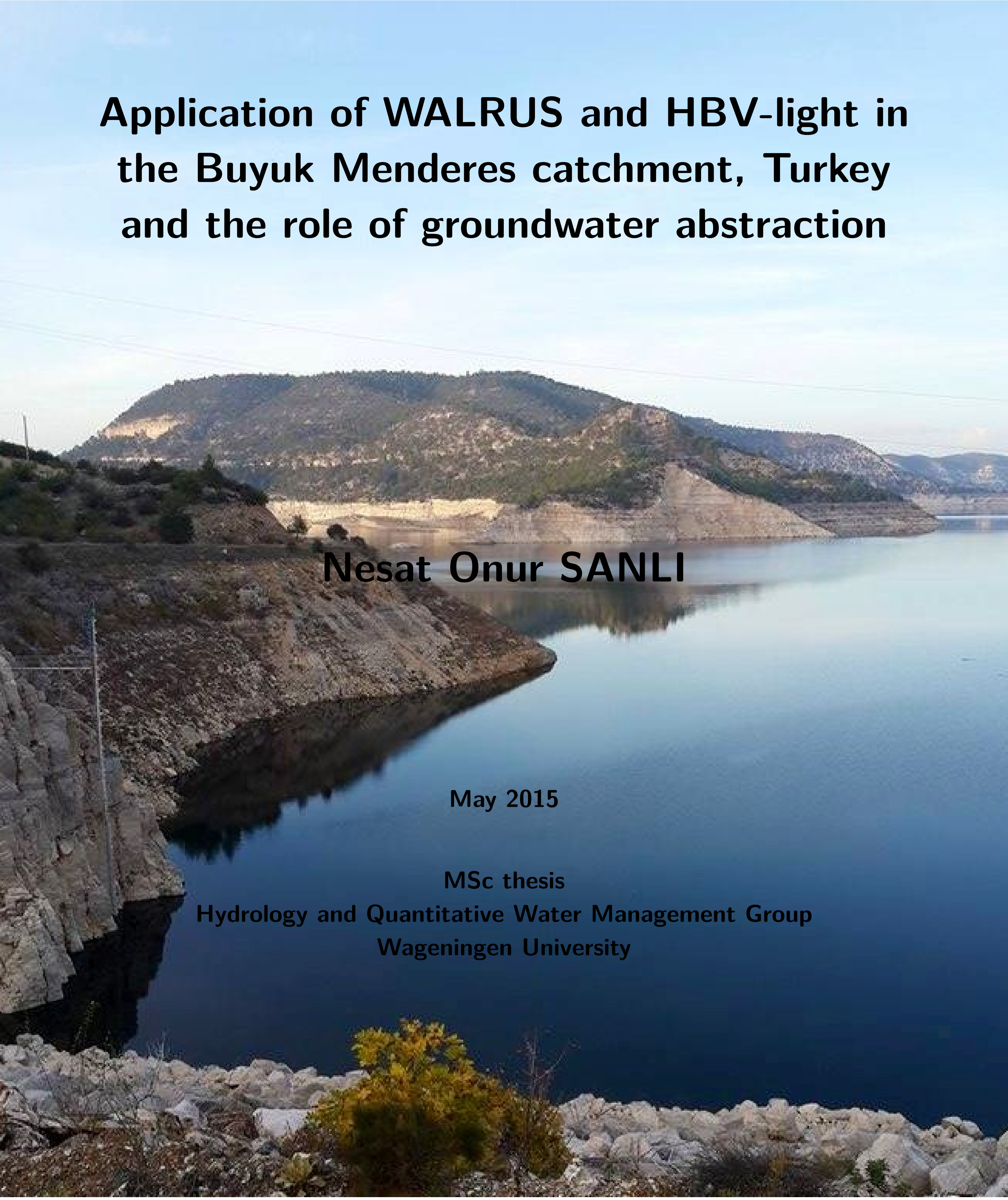

# Application of WALRUS and HBV-light in the Buyuk Menderes catchment, Turkey and the role of groundwater abstraction

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May 2015

MSc thesis
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# Preface

I am using this opportunity to express my gratitude to everyone who supported me throughout the time of research and writing of this thesis.

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# Abstract

Uneven water distribution, groundwater abstraction and lack of data are challenges concerning the water management in Turkey. Rainfall-runoff models can be used in order to provide missing hydrological data. In the present thesis, two lumped rainfall-runoff models were implemented: The Wageningen Lowland Runoff Simulator (WALRUS) and the Hydrologiska Byrans Vattenbalansavdelning (HBV-light).

The WALRUS was designed for lowland catchments having shallow groundwater table and it just requires five calibrated parameters. On the other hand, HBV-light was designed for cold catchments and relatively elevated catchments and it requires ten parameters including both catchment and vegetation zone calibrated ones. The main objective was to investigate the performance of rainfall-runoff models in an area with slight topography, dry climate, catchment size and groundwater abstraction and compare WALRUS to HBV-light. The Adiguzel subcatchment (2285 km$^2$), which is the part of the Buyuk Menderes catchment in Turkey was used as a research area in order to answer the main research question. The Ikizdere (42 km$^2$) subcatchment was also chosen for the comparison between WALRUS and HBV-light.

First, WALRUS parameters were calibrated for the current situation with groundwater abstraction and wastewater treatment effluent. After validation, an average Nash-Sutcliffe efficiency of 0.53 was found. When the same model parameters were used for the naturalised situation, without groundwater abstraction and wastewater treatment effluent, the model efficiency remained at 0.48. In order to ensure the effect of groundwater abstraction, the simulated discharges, the actual evapotranspiration and groundwater level variations were compared. After the end of the process, it was concluded that a) WALRUS underestimates observed discharge in two conditions, b) The effect of the groundwater abstraction and surface water supply is limited and c) There is not a single parameter set for the entire year.

Another research question was to compare two rainfall runoff models. WALRUS was calibrated for three different hydrological years, namely a) dry b) average and c) wet in terms of precipitation. After validation, it was seen that model parameters calibrated for dry conditions were the most optimal ones. Furthermore, it was found that WALRUS performs better when simulating peak discharges during just wet seasons. However, HBV can simulate better recessions, the timing of the peaks and the first peaks after a long dry period. In terms of Nash-Sutcliffe efficiency, average values of 0.56 and 0.72, using the WALRUS and the HBV-light respectively, were found for validation period in the Ikizdere subcatchment.

It can be concluded that the performance of the WALRUS is acceptable both in the Adiguzel subcatchment and Ikizdere subcatchment with provided data and assumptions. The performance of HBV-light is better in Ikizdere catchment. However, it is not easy to compare two models which have been designed for different conditions with different structure. Finally, more research should be conducted and the problems related to data should be solved to enable us to gain better results.

# 1 | Introduction

## 1.1 Water resources challange in Turkey

The motivation of this research comes from the Turkish water challenge. In 2005, Turkey became an Accession Country to the EU, following the decision of the EU Council (Schimmelfennig and Scholtz, 2008). The negotiation chapter on Environment was opened to negotiations in December 2009 with a number of closing benchmarks. The Water Framework Directive, which is aimed at improving water management at river basin level, is a key piece of EU legislation that Turkey is obliged to implement to close the environment chapter in the negotiations. The basin management system divided into twenty-five river basins, each of which handling a different issue in Turkey. In addition to a strong legal drive to adopt EU-water policy, Turkey's water challenges provide an even stronger impetus to plan and implement cost-effective and sustainable measures to deal with the negative effects of climate change, combat the growing water scarcity and halt the on-going environmental degradation of its water resources. Turkey avails of an average of 1.500 $m^3$ per capita per annum (Duranyildiz et al., 2000). Although this is above the globally accepted norm of 1000 $m^3$ per capita per annum (Smith, 2000), its water resources are distributed highly unevenly (Fig. 1.1). The Black Sea region receives in more than 2000 mm of rainfall annually; the western and southern parts of the country receive less than 700 mm per year and less than 500 mm in a number of river basins in the South-West (Ozkul, 2009) (Fig. 1.2)

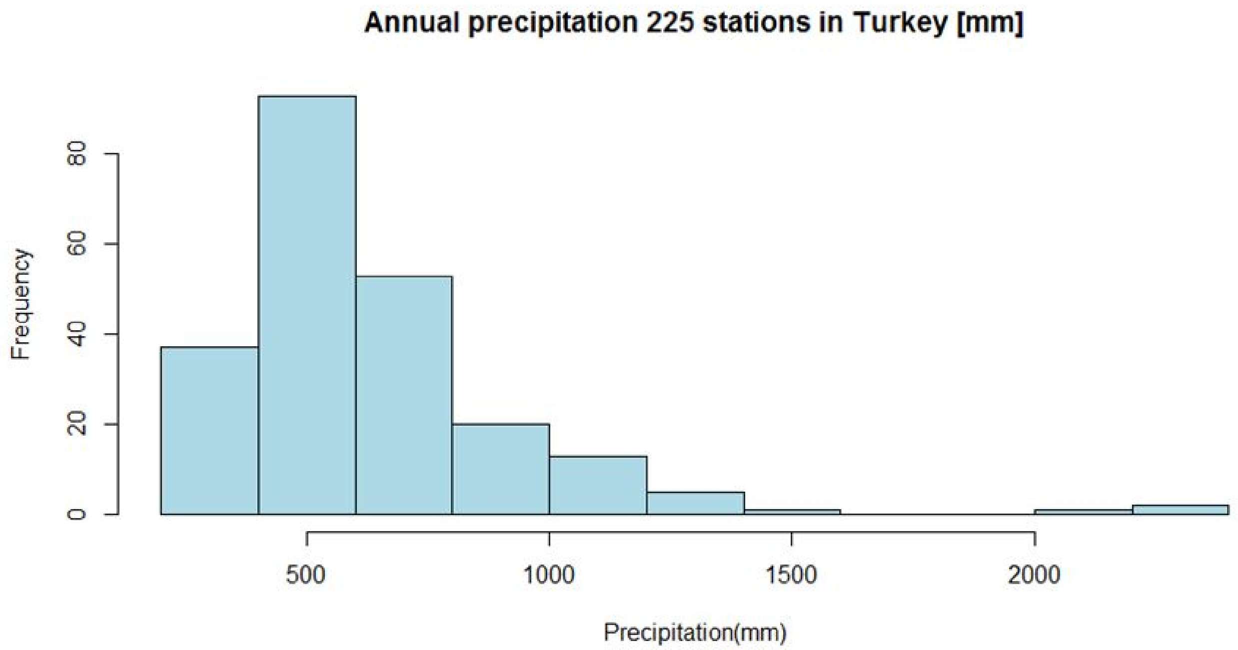


Figure 1.1: Histogram of annual precipitation of 225 stations in Turkey based on precipitation data from General Directorate of Meteorology.

Recent studies indicate that Turkey has one of the highest levels of water scarcity of the countries in Europe. It is densely inhabited and most regions of the country face high or very high stages of water stress. This trouble is likely to increase with the rapidly growing population and the potential droughts associated with rising temperatures (Türkeș et al., 2002). Estimates of changes in runoff are between -52 percent and -61 percent, and reductions of surface waters in the Turkish basins is up to 35 predicted for 2050 (Erlat and Türkeș, 2013). To this end, the Government of Turkey is planning, with EU support, to invest 35 billion euro in water resource management until 2030. A pilot River Basin Management Plan (RBMP) was prepared for the Buyuk Menderes river basin (in 2010) – culminating in a National Implementation Plan and Road Map for the WFD and Dangerous Substances Directive (DSD) (Chon et al., 2010). River Basin Protection Action Plans (RBPAP) were prepared for an additional 10 river basins (2010 – ongoing). In summation, a number of projects were broken to enhance Turkeys' capacity in the theatre

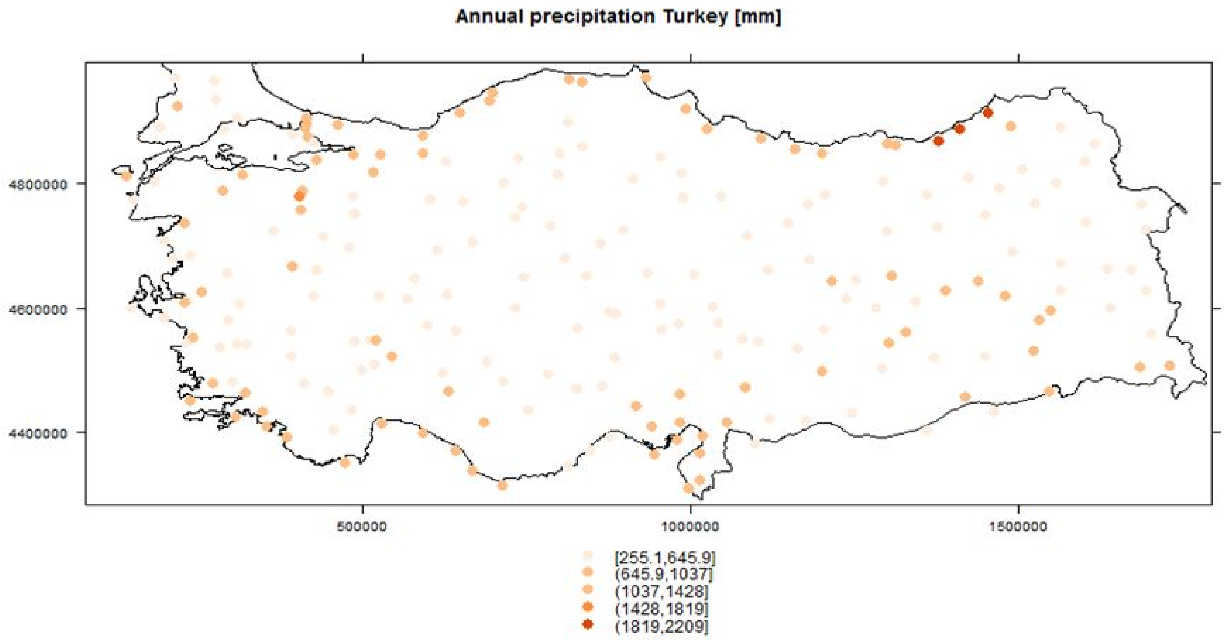


Figure 1.2: Map of meterological stations in Turkey and their annual precipitation values (mm). Measured by General Directorate of Meteorology.

of operations of wastewater handling and management (2009 – 2013). An EU project on monitoring is presently ongoing. Moreover, Turkey is funding the development of flood risk management plans – tendered out as Technical Assistance - for all of its 25 river basins. Similar investment is currently being programmed for the development of RBMPs. The development of RBMPs has been embedded into the first "National River Basin Management Strategy (NRBMS, 2013)" prepared by the newly formed Directorate General (DG) for Water Management under the Ministry of Forestry and Water Affairs. A central component of the NRBMS is the formation of a modelling approach for the management of Turkeys' complex and vulnerable water resources in a virtual manner. To this end, a specialized Water Resource Modelling Department (WRMD) was created in 2013 as a cross cutting department in the DG to help each department to develop modelling tools for their needs. An explicit reference was made to the requirements in the WFD with respect to modelling and the scientific validation of measures and approaches in the set-up of the Modelling section of the Ministry. The DG is looking for the experience of the Netherlands – through its research institutes, individual companies and implementing water management agencies – to make this strong ambition and share its cutting edge knowledge and access. To enhance their knowledge about modelling the DG has provided some students to go abroad to do their master education by focusing on water resource management and modelling. This proposed thesis will do as a demonstrative tool and display case for further replication and knowledge enhancement within the Water Resource Modelling department (WRMD).

## 1.2 Rainfall-Runoff models

When dealing with hydrological modelling, a first question that can be asked is: Why do we need model the rainfall-runoff process of hydrology? Keith Beven answers this question by stating that current limitation in hydrological measurement techniques is the main reason to need modelling. He also indicates that every component of the hydrological system cannot be measured completely. Only a limited range of measurement is possible in space and time. To disseminate available data in both time and space allows hydrologists to assess how the catchments respond to rainfall under different condition in ungauged catchments in the future (Beven, 2011). Analyzing hydrological signals like precipitation or runoff, hydrologists are able to identify the past and future variability of hydrological and climate regimes. This kind of analysis could give valuable information for planning and management of water resources (Partal, 2012). These analyses require rainfall - runoff models. These models also allow water managers to anticipate unexpected results of extreme hydrological conditions. Rainfall-runoff models are some of the most common models used in order to analyze the effect of external (atmospheric) forcing. They are crucially important for the regions where precipitation data are available but runoff data are deficient. This is the one of the most important obstacles in many developing countries with a large need of enhancing their water resources and other structures related to the water, such as dams and infrastructure.

## 1.3 Research Objective

The main aim of this thesis is to contribute to water management projects being implemented recently in the Buyuk Menderes catchment by suggesting that a model can be used for the estimation of the discharge. As the title of the thesis indicates, the main objective of this thesis project is the:

***"Investigate the performance of a rainfall-runoff models, WALRUS and HBV-light in an area with slight topography, dry climate, and catchment size and the effect of the groundwater abstraction."***

This will, in turn, promote up scaling of the thesis project in various ways. Later the first application of WALRUS in selected water bodies of the Buyuk Menderes, I am planning to extend its use to throughout Turkey. The testing of WALRUS in two subcatchments will be the supplementary info for the modelling projects ongoing in WRMD. Meanwhile, on that point is another project run by WRMD department. They are working together with DELTARES to implement another model called RIBASIM in the Buyuk Menderes catchment, Turkey. The primary objective of this project is the application of an EU-compliant tool to confirm the selection of cost-effective measures to satisfy the objectives of the Water Framework Directive in Turkey. This project will primarily concentrate on two substantial components a) Water quantity and b) Water quality. The ultimate ideas behind these projects is finding an appropriate model and alter it for the entire rural area and to determine how this instrument leads to a transparent and integrated approach to water resource management.

## 1.4 Research Questions

In order to reach the research objective, the following research questions will be answered:

1. How does WALRUS perform in industrialized areas where groundwater abstraction and waste water discharge are common (Adiguzel)?

   The Adiguzel subcathment chosen in order to answer the main research question. There are many industries are in service. They abstract groundwater for their operation. The effect of groundwater abstraction on the performance of WALRUS will also be assessed in this thesis. Two sub research questions will be benefited in order to answer this research question.They are:

   - Can WALRUS be applied to mesoscale catchments?

     WALRUS was designed for the conditions of the Netherlands. By testing WALRUS in the Adiguzel effects of the catchment size will be illustrated.

2. Which rainfall-runoff model, WALRUS or HBV-light, performs better for the selected catchment (Ikizdere)?

   WALRUS and HBV-light have been selected for this thesis project. After using these two specific models, results will be compared for Ikizdere subcathcment.

## 1.5 Outline

The outline of the report is as follows. In this chapter, (chapter 1) water challenge in Turkey is introduced and the motivation for rainfall-runoff modelling is presented. Research objective and research inquiries are also mentioned in this chapter. Buyuk Menderes and subcatchments are described in the chapter 2. In chapter 3, all meteorological and hydrological data are analysed before implementing them into the models. In chapter four and five mass balances are assumed and two rainfall-runoff models are introduced. In section 6, results and scenarios will be discussed. In section 7, the discussion will be given and thesis research is finalized with conclusion and recommendations in chapter 8 and 9.

# 2 | Study Areas

## 2.1 Introduction

The Buyuk Menderes river, one of the 25 river catchments of Turkey, is an important water supply for the region. Buyuk Menderes River originates in Dinar, Afyon, passes through Usak, Denizli and Aydin provinces, and disembogues to the Aegean Sea. With its twirly and bent path, it has been a home to many civilizations, and thanks to the alluviums it carries along, the area has the richest soil in Turkey. The Buyuk Menderes River provides irrigation water to many entities, primarily for agricultural purposes. It also provides irrigation water for industrial and tourism sectors. The active enterprises located in the catchment put a lot of pressure onto Buyuk Menderes Catchment. Moreover, water is not used efficiently, in terms of quality and quantity. Water pollution related to agricultural, industrial and domestic wastes creates a threat to the people living in the catchment, 2.5 million in total, and to the ecological balance. The most significant problems encountered in the catchment are lack of available hydrological and meteorological data, measurement errors and the difference between its borders and governmental borders causing water management problems.

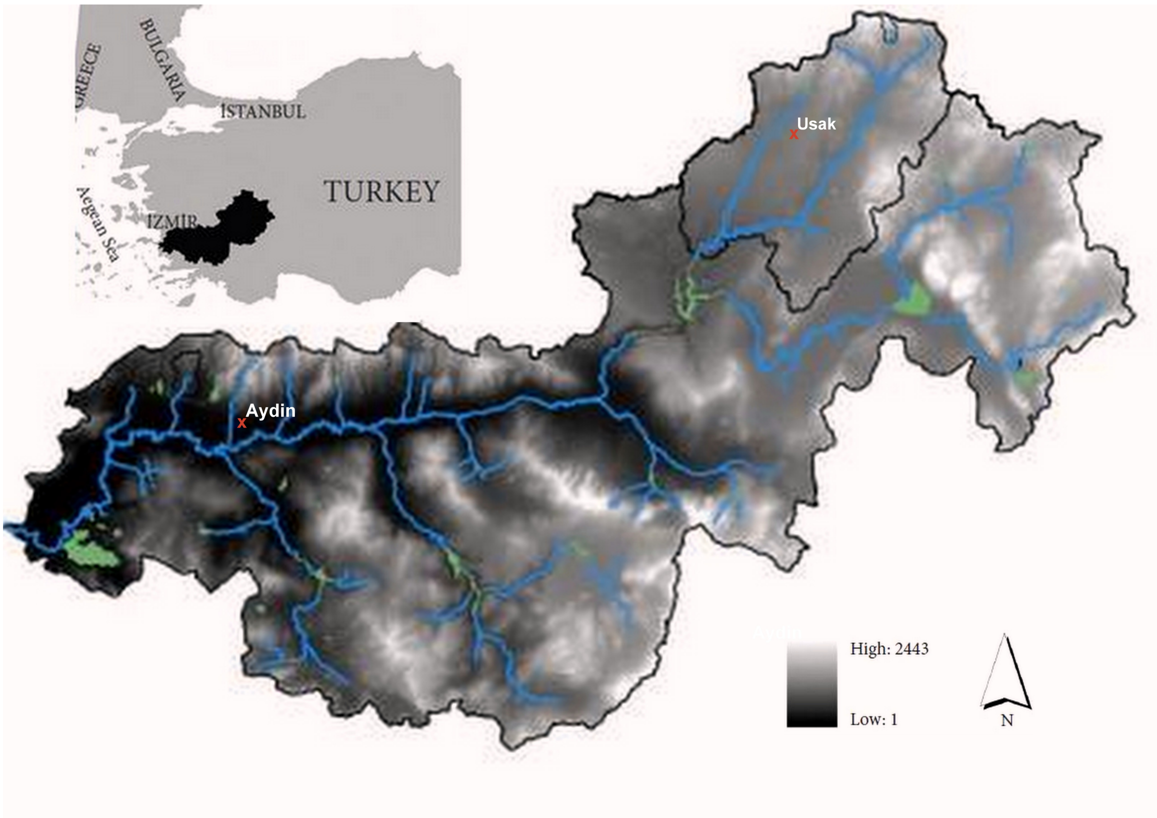


Figure 2.1: Elevation map of Buyuk Menderes catchment.

## 2.2 Catchment characteristics and topography

Buyuk Menderes catchment is located between $37°12' - 38°40'$ northern latitudes and $27°15'$ - $30°15'$ eastern longitudes. It is surrounded with Kucuk Menderes and Gediz catchments in the north, Sakarya catchment in the northeast, Afyon waters closed catchment in east, Burdur Lake catchment and Middle Mediterranean waters catchment in the southeast, West Mediterranean water catchment in the south and finally Aegean Sea in the west (Kazancı et al., 2009). The catchment, which covers 3.2 percent of Turkey's surface area, has a drainage area of 24,976 km$^2$ . It ranges approximately 200 km from west to east.

### 2.2.1 Geology and climate

The Buyuk menderes river originates from a karstic origined resource, which is located in the limestone caves in the northeast of Dinar, and is joined by a second stream, which is formed by the creeks from the high mountains surrounding the Sandikli Plain, and becomes the Buyuk Menderes River in the Civril Plain The valley that Buyuk Menderes River has created does not exhibit the characteristics of a flood plain. It is rather a rift zone caused by the decay of the fault lines in the geological period. The farthermost west section of it, which starts from Söke and ends at the sea coast, is created by the progress of Buyuk Menderes Delta (Koç, 1998). The west and the south of the Buyuk Menderes catchment have a Mediterranean climate; hot and arid in summers, warm and wet in winters. In the north, on the other hand,a terrestrial climate is found: hot and arid in summers, cold and rainy in winters. The average precipitation of the catchment is around 627 mm for many years (Koç, 2010).

### 2.2.2 Agriculture

In the Buyuk Menderes catchment, field crop cultivation especially industrial field crops; cotton and sunflower, is the most important aspect of agricultural output, alongside with fruit and vegetable cultivation and animal husbandry. The crops irrigated by the irrigation networks present in the Adiguzel subcatchment are mostly consisting of sugar beet, grain and feed crop. Agricultural enterprises located in the irrigation networks differ in terms of size on an average scale of 2-25 $km^2$ (Koç, 1998).

### 2.2.3 Water bodies and irrigation systems

Buyuk Menderes River is approximately 584 km in length. The river unites with its third stream, Banaz Creek, in the Adiguzel Dam. Later on it is joined with Curuksu, Dandalas Creek, Akcay and Cine Creek, then disembodied to the Aegean Sea, passing by the west of Bafa Lake. The flow of the river shows diversity through each season: flow rate significantly drops when the side creeks run dry. Thus, for the dry periods, in order to provide sufficient water, Isikli Lake, Adiguzel and Kemer Dams are benefited from their storage abilities. Isikli Lake appears in the northeast of Çivril, Denizli, and is a natural lake. The significant water supplies for storage purposes are Isikli fountain, Kufi Creek and Buyuk Menderes River. Isikli Lake was opened up for enterprises in 1953 and its primary purposes are irrigation and flood prevention. It provides irrigation water to Baklan, Cal and Buyuk Menderes Plains. Adiguzel Dam is situated in north Guney, Denizli, and is a rock fill dam. Its important storage water supplies are Banaz Creek, Hamam Creek and Isikli Lake. It was built in order to satisfy the irrigation, flood prebention and energy needs; it provides irrigation networks for Saraykoy, Nazilli, Akcay, Aydin, Soke, and public irrigations at Buyuk Menderes catchment (Koç, 1998).

## 2.3 Subcatchments (Adiguzel and Ikizdere)

Two different sub-catchments have been selected in order to be inspected further in this thesis project. Adiguzel subcatchment was selected because of its size and industrial operations on it. Furthermore, Ikizdere was selected because its topography and size. These catchments are staged by using 90 meters resolution digital elevation maps, which are prepared by the Shuttle Radar Topography Mission (SRTM), covered by the ARCGIS programme. While determining which catchments were to be picked, their sizes, climate conditions, groundwater abstraction and industrial activities were taken into account.

### 2.3.1 Adiguzel-E07A042

The biggest one, Adiguzel catchment, is located in the northeast of the main catchment, around the Usak province borders, and covers an area of 2285 $km^2$. Figure 2.2 illustrates a general overview of the catchment including the main components of the catchments which are industries, waste water treatment plants, the meteorological station of Usak and discharge stations located outlet of the subcatchment. The water needed for industrial, household and agriculture purposes is pumped from the underground. Elaboration of the data of groundwater abstraction and its usage can be found in the data analysis section. A station operated by General Management of Meteorology, located in Usak province, provides measurements of meteorological data. In addition, discharge stations operated by the DSI, are used in order to obtain measurements of daily discharge at the catchment. This modelling research has

Table 2.1: The main catchment characteristics of the study areas and averaga water budget. Surface water supply indicates treated waste water from waste water treatment facility.

| **Characteristics** | **Units** | ***Ikizdere*** | ***Adiguzel*** |
|---|---|---|---|
| Size | [ $km^2$] | 42 | 2285.5 |
| Studied period | | 2004-2009 | 2005-2010 (2006) |
| Altitude | [m] | 300 | 750 (500-1000) |
| Precipitation | [mm] | 615 | 555 |
| Discharge | [mm/year] | 400 | 90 |
| Pot. evapotranspiration | [mm/year] | 922 | 938 |
| Surface water supply | [mm/year] | 0 | 14.6 |
| Groundwater abstraction | [mm/year] | 0 | 54.8 |
| Temperature | [ °C ] | 18.5 | 13.4 |

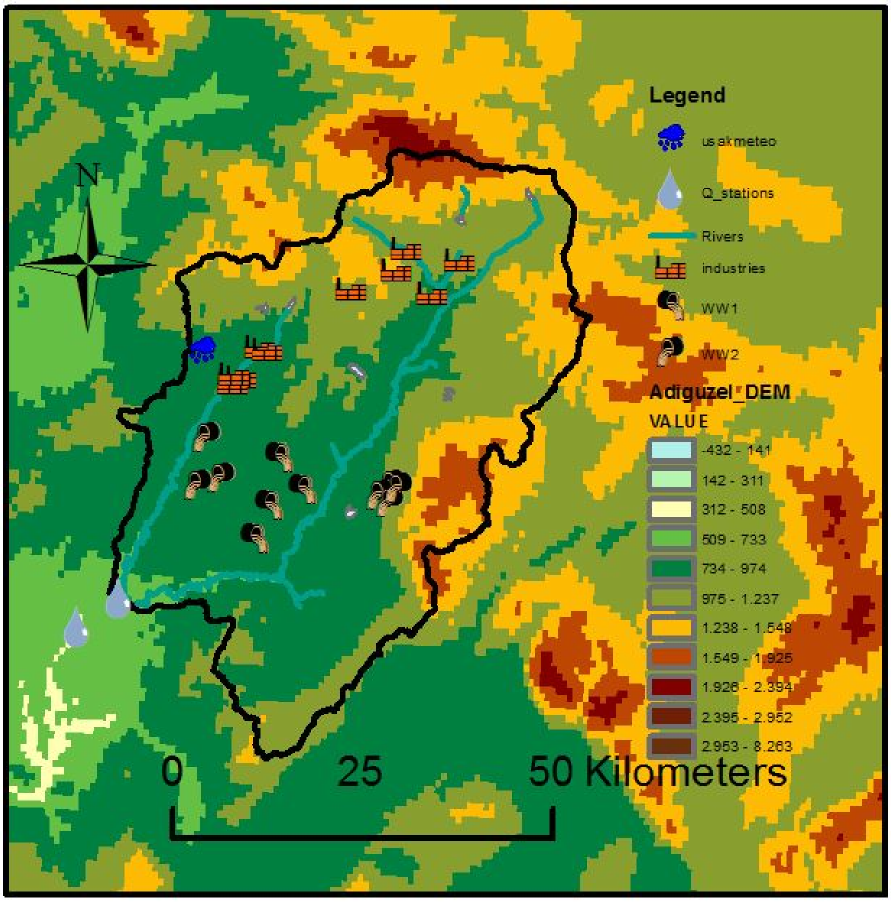


Figure 2.2: The General Overview of Adiguzel subcatchment.

been done with the data taken from the discharge stations, codes are E07A035, E07A042 located at the outlet of the catchments. Another reason of Adiguzel sub-catchment having an importance for Buyuk Menderes catchment is the industrial facilities in action in the organized industrial zone in Usak province. These facilities treat the water they use for their processes, which they abstract from the underground, and discharge it to Dokuz Sele and Banaz Creeks. These discharges alter both the quality and the quantity of the water supplies in Ad,guzel catchment. In addition to the facilities, the residential districts just in the southeast of the catchment as well have a surface water supply to the Dokuz Sele Creek. The discharges and groundwater abstraction happening in the sub-catchment has a massive and negative impact on the water level of the Dokuz Sale Creek. In order to deal with these difficulties and to obtain a sustainable water management plan, various hydrological models have been used. Detailed information of this catchment is given in the Table 2.1

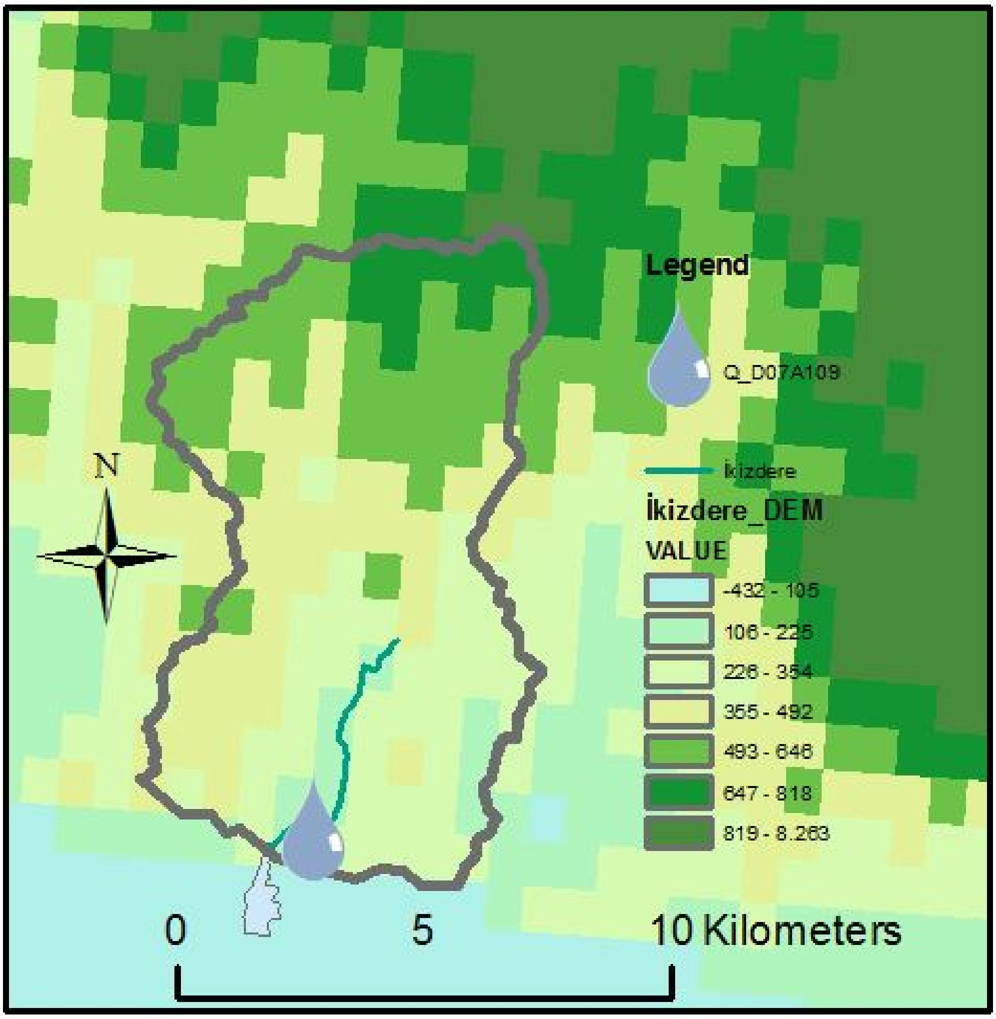


Figure 2.3: Elevation map of Ikizdere subcatchment.

### 2.3.2 Ikizdere-D07A109

Another chosen subcatchment is located at the northwest of Aydın province, which has a 42 km$^2$ catchment area. In addition to it having no industrial activities within its boundaies, the catchment has only one water resource, which is Ikizdere Creek. The creek is disembogued to Hıdırbeyli Pond right downstream of the catchment borders. Since there is a discharge station, managed by the State Water Supply Administration ( with code D07A109 ) the catchment was named as Ikizdere.

Figure 2.4: Some photos from the Adiguzel subcatchment. Top: (1) Banaz brook during wet season,(2) Banaz brook during dry season. Middle: (1) spinning factory located in the Adiguzel subcatchment, (3) industrial waste water treatment plant, Usak. Bottom (1) water quality near treatment plant and (2) Dokuzsele creek during wet season.

# 3 | Data Analysis

The data requirements of WALRUS and HBV-light are comparable: as inputs WALRUS needs precipitation, potential evapotranspiration and discharge time series (used for calibration), whereas HBV-light only requires average temperature data as addtional input. All data will be elaborated in the following sections. Their source, verification method, and data selection will be explained briefly.

## 3.1 Precipitation

The precipitation time series have been provided by the Turkish General Directorate of Meteorology (MGM) for subcatchments. These data are not open source, all data are stored in the system of MGM so called TUMAS, and this system serves as a data bank. Data are all free to charge for scientific employment of researchers from ministries and universities. Other companies or individual researchers have to pay in order to get any data. These data are collected from automatic ground meteorological stations by using synoptic technique. Existing stations are limited for these catchments. There are only two meteorological stations for selected sub catchments. The first one is Usak meteorological station located in the Adiguzel catchment. However, there is no precipitation measurement station is located exactly in the İkizdere catchment. Precipitation data have been gathered from the nearest station is Aydın, which is about 14 km southeast of outlet, .

Since provided discharge data covered only 5 years, starting from 01.12.2004 to 12.31.2009, only 5 years have been analysed for the İkizdere catchment. In total 5 years of time series were selected, including extreme years; a) 2004 was a dry year b) 2007 was a normal year and c) 2009 was a wet year. Due to the fact that, data availability is one of the biggest challenges in this research project precipitation is assumed well distributed in the subcatchments. All catchments characteristics and orographic effects have been neglected.

### Comparing Precipitation time series

The ripple diagram has been used in order to check the consistency of the provided precipitation records. The cumulative precipitation sums have been plotted against years.

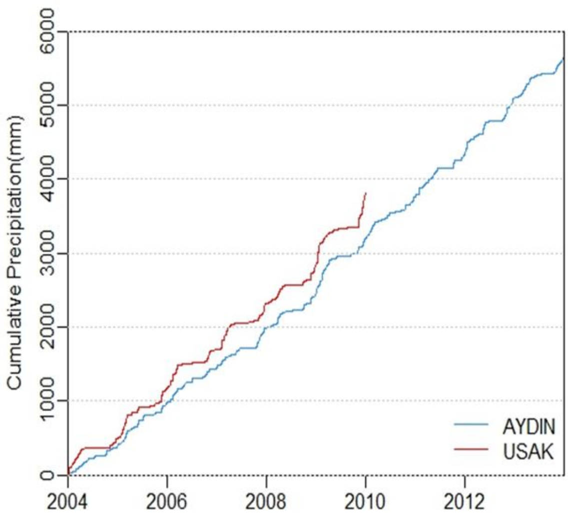


Figure 3.1: Cumulative precipitation for two meteorological stations.

A ripple diagram is used in order to determine the consistency of precipitation records. The ripple diagram is a display of the cumulative precipitation sums of the each precipitation station for a given time period and aids to analyse if each individual precipitation stations has any sudden shift or consistent differences. These consistence differences may also be real like in this research. Figure 3.1 illustrates some horizontal lines which are due to the fact

Table 3.1: The overview of the meteorological stations; their locations, altitude and duration.

| Station | Number | X (m) | Y (m) | Altitude (m) | Start date | End date |
|---|---|---|---|---|---|---|
| **Aydin** | 17234 | 456790 | 4616779 | 56 | 1.1.2004 | 31.12.2009 |
| **Usak** | 17188 | 599685 | 4700389 | 919 | 1.1.2004 | 31.12.2013 |

Table 3.2: illustration of yearly sum of the measured open water evaporation and calculated potential evapotranspiration (mm).

| Years | USAK | | AYDIN | |
|---|---|---|---|---|
| | $\mathbf{ET}_{\text{pen}}$ | $\mathbf{ET}_{\text{open}}$ | $\mathbf{ET}_{\text{pen}}$ | $\mathbf{ET}_{\text{open}}$ |
| 2004 | NA | NA | 1563.7 | 2171.8 |
| 2005 | 1205. | 1777.6 | 1276.8 | 1883.2 |
| 2006 | 1175.4 | 1655.5 | 1251.2 | 1762.3 |
| 2007 | 1389.8 | 1903.8 | 1344.7 | 1842.1 |
| 2008 | 1347. | 1862.6 | 1276.3 | 1764.2 |
| 2009 | 1332.6 | 1692.4 | 1289.7 | 1637.9 |
| 2010 | 1346.1 | 1800.9 | NA | NA |

that absence of precipitation in a long period of time. Additionally, ripple diagram shows that western part of the Buyuk Menderes (Aydin) is receiving relatively precipitation than the southern part of the catchment.

## 3.2 Temperature

Temperature data have also been provided by MGM from these stations for HBV-light model. Daily averages of values have been used, which were calculated by averaging the daily maximum and daily minimum. Annual average can be assumed 18.5 °C for İkizdere subcatchment and 13.4 for the Adiguzel catchment. The reason of this temperature gradient can be explained with their elevation and location.

## 3.3 Potential Evapotranspiration

Potential evapotranspiration ($\text{ET}_{\text{open}}$) is another input for WALRUS and HBV-light. MGM measures open water evaporation (ETopen) in the Turkey by using the Pan method. However, potential evapotranspiration (ETpen) is calculated by using Penman Monteith equations based on meteorological variables such as global radiation, wind speed, temperature and humidity. DSI assumes that PAN coefficient is about 0.7 during between March to August ($\text{ET}_{\text{open}} \times 0.7 = \text{ET}_{\text{pen}}$) and these coefficient increases to 0.8 from September to October. In addition to them, there is no open water evaporation measurement from November to February.

Since the soil of the study areas is not well watered. $\text{ET}_{\text{pen}}$ has been chosen as potential evapotranspiration values for this study. The average value is about 940 mm/year for the Adiguzel subcathment and 924 mm/year for the Ikizdere subcathment. In order to be able to calculate actual evapotranspiration, reduction should be known. However, this reduction factor is unknown. Three different assumptions have been made. These assumptions will be explained in detail in the water balance section. Additionaly, the reduction factor can be calculated by WALRUS and HBV-light based on soil moisture storage.

## 3.4 Discharge

Discharge (Q) time series are needed in order to calibrate and validate the models. All discharge data have been provided by DSI discharge stations. There are 32 discharge measurement gauges located in the entire Buyuk Menderes catchment.

The discharge is measured by measuring water level and using a rating curve at the catchment outlet. The basic idea of the marograpgh method is curve shows the relation between stage and discharge of a stream at a hydrometric station. If digitized, it is a rating table. The cross section of the river or brook has been measured and calculated during dry periods. Afterwards, the cross section is divided, into the relatively small cross-section. Each month of

Table 3.3: Characteristics of the discharge stations for selected catchments

| ***Station*** | ***Catchment*** | ***Station code*** | ***X (m)*** | ***Y (m)*** | ***Available data*** | ***Measurement type*** |
|---|---|---|---|---|---|---|
| 1 | Ikizdere | D07A109 | 444124 | 463521 | 01.01.2004-12.31.2009 | Measured |
| 2 | Adiguzel | E07A035 | 583186 | 4664019 | 01.01.2004-12.31.2013 | Measured-modelled |
| 3 | Adiguzel | E07A042 | 589336 | 4667763 | 01.01.2005-30.09.2010 | Measured |

the year river stage and velocity of the sub cross-section based on their depth is measured by hydrology technicians, by using continuity equation (Q$=A\times$V ) they are able to calculate daily discharge for that day. They repeat this action every month and they plot calculated discharge values in logarithmic axes against river stage, by interpolating this 12 measurement points, they create a rating curve. In addition to that, the limnimeters are installed in order to measure daily river stages. This tool transfer all measured averaged daily stage to DSI. By using a rating curve and daily stage, daily discharge can be calculated.

The biggest data problem is unfortunately from discharge time series. Not only availability (the percentage of available data are only forty percent for the last ten years) but also reliability is a challenge. All difficulties will be explained in the results and discussion parts of the project. Three discharge stations are in progress in the subcathcment, two of them are located in the Adiguzel catchment. One of them is located at the outlet of the Ikizdere catchment.

In order to be able to match precipitation data with discharge data, availability of the discharge time series have been taken into account. For instance, precipitation values have been evaluated from the Aydın catchment only from 2004 till 2009.

## Verification of the discharge

As indicated in the table above, some data are gathered as a combination of measurement and modelled, this causes reliability problem. Additionally, discharge data from E07A042 has some sudden jumps and decreases. In order to remove these measurement errors, some data have been interpolated from E07A035. In order to overcome those errors, data interpolation is carried on using the nearest observation station data. The crucial steps for interpolation are as follows.

### Detecting measurement errors in the provided time series

In order detect measurement errors of discharge data, the data are plotted as mm/day (Figure 3.2.)

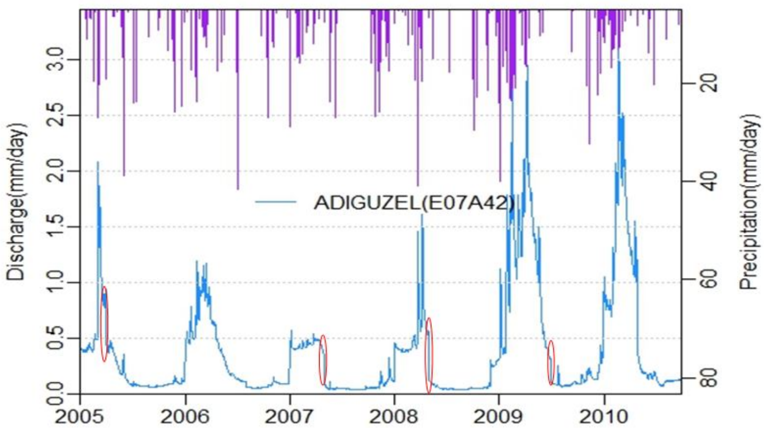


Figure 3.2: Discharge time series for E07A042.

The plot illustrates discharge values from 01.01.2005 till 09.30.2010. Two important points attract attention from this plot. First of all, since all years have started and ended with average wetness condition (01.January-31.December), base flow is high approximately 0.4 mm/day of every year. Secondly, there are four sudden decreases in 2005, 2007, 2008 and 2010, which are considered to result from measurement errors. Next steps will be about removing these errors from time series.

**Choosing the nearest measurement station and plotting their cumulative discharge against each other for the same period**

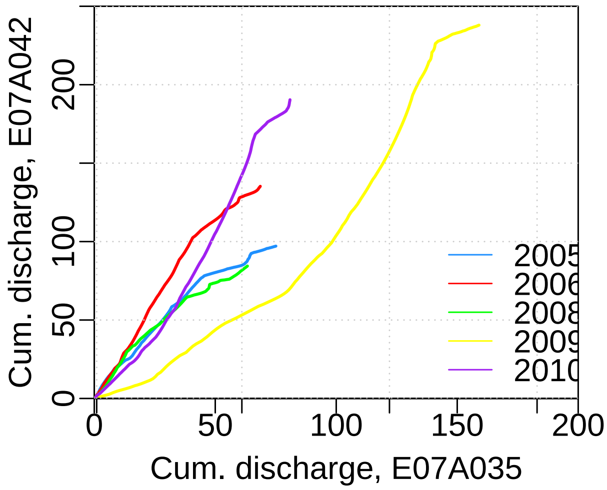


Figure 3.3: Cumulative discharge of two discharge stations for 2005, 2006, 2008, 2009 and 2010

Station number E07A035 was chosen as nearest discharge station. This station is located 14 km further downstream, and representative area is about 3000 ($km^2$). Cumulative discharge data have been plotted against each other in order to see the correlation between two discharge stations. As illustrated in the figure 3.3, correlation is really high for these two catchments.

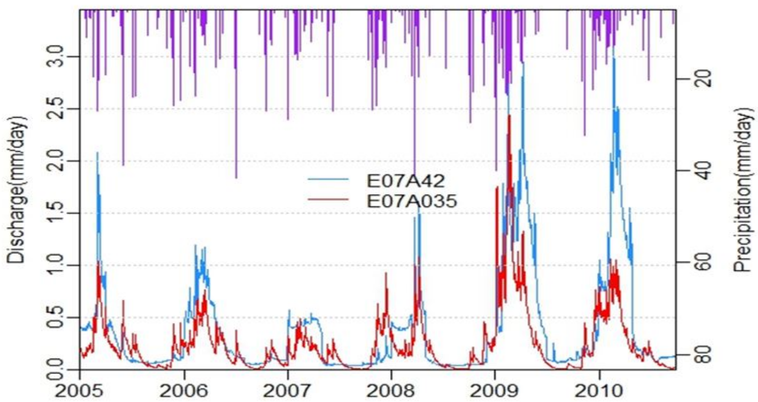


Figure 3.4: Illustration of discharge time series for E07A042 and E07A035.

As a result of plotting cumulative discharges against each other and plotting them on the same graph, it is concluded that E07A035 is the appropriate station to interpolate data which have measurement error. The original form of discharge data is used for this process. These data were given as ($m^3$/sec) units and the concerned station is located at the outlet of the catchment. Thus the data are adjusted according to the catchment area and is converted into appropriate units; mm/day. Finally fixed time series has been able to obtain as follows.

Since 2007 has large errors compared to the other years, this year is not analysed. WALRUS has been also calibrated for discharge station E07A035 with different conditions for different years. However, the problem of the station is its data, especially first four months, discharge data are obtained by a combination of measurement and

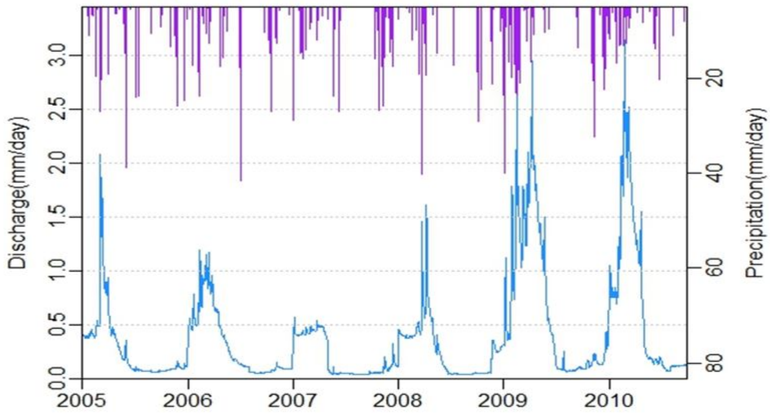


Figure 3.5: Fixed discharge time series.

Table 3.4: The overview of groundwater abstraction, discharge from industries and household waste water plants. Source (TUBITAK, 2005)

| ***Groundwater Abstraction and Surface Water Supply*** | | | | |
|---|---|---|---|---|
| | **Unit** | **2004** | **2008** | **2010** |
| Household purpose | ( $m^3$/year) | $2\times10^7$ | $2\times 10^7$ | $2\times 10^7$ |
| Agricultural purpose | ($m^3$/year) | $1.35\times10^8$ | $1.35\times 10^8$ | $1.35\times 10^8$ |
| Industrial purpose | ($m^3$/year) | $2\times10^7$ | $2\times10^7$ | $2\times10^7$ |
| Total abstraction | ($m^3$/year) | $1.75\times 10^8$ | $1.75\times 10^8$ | $1.75\times 10^8$ |
| Total abstraction | (mm/day) | 0.15 | 0.15 | 0.15 |
| Industrial discharge | ($m^3$/year) | $1.6\times 10^7$ | $1.9\times 10^7$ | $1.9\times 10^7$ |
| Househould discharge | ($m^3$/year) | $1.35\times 10^7$ | $1.35\times 10^7$ | $1.35\times 10^7$ |
| Total discharge | ($m^3$/year) | $2.95\times 10^7$ | $3.2\times 10^7$ | $3.2\times 10^7$ |
| Total discharge | (mm/day) | 0.034 | 0.036 | 0.036 |

modelling source. The calibrated parameter set and results will be shown at the end of this chapter at station number E07A035.

## 3.5 Groundwater abstraction and surface water supply

The Adiguzel catchment is located in the north-eastern part of the Buyuk Menderes catchment. The area is mainly agricultural area, farmers use groundwater in their irrigation system. The area also covers an industrial area so called Usak organized industrial zone. These industries abstract groundwater in order to use in their process. They discharge their process water after wastewater is treated into the Banaz brook. Because the surface water is not clean for household purpose, the source of household water is also from ground water in the subcatchment.

The wastewater treatment plants are connected to Dokuz Sele brook in the subcatchment. The challenge regarding the modeling of groundwater abstraction is that the exact amount of abstraction is unknown. The groundwater abstraction rates were collected from previous surveys of Buyuk Menderes catchment done by TUBITAK. In this survey, only the location and the yearly sum of groundwater discharge are provided. Since they do not clarify whether this abstraction is constant or variable during the year, it is assumed that daily groundwater abstraction is constant. The waste water discharge values from industrial zone and treatment plants have been provided by the Ministry of Environment and Urbanisation.

As shown in the Table 3.4, 78 percent of groundwater abstraction is used for agricultural purpose, meaning that groundwater abstraction is not coming back to the system. The rest is divided two equal parts, household and industrial purposes. These amounts are partly coming back to the system. Groundwater abstraction flux will be applied WALRUS as seepage ($f_{\mathrm{XG}}$) which is 0.15 mm/day and discharge is applied as surface water supply ($f_{\mathrm{XS}}$) which is varying for selected hydrological years 0.036, 0.037 and 0.038 respectively.

## 3.6 Groundwater depth

Groundwater depth is one of most important missing data in the catchment. No information on groundwater depths is available. Even though the most important water source is the groundwater discharge, there is no available data or survey referring about groundwater depth and storage. In this research initial groundwater level is assumed as based on discharge originating from drainage.

## 3.7 Geographical Information

A digital elevation model of the Buyuk menders catchment is available from SRTM at 90m resolution in TIFF file format. Since the Buyuk Menderes basin was on the border of available images, these images were merged and clipped to the catchment outline using ArcGIS. Finally, DEMs have prepared for subcatchment (Adiguzel and İkizdere). The shape files with the catchment boundary, water bodies, subcatchments, rivers and open water have been provided by SYGM.

# 4 | Mass Balance

## 4.1 Water Balance

The water balance is an important method to check the performance of the WALRUS in different conditions and selected hydrological years (dry, normal and wet). The main concept of water balance is the difference between water coming into the system and water going out of the system within a specific time period, in this case the yearly time step. The formula below illustrates the basic formula of the balance equation:

$$\Delta S = \int_{t_1}^{t_2} Q_{in}\,(t)\,dt - \int_{t_1}^{t_2} Q_{out}\,(t)\,dt \tag{4.1}$$

$\Delta S$ is referring to water storage change in the system within the selected period and $Q_{\mathrm{in}}$ refering all incoming water and $Q_{\mathrm{out}}$ refering all outgoing water.Two study areas are considered as subcatchments in this thesis research. Each of these areas has different components. Therefore, two different equations, originated from same equations, have been formulated. They will be evaluated one by one. Another important point is the evapotranspiration reduction of the study areas, since the reduction rate is not know three different scenarios have been considered in each case. They will also be explained.

## 4.2 Water Balance for the Adiguzel subcathment

This area is known with its industrial areas, groundwater abstraction and water discharge from treatment plants. These components should be taken into account for water balance, whereas seepage and infiltration have been neglected in order to keep the formula as simple as possible. By putting all components together, an equation has been formulated as follows,

$$B = P - ET_{act} - GW_{abs} - Q + WW + \frac{dS}{dT} \tag{4.2}$$

- B: Balance (mm)
- P: Annual precipitation (mm)
- $ET_{\mathrm{act}}$ : Actual evapotranspiration (mm)
- $ET_{\mathrm{act}} = ET_{\mathrm{pot}} \times \beta$ (mm)
  $ET_{\mathrm{pot}}$ : Potential evapotranspiration (mm)
  $\beta$: Evapotranspiration reduction factor
- Q: The sum of discharge (mm)
- WW: The sum of the purified waste water discharge from waste water plants (mm)
- $\Delta$S $= \frac{dS}{dT}$ : The storage change which has been neglected in this case due to chosen long time series.
- $GW_{\mathrm{abstraction}}$: Yearly groundwater abstraction (mm)

When water balance is considered over a whole year $\Delta$S is much smaller than the other terms, because $\Delta$S is a difference and the others are sums. In addition, the storage is usually back at its original level after a whole year. However, this assumption would not be true if the conditions were extremely dry or wet or the time was short. Due to the fact that the reduction factor is not known, it was hard to estimate actual evapotranspiration in this research. Three scenarios have been taken into account for the evapotranspiration reduction factor.

### The evapotranspiration assumptions of Adiguzel

Figure 4.1 shows an illustration of evapotranspiration reduction assumptions done for Adiguzel subcathment.

Assumption 1 states that the reduction factor ($\beta$) is 1 meaning actual evapotranspiration is equal to potential evapotranspiration ($ET_{\mathrm{act}}$= $ET_{\mathrm{pot}}$). With this assumption all balances have negative values indicating that the water, leaving out of the system is higher that water coming into the system. If the situation was true, water in the

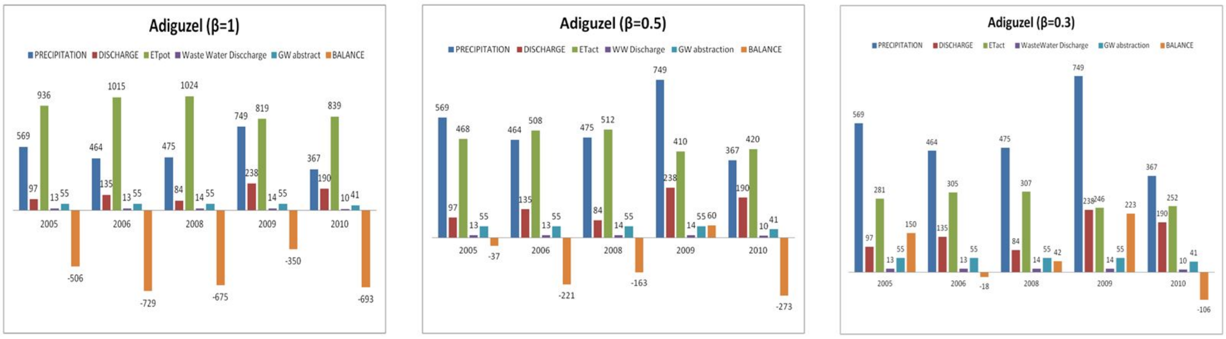


Figure 4.1: Three $\beta$ assumptions for Adiguzel.

soil would decrease. There might be several reasons for this case. First of all, actual evapotranspiration is assumed exactly same with calculated evapotranspiration, which is extremely high in this case. Reduction factor should be taken into account. Another reason might be neglected input such as infiltration. Finally, measurement errors might be the reasons for negative balance. In order to see the effect of reduction factor on water balance, other scenarios have been considered.

Assumption 2 states that the reduction factor is 0.5 meaning actual evapotranspiration is half of the potential evapotranspiration ($ET_{\mathrm{act}}$= 0.5× $ET_{\mathrm{pot}}$). Compared to the assumption 1, water balance has increased; three years still have a negative balance because of high evapotranspiration and relatively low precipitation. Only 2009 has positive balance in this situation, thanks to high precipitation.

Assumption 3 states that the reduction factor is 0.3 meaning actual evapotranspiration is only one third of the potential evapotranspiration ($ET_{\mathrm{act}}$= 0.3 × $ET_{\mathrm{pot}}$). The last scenario indicates actual evapotranspiration is equal to one third of the potential evapotranspiration. Only last year, which is 2010, has still quite a high storage deficit.

As a consequence of these three assumptions, it can be indicated that, all components should be taken into account for water balance including the seepage and infiltration. High potential evapotranspiration and measurements error should also be examined carefully.

## 4.3 Water Balance for the Ikizdere subcathment

Ikizdere has been considered as a subcatchment located in the Buyuk Menderes delta, since there is no industry and waste water operations in the subcatchment, water balance can be formulated more compare to Adiguzel catchment.

$$B = P - ET_{act} - Q + \frac{dS}{dT} \tag{4.3}$$

Water balance includes precipitation, Evapotranspiration, discharge and storage change. As already indicated previous situation, storage can be neglected in long time series unless there is extremely dry or wet period. These situations are not the case in selected period. Due to unknown, reduction rate, three assumptions have also been considered for this subcatchment.

### The $\beta$ assumptions of Ikizdere

Figure 4.2 shows an illustration of evapotranspiration reduction assumptions done for Ikizdere subcathment.

Assumption 1 assumes that the reduction factor is 1 meaning actual evapotranspiration is equal to potential evapotranspiration ($ET_{act}$=$ET_{pot}$). Due to the high potential evapotranspiration and low precipitation, storage deficit is really high. Water balance is always below zero which is not possible in the hydrology. In order to decrease storage deficit, two other scenarios have been considered with different evapotranspiration factors as illustrated in following scenarios.

Assumption 2 assumes that the reduction factor is 0.5 meaning actual evapotranspiration is half of the potential evapotranspiration ($ET_{act}$=0. 5*$ET_{pot}$). Assumption 2 exhibits that negative balance is still the case with decreasing evapotranspiration reduction factor. The balance is negative, even in the wet hydrological year.

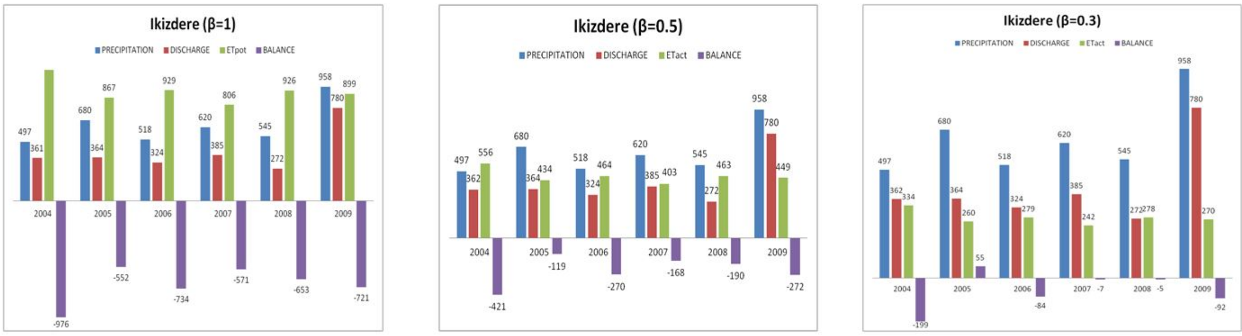


Figure 4.2: Three $\beta$ assumptions for Ikizdere.

Assumption 3 assumes that the reduction factor is 0.3 meaning actual evapotranspiration is one third of the potential evapotranspiration ($ET_{act}$=0. 3*$ET_{pot}$). Although, water balance decreased a lot compare to first two assumptions, all years still show a negative balance with basic components in the Ikizdere catchment. While the most important reasons are high potential evapotranspiration, measurement errors have also a significant effect on the water balance. Furthermore, other components such as seepage and infiltration should be taken in order to reach a reasonable water balance.

## 4.4 Calculating the average $\beta$ for subcatchments

After three assumptions have been applied for two subcatchments. It was deducted that the evapotranspiration factor should be between assumption 2 and assumption 3 in order to have reasonable results for water balance.To be able to calculate the average reduction factor. Evapotranspiration reduction factor was deriven from balance equation ( Equation 4.2) as follow;

$$\beta = \frac{P - GW_{abs} - Q + WW}{ET_{pot}} \tag{4.4}$$

Equation 4.3 shows equation of potential reduction for Adiguzel subcatchment. The differences between Adiguzel and Ikizdere are absence of groundwater abstraction and surface water supply in the Ikizdere cathcment. Equation can be reformulated easily by extracting groundwater discharge and surface water supply for Ikizdere catchment from equation. These formulas have been applied all data in order to find mean reduction factor for each subcatchment.

Table 4.1: Calculated evapotranspiration reduction factors of Adiguzel and Ikizdere catchments for provided years.

| Year | P | ET | Q | GW | WW | $\beta$ |
|---|---|---|---|---|---|---|
| | | | **Adiguzel** | | | |
| 2005 | 569.3 | 936.1 | 98.7 | 54.8 | 14.6 | 0.46 |
| 2006 | 463.6 | 1015.5 | 112 | 54.8 | 14.6 | 0.31 |
| 2008 | 467.7 | 1023.9 | 94.2 | 54.8 | 14.6 | 0.33 |
| 2009 | 748.5 | 819.4 | 237.5 | 54.8 | 14.6 | 0.57 |
| 2010 | 365.4 | 839.2 | 188 | 54.8 | 10.9 | 0.18 |
| Average ($\beta$) | | | 0.37 | | | |
| | | | **Ikizdere** | | | |
| 2004 | 497.2 | 1113.7 | 362.3 | NA | NA | 0.12 |
| 2005 | 679.5 | 867.4 | 364.5 | NA | NA | 0.36 |
| 2006 | 518 | 928.6 | 323.8 | NA | NA | 0.21 |
| 2007 | 619.8 | 806.2 | 384.6 | NA | NA | 0.29 |
| 2008 | 545 | 926.1 | 272.2 | NA | NA | 0.29 |
| 2009 | 957.9 | 898.9 | 780.2 | NA | NA | 0.20 |
| Average ($\beta$) | | | 0.25 | | | |

Table 4.1. shows results of yearly potential evapotranspiration reduction factors and average evapotranspiration reduction factors based on Equation 4.4. The average evapotranspiration redution factor is 0.37 including 2010 and 0.42 excluding 2010 for the Adiguzel subcatcment. The reason why reduction factor decreases dramatically in the 2010 is only 9 months data (from 01-01-2010 till 09-31-2010) were provided. It can be concluded that the mean reduction factor is between assumption 2 and assumption 3. Conversely, the average reduction factor stays around 0.25 with deriven formulas which is even less than assumption 3. The main purposes of assuming three different assumptions and comparing them with results from derived formula are firstly showing importance of reduction factor on the water balance. Additionally, catchments where the soil is not well watered, reduction factor is relatively low meaning evapotranspiration reduction is high.

# 5 | Methodology

## 5.1 WALRUS

The Wageningen Lowland Runoff Simulator (WALRUS) has been developed by Claudia Brauer Brauer et al. (2014) as a water balance model. The catchments are assumed as a single system whose components are land surface, surface water, vadose zone within the soil reservoir, groundwater zone within the soil reservoir, quick flow reservoir and surface water. These components are integrated each other with different fluxes. All processes are explained by Brauer et al. (2014) as follows, Precipitation (P) enters the model in the land surface component. A certain amount is directly falling on the surface water reservoir ($P_s$). The soil wetness index determines which part of the the remaining amount of precipitation will go to the vadose zone ($P_v$) and which part will directly go to the quick flow reservoir (Q).the storage deficit ($d_v$) controls the soil wetnes index (W) and the reduction of evapotranspiration ($\beta$).Both surface water infiltration and drainage of groundwater ($f_{GS}$) are depending on groundwater depth ($d_G$) and surface water level ($H_S$) Extrenal fluxes are seepage/extraction ($f_{XG}$), surface water supply/extraction and discharge(Q). Discharge is determined from the surface water level ($h_s$). The change of water level in the quick flow reservoir ($h_Q$) is determined by the difference between the water that is flowing into the quick flow reservoir ($P_Q$) and the water that is leaving the reservoir ($f_{QS}$) divided by the groundwater reservoir area fraction.

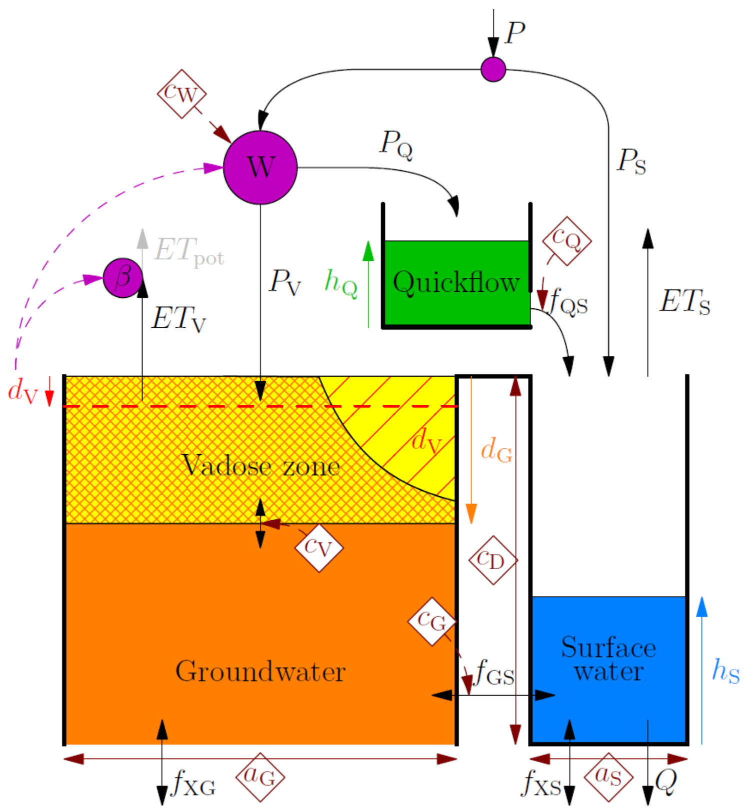


Figure 5.1: Overview of the model structure of the WALRUS with the five components. Source: (Brauer et al., 2014)

Fig. 5.1 gives an overview of WALRUS Brauer et al. (2014) contains elaborated model description. The substantial reasons why WALRUS has been chosen for this thesis research are a) Model structure are easy to understand and b) Data needs are simple and low. Bergström (1991) states in his study, the initial decision of intricacy level of the model structure is a critical choice in the displaying procedure. It will influence the need of computer limit and the data necessity and subsequently the applicability of the model. Ideal unpredictability is the point we ought to attempt to reach for every particular issue (Bergström, 1991).

### 5.1.1 Calibration of WALRUS

In order to have WALRUS to obtain accurate discharge simulations from precipitation and potential evaporation, it should be calibrated on historical data. Calibration is a mathematical procedure where adjustment of parameter values are adjusted to reproduce the response of reality within the range of accuracy specified in the performance criteria (Refsgaard and Henriksen, 2004). The parameters from different models of catchments across the country are not eligible to use because of the significant difference of heterogeneity in soil characteristics, geology and geomorphology (Refsgaard and Henriksen, 2004). The field observations may cause errors in some of the parameters in WALRUS because these parameters represent either the total catchment or sub-catchments including heterogeneity, thus should be calibrated. Five model parameters were adjusted to optimize for the Buyuk Menderes catchment: Required model parameters for calibration are explained by Brauer et al. (2014) as follows:

1. **Wetness index parameter (cW)** is a threshold value determining the soil wetness index which is the fraction of the remaining precipitation which percolates slowly through the soil matrix and the fraction which flows towards the surface water via quick flow routes. When the storage deficit exceeds cow, no precipitation will be lead to the quick flow reservoir. (mm)
2. **Vadose zone relaxation time (cV)** determines how quickly the system advances towards a new equilibrium. (h)
3. **Groundwater reservoir constant (cG)** represents the combined effect of all resistance and variability. Furthermore cG depends on soil type (hydraulic conductivity) and drainage density. (mmh)
4. **Quick flow reservoir constant (cQ)** determines how fast outflow of the quick reservoir is decreased, it is asymptotical, so it w,ll never get to zero (h)
5. **Bankfull discharge (cS)** corresponds to the discharge at the catchment outlet when the surface water level reaches the soil surface. Calibration of cS is necessary due to the fact that discharge-stage (Q-h) relation is not present. ($mmh^{-1}$)

Table 5.1: Calibrated model parameters for WALRUS with lower and upper boundaries

| | Unit | Lower Boundary | Upper Boundary |
|---|---|---|---|
| **cW** | mm | 100 | 700 |
| **cV** | h | 4 | 100 |
| **cG** | mmh | 1.00E+05 | 1.00E+08 |
| **cQ** | h | 1 | 150 |
| **cS** | $mmh^{-1}$ | 10 | 100 |

Based on experience it could be said that cW, cG and cQ are easy to detect in the discharge data, however cW is hard to approximate (Brauer et al., 2014b).The other catchment characteristics such as cD and aS can be obtained with field observations. For this thesis research, channel depth is assumed as 2.5 meter and surface water fraction is approximated by using provided maps. The estimation of surface water area fraction for each catchment is shown in the annex. For calibration, an automated calibration algorithm called HydroPSO Zambrano-Bigiarini and Rojas (2014) was used . During modelling performance hydroPSO has given two outcomes: this technique never fails to deliver results (simulated discharges), however, the calculations of it is time consuming (more than one day). Other available techniques such as Monte Carlo were not performed in this thesis. In this research WALRUS have been calibrated several times in order to answer research questions. For the Adiguzel catchment WALRUS has been calibrated with groundwater abstraction and waste water discharge for different hydrological years. On the other catchment so called Ikizdere (D07A109) WALRUS calibrated with three different hydrological years (dry, average and wet) years. Calibrated parameter will be shown in the results section. The main purpose of the calibration is increasing Nash-Sutchliffe efficieny which is the criteria used to assess model performance.

### 5.1.2 Validation of WALRUS

Validation is the substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. The most important question of the validation process is **"How does calibrated model fit with new data?"** (Beven and Binley, 1992). In order to answer this question calibrated parameters have been validated on different years for each catchment respectively. These results will also be elaborated in the results section of the report.

## 5.2 HBV-LIGHT

The HBV is a rainfall-runoff model and was developed by Sten Bergström Bergström et al. (1995) at SMHI (Swedish Meteorological and Hydrological Institute). The model has been applied in many studies, with varying catchment size, topography and climate (SMHI, 2014). The SMHI-HBV model has been modified many times due to two main reasons; a) user friendliness, particularly considering the use in educational purpose and b) different climatic conditions. One latest edition is HBV light developed at Uppsala University (Seibert, 2005). The HBV-light is a lumped presentation of the original. Precipitation, average temperature and evapotranspiration are used on a daily time step as input. Figure 5.2 illustrates an overview of the HBV light model.

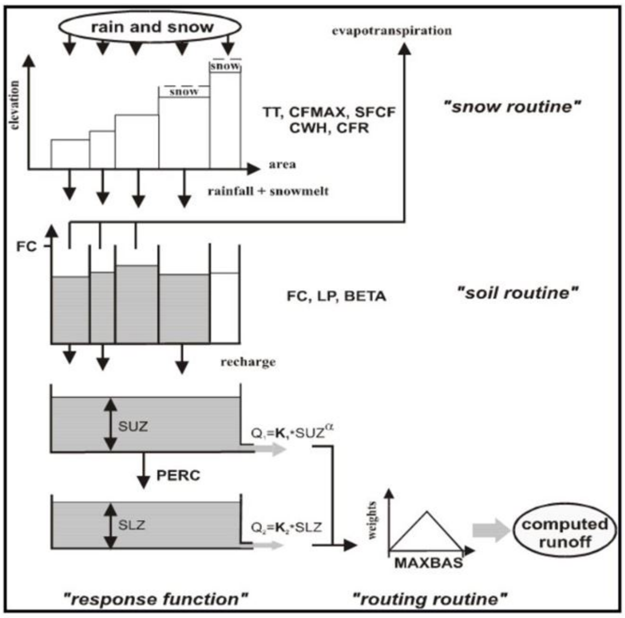


Figure 5.2: Overview of the model structure of the HBV. Source: (Seibert, 1996).

Model has 18 parameters and includes snow routine, soil routine, response function and routing routine. The daily discharge is simulated by using three main inputs; daily rainfall, mean temperature and potential evapotranspiration. Precipitation enters the model through the snow routine. Depending on the air temperature, i.e. above or below °C, precipitation falls either as snow or rainfall. Therefore, the model copes with both rainfall and snow and can model the growth and decline of the snowpack. The model furtheraccounts for processes and states that occur in the catchment: snow accumulation and melt, potential and actual evaporation and evaporation from interception, storage in the soil as well as various runoff routines such as from rainfall or melting snow.

### Calibration of HBV-light

Model calibration can be done by using different methods provided by HBV-light model;

- Batch simulation
- GAP simulation
- Monte Carlo simulation

In this research only GAP simulation was used in order to calibrate model. By using genetic calibration algorithm, with the genetic calibration algorithm, optimized parameter sets are found by an evolution of parameter sets using selection and recombination. Required model parameters for calibration are explained in the Seibert (2005) as follows;

**TT** (°C), threshold temperature (precipitation can be modelled either as snow or precipitation. By using threshold temperature, precipitation can be simulated either snow or rain depending on whether. If the temperature is below threshold temperature level, all precipitation is simulated as snow, else simulated as rain.

Then, simulated snow is corrected by snowfall correction factor, **SFCF** (-). Melt water and rainfall are kept in the snowpack as far as it goes over a certain limit of water fraction, **CWH** [-], which is the equivalent of the snow. Liquid water in the snowpack freezes again on the basis of a refreezing coefficient, **CFR**. While the half of rainfall and snowmelt **(P)** is separated as water filling the soil box, the other half is kept as groundwater recharge on the basis of the relation between water content of the soil box (**SM** [mm]) and its largest value (**FC** [mm]). If **SM/FC** is higher than **LP** [-], actual evaporation from the soil box is equivalent to the potential evaporation; however, if **SM/FC** is lower than **LP**, a linear reduction is needed. Groundwater recharge is incorporated into the upper groundwater box (**SUZ** [mm]). **PERC** [mm $t^{-1}$] delineates the maximum percolation rate from the upper to the lower groundwater box (**SLZ** [mm]). Precipitation and evaporation in the lakes are added or subtracted straightly from the lower box. Runoff from the groundwater boxes is calculated as the sum of two or three linear outflow equations based on whether **SUZ** is above a threshold value, **UZL** [mm], or not. The runoff in question is lastly altered by a triangular weighting function defined by the parameter **MAXBAS** in order to give the simulated runoff [mm $t^{-1}$ ].

## 5.3 Evaluation of the models (WALRUS and HBV-light) performance

The reliability of the model results is verified by using the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970).

$$NS = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}(t) - Q_{mod}(t))^2}{\sum_{i=1}^{n}(Q_{obs}(t) - \overline{Q_{obs}(t)})^2} \tag{5.1}$$

Formula 5.1 illustrates the overview of the Nash-Sutcliffe efficiency, where $Q_{obs}(ti)$ is the observed discharge (mm/day), $Q_{obs}$ is the simulated discharge (from WALRUS and HBV-light) and Qobs is the arithmetic average of the observed discharge. The NSE values can vary from $-\infty$ to 1 and 1 indicates that the observed discharge values actually can be modelled to reality. The maximum NSE value is 1 meaning a perfect fit between observed and modelled discharge. If the NSE values have a negative sign, the average observed data should be used instead of the model results.

# 6 | Results

## 6.1 Implementing WALRUS in Adiguzel subcatchment

Calibration process, as described in the methodology chapter, has been performed for all hydrological years with groundwater abstraction ($f_{\mathrm{XG}}$=0.15 mm/day) and surface water supply ($f_{\mathrm{XS}}$=0.04 mm/day). Table 6.1 shows calibrated parameters for each hydrological year.

Table 6.1: Calibrated Model Parameters of WALRUS.

| year | *ndays* | cW (mm) | cV(h) | cG (mmh) | cQ (h) | cS (mm$^{-1}$) |
|---|---|---|---|---|---|---|
| 2005 | 365 | 308 | 0.1 | 13460312 | 149.6 | 104.14 |
| 2006 | 365 | 155 | 65.6 | 12311806 | 32.2 | 88.6 |
| 2008 | 365 | 465 | 108 | 3052804 | 84.9 | 10.4 |
| 2009 | 365 | 56 | 108.3 | 26867005 | 66 | 20.22 |
| 2010 | 270 | 135 | 132.1 | 53238948 | 99.5 | 23.86 |

As it can be clearly seen after calibration, model parameter values differ between years. All model parameters have been also validated for other hydrological years. On the one hand, one parameter-set works perfectly in one hydrological year,for instance the wet year. On the other hand, its efficiency decreases drastically in the dry year. In addition, average efficiency is about 0.60 with groundwater abstraction and 0.54 without groundwater abstraction and waste water discharge. Efficiencies are illustrated in the Annex A.3 for all years. These results indicate that there is not one optional parameter set for WALRUS model in this catchment for different years. Furthermore, during the calibration process, some parameters stuck in either upper or lower boundary. Even though calibrated model parameters seem that they are the best parameters in fact they are not .

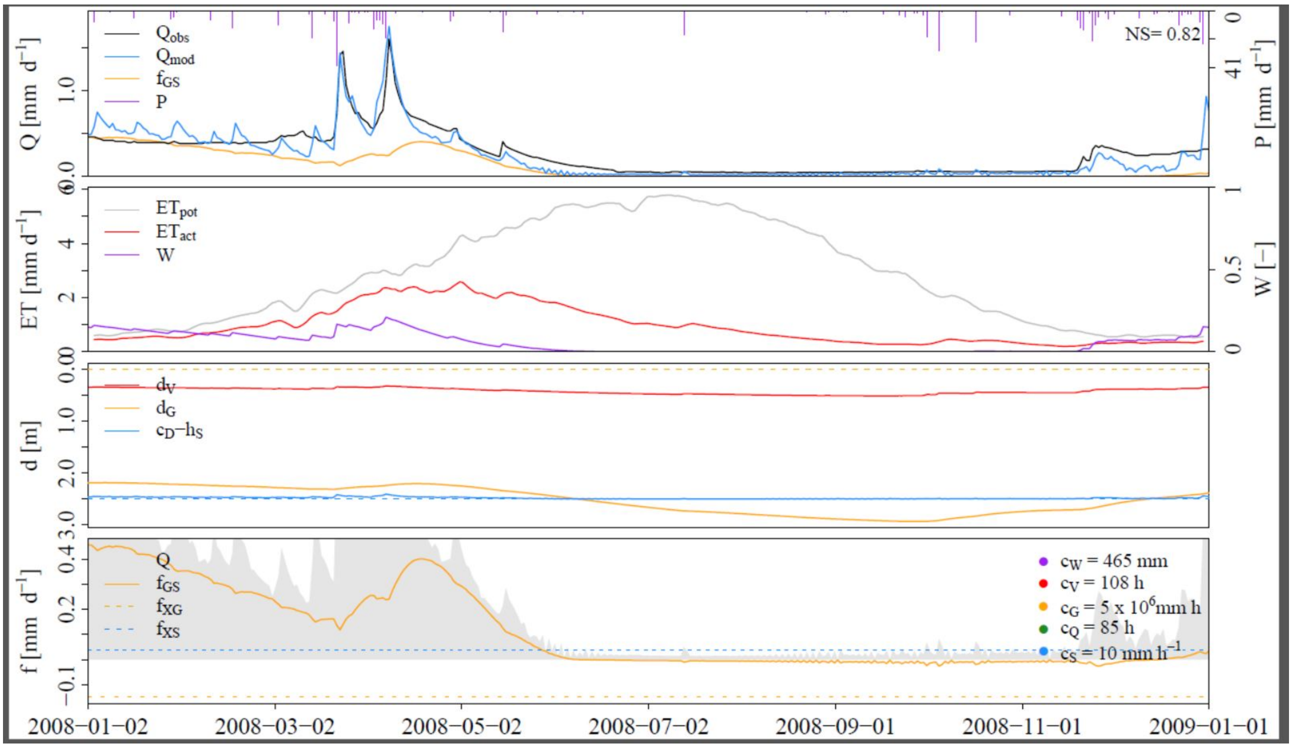


Figure 6.1: WALRUS output of Adiguzel subcatchment, 2008 after calibration with observed discharge ($Q_{\mathrm{obs}}$), simulated discharge ($Q_{\mathrm{mod}}$), precipitation (P), potential evaporation ($ET_{\mathrm{pot}}$), actual evaporation ($ET_{\mathrm{act}}$) and wetness index (W).

Figure 6.1 is a typical WALRUS result with calibrated parameters consisting of four panels. These panels give clear information about the model comes up this simulation. This is one of the biggest advantages of WALRUS;

other processes can also be seen instead of observing only the output of the simulation discharge. The top panel is the most significant one, with simulated discharge (blue) and also observed discharge (black). Purple lines are observed precipitation. It can be clearly seen that discharge has explicit variability with peaks in the winter and low values during the summer. The first two peaks of the discharge can be reproduced by the model. The behaviour of the recession period looks the same, but, WALRUS can simulate recession with underestimation. Finally, the first peak after a long dry period is reproduced by the model with slight underestimation. The efficiency of the model can also be seen on the upper right-hand corner on the panel. In terms of Nash Sutcliffe, the given simulation is which is 0.82. In the second panel, potential evapotranspiration which (grey) and modelled actual evapotranspiration (red) can be seen. Because of high storage deficit (dV), they do not overlap in the Adiguzel catchcment. The evapotranspiration reduction factor ($\beta$) is estimated approximately 0.33, which is close to scenario 3 discussed in the water balance section. The purple line in this panel also illustrates wetness index that is the evidence of the seasonal change in the Adiguzel catchcment. The third panel is an illustration of the groundwater level, surface water level and their relation. Due to high storage deficit, groundwater level drops below surface water after summer. Groundwater abstraction, surface water supply and simulated discharge can be seen in the last panel. Since surface water supply is relatively low, it is hardly visible. Grey background shows simulated discharge. Last panel also includes calibrated model parameter in the bottom right corner. As figures illustrate, channel dry out during the summer season. Two situations: a) during wet season and b) dry season are illustrated in study area section Fig. 2.4.

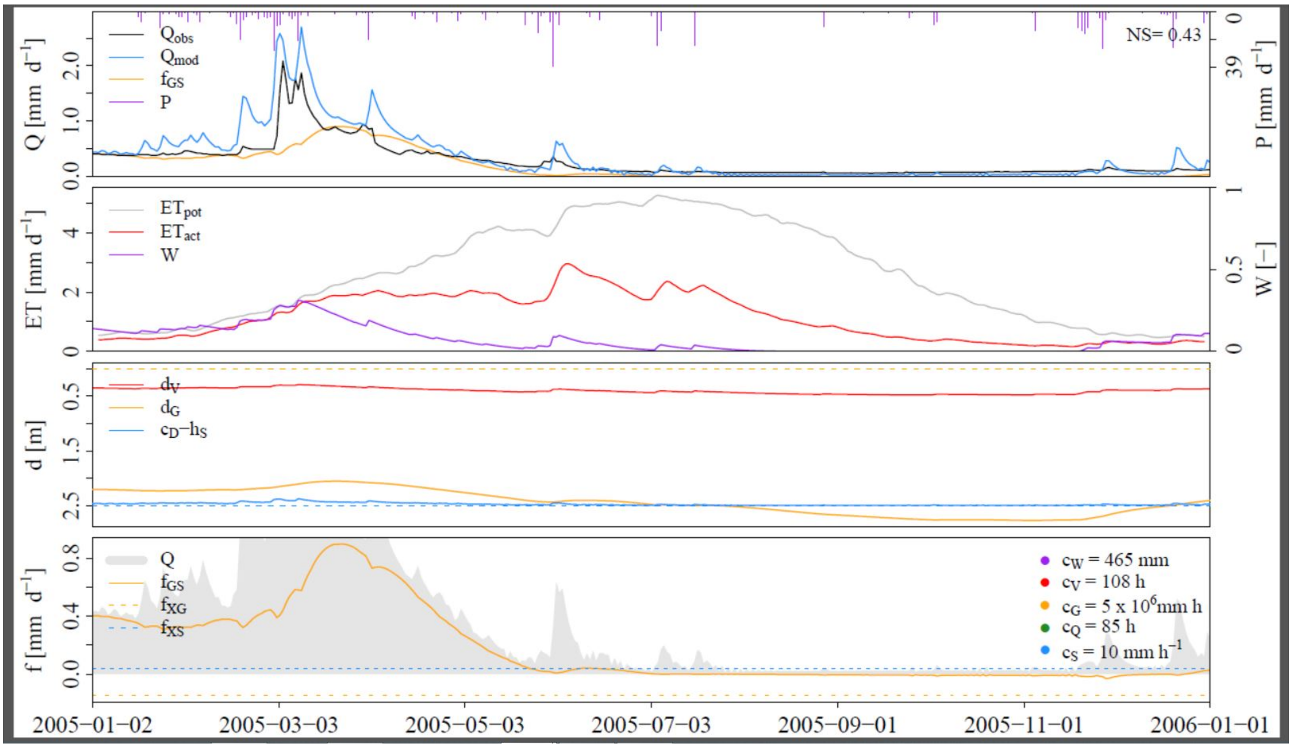


Figure 6.2: Model output of Adiguzel subcatchment in 2005 with model parameters calibrated for 2008

Figure 6.2 shows the validation period with the same calibrated model parameters WALRUS is not able to simulate discharge with the same efficiency in another hydrological year. For instance, parameters calibrated for 2008, have been validated in 2005. In terms of NS efficiency, it decreased from 0.82 to 0.43. WALRUS overestimates observed discharge with these parameters.

The best simulation run calculated with the calibrated parameter set in terms of Nash-Sutcliffe efficiency, is obtained for the year 2010 with groundwater abstraction and waste water discharge shown in figure 6.3. Even though it seems as the best simulation, in fact, it is not. WALRUS is not able to reproduce the peak discharge good enough with these parameters set. There is a delay between the peak discharges, and the recessions are also overestimated.

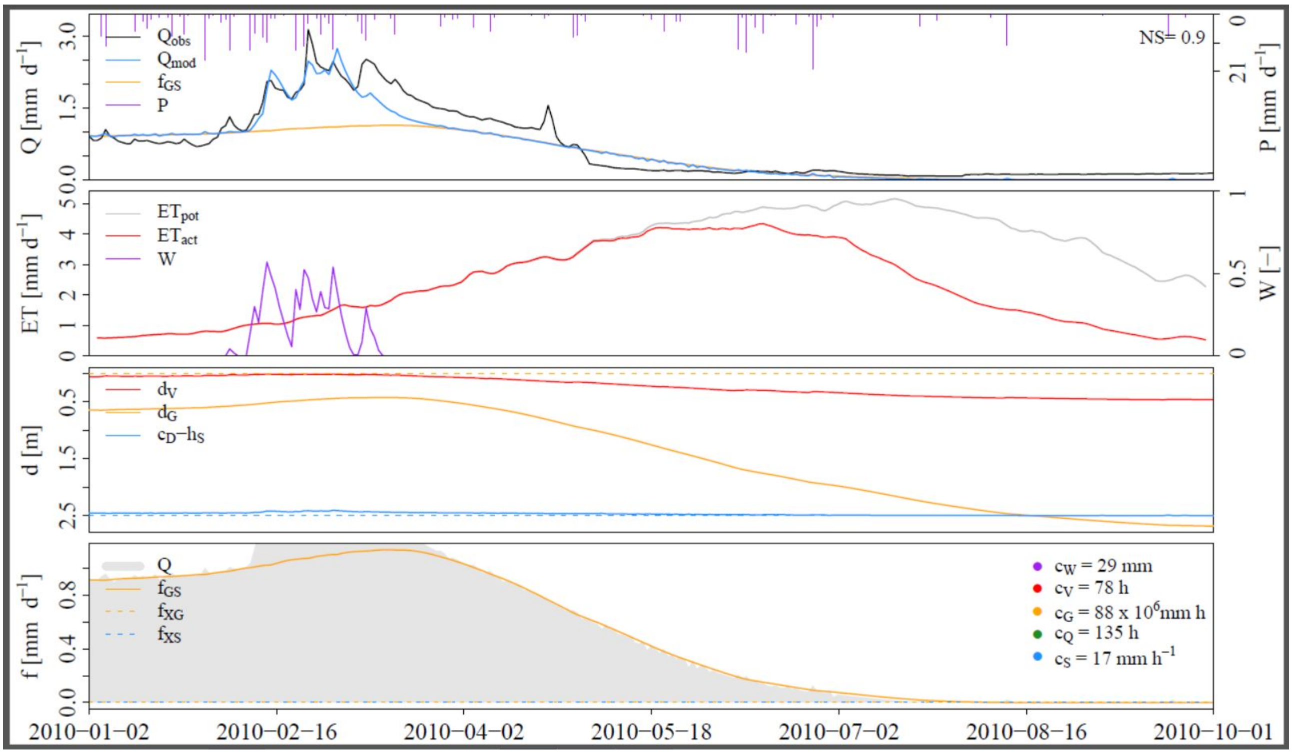


Figure 6.3: WALRUS output of Adiguzel subcatchment in 2010

### Comparing WALRUS results in current and naturalised situations

As the title indicates, the main objective is investigating the performance of WALRUS in the mesoscale catchment where groundwater abstraction and wastewater discharge from treatment plants are common. As discussed in the methodology chapter WALRUS has been calibrated with groundwater abstraction and waste water discharge (surface water supply).

In order to be able to see the difference, evapotranspiration reduction factor and simulated discharge should be able to compare. The following graphs illustrate the yearly amount of simulated discharge and actual evapotranspiration.

Results in Figure 6.4 and 6.5 show that total potential evapotranspiration is 4635 mm and observed discharge is 730 mm for five years; 2005, 2006, 2008, 2009 and 2010 (2007 is excluded because of measurement errors). However, WALRUS is able to simulate 663.1 mm discharge in current situation and 663.6 mm discharge for naturalised situation with parameters calibrated for the current situation. The mean difference is approximately 0.1 mm/year, meaning 618 m$^3$/day more discharge produced can be simulated in naturalised condition. As a result, discharge is overestimated in two conditions (with and without groundwater abstraction and surface water supply). Furthermore, total actual evapotranspiration is 2390 mm for the naturalised situation (without Ground water abstraction and surface water supply) and 2296 mm for the current situation. The average evapotranspiration reduction factors are 0.49 for current and 0.52 for naturalised situation. These results are able to be enhanced with better observation data. For instance, the daily groundwater abstraction amount and frequency of abstractioon would provide better results.

Figure 6.4 shows simulated discharge by WAIRUS for two different conditions. In general WALRUS underestimates the observed discharge. The sum of the simulations are always really close to each other.According to right hand-side chart, the yearly sum of actual evapotranspiration is always slighlty higher without groundwater and surface water supply. The maximum reduction factors are 0.64 for naturalised and 0.61 for the current situation in 2010. Conversely, the minimum reduction factors have been gained, in 2008 which are 0.35 and 0.33 respectively.

Figure 6.5 shows the comparison in more detail. Discharges are simulated during wet session quite well. However, the peak is not reproduced in the case without groundwater abstraction and surface water supply. Furthermore, the recession period is not simulated and timing is too fast. The model does not reproduce small peaks.

Graph in the right hand-side shows ground water level variation for 9 months in the Adiguzel catchment in 2010. The total groundwater decreasing is 1669 mm for the current situation and 1630 mm for the naturalised situation.

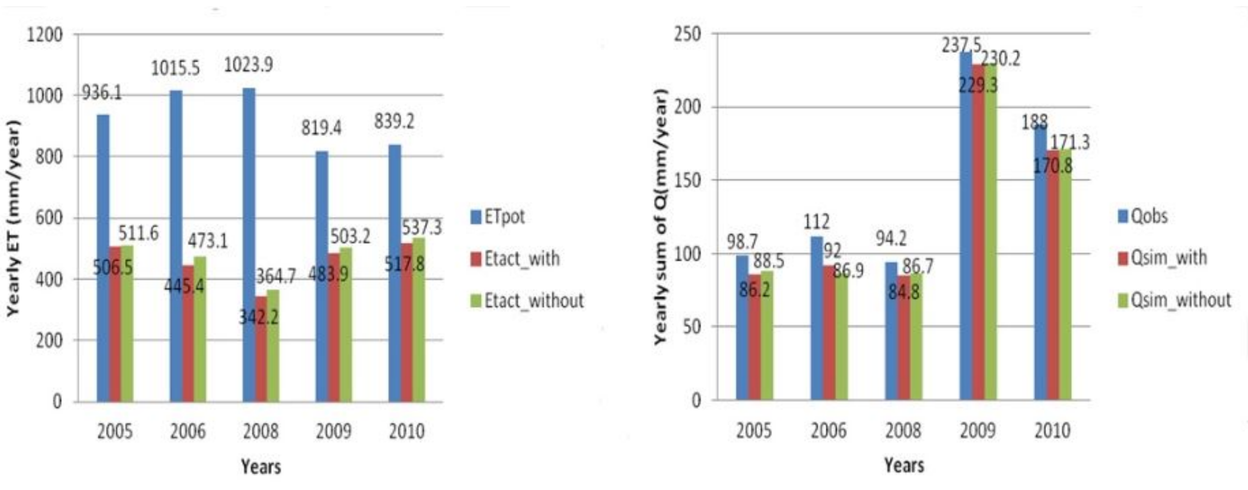


Figure 6.4: Simulated actual evapotranspiration and dicharge in two conditions: with and without Groundwater abstraction and surface water.

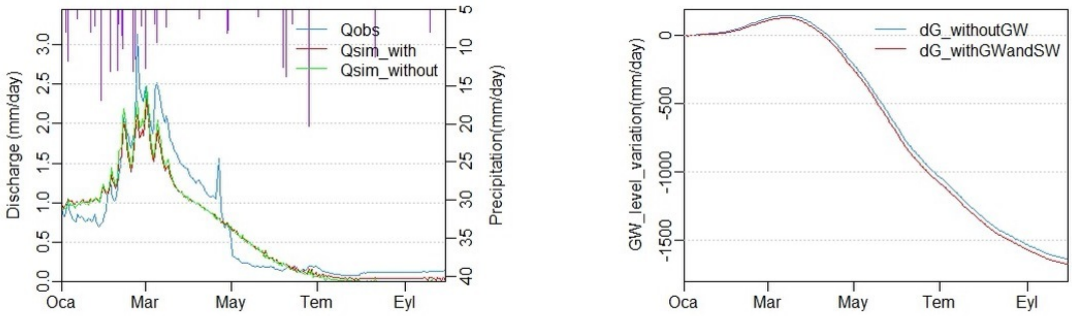


Figure 6.5: Comparison simulated discharge and groundwater level variation.

As it could be seen from the graph, the simulated groundwater level is slightly different, between two the different set-ups. The relative difference is approximately 30 mm/year.

Last but not least, even though some data interpolation process has been applied in order to remove measurement errors. Discharge data is still not completely accurate, it has some small jumps and inconsistent points.

## 6.2 Implementing HBV-light in the Adiguzel subcatchment

Groundwater abstraction and surface water supply can not to be simulated by current HBV-light model. So it can be expected that model compansate. However, it was calibrated for Adiguzel catchment.

Figure 6.6 shows a general result of HBV-light simulations. The first two panels show the temperature and precipitation during the year. Furthermore, HBV-light is able to simulate snow, which is the green line in the second panel. The third panel shows simulated and observed discharge. Base flow and observed peak flows are underestimated. Recession is too steep and timing is early with the HBV - light model. Model can simulate observed discharge after dry period.

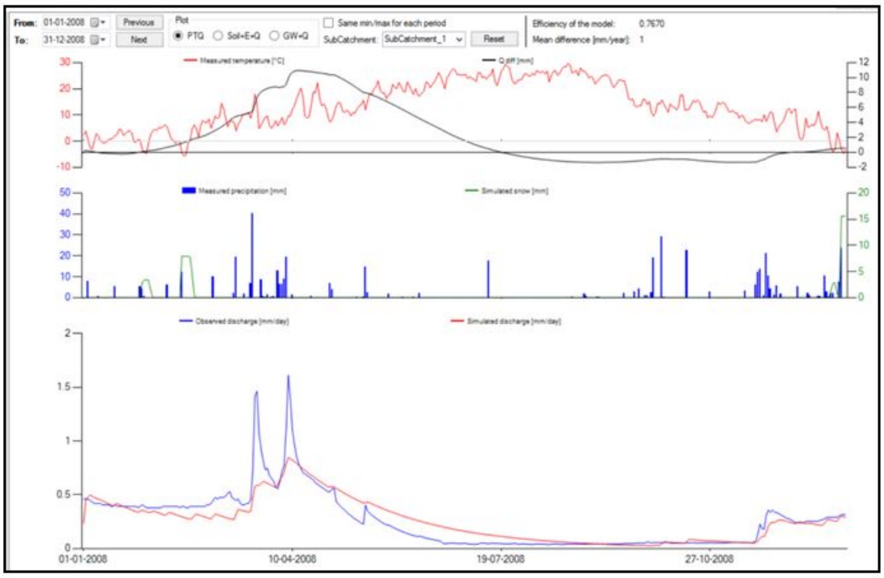


Figure 6.6: HBV-light model output of Adiguzel subcatchment.

## 6.3 Implementing WALRUS in the Ikizdere Subcatchment

Ikizdere catchment located in the Aydın province is selected in order to investigate the performance of WALRUS in three different hydrological years; dry, normal and wet respectively. All parameters have been calibrated by using discharge time series provided by DSI for three different hydrological years. Calibrated WALRUS model parameters are given in Table 6.2.

Table 6.2: Calibrated model parameters of Ikizdere subcatchment for three hydrological years

| Ikizdere (D07A109) | | | | |
|---|---|---|---|---|
| Parameters | Unit | 2004 | 2007 | 2009 |
| aS | - | | 0.00035 | |
| cD | mm | | 2500 | |
| dG | m | | - | |
| cW | mm | 499 | 599 | 499 |
| cV | h | 47.31 | 36.56 | 2 |
| cG | mm.h | 59700000 | 58200000 | 52800000 |
| cQ | h | 84.3 | 40 | 32.5 |
| cS | mmh-1 | 90 | 42.5 | 31 |

Afterwards, calibrated parameters were applied all year in order to see in which year WALRUS is able to reproduce discharge best. To be able decide which year is best; results have been analysed as follows.

### The best results of chosen hydrological years

The best results in terms of NS efficiency have been obtained for dry year for this subcatchment which is 2004 (01.01.2004 till 12.31.2004). WALRUS has been calibrated for dry condition with the help of observed discharge data. Afterwards, WALRUS runs with calibrated parameters. Model efficiency was 0.84 which is quite high, possibly because there is no discharge for about 6 months. In the first two months WALRUS can reproduce the observed signal well, but afterwards, it overestimates discharge fluctuations. At the end of the year, WALRUS can slightly reproduce to discharge because of a long dry period. Actual and potential evapotranspiration overlap up until May. Afterwards, actual evapotranspiration starts decreasing because of storage deficit. The evapotranspiration reduction factor is about 0.4. The groundwater level drops below water surface after seven months and it cannot recover that is a problem because simulated storage is low for a long time and underestimate peaks after summer.

Afterwards, the 3 parameter sets have been validated all other years. Average model efficiency decreased to 0.63. Finally, water balance has been checked for the all years. The modelled water balance including storage in the reservoirs are zero. Average reduction for the potential evapotranspiration is 0.5 which is exactly equal to the assumption 2. Finally, observed discharge and simulated discharges have been compared. The sum of the observed discharge is 2487 mm for 5 years and simulated discharge is 2214 mm.

## 6.4 Comparing results of WALRUS and HBV-light in the Ikizdere subcatchment

The last research question is comparing results from WALRUS and HBV-light. The most important reason for choosing this subcatchment is that there is neither groundwater abstraction nor wastewater discharge into the system. Even though, these components can be implemented WALRUS by using $f_{\mathrm{XG}}$ and $f_{\mathrm{XS}}$, it is not possible to simulate them with the current version of the HBV-light. Results from HBV-light and WALRUS have been plotted on the same graph in order to be able to investigate which model can simulate discharge better. Besides that, using three different hydrological years help us to explore in which year WALRUS works better in that climate.

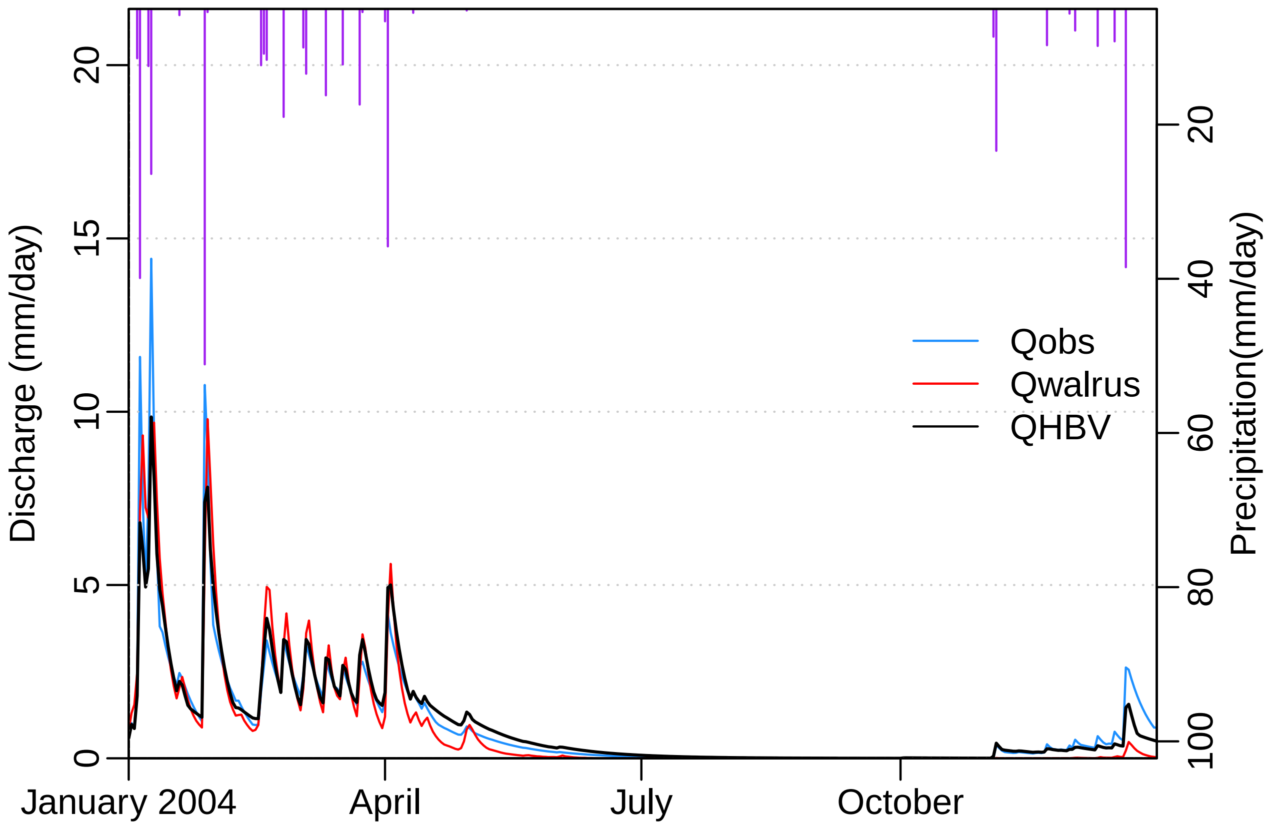


Figure 6.7: Comparison of WALRUS with model parameters calibrated for dry conditions and HBV-light

The Figure 6.7, Figure 6.8 and Figure 6.9 show comparisons between WALRUS and HBV-light in three hydrological years. The first attention-grabbing point of the figure is clear seasonal effect which is dry summer and winter peaks. As clearly seen, both models are not able to simulate observed peaks well. Compared to HBV-light, WALRUS simulates more flashy peaks which is closer to the observed peak discharges. However, HBV is also better in the recession period. While WALRUS calibrated for a wet condition completely underestimates and fluctuates during the recession period. Controversy, HBV-light is able to produce the same behaviour as the observed discharge.

As explained in the previous section, the best results was obtained by WALRUS with model parameters calibrated for dry conditions. Figure 6.10 is an illustration of comparison two models for five years. Accoring to this figure, WALRUS and HBV-light are quite well able to simulate the hydrological response of the Ikizdere subcatchment. Table 6.3. gives statistical information about models.

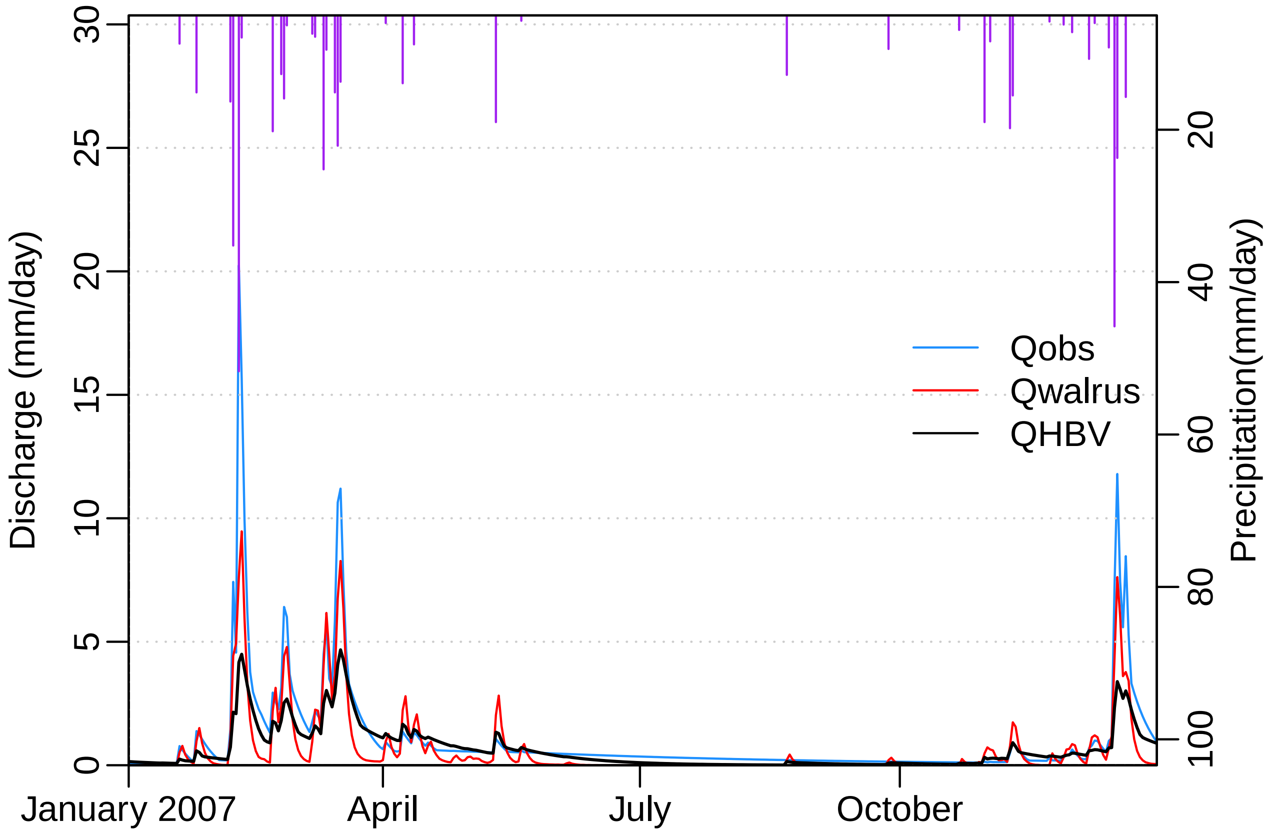


Figure 6.8: Comparison of WALRUS with model parameters calibrated for average conditions and HBV-light

Table 6.3: Observed and simulated mean and maximum discharge (in mm/day), their median, standard deviation (SD), first and third quartile for the period January 2004 through December 2009.

| | Min | 1st quar. | Median | Mean | 3rd Quar. | Max |
|---|---|---|---|---|---|---|
| **Observed** | 0 | 0.129 | 0.449 | 1.135 | 1.271 | 33014 |
| **WALRUS** | 0 | 0.001 | 0.059 | 0.645 | 0.64 | 11.93 |
| **HBV-light** | 0.001 | 0.078 | 0.383 | 0.825 | 1.072 | 11.21 |

Especially, the simulated models perform best during the wet season of the years. According to this figure, the recession period can be simulated well by WALRUS. However, simulated peaks are even lower in this case. The parameters found for the average year lead to the same behaviour as for the wet year. Recession period is not well simulated and peaks are close observed discharge. To sum up, it could be said that the effect of parameter values is large by looking at all figure and results. However, other calibration might be able to give better results. In conclusion, HBV-light is able to reproduce observed discharge better than WALRUS with one parameter sets in the İkizdere subcatchcment. WALRUS needs different parameters for different hydrological conditions in order to be able to simulate all processes. However, to be able to judge the performance of the any model is quite hard in this research because of the data reliability.

### Peak flows and low flows

Another important criteria that should be taken into consideration while comparing two rainfall-runoff models is focusing on the peak and low flows. As table 6.3 illustrates, peak discharge is underestimated by the models. It was challenging to compare low flows because the channel is dry during the dry season. The only attention grabbing point of low flow is HBV overestimates observed discharge. However, the peak flows are easy to discriminate in order to compare two models. Table 6.4 illustrates an analysis of the six highest daily peak flows during the wet season and six highest daily discharges after the dry season, as observed and simulated. Maximum peak discharges discover

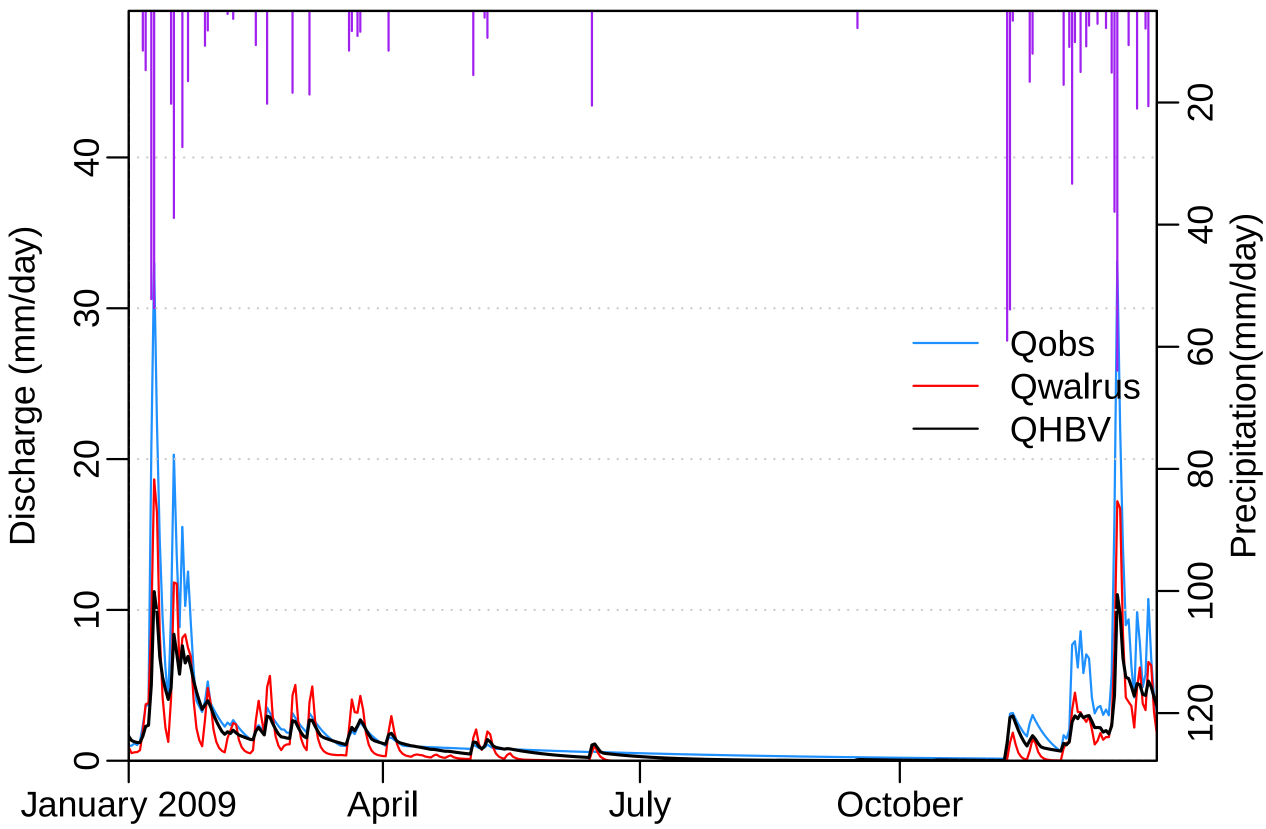


Figure 6.9: Comparison of WALRUS with model parameters calibrated for wet conditions and HBV-light

that both WALRUS and HBV-light underestimate the same peaks. On the one hand, WALRUS is able to simulate relatively better peaks during the wet season, controversially, HBV-light is better after a dry period at simulating peak discharge. Additionally, it also illustrates that WALRUS tends to delay peaks compare to HBV-light model while HBV-light simulates the timing of the peaks in the time. As indicated in Te Linde et al. (2008) the degree of the underestimation is also based on calibration period. For instance, the peak of 2004 included in the calibration period is rather close to the observed discharge.

Table 6.4: Analysis of peak flows at the outlet of the Ikizdere subcatchment (D07A109) showing observed maximum discharge (d*max.$Q_{\mathrm{obs}}$), relative difference between observed and simulated maximum discharge (dmax.$Q_{\mathrm{sim}}$), difference in peak timing (dT).

| **Analysis of peak flows in wet season** | | | | | | |
|---|---|---|---|---|---|---|
| **Peak Flows** | 9.1.2004 | 1.3.2005 | 14.3.2006 | 9.2.2007 | 7.4.2008 | 10.1.2009 |
| Max ($Q_{\mathrm{obs}}$) (mm/day) | 14.414 | 11.176 | 11.6 | 20.242 | 6.117 | 33.011 |
| dmax ($Q_{\mathrm{sim}}$) WALRUS (%) | -49.93 | -70.19 | -48.73 | -119.29 | -67.67 | -93.81 |
| dmax ($Q_{\mathrm{sim}}$) HBV-light | -49.93 | -83.31 | -73.49 | -127.33 | -67.41 | -98.57 |
| dT WALRUS days | 1 | 1 | 1 | 1 | 1 | 1 |
| dT HBV days | 0 | 1 | 1 | 1 | 0 | 0 |
| **Analysis of peak flows after dry season** | | | | | | |
| **Peak Flows** | 20.12.2004 | 26.11.2005 | 3.11.2006 | 17.12.2007 | 21.12.2008 | 17.12.2009 |
| Max ($Q_{\mathrm{obs}}$) (mm/day) | 2.621 | 8 | 3.735 | 11.793 | 6.071 | 33.143 |
| dmax ($Q_{\mathrm{sim}}$) WALRUS (%) | -138.970 | -93.678 | -121.726 | -114.535 | -80.889 | -96.583 |
| dmax ($Q_{\mathrm{sim}}$) HBV-light (%) | -49.7 | -83.843 | -61.280 | -110.751 | -78.518 | -100.229 |
| dT WALRUS (days) | 1 | 1 | 1 | 1 | 1 | 1 |
| dT HBV (days) | 1 | 1 | 0 | 0 | 0 | 0 |

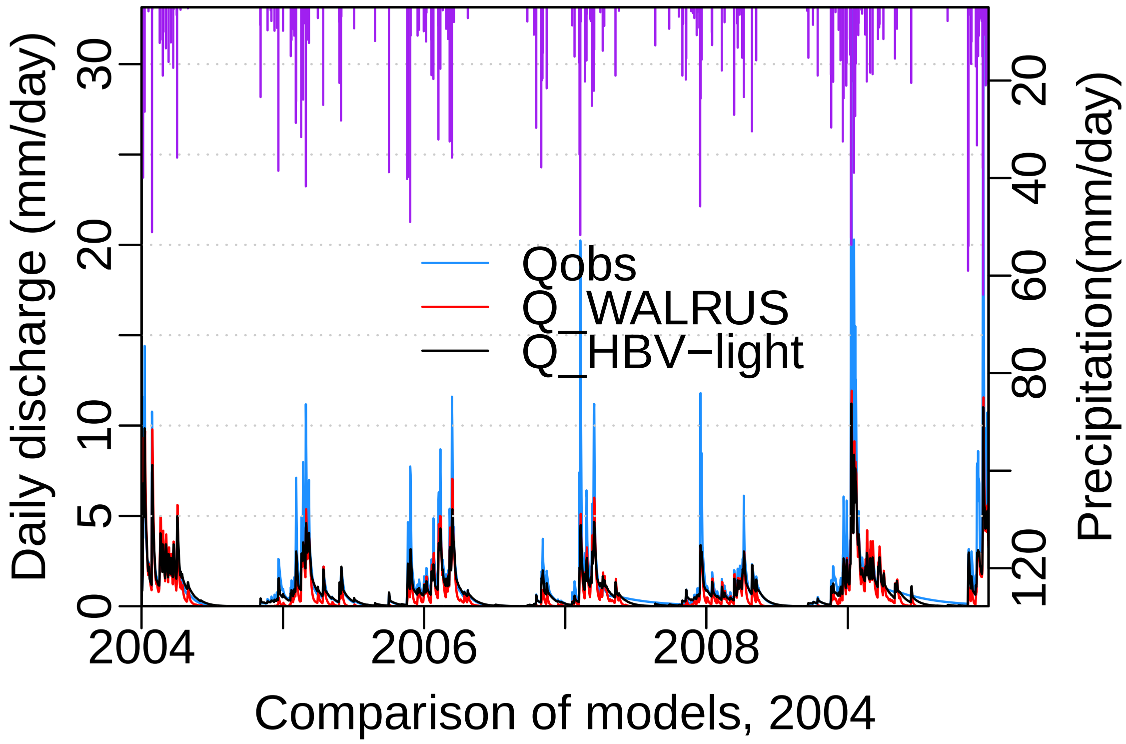


Figure 6.10: Comparison of WALRUS with model parameters calibrated for dry conditions and HBV-light for all provided years.

* Equation 6.1 shows how to calculate relative difference (dmax) between observed and simulated maximum discharge

$$dmax = \frac{Q_{sim} - Q_{obs}}{\frac{Q_{sim}+Q_{obs}}{2}} \times 100 \tag{6.1}$$

# 7 | Discussion

Many challenges have been experienced during the modelling process concerning mainly the data availability and quality for Adiguzel catchment.

### Groundwater abstraction

A first challenge faced with was related to the groundwater abstraction. Provided data indicated that the annual amount of groundwater abstraction is about 175 million cubic meter (TUBITAK, 2005). However, this data has remained the same for the last 10 years. It is unknown whether the ground water abstraction retained in the same levels all day during the year or if it is shifted depending on the time of year. Since no detailed explanation was given, constant abstraction was assumed during the whole day, which is roughly 0.15 mm/day. Another challenge related to the ground water abstraction is the existence of illegal wells in the region. The research done by independent researchers assumed that there were more than 300 illegal wells used in order to abstract water in the Adiguzel basin. The water for irrigation purpose was another issue. There was not clear data showing the portion of the lost water due to irrigation or the percentage coming back to the system. Water use efficiency in the irrigation should be provided to make appropriate water balance. In order to certify its performance, more research with more precise data is needed. Additionaly, since there was no data about ground water levels, it was assumed that the initial groundwater level was based on discharge originating from drainage.

### Measurement stations and data quality

The discharge measurement stations were neither enough nor well maintained in the catchment. There were only four discharge measurement stations installed in the Adiguzel catchment which were not sufficient to represent such a big subcatchment properly. Even though there were only four discharge stations, collected data was not precise because of two main reasons, a) measurement errors; sudden decrease and jumps had been experienced during the data preparation of the model, b) modelled data was used in order to improve existing data quality in the catchment. Measured data and modelled data were combined to be stored afterwards in the database of DSI. It was challenging to discriminate discharge time series, part of which was derived from modelling and other was measured data. This process became even harder to accomplish without knowing discharge-height (Q-h) relationship. Furthermore, the surface water supply from Industries and domestic treatment plants flew into the system. However, during the data storage process, waste water was not taken into account by DSI. Neglecting waste water discharge definitely causes underestimation of the resulted modelled data. Reliability of the precipitation measurement was better compared to the discharge measurement. These stations were operated by general directorate of meteorology. Not any model or assumption was used in order to collect and store their data. Even though reliability was high, some challenges still existed. First of all, there was only one existing measurement station (Usak) in order to gain all the necessary meteorological data in the catchment. It was located in a relatively hilly part of the catchment, whereas the outlet of the catchment was located 600 meters above the sea level. Ikizdere subcathment did not have any meteorological stations. The nearest station was about 14 km away from the outlet of the catchment used. It was assumed that precipitation was well distributed in the subcatchment. Besides, minimum time step was considered to be the daily time step. WALRUS can work with any time step, but the system may have had response time shorter than one day. For instance, the discharge responded to rain within one day.

### Model Calibration and judgement of the efficiency

Regarding the judgement of the model, there was only one criterion used to investigate the performance, namely the Nash-Sutcliffe efficiency. Calibration is done by using hydroPSO and Gap optimization. During some calibration, WALRUS stuck either in the upper or lower boundary for the parameters. After the completion of the calibration step, the parameters were assumed to be the optimal ones if they were not in reality. Other calibration techniques could also be implemented in other researches in order to increase model efficiency. The quality of the observation is the most important components for good modelling project. Since parameters were seasonally dependent, choosing the best parameters was not clear for the present research. WALRUS had been calibrated for different hydrological years. The results also lead me to the conclusion that forcing data has a considerable influence on model performance, irrespectively to the type of model structure. It emphasizes the need for good quality of ground-based hydrological and meteorological measurements. The conclusion as to the application of hydrological models in climate scenario studies, then, is that for the Buyuk menderes basin HBV-light is preferred, since it has shown better overall performance and seems to be more robust than WALRUS. The timing is fast with extreme peaks with HBV-light.

### Assumptions

Channel depth was assumed to be 2.5 meters for all catchments, but it should be modified by doing an area excursion. It might be different from assumed data. Averaged channel depth was also assumed 2.5 meters; it can vary from one river to another though. Since there was not sufficient amount of rain gauge stations in the catchment, precipitation distribution was assumed uniform. All geographic effects, such as oreographic (mountain effect) were neglected. For the new research, it would be better to find new resources for rain data, as for instance radar data. However, the existing information is not clear. Previously conducted surveys have indicated the yearly sum of the abstraction. For this research, Adiguzel catchment was assumed as a complete catchment which is not completely true due to the elevation differences in the catchment. Elevation was averaged out at about 750 meters. This assumption was required because there was only one discharge station measuring discharge in the catchment. However, elevation zones have to be applied in the HBV-light model in order to define its performance.

# 8 | Conclusions

Uneven water distribution, groundwater abstraction and lack of data are challenges concerning the water management projects in Turkey. Rainfall-runoff models can be used in order to provide missing hydrological data. In the present thesis, two lumped rainfall-runoff models were applied: The Wageningen Lowland Runoff Simulator (WALRUS) and the Hydrologiska Byrans Vattenbalansavdelning (HBV-light) in the two subcatchments of Buyuk Menderes catchment, Turkey. WALRUS was designed for lowland catchments having shallow groundwater tables and it requires only five parameters to be calibrated. On the other hand, HBV-light was designed for cold and relatively elevated catchments and it requires fourteen parameters including both catchment and vegetation zone calibrated ones. The main objective was to investigate the performance of rainfall-runoff models: WALRUS to HBV-light and the role of groundwater abstraction. Three main research questions have been formulated in order to reach the research objective.

### The performance of WALRUS and the effect of groundwater abstraction

The first two research questions of the present research were to investigate the performance of WALRUS in the selected subcatchment and to explore the effect of the groundwater abstraction on the performance of the WALRUS. Adiguzel subcatchment was selected in order to answer these questions. The water balance was taken into consideration as first step. Since there was no exact data available that illustrated the potential evapotranspiration reduction factor, three different evapotranspiration reduction factors were assumed in order to emphasize the effect of the evapotranspiration reduction factor in the water budget. After applying three assumptions, it was concluded that the average reduction factor should be in the range of 0.5 to 0.3 in order to have reasonable water budget closure in the Adiguzel subcatchment. Afterwards, a formula was derived from the main water budget formula by neglecting storage change to find the mean reduction factor. The resulting factor was approximately 0.37 indicating that average evapotranspiration reduction was quite high. WALRUS can also estimate evapotranspiration reduction factor based on soil moisture: the average evapotranspiration reduction factor as estimated by WALRUS was similar with 0.45. Furthermore, the five model parameters of WALRUS were calibrated for the current conditions; provided data illustrated that there was daily groundwater abstraction of about 0.15 mm and daily surface water supply from industries and household waste water treatment plant of 0.036 mm in current condition, for each year from 2005 to 2010 (only 9 months data had been provided for 2010). The performance of WALRUS was acceptable in terms of Nash-Sutcliffe efficiency; the average efficiency was 0.8 for the calibration period and 0.53 for the validation period, with provided catchment characteristics and topographical features. However, observed discharges were underestimated by WALRUS in general; especially it was a challenge for WALRUS to simulate discharge peaks after a dry period. Furthermore, the best efficiency of the validation was deducted by model parameters calibrated for the wet hydrological year, 2009. The average model efficiency was 0.84 for calibration period and the average stayed 0.65 during validation period. The yearly amount of precipitation for this year was about 750 mm. Parameters calibrated for dry conditions do not give good results in terms of NS efficiency during wet years. The results illustrated that there was not only one parameter set for all years. Lastly, in order to evaluate groundwater abstraction and surface water supply on the performance of WALRUS, calibrated parameters had been applied for naturalised situation (without ground water abstraction and surface water supply) in the Adiguzel subcatchment. The average model performance during calibration and validation period in terms of NS efficiency were 0.78 and 0.48 respectively; this showing that the groundwater abstraction and surface water supply were not very important for WALRUS performance in the Adiguzel subcatchment. In order to ensure model performance, the water budget was also compared in terms of simulated discharge, actual evapotranspiration and ground water level. Likewise the NS efficiency, all these simulated components show slight differences between current and naturalised conditions.

The conclusion of these research questions based on the provided data was that the performance of the WALRUS was acceptable and external forces did not have significant effect on modelling performance. However, more research should be done on the effect of groundwater abstraction with accurate data.

### Comparison of models WALRUS and HBV-light

The second research question was to compare two rainfall runoff models, WALRUS and HBV-light, by testing their performance for simulating historical discharge in the Ikizdere subcatchment. Slightly different meteorological data (average temperature data are needed for HBV-light model) was used as model input for HBV-light and WALRUS. The crucial reason to focus on this subcatchment was the absence of groundwater abstraction from and surface water supply into the Ikizdere subcatchment. Just as in the Adiguzel subcatchment, the first step was to analyse the effect of the evapotranspiration reduction in the water budget. Reduction factor, decreased to 0.27. The average reduction factor simulated by WALRUS and HBV-light were 0.47 and 0.44 respectively. WALRUS and HBV-light were calibrated. Likewise the Adiguzel subcatchment, WALRUS had different optimal parameter sets for different hydrological years: dry, average and wet years in terms of precipitation respectively. However, the parameters in the HBV-light were less sensitive to the selection of the hydrological year. The average efficiency of the calibration period was 0.78. Calibrated parameters have been validated for all year. The average efficiency decreased to 0.46. In terms of NS efficiency best results have been reached from model parameters calibrated according to the dry year: 0.84 for calibration period 0.56 for validation period. The HBV - light was also implemented in this catchment: in the calibration period it gave a NS efficiency of 0.85 and 0.72 in the validation period. WALRUS was able to reproduce relatively more peaky discharges compared to HBV-light during wet season. However HBV worked better during the recession period and at the first peaks after a dry period. That might be because of topography, the elevation of meteorological inputs could be adjusted by using catchment properties functions in the HBV-light. Even though, each model was able to simulate observed discharge quite well, both of them underestimated peak discharges. In order to compare two models in detail, peak and low flows have also been analysed. Firstly, low flows were analysed. It was challenging to compare two models during low flows because channels dry out during summer season. However, the attention grabbing point was, the HBV-light overestimated low flows, especially when the channels are completely dry. The minimum discharge simulated by HBV-light during dry period was 0.01 mm/day. Secondly, peak flows were compared in two different seasons: wet season and after dry season respectively. The mean relative difference was used for six biggest peaks for two different periods. The minimum relative difference (dmax Qsim -0.49, peaks are overestimated) were obtained in 2004 which was calibration period. During wet seasons WALRUS was able to simulate peak slightly better than HBV-light. However, timing (dT) was better at HBV-performance. WALRUS tended to delay peaks with 1 day. On the other hand, WALRUS was weak to reproduce peak discharge the average relative difference was (dmax Qsim -110 with 1 day delay) on the other hand, the average relative difference was (dmax Qsim -80 without delay). It can be concluded that the performance of the HBV-light is better than WALRUS in terms of NS efficiency during the validation period and to simulate peaks after a dry period. It was concluded that WALRUS was able to simulate peak better than HBV-light during the wet season, whereas HBV-light was more robust when the performance of the calibration period and validation period. It had also advantages over WALRUS after a dry season in terms of timing and simulating more peak discharge. WALRUS had one day delay in estimating peak discharges in general. The other advantage of HBV over WALRUS was that HBV had short calibration times.

The conclusion as to the application of rainfall runoff modeling, then, was that for the Ikizdere subcatchment HBV-light should be preferred, since it showed better overall performance and seemed to be more robust than WALRUS. Two main reasons might lead its robustness, the first one is optimaztion technique that used during calibration and calibrated parameters both vegetation zone and catchment parameters were calibrated. The second one is catchment elevation and areas and height increment variables are adjustable in the HBV-light model but not in WALRUS.

# 9 | Recommendations

The recommendations given in that sections are mainly based on the difficulties experienced during the present research project. These recommendations could be grouped under four main headings as following.

1. **Data storage, validation and accessibility,**

   The most important challenge is definitely the data availability and the errors in existing data. Even though the basic forcing data (already described in the data analysis section) is needed for implemented models, which are not really complicated, its acquisition from different sources is time consuming these sources are generally public institutes and universities. It is also challenging to input provided data in the homogenizing data formats. For instance, provided discharge data was stored in word format which is not convenient for the modelling project. Data gap and storage errors should be removed and existing data should be validated. Finally, all data should be stored in one database even though it is challenging and expensive to install this kind of national system. The national data bank is needed in order to collect, save and validate all data sets in a convenient manner by researchers, engineers and experts.

2. **Measurements stations and data mising data**

   Another recommendation that I would like to mention is measurement stations, which were not representative and well-maintained. By maintaining existing measurement stations and installing ones as well as developing new techniques, data gap will be able to be faced. More continuous data sets at the same location should be collected. Some variables have not been measured in the catchment which hampers water management projects. Groundwater level, for instance, was not known in the catchment. These levels should be monitored by using appropriate techniques such as boreholes. By measuring groundwater levels, groundwater capacity can be calculated or estimated. It is also easy to maintain boreholes after installatio.

3. **Water Management**

   Due to the fact that potential evapotranspiration is high up to more than 900 mm/year in most of the area. Evaporation resistant plants should be chosen in the agricultural areas. Overexploitation of water resources should be prevented in the area with mainly the groundwater abstraction being under control. The main reason for abstracting groundwater is agricultural due to unusable polluted surface water. The improvement of the water quality in the Adiguzel catchment is the first thing that should e taken into consideration. Secondly, the decrease of the groundwater abstraction by changing the current irrigation and agriculture habits in the area. Alternatively, rain fed agriculture is highly recommended. Rain fed agriculture is an innovative system appropriate for sustainable and environmentally friendly drip irrigation. It is a state of the art technology used in order to avoid water losses in the irrigation. Additionally, the number of illegal wells for groundwater abstraction was quite high in the Adiguzel subcatchment. By monitoring area frequently, these illegal wells could be prevented.

4. **Field visits**

   Field observations have significant importance of similar research projects. It would be efficient for researchers if they had available a field excursion before starting their projects, especially to investigate catchment characteristics.

   Lastly, it is worth mentioning that in order to have good modelling results, first step should be the good data preparation for the model. Each model can reproduce systems following logical assumptions, but acquisition of good results requires accurate and validated data set applied to the optimal model.

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# A Annexes

## A.1 Abbreviation list

- BM: Buyuk Menderes Catchment
- DEM: Digital Elevation model
- DSD: Dangerous Substances Directive
- DSI: General Directorate for State Hydraulic Works
- $ET_{\mathrm{act}}$: Actual evapotranspiration
- $ET_{\mathrm{open}}$ : Measured evaporation by PAN method.
- $ET_{\mathrm{pen}}$: Calculated potential evapotranspiration values by Penman-Monteith equation
- $ET_{\mathrm{pot}}$: Potential evapotranspiration
- EU: European Union
- HBV: Hydrologiska Byrans Vattenbalansavdelning
- MGM: General Directorate of Meteorology
- NRMBS: National River Basin Management Strategy
- NSE: Nash-Sutcliffe efficiency
- SRTM: Shuttle Radar Topography mission
- SYGM: General Directorate of Water Management
- TUBITAK: The scientific and technological research council of Turkey
- WALRUS: Wageningen Lowland Runoff Simulator
- WFD: Water framework directive
- WRMD: Water Resource Modelling department

## A.2 Results with calibrated parameters

Table A.1: Results with calibrated model parameters for two situations

| | ***NS.*** | | ***Observations*** | | | ***Simulations*** | | | | | ***States*** | | | **Water** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Year*** | ***Eff.*** | ***P*** | ***Etpot*** | ***Qobs*** | ***ETact*** | ***Qsim*** | ***Bal.*** | ***fGS*** | ***fQS*** | ***dV*** | ***dG*** | ***hQ*** | ***hS*** | **Balance** |
| | | | | | | **Current Situation** | | | | | | | | |
| 2005 | 0.89 | 569.3 | 936.1 | 98.7 | 506.5 | 86.2 | -23.4 | 61 | 11.6 | -63.2 | -303.9 | 0 | -0.3 | ***-0.4*** |
| 2006 | 0.91 | 463.6 | 1015.5 | 112 | 445.4 | 92 | -73.8 | 77.8 | 0 | -113.9 | -525 | 0 | 0 | -0.1 |
| 2008 | 0.82 | 467.7 | 1023.9 | 94.2 | 342.2 | 84.8 | 40.7 | 40.5 | 31.7 | -1.4 | -194.3 | 1.8 | 0 | ***0.1*** |
| 2009 | 0.82 | 748.5 | 819.4 | 237.5 | 483.9 | 229.3 | 35.3 | 214.9 | 0 | -4.8 | -317.8 | 0 | 0 | -0.1 |
| 2010 | 0.88 | 365.4 | 839.2 | 188 | 517.8 | 170.8 | -323.2 | 132.4 | 28.9 | -353.1 | -1669 | 0 | -0.1 | -0.2 |
| | | | | | | **Naturalised Situation** | | | | | | | | |
| 2005 | 0.84 | 569.3 | 936.1 | 98.7 | 511.6 | 88.5 | -30.8 | 80.1 | 8 | -30.8 | -152.2 | 0 | 0 | ***0.0*** |
| 2006 | 0.88 | 463.6 | 1015.5 | 112 | 473.1 | 86.9 | -96.4 | 86.5 | 0 | -96.3 | -449.8 | 0 | 0 | -0.1 |
| 2008 | 0.77 | 467.7 | 1023.9 | 94.2 | 364.7 | 86.7 | 16.3 | 49.5 | 37.2 | 13.8 | -122.7 | 2.4 | 0.1 | ***0.1*** |
| 2009 | 0.79 | 748.5 | 819.4 | 237.5 | 503.2 | 230.2 | 15.1 | 229.2 | 0.2 | 15.1 | -235.3 | 0 | 0 | 0.0 |
| 2010 | 0.9 | 365.4 | 839.2 | 188 | 537.3 | 171.3 | -343.2 | 137.1 | 34.9 | -343 | -1629.4 | 0 | -0.1 | -0.3 |

## A.3 Validated results

Table A.2: Validated results for current situation, $f_{\mathrm{XG}}$ is -54.8 mm/year and $f_{\mathrm{xs}}$ is 14.6 mm/year

| | ***NS.*** | ***Observations*** | | | ***Simulations*** | | | ***States*** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Year*** | ***Eff.*** | ***P*** | ***Etpot*** | ***Qobs*** | ***ETact*** | ***Qsim*** | ***Bal.*** | ***fGS*** | ***fQS*** | ***dV*** | ***dG*** | ***hQ*** | ***hS*** | ***Balance*** |
| 2005 | 0.9 | 569.3 | 936.1 | 98.7 | 507 | 86 | -23 | 61 | 11.6 | -63.2 | -303.9 | 0 | -0.3 | -0.42 |
| 2006 | 0.9 | 463.6 | 1015.5 | 112 | 475 | 84 | -96 | 62.1 | 9.1 | -135.3 | -643.9 | 0 | -0.5 | -0.55 |
| 2008 | 0.5 | 467.7 | 1023.9 | 94.2 | 424 | 56 | -12 | 41.8 | 1 | -51.6 | -253 | 0 | -0.3 | -0.22 |
| 2009 | 0.2 | 748.5 | 819.4 | 237.5 | 445 | 252 | 52 | 128.7 | 109.3 | 11.3 | 54.7 | 0 | 0.1 | 0.10 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 438 | 148 | -221 | 94.7 | 43.1 | -249.9 | -1182.3 | 0 | -0.9 | -0.89 |
| 2005 | 0.7 | 569.3 | 936.1 | 98.7 | 480 | 92 | -3 | 77.6 | 0 | -42.6 | -286.4 | 0 | 0 | -0.31 |
| 2006 | 0.9 | 463.6 | 1015.5 | 112 | 445 | 92 | -74 | 77.8 | 0 | -113.9 | -525 | 0 | 0 | -0.14 |
| 2008 | 0.5 | 467.7 | 1023.9 | 94.2 | 396 | 62 | 11 | 47.3 | 0 | -29.6 | -292.2 | 0 | 0 | 0.09 |
| 2009 | 0.4 | 748.5 | 819.4 | 237.5 | 416 | 264 | 68 | 246 | 2.7 | 28.2 | -55.7 | 0 | 0 | 0.01 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 406 | 147 | -188 | 136.4 | 0 | -217.4 | -1000.2 | 0 | 0 | -0.18 |
| 2005 | 0.4 | 569.3 | 936.1 | 98.7 | 413 | 130 | 26 | 64.1 | 53 | -14.3 | -199.8 | 0 | 0 | 0.59 |
| 2006 | 0.7 | 463.6 | 1015.5 | 112 | 382 | 120 | -39 | 65.8 | 42 | -79.2 | -363.6 | 0 | -0.1 | -0.13 |
| 2008 | 0.8 | 467.7 | 1023.9 | 94.2 | 342 | 85 | 41 | 40.5 | 31.7 | -1.4 | -194.3 | 1.8 | 0 | 0.10 |
| 2009 | -1 | 748.5 | 819.4 | 237.5 | 331 | 336 | 82 | 162.9 | 158.7 | 39.2 | -64.8 | 2.1 | 0.1 | 0.11 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 332 | 174 | -141 | 105.1 | 59.3 | -170.6 | -759.4 | 0 | -0.2 | -0.16 |
| 2005 | 0.6 | 569.3 | 936.1 | 98.7 | 531 | 85 | -47 | 71.8 | 0 | -87.2 | -562.5 | 0 | -0.1 | -0.23 |
| 2006 | 0.9 | 463.6 | 1015.5 | 112 | 498 | 88 | -121 | 74.8 | 0 | -161.5 | -760.6 | 0 | -0.1 | -0.16 |
| 2008 | 0.4 | 467.7 | 1023.9 | 94.2 | 442 | 62 | -36 | 49 | 0 | -76.3 | -578.8 | 0 | -0.1 | -0.13 |
| 2009 | 0.8 | 748.5 | 819.4 | 237.5 | 484 | 229 | 35 | 214.9 | 0 | -4.8 | -317.8 | 0 | 0 | -0.10 |
| 2010 | 0.7 | 365.4 | 839.2 | 188 | 467 | 150 | -251 | 140.3 | 0 | -281.3 | -1302 | 0 | -0.1 | -0.10 |
| 2005 | 0.6 | 569.3 | 936.1 | 98.7 | 584 | 84 | -99 | 70.7 | 0 | -139.1 | -852 | 0 | -0.1 | -0.15 |
| 2006 | 0.8 | 463.6 | 1015.5 | 112 | 553 | 88 | -177 | 75 | 0 | -216.8 | -1045.5 | 0 | -0.1 | -0.18 |
| 2008 | 0.4 | 467.7 | 1023.9 | 94.2 | 493 | 66 | -91 | 52.8 | 0 | -131.2 | -886 | 0 | -0.1 | -0.05 |
| 2009 | 0.3 | 748.5 | 819.4 | 237.5 | 518 | 238 | -8 | 135.3 | 88.6 | -48.5 | -578.8 | 0 | 0 | -0.02 |
| 2010 | 0.9 | 365.4 | 839.2 | 188 | 518 | 171 | -323 | 132.4 | 28.9 | -353.1 | -1669 | 0 | -0.1 | -0.22 |

Table A.3: Naturalised situation(without Groundwater abstraction and surface water supply)

| | **NS.** | **Observations** | | | **Simulations** | | | **States** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Year*** | ***Eff.*** | ***P*** | ***Etpot*** | ***Qobs*** | ***ETact*** | ***Qsim*** | ***Bal.*** | ***fGS*** | ***fQS*** | ***dV*** | ***dG*** | ***hQ*** | ***hS*** | ***Balance*** |
| 2005 | 0.8 | 569.3 | 936.1 | 98.7 | 511.6 | 88.5 | -30.8 | 80.1 | 8 | -30.8 | -152.2 | 0 | 0 | -0.011 |
| 2006 | 0.8 | 463.6 | 1015.5 | 112 | 480.7 | 83.3 | -100.4 | 77.8 | 5.1 | -100.4 | -464.9 | 0 | 0 | -0.035 |
| 2008 | 0.6 | 467.7 | 1023.9 | 94.2 | 430.5 | 54.4 | -17.2 | 53.5 | 0.5 | -17.1 | -79.9 | 0 | 0 | -0.106 |
| 2009 | -0 | 748.5 | 819.4 | 237.5 | 438.5 | 271 | 39 | 189.3 | 80.4 | 38.8 | 180.7 | 0.1 | 0 | 0.1136 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 433.4 | 144.5 | -212.5 | 118.7 | 25.6 | -212.4 | -997.6 | 0 | 0 | -0.174 |
| 2005 | 0.7 | 569.3 | 936.1 | 98.7 | 506.3 | 88.1 | -25.1 | 87.7 | 0 | -25 | -207.4 | 0 | 0 | -0.109 |
| 2006 | 0.9 | 463.6 | 1015.5 | 112 | 473.1 | 86.9 | -96.4 | 86.5 | 0 | -96.3 | -449.8 | 0 | 0 | -0.134 |
| 2008 | 0.5 | 467.7 | 1023.9 | 94.2 | 423.1 | 55.4 | -10.8 | 55.1 | 0 | -10.8 | -208.5 | 0 | 0 | -0.004 |
| 2009 | 0.4 | 748.5 | 819.4 | 237.5 | 434.8 | 266.3 | 47.4 | 260.8 | 4.2 | 47.4 | 31 | 0 | 0 | 0.0166 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 426.4 | 146.2 | -207.2 | 146.1 | 0 | -207.2 | -958.6 | 0 | -0.1 | -0.072 |
| 2005 | 0.2 | 569.3 | 936.1 | 98.7 | 434.6 | 132.9 | 1.8 | 73.8 | 59.2 | 1.1 | -133 | 0.8 | 0 | -0.099 |
| 2006 | 0.6 | 463.6 | 1015.5 | 112 | 405.5 | 120.6 | -62.5 | 74.7 | 45.9 | -62.3 | -295 | 0 | -0.1 | -0.222 |
| 2008 | 0.8 | 467.7 | 1023.9 | 94.2 | 364.7 | 86.7 | 16.3 | 49.5 | 37.2 | 13.8 | -122.7 | 2.4 | 0.1 | 0.1056 |
| 2009 | -1 | 748.5 | 819.4 | 237.5 | 347.5 | 344.6 | 56.4 | 175.3 | 168.1 | 53.7 | 7.2 | 2.6 | 0.1 | 0.1197 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 350 | 175.8 | -160.4 | 113.6 | 62.4 | -160.3 | -719.2 | 0 | -0.2 | -0.156 |
| 2005 | 0.6 | 569.3 | 936.1 | 98.7 | 558.3 | 79.6 | -68.6 | 79.7 | 0 | -68.6 | -486.8 | 0 | -0.1 | -0.024 |
| 2006 | 0.8 | 463.6 | 1015.5 | 112 | 525.6 | 81.8 | -143.8 | 81.9 | 0 | -143.7 | -688 | 0 | -0.1 | -0.15 |
| 2008 | 0.4 | 467.7 | 1023.9 | 94.2 | 469.9 | 54.5 | -56.7 | 54.8 | 0 | -56.7 | -497.1 | 0 | -0.1 | -0.02 |
| 2009 | 0.8 | 748.5 | 819.4 | 237.5 | 503.2 | 230.2 | 15.1 | 229.2 | 0.2 | 15.1 | 235.3 | 0 | 0 | 0.0053 |
| 2010 | 0.8 | 365.4 | 839.2 | 188 | 487.8 | 148.8 | -271.2 | 149.3 | 0 | -271.1 | -1262.2 | 0 | -0.1 | -0.195 |
| 2005 | 0.6 | 569.3 | 936.1 | 98.7 | 612.5 | 77.7 | -120.9 | 77.2 | 0.1 | -120.2 | -777.1 | 0 | -0.1 | -0.742 |
| 2006 | 0.8 | 463.6 | 1015.5 | 112 | 582.1 | 80.7 | -199.2 | 81.1 | 0 | -199.1 | -974.8 | 0 | -0.1 | -0.17 |
| 2008 | 0.4 | 467.7 | 1023.9 | 94.2 | 522.1 | 57.2 | -111.6 | 57.4 | 0 | -111.5 | -111.5 | 0 | -0.1 | -0.139 |
| 2009 | 0.2 | 748.5 | 819.4 | 237.5 | 537.3 | 239.8 | -28.6 | 140.2 | 99 | -28.5 | -499 | 0 | 0 | -0.11 |
| 2010 | 0.9 | 365.4 | 839.2 | 188 | 537.3 | 171.3 | -343.2 | 137.1 | 34.9 | -343 | -1629.4 | 0 | -0.1 | -0.32 |