. In that case, the inhabitants of Beirut get the same possibility to access the water. The change from water sensitive crops to water insensitive crops could help optimising the water allocation. The water insensitive seasonal crops groundnut and tobacco are more profitable compared to the water sensitive seasonal crops wheat and maize, and less dependent of the water availability. This measure could help to increase the profits generated from the deviation of water, but the profits can also be remained at the same level. Less water is needed to achieve these profits with the water insensitive crops. The water which is not needed anymore in the agricultural sector can be supplied to Beirut.

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A

Parameters

Some of the exogenous parameters used for the optimisation of water allocation in the LRB are described in this appendix. The three sectors using water (agriculture, hydropower generation and domestic water supply) are the most important for the optimisation. Factors corresponding these three sectors are given and explained in this appendix.

A.1. Agricultural Crop Factors

Several crop characteristics are needed in order to determine the profits that can be generated out of the derivation of water in the agricultural sector. Factors that are needed are: crop coefficient, yield response factor, maximum yield and the selling price. In this section the values used for these factors are given and described.

The crop coefficient (k_c) indicates the crops water use. Crop water use is equal to the reference evaporation multiplied by the crop coefficient. The crop coefficient depends on the type of crop and stage of growing in which the crop currently is. The crop coefficient of the most common crops in Lebanon are given in Table A.1. The values are based on the data of FAO, by Doorenbos and Kassam (1979). To determine the values, the climate of Lebanon is considered to be subtropical and between humid and dry.

Table A.1: Crop coefficient of the most common crops of Lebanon (Doorenbos and Kassam, 1979).

	Permanent crops				**Seasonal crops**				
	Olives	Banana	Citrus	Grapes	Groundnut	Maize	Potato	Tobacco	Wheat
January	0.500	1.10	0.750	-	-	-	-	-	1.12
February	0.500	0.750	0.750	-	-	-	-	-	0.670
March	0.500	0.750	0.700	0.250	-	-	-	-	0.670
April	0.500	0.700	0.700	0.450	-	-	-	-	0.220
May	0.500	0.720	0.700	0.620	0.450	0.400	0.450	0.350	-
June	0.500	0.800	0.650	0.720	0.750	0.820	0.750	0.750	-
July	0.500	1.00	0.650	0.720	1.02	1.12	1.12	1.10	-
August	0.500	1.15	0.650	0.670	0.750	0.850	0.900	0.950	-
September	0.500	1.15	0.650	0.550	0.570	0.570	0.720	0.800	-
October	0.500	1.15	0.700	0.450	-	-	-	-	0.350
November	0.500	1.10	0.700	0.350	-	-	-	-	0.750
December	0.500	1.10	0.700	-	-	-	-	-	1.12

The crop factors are not the only important factors to determine the profit that can be generated from water. Therefore, the actual yield and the selling price are also needed. The actual yield depends on the following factors: yield response factor (k_y) and the maximum yield (Y_{max}). The values used for these factors are given in Table A.2.

k_y is the response of yield to the water supply. If k_y is larger than 1, it is a water sensitive crop. This means that there is a significant drop in the actual yield. When k_y is smaller than 1, it is a water insensitive crop and the impact of the drop in actual yield will be less significant. The Y_{max} is the maximum yield that can be achieved when the water supply is not limited. Both factors are based

on the data of Doorenbos and Kassam (1979). To determine the selling price of the cultivated crops averaged data of the last 10 years is used. Several data sets are used in order to get all the selling prices. The source used for each crop type is given in Table A.2.
The last crop related factor is the soil water depletion factor for no stress (p). This is a fraction of the soil water that can be depleted from the soil water before moisture stress occurs. The factors are based on the data of Doorenbos and Kassam (1979) and specified for Lebanon based on the maximum evapotranspiration of 4 mm/day.

Table A.2: Crop factors for the most common crops of Lebanon

	Permanent crops				**Seasonal crops**				
	Olives	Bananas	Citrus	Grapes	Groundnut	Maize	Potato	Tobacco	Wheat
k_y [-]	0.500	1.20	1.20	0.850	0.700	1.25	1.10	0.900	1.10
Y_{max} [tonne/ha]	33	50	30	7.5	4.0	8.0	30	2.0	5.0
p [-]	0.700	0.475	0.600	0.475	0.600	0.700	0.350	0.700	0.600
Price [USD/tonne]	4500 (Indexmundi, 2017)	545 (FAO, 2017)	847 (Indexmundi, 2017)	1300 (FAO, 2017)	1893 (FAO, 2017)	282 (FAO, 2017)	1145 (FAO, 2017)	2375 (FAO, 2017)	298 (FAO, 2017)

A.2. Qaraoun Lake

Water of the Qaraoun Lake is used for several purposes. The water can be used for the production of hydropower, for supply of domestic water or it can flow to the downstream area and be used for irrigation. Like the subbasins, the lake is filled by precipitation and runoff of upstream subbasins and emptied by the sectors using water and evapotranspiration. The sectors that use water and the corresponding variables will be described in this paragraph. The variables are summarised in Table A.3. In total 220 million m^3 of water can be stored in the Qaraoun Lake. The model used for the optimisation of the water allocation starts in January. Since January is in the wet season, it is assumed that 165 million m^3 of water is stored in the Lake at the start.

Production of Hydropower

The maximum amount of energy that can be produced by the hydropower stations is 190 MW, 34m^3/s of water is needed to generate this energy (Bou-Fakhreddine et al., 2016). The three hydropower stations of the LRB, Markaba, Awali and Joun, work in a cascade system. This means that the water used by the one station can be used in the next hydropower station as well (Bou-Fakhreddine et al., 2016). The paper of Bou-Fakhreddine et al. (2016) shows the power that can be produced for several discharges. Based on this data, the linear trend line for converting flow to power (kWh) is:

$$P_{hydro} = 0.0537Q_{hydro} + 15361 \tag{A.1}$$

This trend line as determination coefficient (R^2) of 0.9943. This formula will be used to convert the flow to the hydropower stations to the generated power.

Supply of Domestic Water

The water used for the supply of domestic water is a fixed amount of water, which is 25 million m^3 per year. It is assumed that this water is taken out equally divided over the year, except the 'dry' months, so approximately 3 million m^3 per month. This water is sold to the households, who pay between 0.1 and 0.3 USD/m^3 (FAO and Aquastat, 2017). If water is also supplied to Beirut, the total domestic water supply will be 118 million m^3 per year.

Water to Downstream Subbasins

Another option for the water in the Qaraoun Lake is to flow to the downstream subbasins. This will be a factor between zero and one of the total storage in the lake. This factor will vary over time, since the model tries to maximise the profit. This variable is represented in the constraints described in **??**. However the outflow to the downstream basins is limited by the maximum outflow of the dam, which is represented in the next equation (Litani River Authority, 2012b):

$$Q_{max} = 0.607KV^{0.295}h^{1.24} \tag{A.2}$$

K = Overtopping multiplier = 1 $[-]$
V = Reservoir volume = 220 million $[m^3]$
h = height of dam breach = 60 $[m]$

Table A.3: Hydropower related factors to determine the profit that can be generated out of water

Factor	**Value**	**Source**
$S_{dam,0}$	110 million m^3	*assumption*
$S_{dam,84}$	100 million m^3	*assumption*
$S_{dam,max}$	220 million m^3	(FAO and Aquastat, 2017)
$Q_{hydromax}$	90 million m^3/month	(FAO and Aquastat, 2017)
$Q_{hydro,0}$	30 million m^3/month	*assumption*
$Q_{hydro,84}$	29 million m^3/month	*assumption*
Price [USD/kWh]	0.036	Lebanon Electricity Tariffs (2017)
$h_{dam,max}$	860 m	USAID
Q_{max}	39.38 m^3/sec	USAID
$Q_{domestic}$	2083333 m^3/month	(FAO and Aquastat, 2017)
$Q_{domestic,Beirut}$	9833333 m^3/month	(FAO and Aquastat, 2017)
Price domestic water [USD/m^3]	0.2	(FAO and Aquastat, 2017)

A.3. Irrigation

In Lebanon, 51.4% of the agricultural area is equipped for irrigation (FAO and Aquastat, 2017). However, details about how this is divided over the country are unknown. It is assumed that this percentage of 51.4% also holds for the LRB, but also within the LRB percentages might vary. Based on meetings with inhabitants of the LRB (executed by Unesco-IHE), some details of the deviation of irrigation over the area are known. The precipitation in the West and South is higher and therefore the irrigation is lower. Furthermore, olives and fruits are mostly rain-fed. Based on this information, four categories of irrigation are defined. The numbers corresponding to the categories are calibrated to the given percentage of irrigation of 51.4% of the agricultural land by FAO and Aquastat (2017). Based on the numbers given in Table A.4, precipitation data and crop data of the LRB, in the model 51.2% of the agricultural land in the LRB is equipped for irrigation. An overview of the irrigation percentages is given in Figure A.1. This figure shows that the the area equipped for irrigation is smaller in the South and West, since the precipitation is higher in these areas. The model uses total area basins instead of agricultural areas and therefore the irrigation percentages have to be converted. These values are given in Table A.5 and are calculated by using the following equation:

$$\text{Irrigation} = \frac{A_{agri} * Irr_{agri}}{A_{total}} \tag{A.3}$$

Table A.4: Irrigation categories used for the LRB. The numbers are percentages of the agricultural land.

	P $\leq \bar{P}$	P $\geq \bar{P}$
$A_{fruit,olive} \leq \bar{A}_{fruit,olive}$	0.9	0.43
$A_{fruit,olive} \geq \bar{A}_{fruit,olive}$	0.7	0.3

Table A.5: Part of the total area of a subbasin that is equipped for Irrigation

Subbasin 1	0.29	**Subbasin 21**	0.067	**Subbasin 41**	0.80
Subbasin 2	0.009	**Subbasin 22**	0.39	**Subbasin 42**	0.88
Subbasin 3	0.074	**Subbasin 23**	0.059	**Subbasin 43**	0.90
Subbasin 4	0.31	**Subbasin 24**	0.18	**Subbasin 44**	0.85
Subbasin 5	0.42	**Subbasin 25**	0.52	**Subbasin 45**	0.89
Subbasin 6	0.42	**Subbasin 26**	0.36	**Subbasin 46**	0.74
Subbasin 7	0.24	**Subbasin 27**	0.90	**Subbasin 47**	0.61
Subbasin 8	0.35	**Subbasin 28**	0.072	**Subbasin 48**	0.36
Subbasin 9	0.30	**Subbasin 29**	0.59	**Subbasin 49**	0.90
Subbasin 10	0.88	**Subbasin 30**	0.90	**Subbasin 50**	0.21
Subbasin 11	0.79	**Subbasin 31**	0.90	**Subbasin 51**	0.43
Subbasin 12	0.81	**Subbasin 32**	0.70	**Subbasin 52**	0.42
Subbasin 13	0.78	**Subbasin 33**	0.60	**Subbasin 53**	0.16
Subbasin 14	0.70	**Subbasin 34**	0.33	**Subbasin 54**	0.21
Subbasin 15	0.86	**Subbasin 35**	0.22	**Subbasin 55**	0.30
Subbasin 16	0.14	**Subbasin 36**	0.037	**Subbasin 56**	0.17
Subbasin 17	0.10	**Subbasin 37**	0.82	**Subbasin 57**	0.38
Subbasin 18	0.60	**Subbasin 38**	0.17	**Subbasin 58**	0.092
Subbasin 19	0.43	**Subbasin 39**	0.35	**Subbasin 59**	0.078
Subbasin 20	0.69	**Subbasin 40**	0.53	**Subbasin 60**	0.084

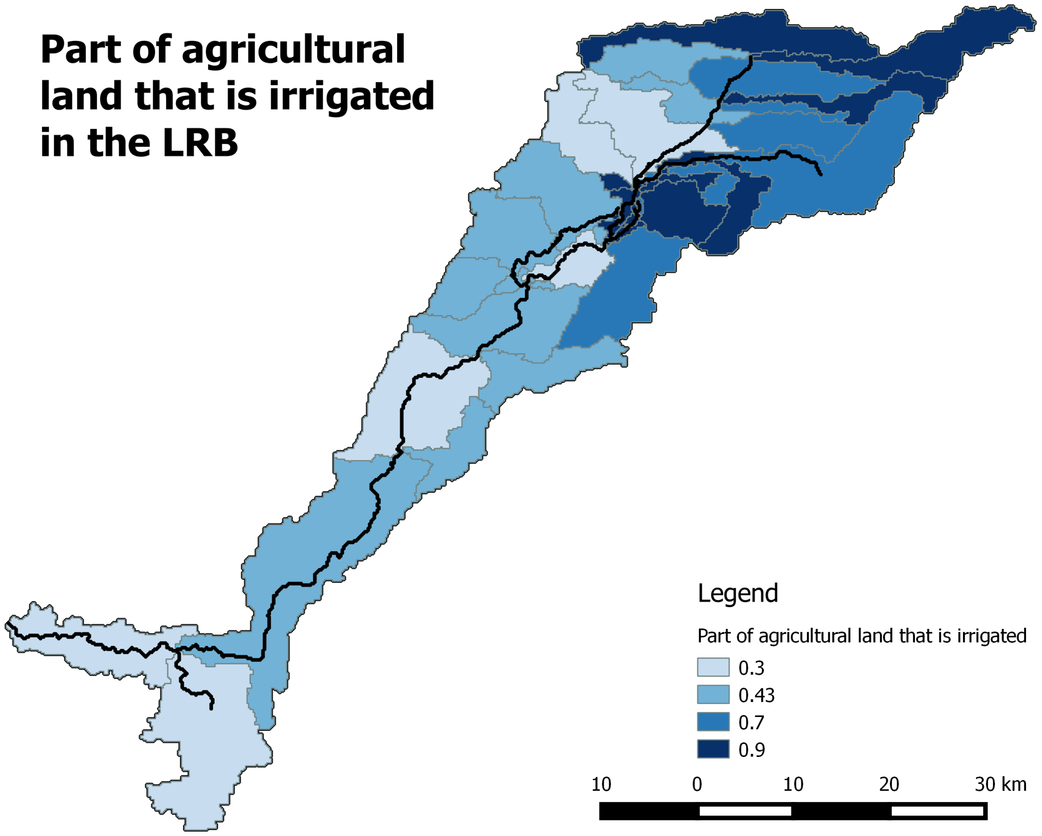

Figure A.1: An overview of the part of the agricultural area that is equipped for irrigation. These numbers are based on the four categories of Table A.4 and the fact that on average 51.4% of Lebanon is equipped for irrigation (FAO and Aquastat, 2017).

B

Prices Agricultural Products

In order to determine the marginal values in the subbasins of the LRB, purchase prices of the crops are needed. In order to determine these values, several sources are used. It is difficult to determine which exact types of crops are growing in an area and which density is applied. Therefore, average prices, average densities and average lifespans are used in order to determine the prices. In Table B.1 an overview is given of the data used, the corresponding data sources and the total costs based on the numbers.

Table B.1: Prices used for the determination of the Lagrangian multiplier. The prices, trees/seeds per hectare and lifespans are obtained via several sources

Crop type	**Total costs [USD/ha/year]**	***Cost components***
Maize	20 (Vroegindewey and Crawford)	Not applicable
Olives	560	\$60 per tree (TyTy)
		650 trees per ha (The olive oil source)
		Lifespan is 70 years (SF Gate)
Banana	48000	\$80 per tree (TyTy)
		6000 trees per ha (TNAU and ICAR)
		Lifespan is 10 years (Sanders)
Citrus	111	\$50 per tree (Bloomszs)
		300 trees per ha (NewCrop)
		Lifespan is 135 years (Sanders)
Grapes	10000	\$50 per tree (ttoo-shotz)
		10000 trees per ha (Hemming)
		Lifespan is 50 year (SF Gate)
Groundnut	70	45 kg seeds per ha (Pradesh)
		\$1.56 per kg seeds (Theorganicfarmer)
Tobacco	4 (Ur Rahman)	Not applicable
Wheat	75 (Stiles)	Not applicable
Potato	18000	2000 kg per ha (Aardappelpagina)
		\$8.82 per kg (GrowOrganic)

C

Directed Graph of Subbasins

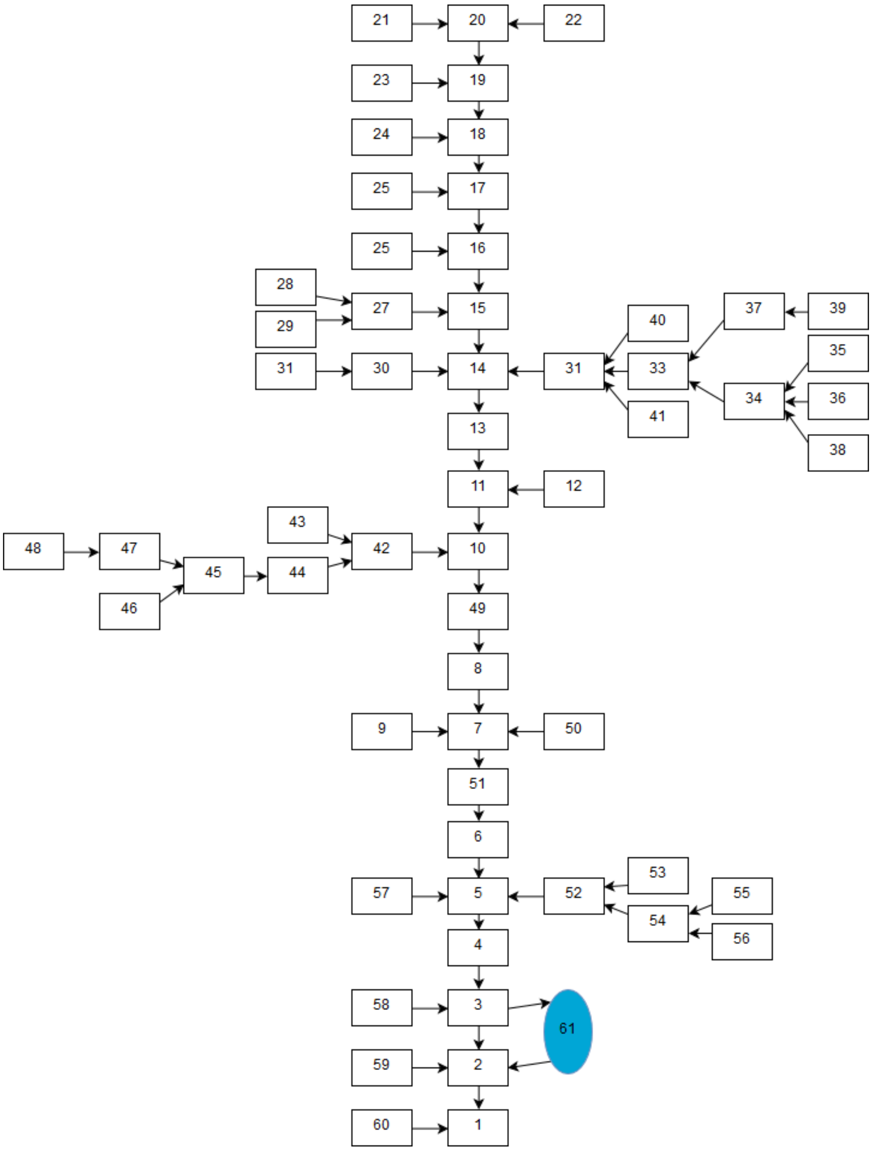

Figure C.1: An overview of how the subbasins of the LRB are linked to each other. The water flows in the direction of the arrows. Subbasin 61 is Lake Qaraoun.

D

Difference between Actual Water Allocation and Optimal Water Allocation

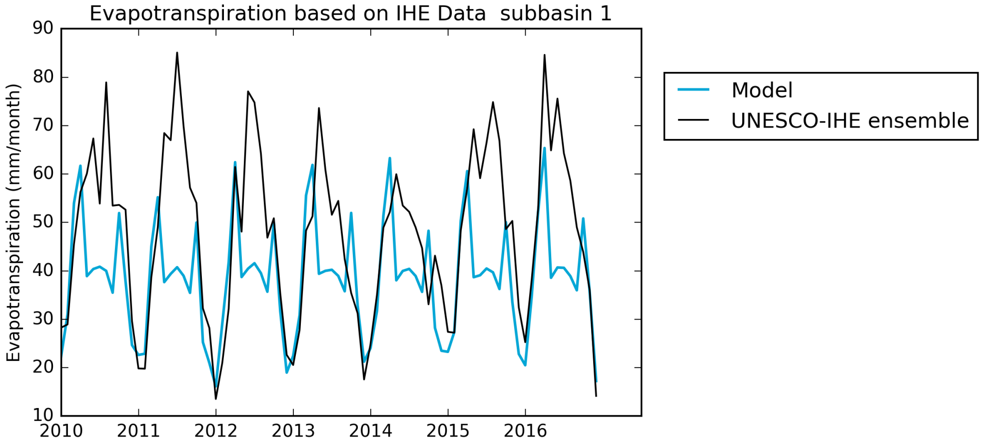

Figure D.1: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 1.

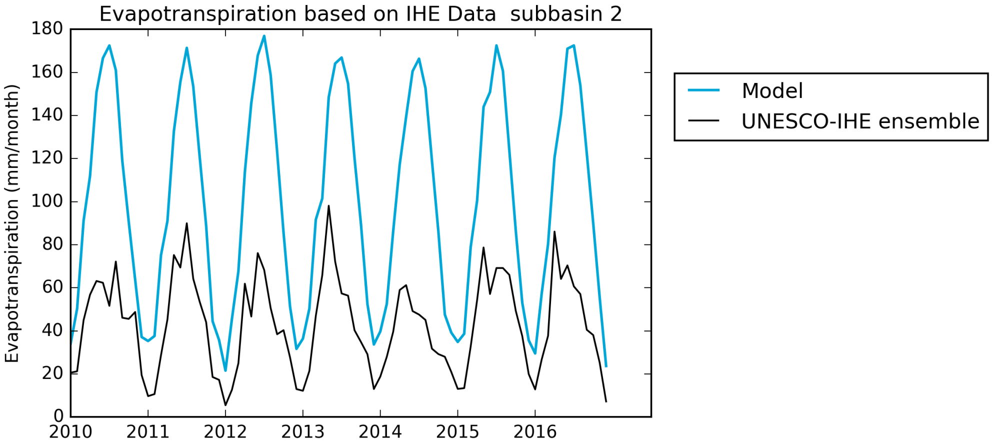

Figure D.2: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 2.

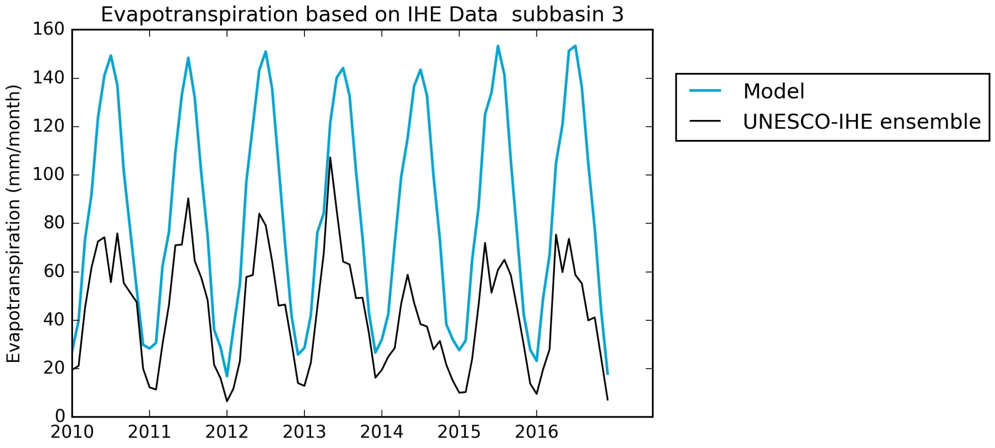

Figure D.3: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 3.

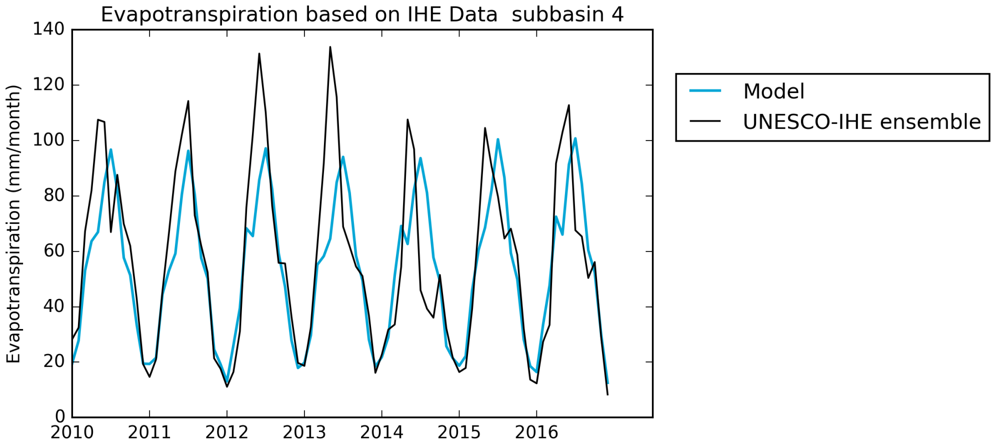

Figure D.4: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 4.

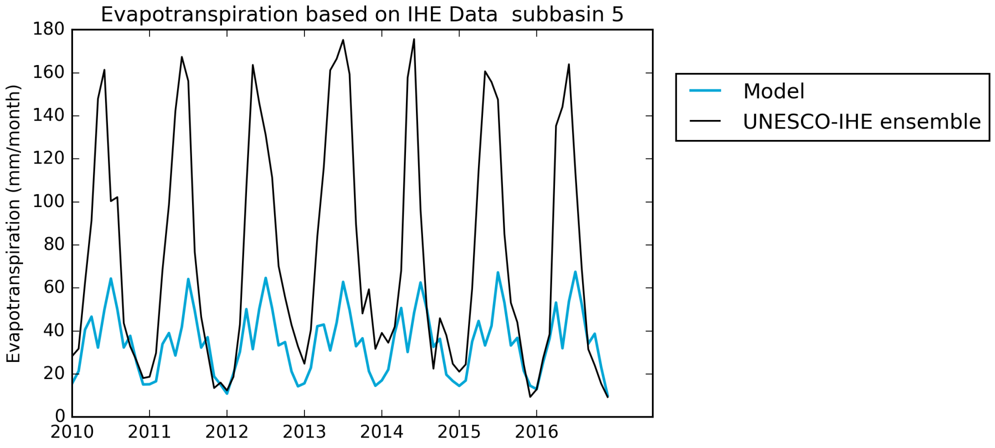

Figure D.5: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 5.

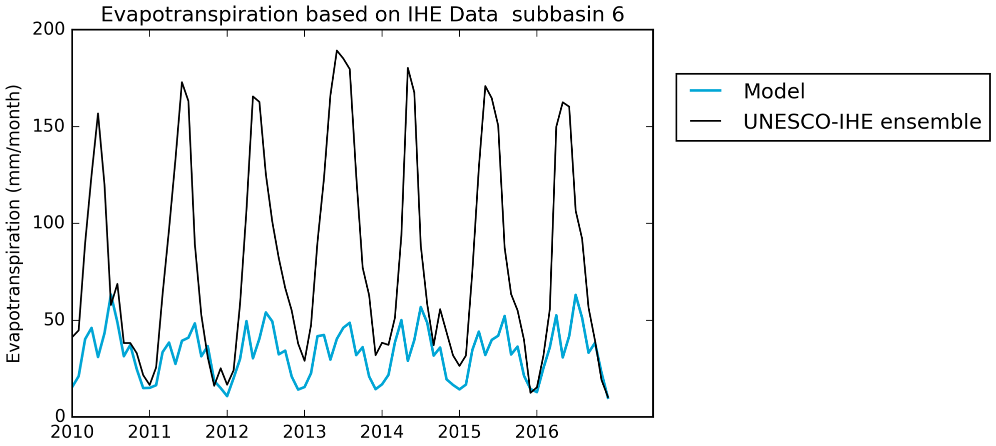

Figure D.6: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 6.

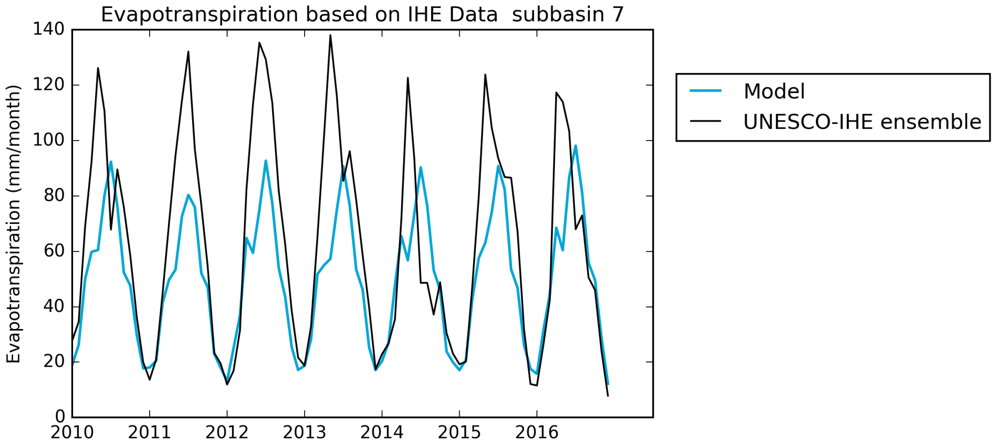

Figure D.7: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 7.

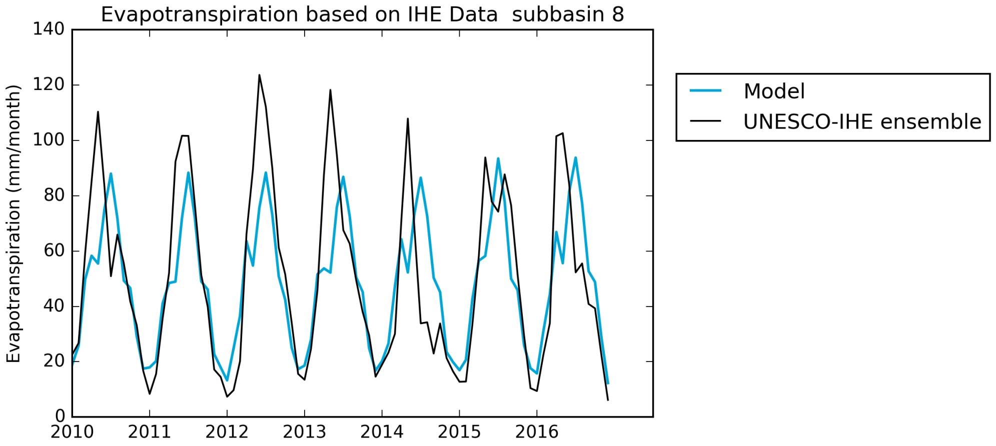

Figure D.8: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 8.

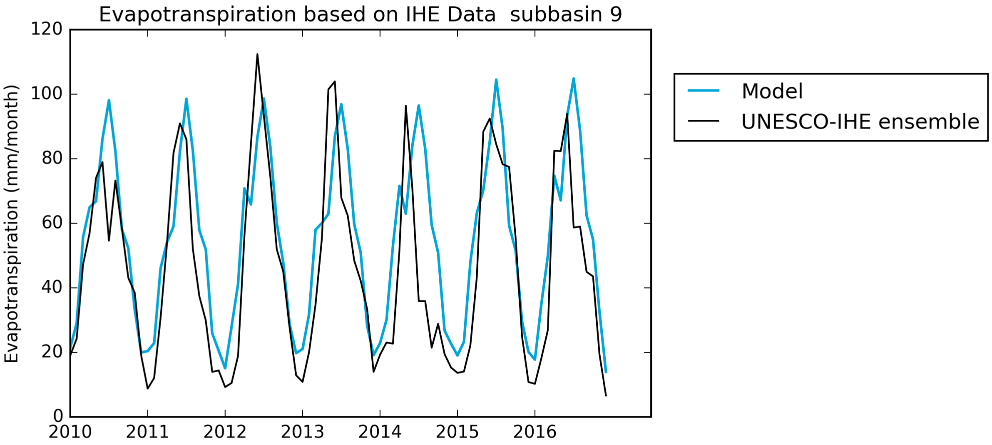

Figure D.9: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 9.

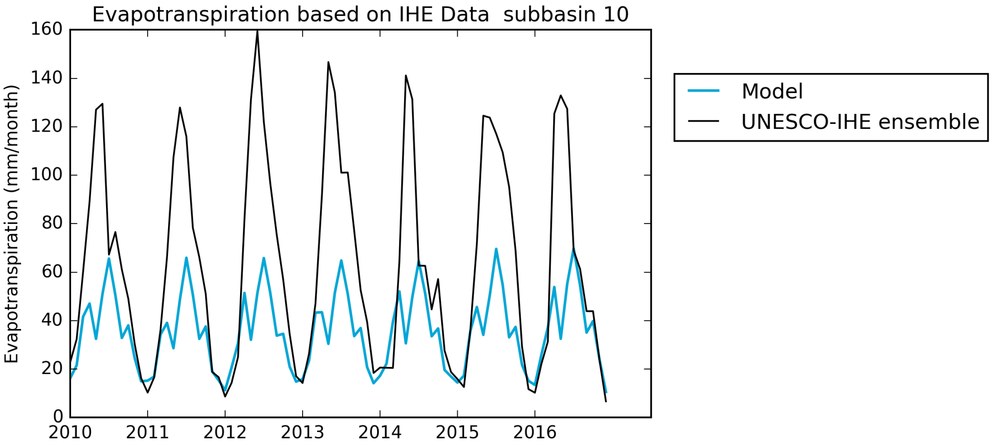

Figure D.10: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 10.

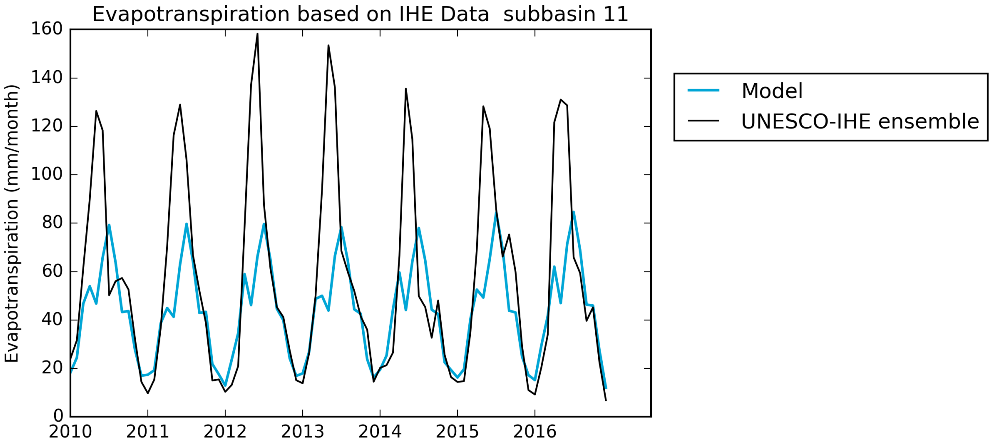

Figure D.11: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 11.

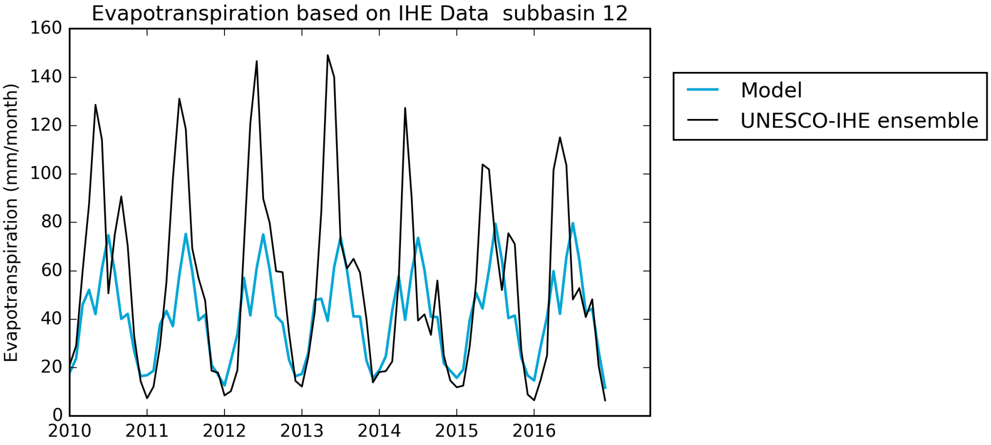

Figure D.12: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 12.

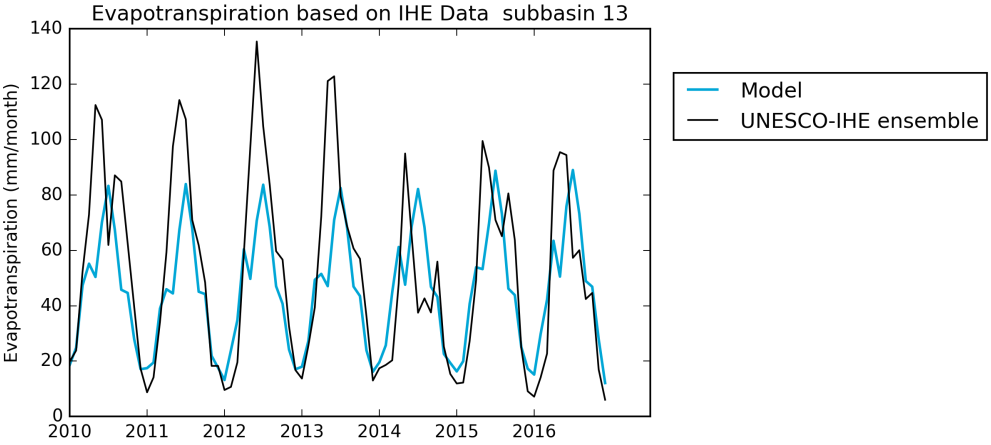

Figure D.13: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 13.

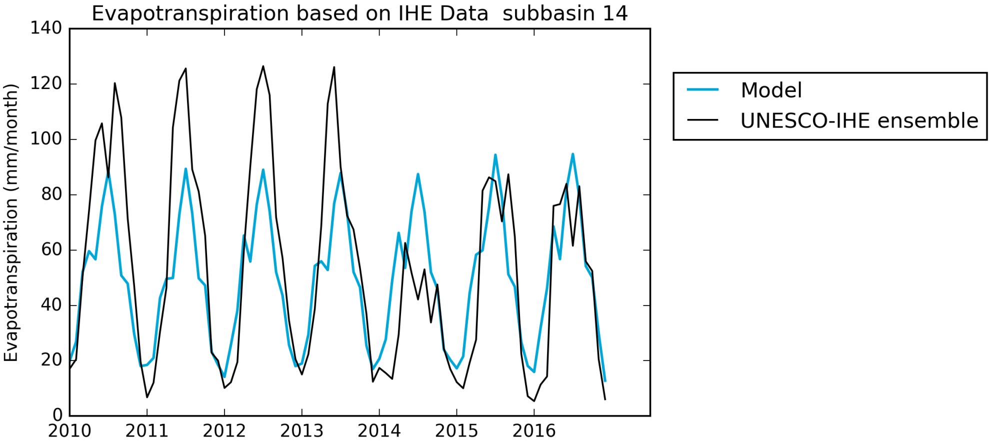

Figure D.14: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 14.

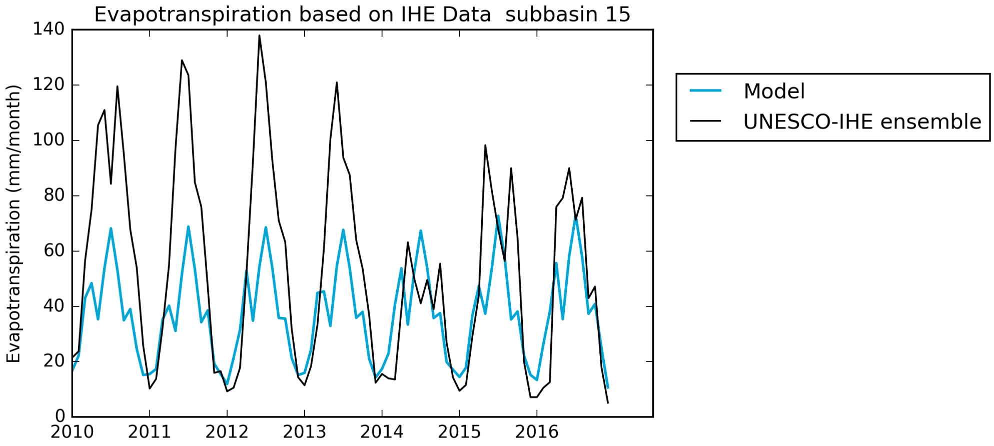

Figure D.15: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 15.

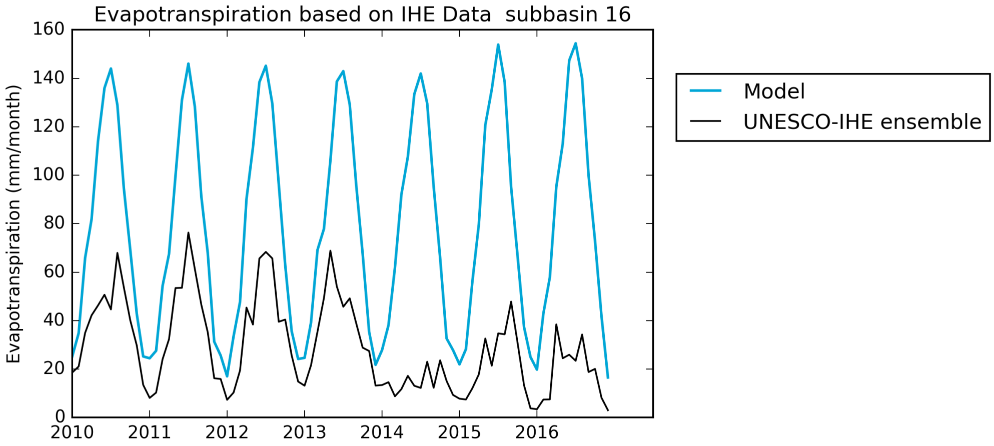

Figure D.16: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 16.

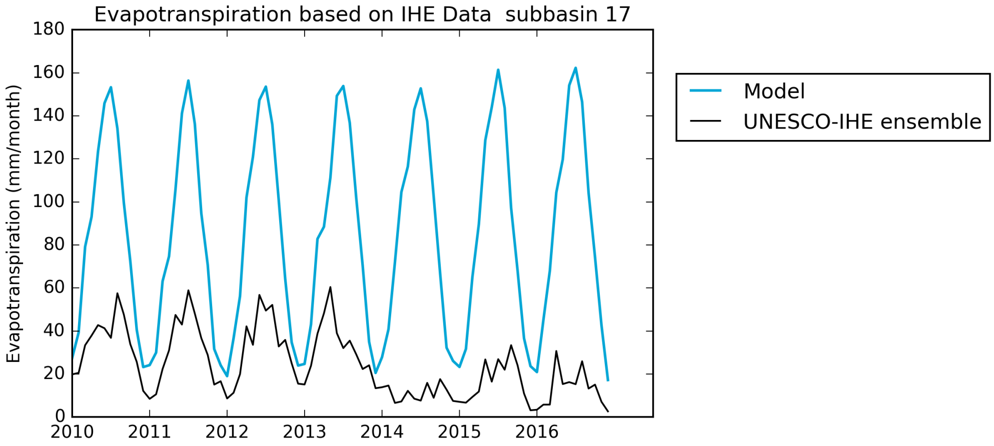

Figure D.17: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 17.

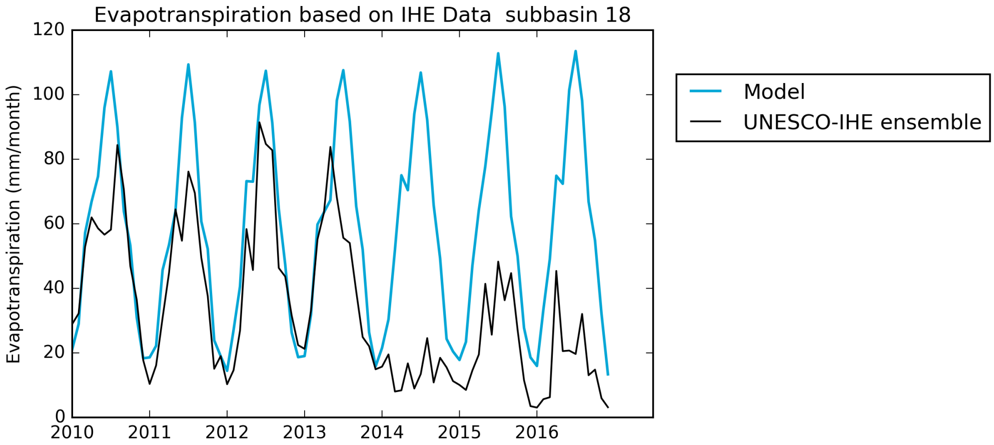

Figure D.18: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 18.

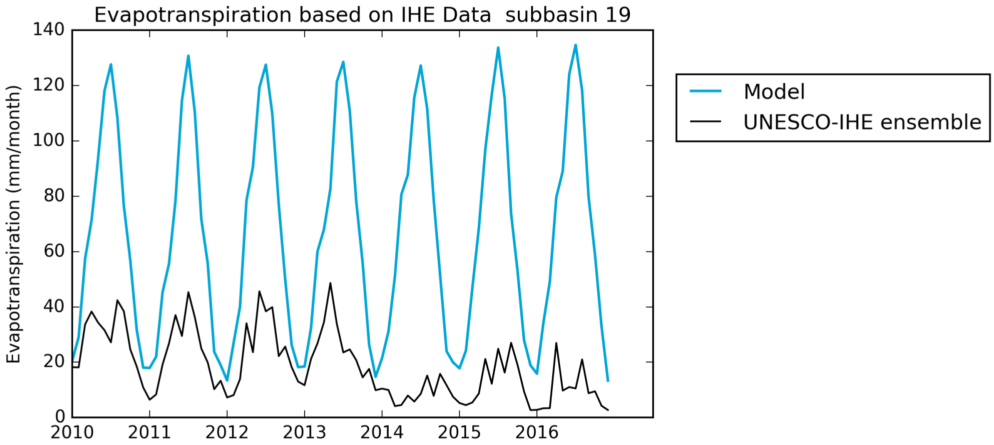

Figure D.19: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 19.

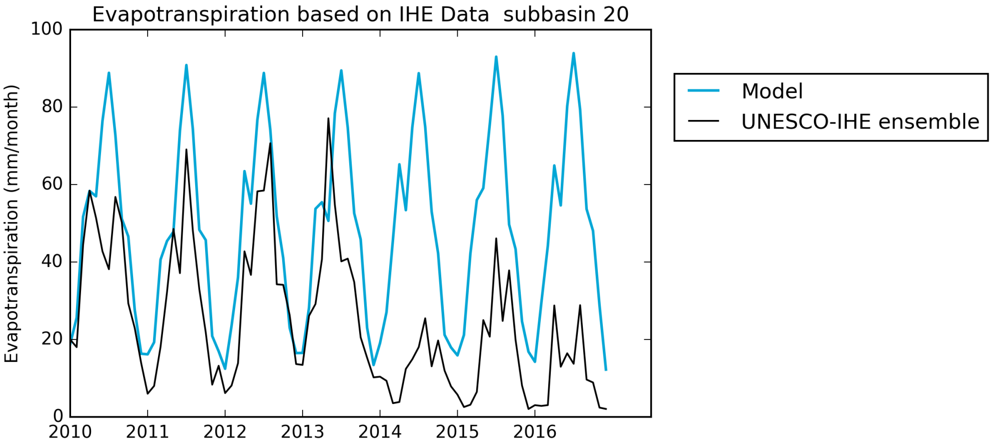

Figure D.20: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 20.

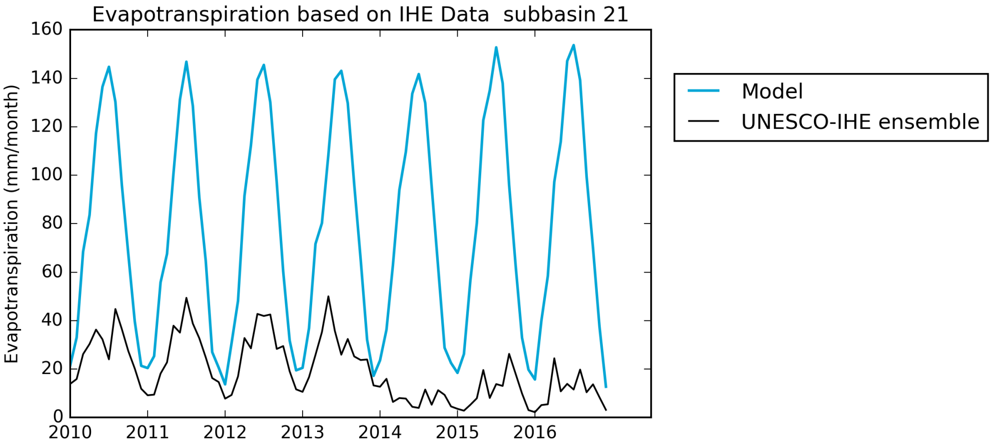

Figure D.21: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 21.

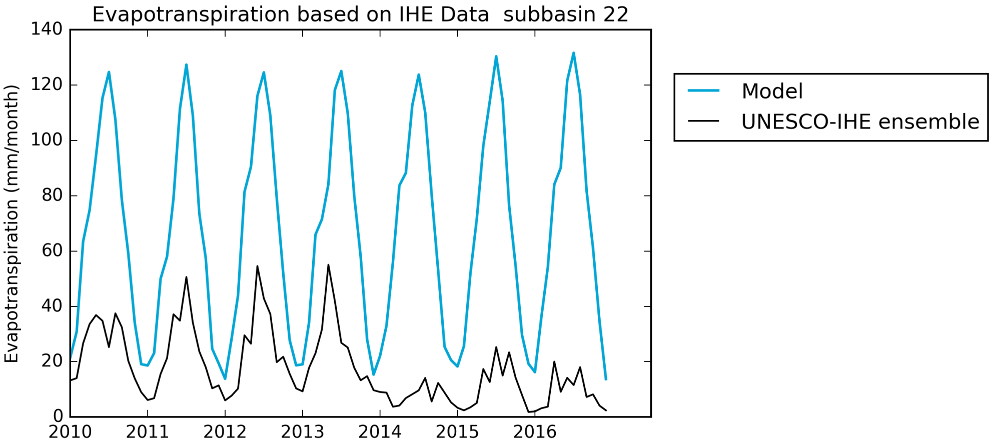

Figure D.22: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 22.

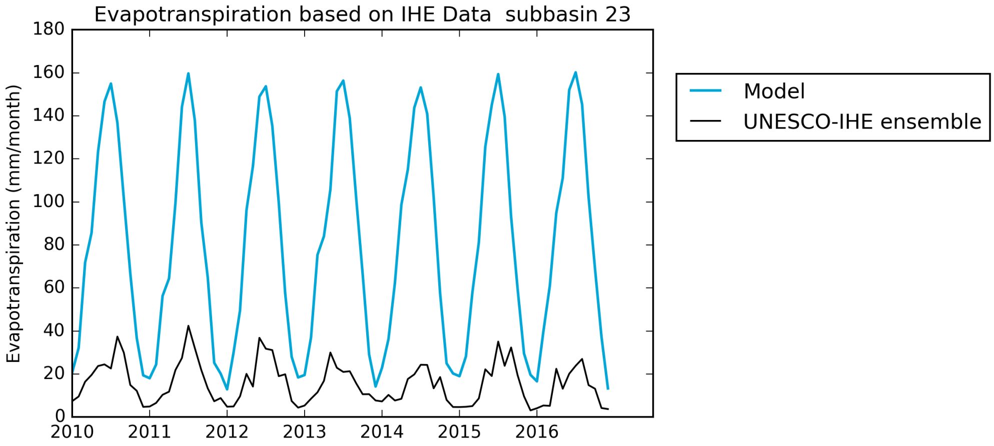

Figure D.23: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 23.

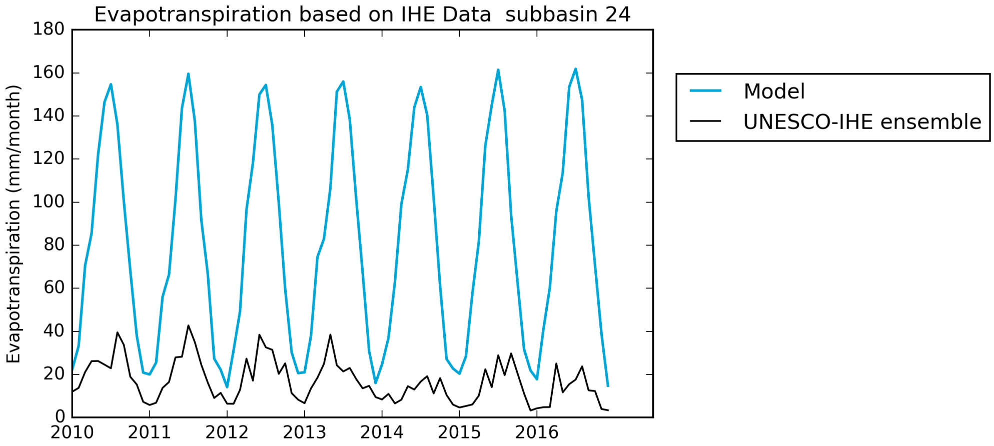

Figure D.24: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 24.

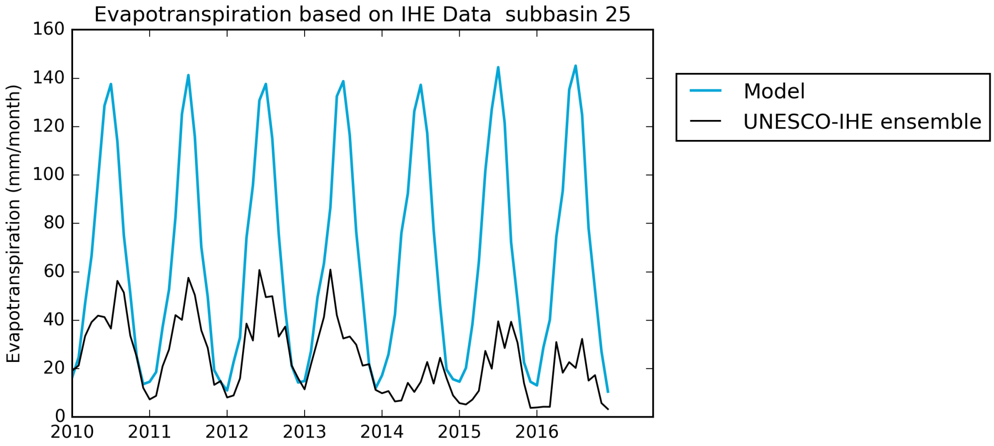

Figure D.25: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 25.

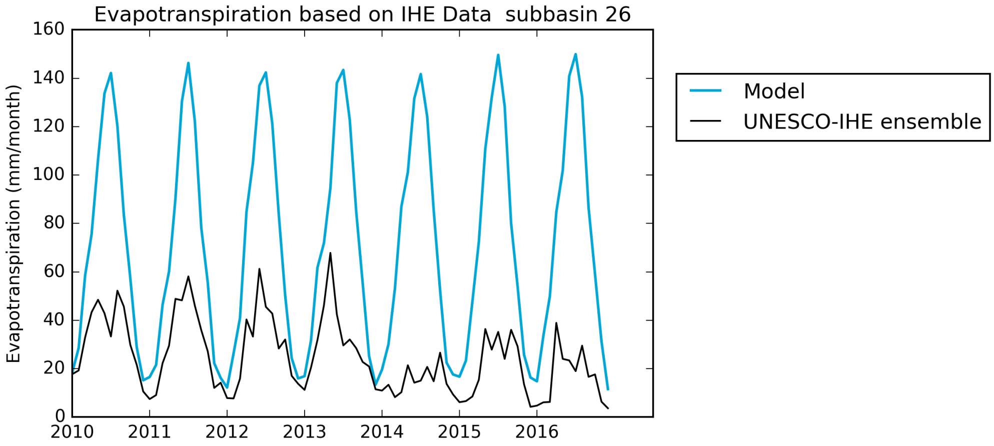

Figure D.26: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 26.

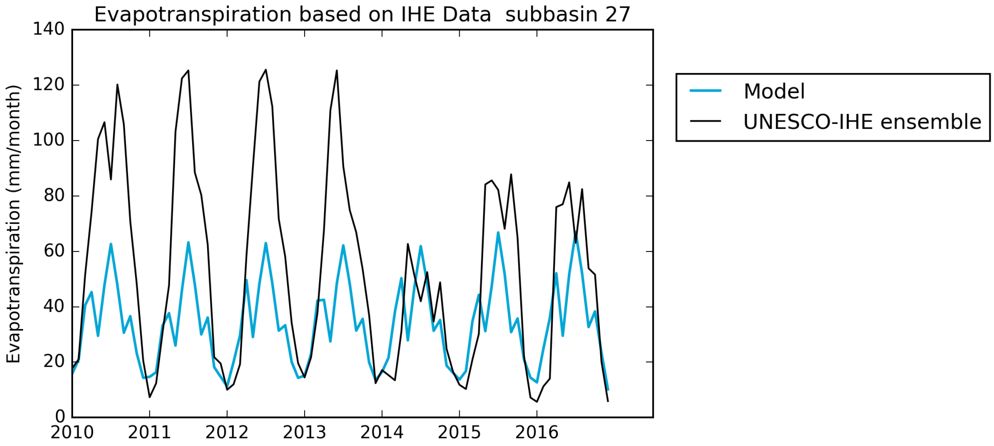

Figure D.27: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 27.

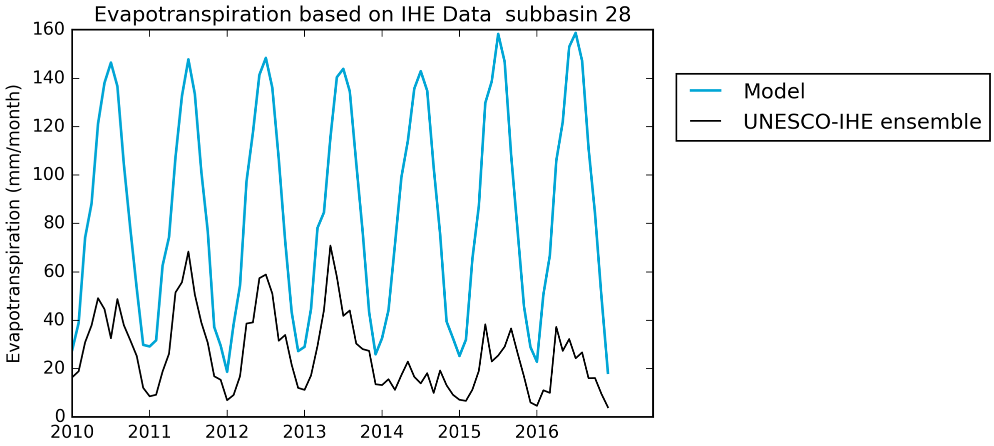

Figure D.28: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 28.

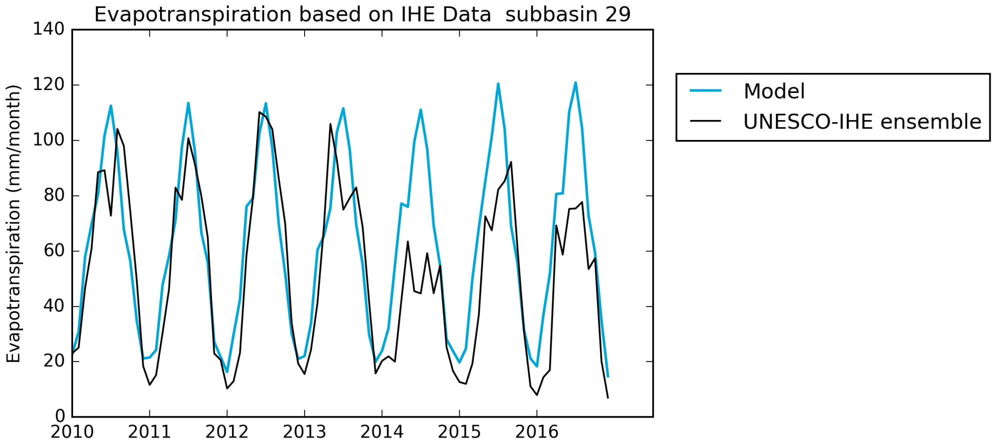

Figure D.29: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 29.

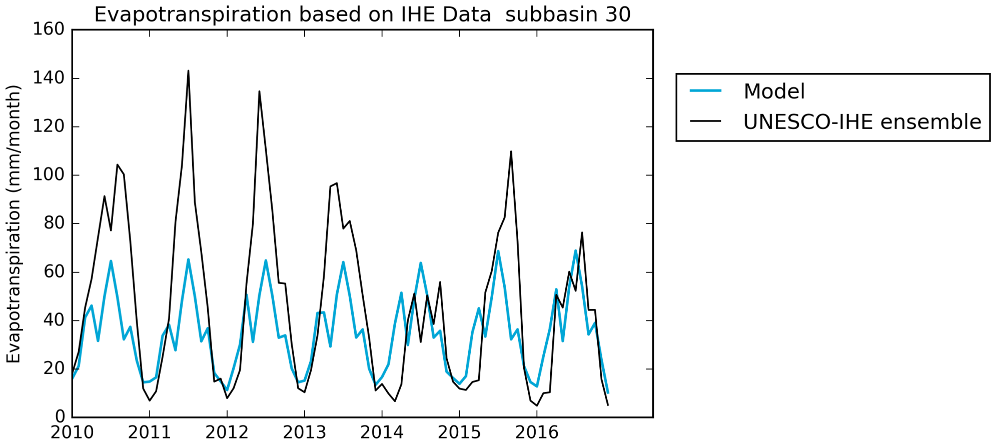

Figure D.30: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 30.

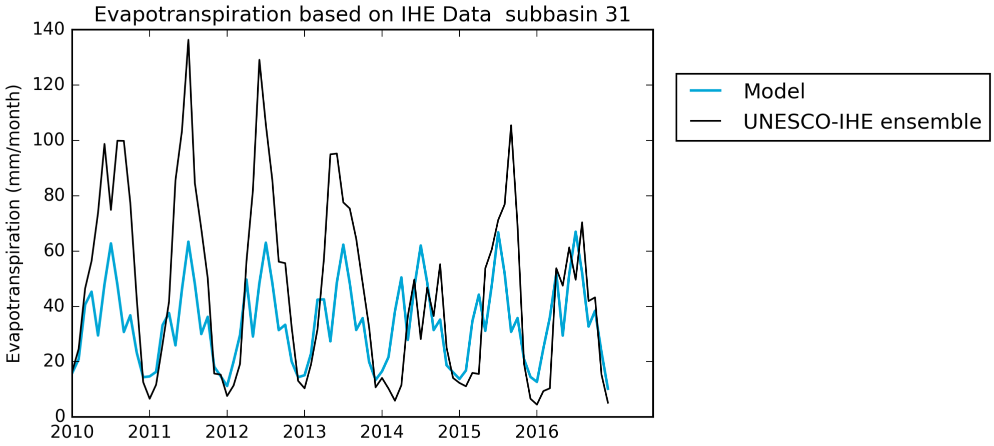

Figure D.31: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 31.

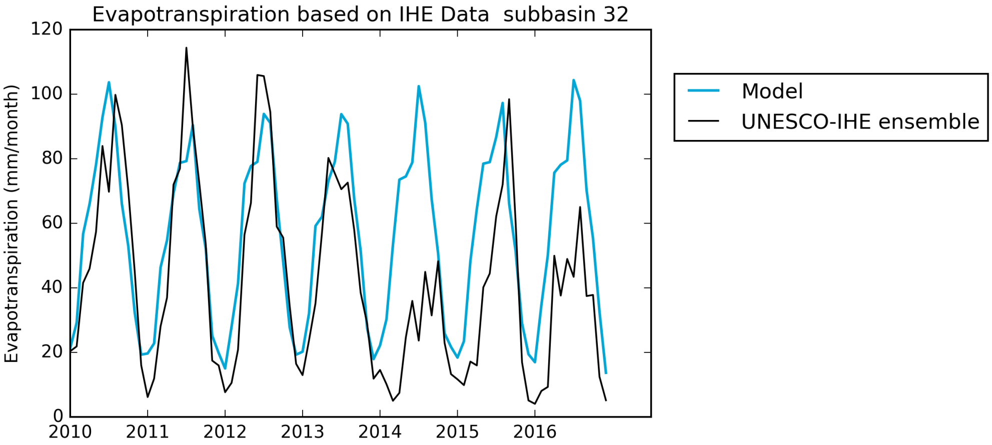

Figure D.32: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 32.

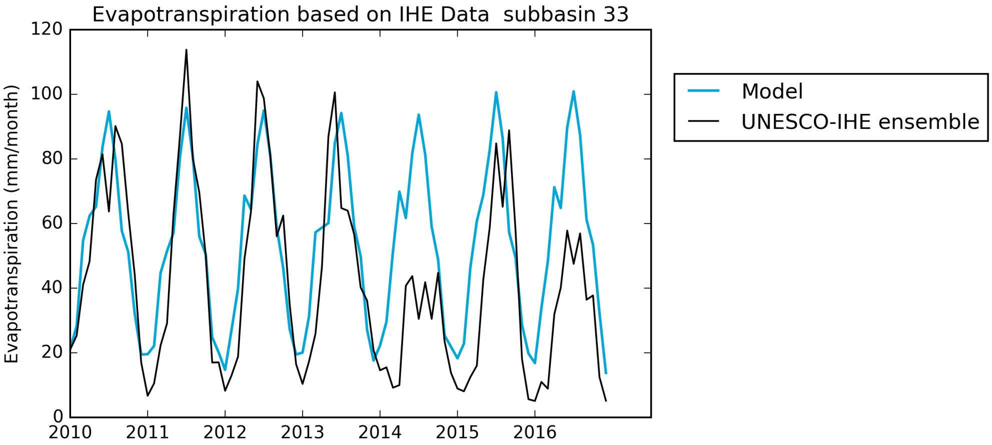

Figure D.33: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 33.

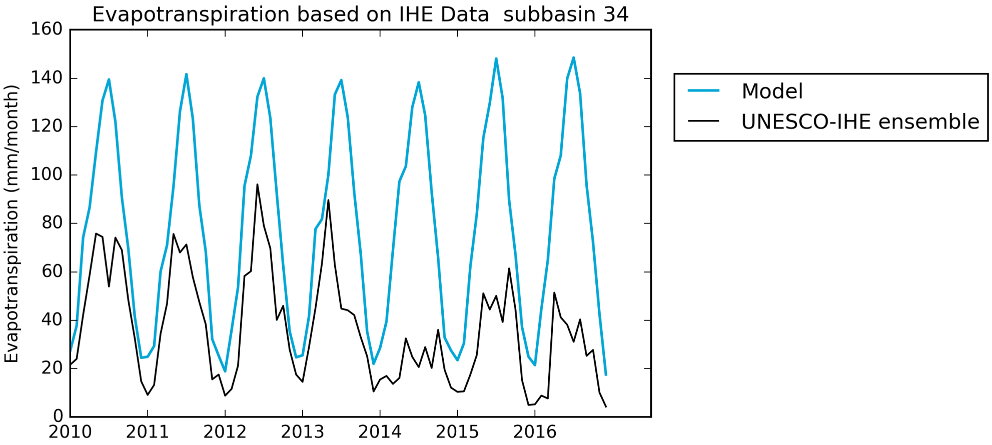

Figure D.34: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 34.

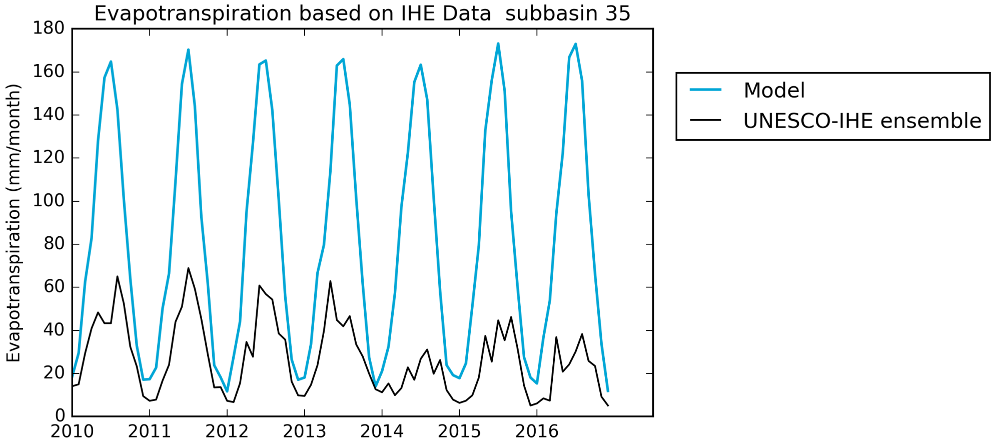

Figure D.35: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 35.

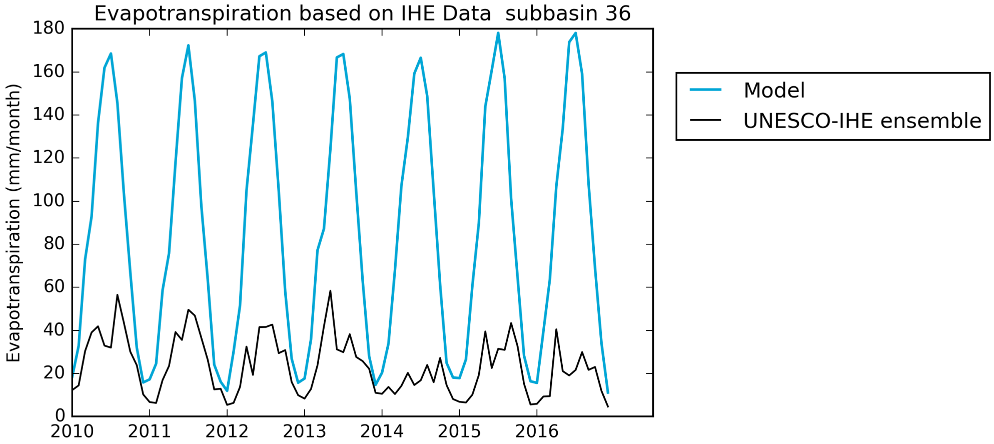

Figure D.36: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 36.

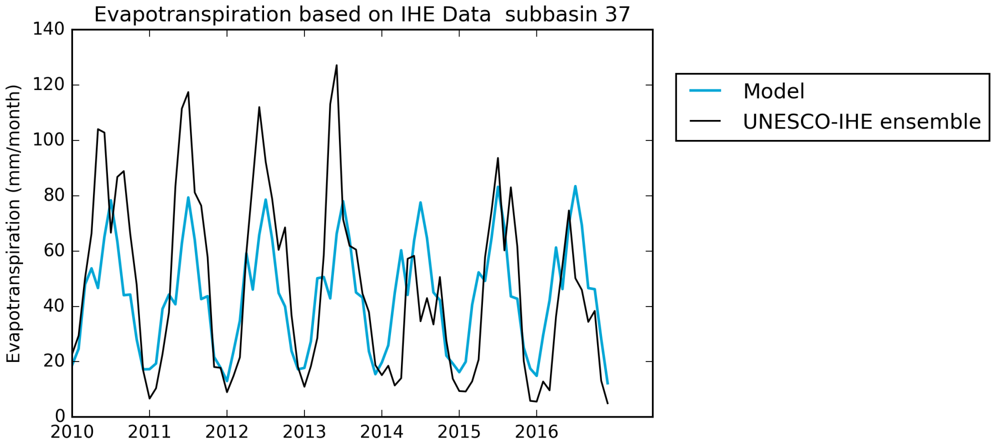

Figure D.37: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 37.

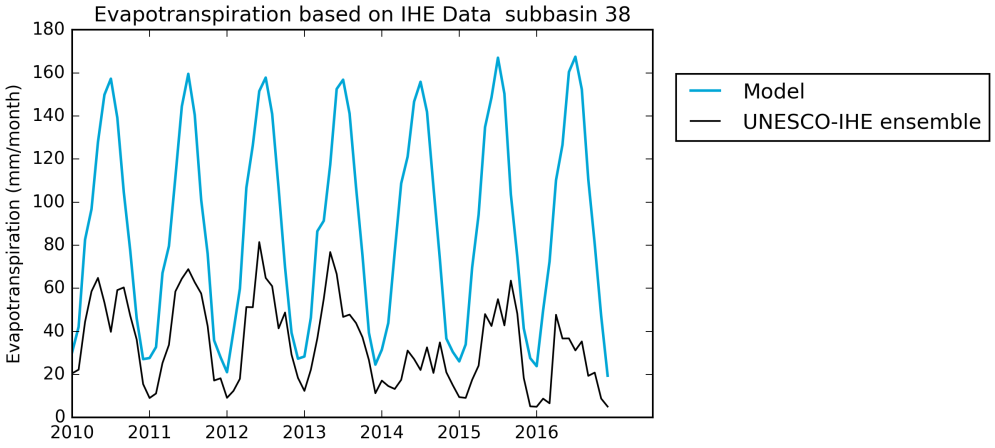

Figure D.38: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 38.

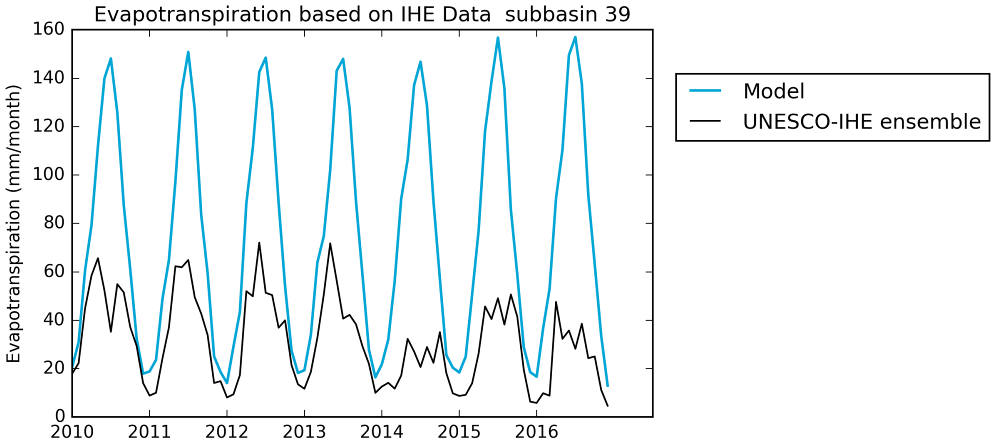

Figure D.39: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 39.

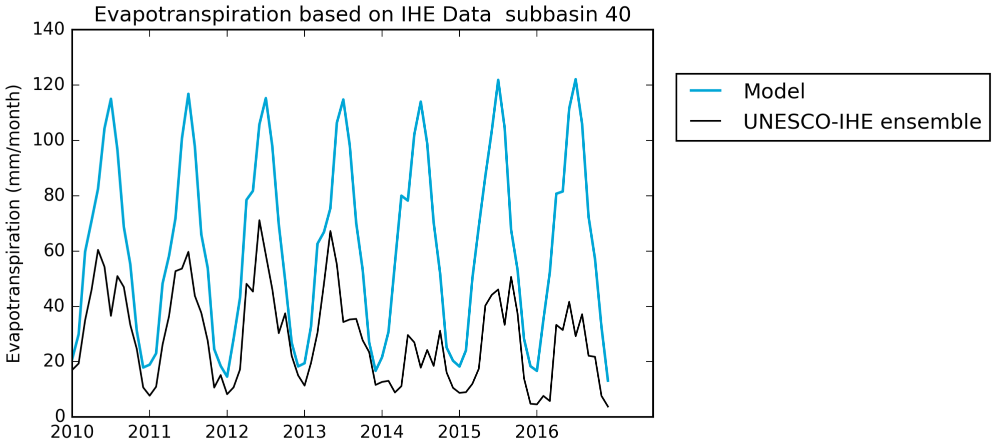

Figure D.40: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 40.

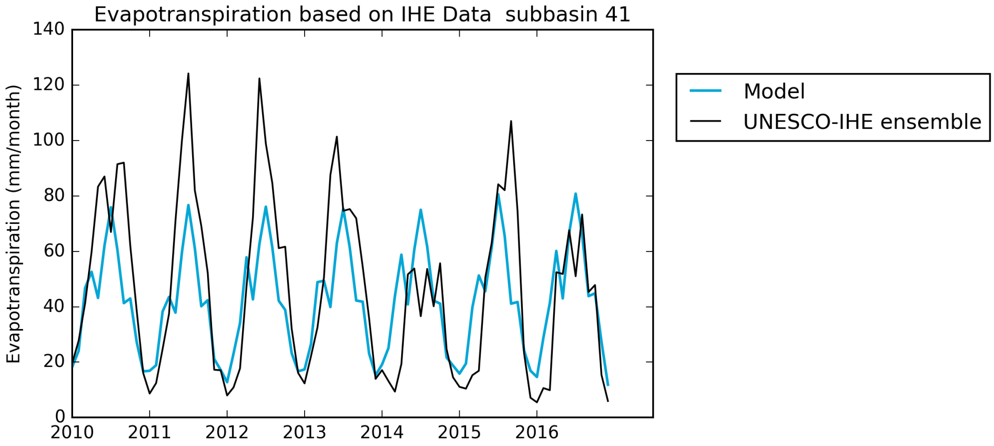

Figure D.41: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 41.

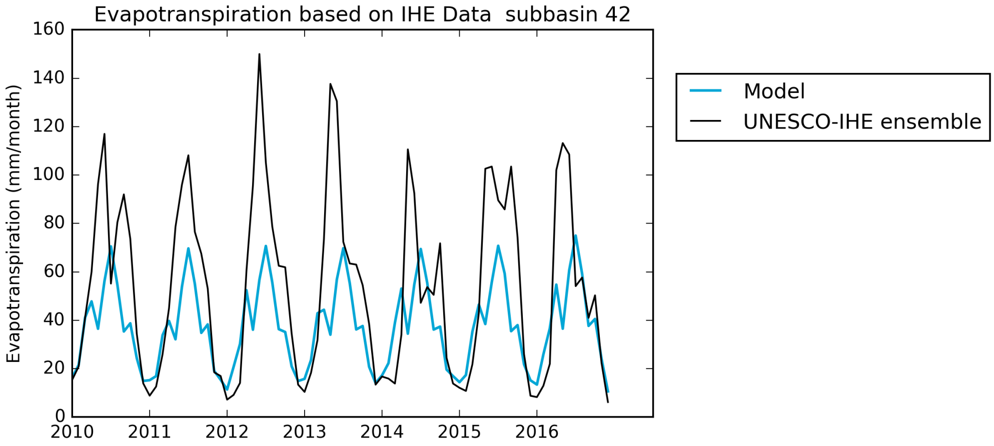

Figure D.42: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 42.

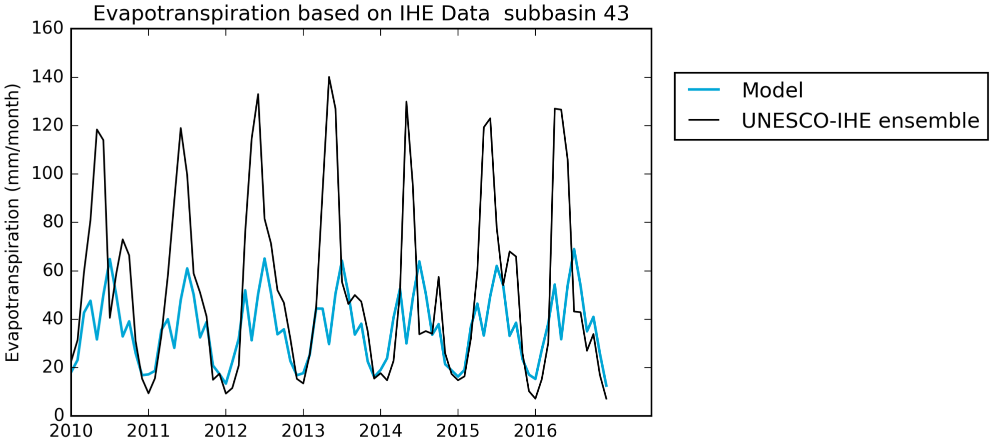

Figure D.43: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 43.

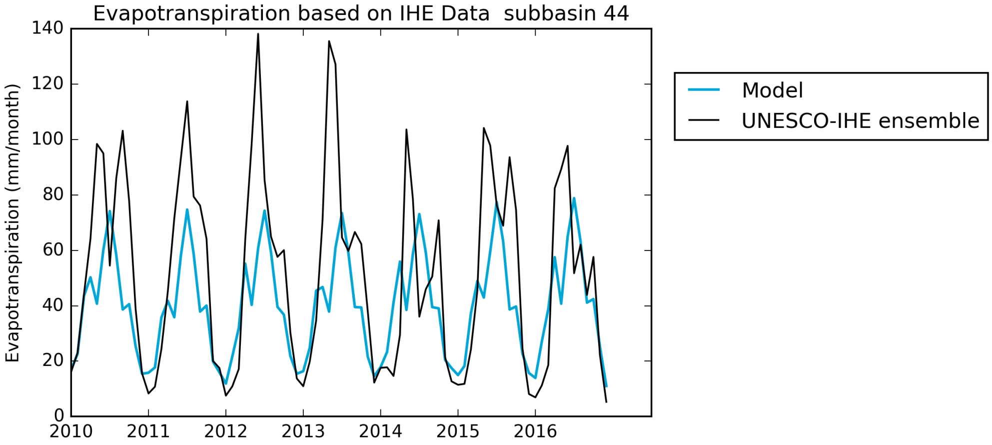

Figure D.44: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 44.

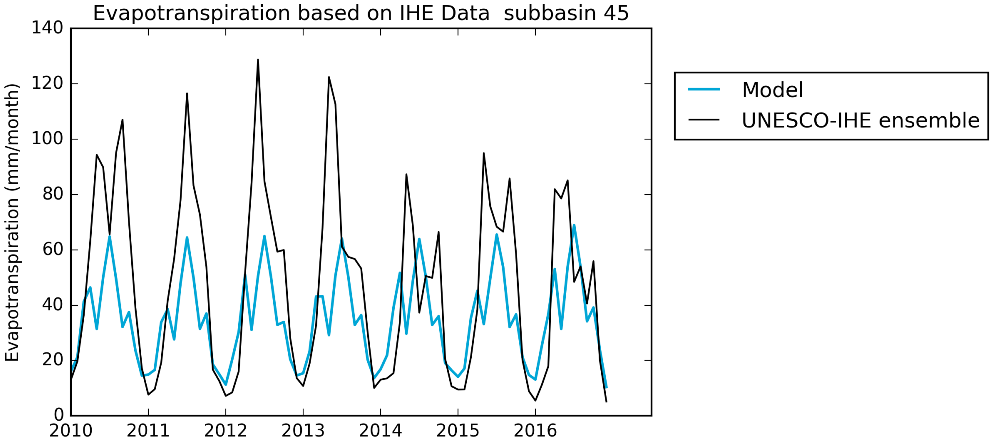

Figure D.45: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 45.

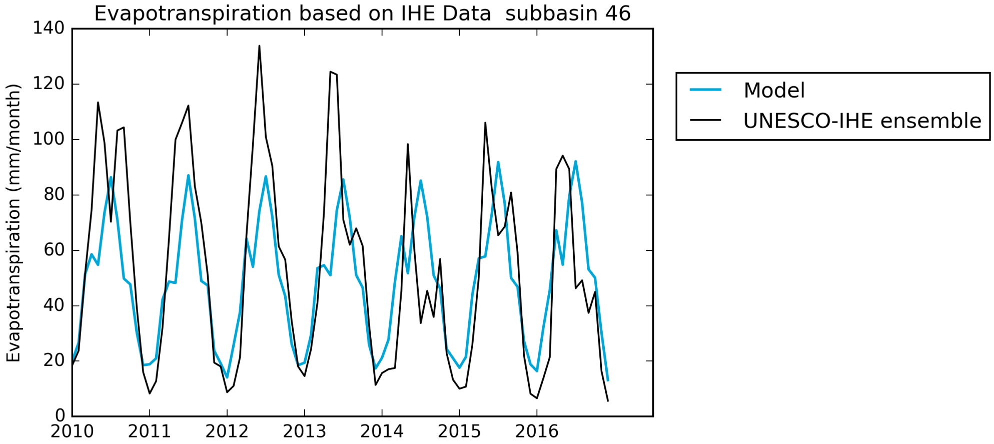

Figure D.46: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 46.

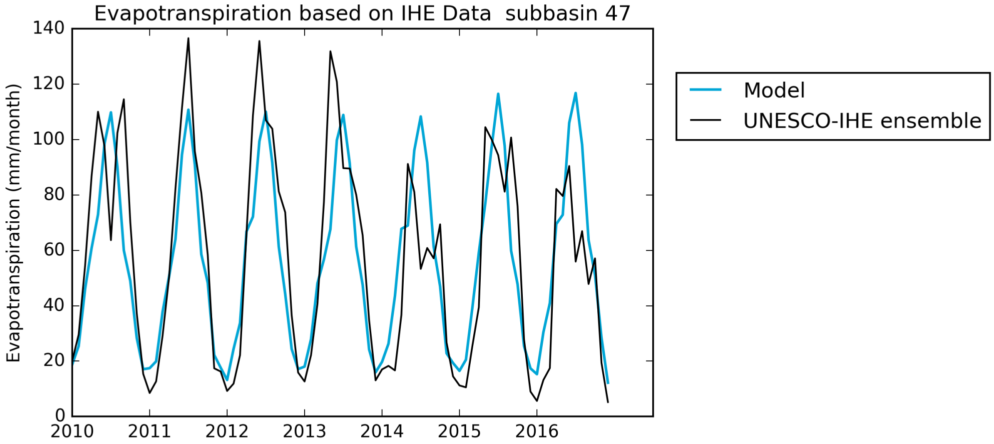

Figure D.47: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 47.

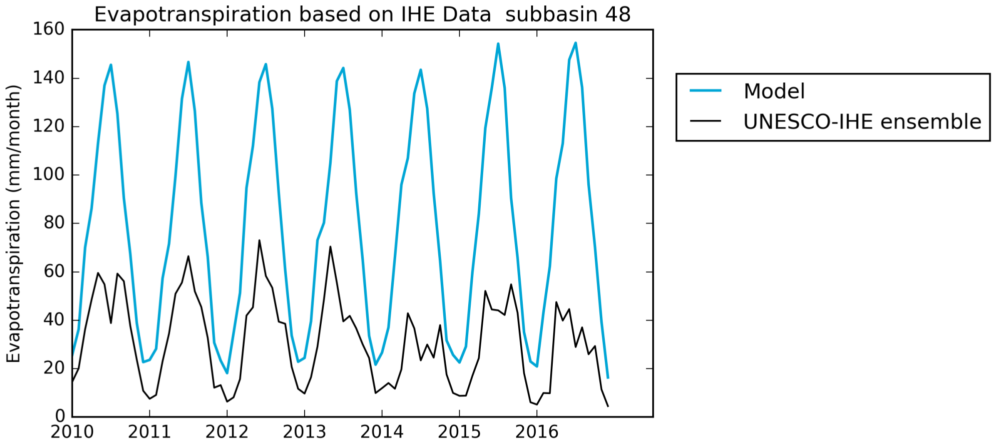

Figure D.48: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 48.

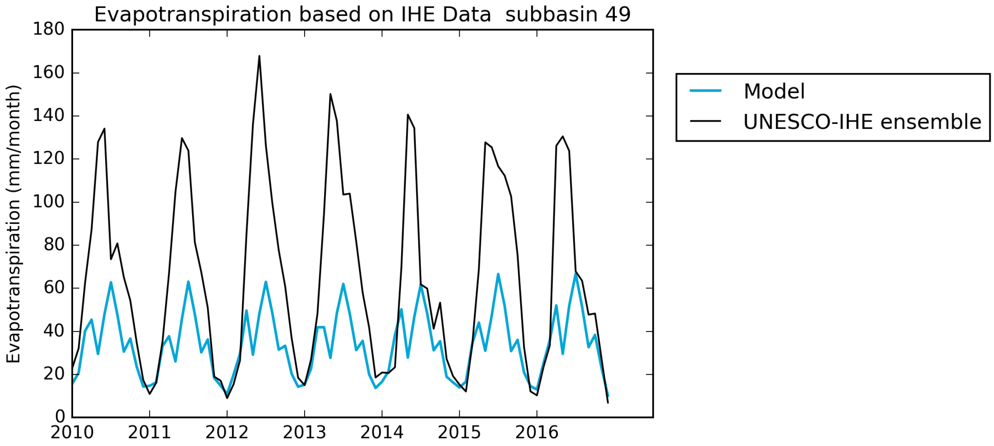

Figure D.49: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 49.

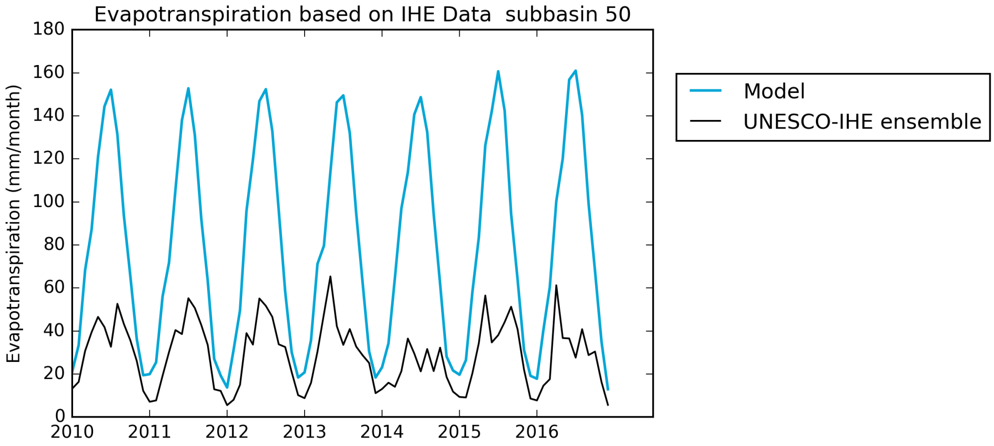

Figure D.50: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 50.

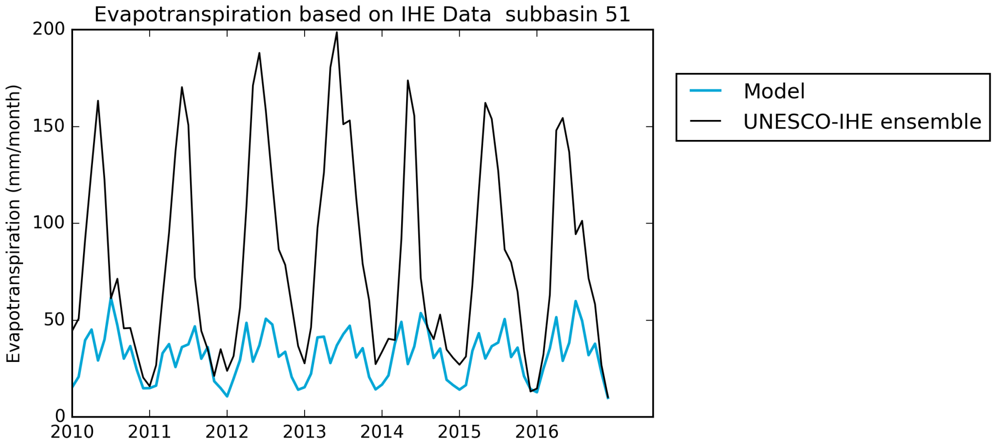

Figure D.51: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 51.

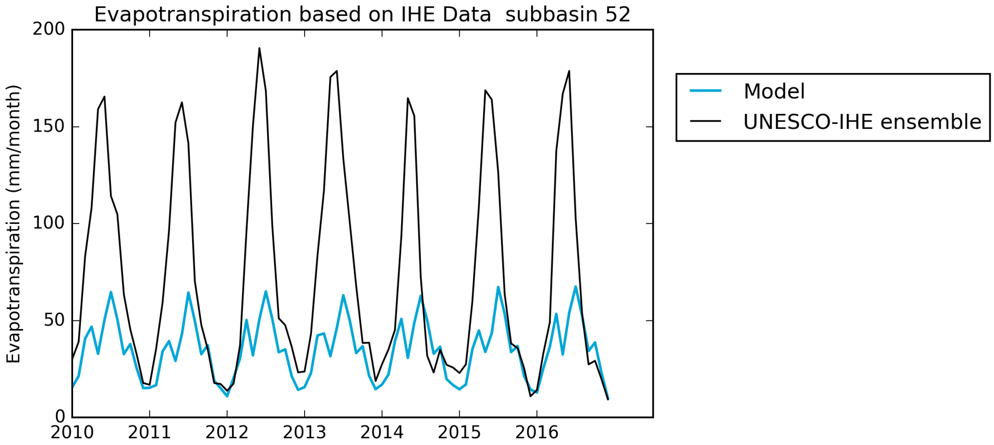

Figure D.52: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 52.

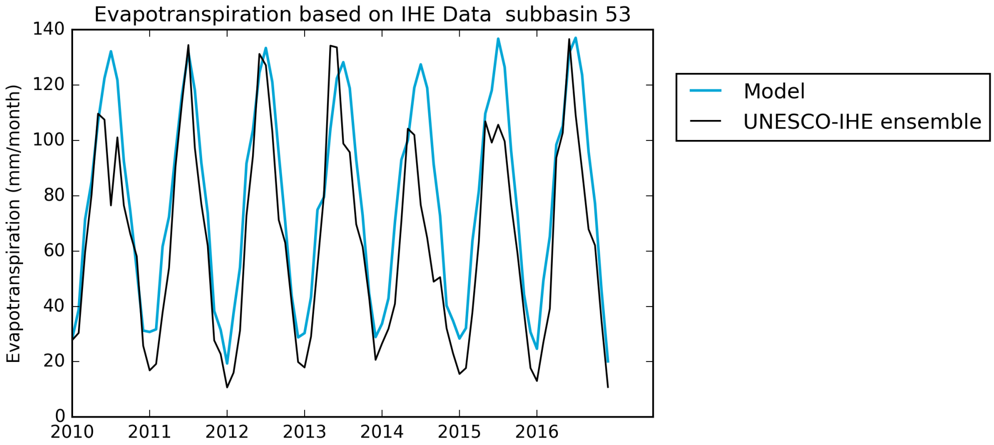

Figure D.53: The ’actual’ evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 53.

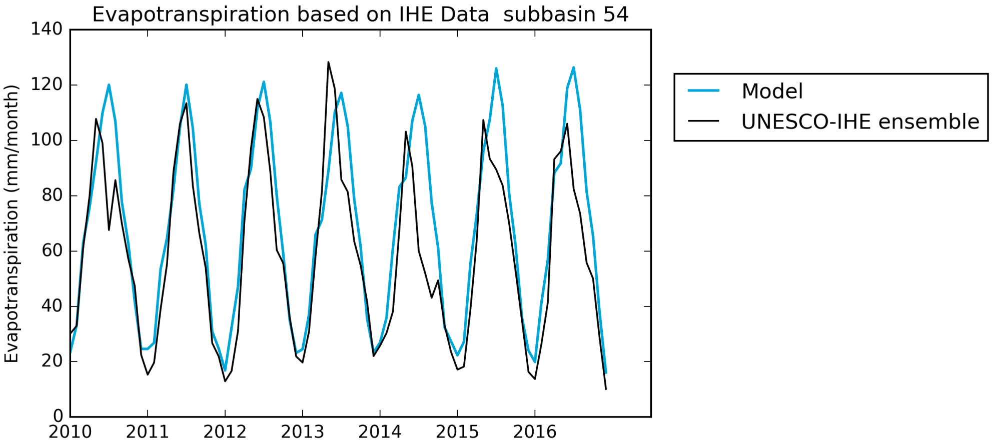

Figure D.54: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 54.

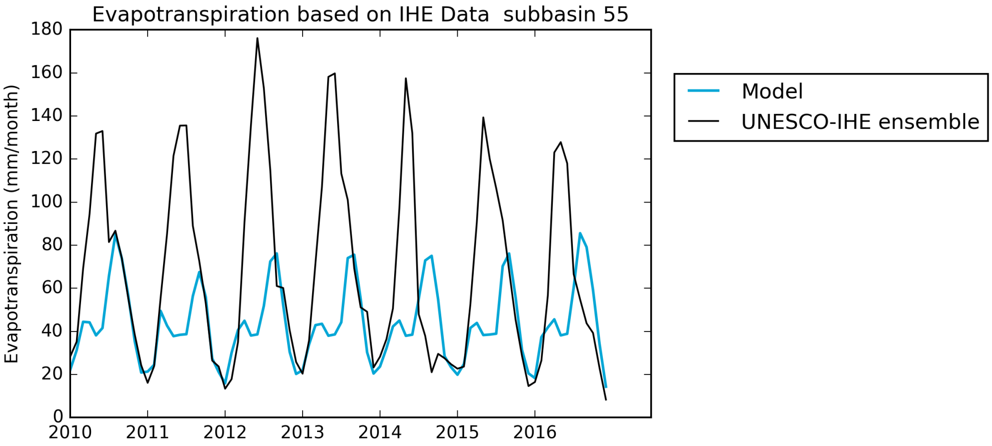

Figure D.55: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 55.

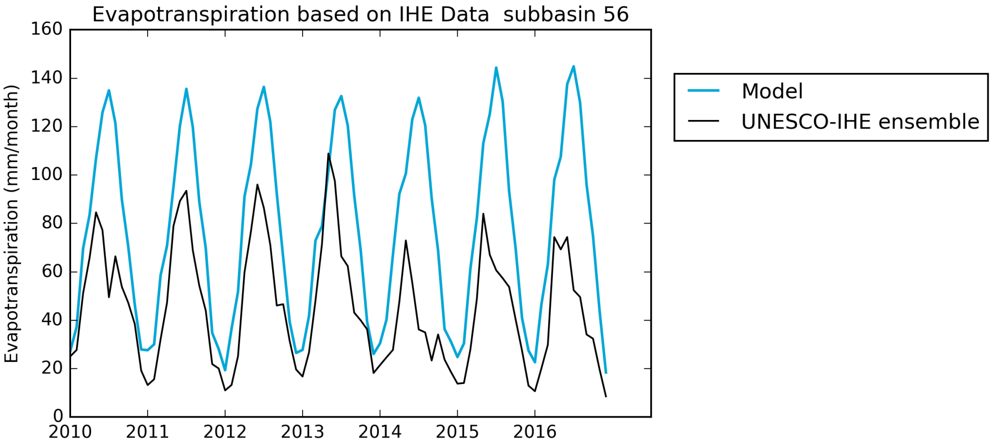

Figure D.56: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 56.

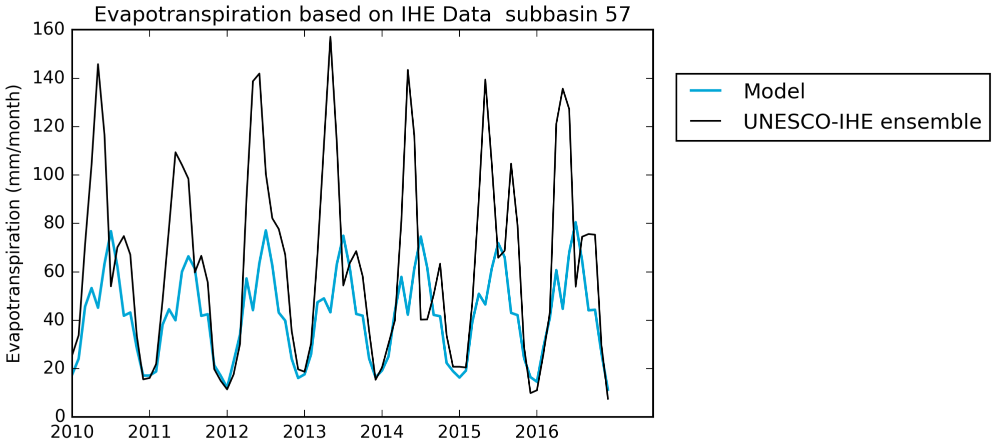

Figure D.57: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 57.

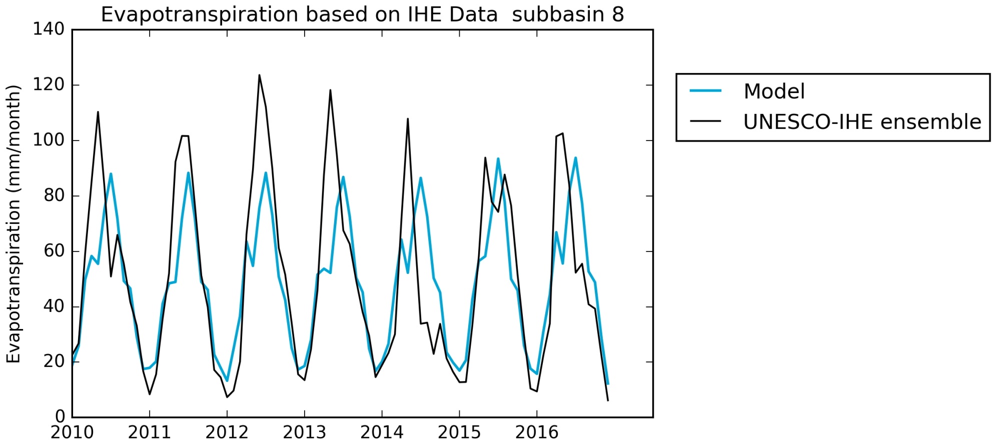

Figure D.58: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 58.

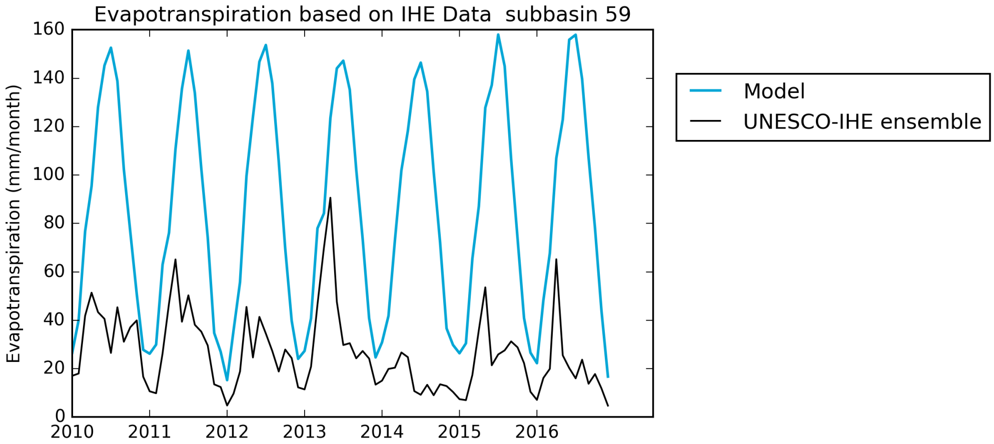

Figure D.59: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 59.

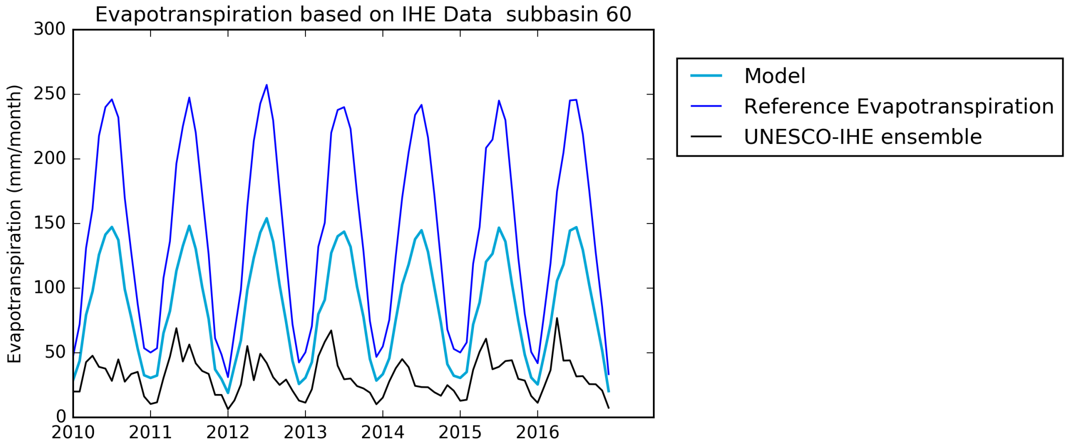

Figure D.60: The 'actual' evapotranspiration based on the data of (Espinoza-Dávalos and Bastiaanssen, 2017) and the modelled evapotranspiration of subbasin 60.

E

Files used for the Optimisation

On the next page, an overview of the files used in *Python* in order to execute the water allocation optimisation of the LRB. How the files are connected to each other is represented in the figure.

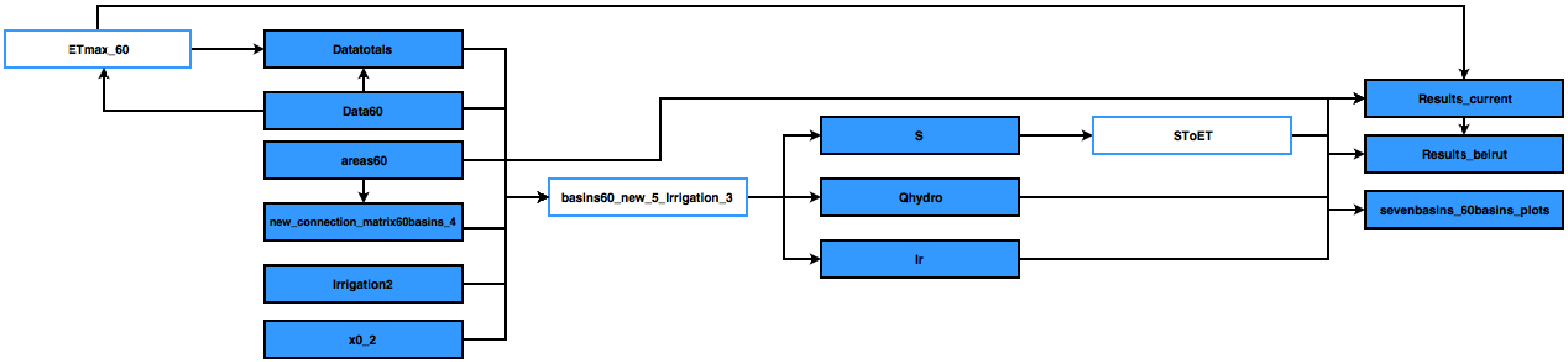

Figure E.1: An overview of the *Python* files which are used for the water allocation optimisation in the LRB and how these files are connected to each other.