CHALMERS

A Sea Barrage in the Göta Älv River – Possible or Impossible?

Master's Thesis in the International Master's Programme Geo and Water Engineering

MASOUD IRANNEZHAD

Department of Civil and Environmental Engineering
Division of Water Environment Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Thames barrier in Thames River at London, United Kingdom

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ABSTRACT

The global warming has influenced the weather of the world and will cause changes in amount and pattern of precipitation, evaporation rate, and mean sea level. The IPCC reports suggest the mean temperature will be added by +3.5 °C at most, and the mean sea level will be raised by +1m during the 21st century due to the melting of continental ice and increases in ocean temperatures. This sea level rising will increase the flood risks in coastal cities.

Gothenburg is one of the cities on the south-west coast of Sweden. It is located on the North Sea, and a huge river which is called "Göta älv" is running through that. The sea level is the most important factor that affects the water level in the Göta älv within Gothenburg city limits. This study investigates if it is possible to balance the water level between the Göta älv and the North Sea during the 21st century by protective barrage techniques.

Two sea barrages are suggested to achieve this goal, one for controlling of sea level rising, and another to divert the flow of the Göta älv. At first, the best locations of barrages along the river are selected according to the three criteria of topography, geology, and river characteristics. Then, the reservoir volume between the two barrages is calculated by the measurement of surface areas at each contour level and the elevation between each one for substituting in trapezoidal rule equation in MATLAB program.

In the next step, the statistical hydrology analysis is done for the data of 2006-2008 to predict the future runoff which is as an inflow to the reservoir. In addition, the variation of water level in the reservoir is computed based on the generated runoff and the reservoir volume when the barrages are closed. Finally, the outflow from barrages is calculated based on the head between sea level and water level inside the reservoir. The strategies for operating the barrages are suggested by comparing the variation of water level at the barrages and sea level variation in order to make a balance between them, and to protect Gothenburg against flooding.

The best locations of barrages are one at upstream and another at downstream of Gothenburg. According to results, the extreme weather occurs mostly in January, February, June and July for today and future extreme weather condition. The risk of flooding caused by runoff is high in June and July due to the heavy rainfall, and the risk of flooding caused by sea level rising is high in January, February, and March. Also, based on the comparison of water level variation in the reservoir and the sea level variation in the North Sea, it is possible to use these barrages for protecting Gothenburg against flooding events during the 21st century.

Key words: Rising sea level, climate change, flood risks, sea barrage, precipitation- runoff model, reservoir volume, statistical hydrology, water level balance equation

Contents

Preface

This project has been carried out in cooperation with the Water Environment Technology Division at Chalmers University of Technology, and the Stadsbyggnadskontoret division of Göteborgs Stad, from January to August 2009.

The study focuses on the protection of Gothenburg city against flooding events during the 21st century by using the protective barrage techniques. The climate change effects on water related variables are considered and applied to balance water level between the North Sea and the Göta älv River which is running through the city.

Göteborg August 2009
Masoud Irannezhad

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1 Introduction

1.1 Background and scope

The consequences of global warming are unknown, but will have effects on the climate and weather of the world. It will change the amount and pattern of precipitation and will cause sea level to rise due to the melting of continental ice and increases in ocean temperatures. Thus, the risk of flooding will increase for coastal areas like London, Rotterdam, and New York. Flood control structures like seawalls, sea barrages and tidal barriers have been built to protect coastal areas against flooding, and have provided an adequate level of protection so far, like Thames barrier in London.

Gothenburg in Sweden is one of coastal cities which need be protected against floods. The Göta älv is a huge river which passes through the city of Gothenburg, and the sea level is the most important factor that affects the water level in it. Based on the IPCC reports, the mean sea level will be increased by +1m during the 21st century, while the safe water level for today extreme weather is considered +1m in the Göta älv River, and the safe water level in the Göta älv will be +2.5m by 2100. It means the most part of Gothenburg city will be flooded during the 21st century.

Therefore, the question is whether it is possible to apply the same techniques in Gothenburg as London or Rotterdam to protect the city against present and future extreme weather. In this study, the principles of flood risk management and engineering hydrology as well as the climate change predictions are described and used for flooding estimation.

1.2 Outline

General information of climate change is described in Part 2 such as different scenarios, observed and projection of changes in water-related variables, and climate change in Europe especially in Sweden.

Part 3 explains about floods like types of flood, floodplain and flood way, flood hazards, flood control policies and flood control structures to have a good background about floods.

In Part 4, the engineering hydrology tries to describe a river basin, and the processes of runoff generation such as precipitation and evaporation. In last section of this chapter the water balance equation is given to find how the water level is modified between a river and a sea.

Part 5 describes the scope and purpose of study, assumptions, available data, considerate scenarios, and method of this study; also, it is explained how the water balance equation is computed by MATLAB program, and which parameters are considered in it.

The results will be illustrated in Part 6 for the extreme weather condition of today and future; also, the operation systems of barrages are introduced. Part 7 is a discussion about the cost and period of construction, and answers to some other general questions. The conclusion has been located in Part 8, and a suggestion of future studies has been included in Part 9.

2 Climate Change

Nowadays, climate change is the main environmental debate, overlooking the scientific media, and research schedule. Most scientists agree that peculiar changing in weather patterns are related to the greenhouse effect, which has been increased by human activities.

The Intergovernmental Panel on Climate Change (IPCC) predicts that the global surface temperature will be raised 1 – 3.5°C till 2100. Based on this prediction, changes in the temporal and spatial patterns of precipitation, and rising sea level of 15-95 cm over next hundred years can be assumed.

The consequences of climate change will increase the risk of flooding for the coastal areas such as London, New York, Gothenburg, etc (Davie, 2002). Thus, flood control structures to protect these areas against floods can be considered. At first, the background knowledge of future climate and its relation to the hydrological cycle is the most important part to find how these flood control structures must be operated; hence this chapter refers to the climate change background.

2.1 Different scenarios of climate change

The Intergovernmental Panel on Climate Change, IPCC, has published a number of 40 different scenarios of climate change based on future anthropogenic emissions rates. All of them refer to the six marker scenarios which represent a different direction, i.e. towards globalization, towards fossil fuel, effective use of resources etc (Lind & Kjellström, 2008). However, these six marker scenarios are included in A1, A2, B1 and B2 which are called scenario families (IPCC, 2000). A2 and B2 are described below, but for more information please check the IPCC website[1].

2.1.1 A2 scenario family

In this scenario family the world is considered very heterogeneously, and global population increase is very slow. Also, there is a regionally economic development and the change of technology is slower than other scenario families.

2.1.2 B2 scenario family

In this scenario family the sustainable development, economic and social sustainability is based on local solutions. The rate of population increases is less than A2 scenario, and B2 is more toward environmental protection and social equity in local level.

2.2 Climate change and water-related variables

Climate system includes atmosphere, hydrosphere, cryosphere, land surface and biosphere. Thus, climate change affects water which is involved in all of climate systems (IPCC, 2008). Below, the observed recent changes of water-related variables, the projection to future changes, and impact of climate change in Europe, especially in Sweden, will be discussed.

2.2.1 Observed recent changes

Atmospheric temperature and radiation balance affect the hydrological cycle directly. The best way to understand those changes is watching the increase of ocean and average air temperature, development of melting of the continental ice and rise of global sea level due to the warming of sea water (IPCC, 2008).

The hydrological variables such as precipitation patterns, intensity and extreme, snow and ice melting, water vapor in atmosphere, evaporation rates, soil moisture and runoff have been affected by climate warming. Keep in your mind, there is an important uncertainty about the movements of these

[1] Available online on: http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

variables due to large regional differences, and limitations in the temporal and spatial monitoring condition (IPCC, 2008).

Generally, the mean precipitation over land and heavy rainfall events have been increased during the 20th century. The atmospheric water vapor, which is generated due to climate warming, is the main reason for extreme precipitation. Based on the control processes of mean and extreme precipitation, the climate models and theoretical studies expect the change extreme precipitation will be greater than the change mean precipitation in future. The trend of annual precipitation amounts during 1901-2005(upper, % per century), and 1979- 2005 (lower, % per decade) are represented in figure 1, as a percentage of the 1961-1990 precipitation average, (IPCC, 2008).

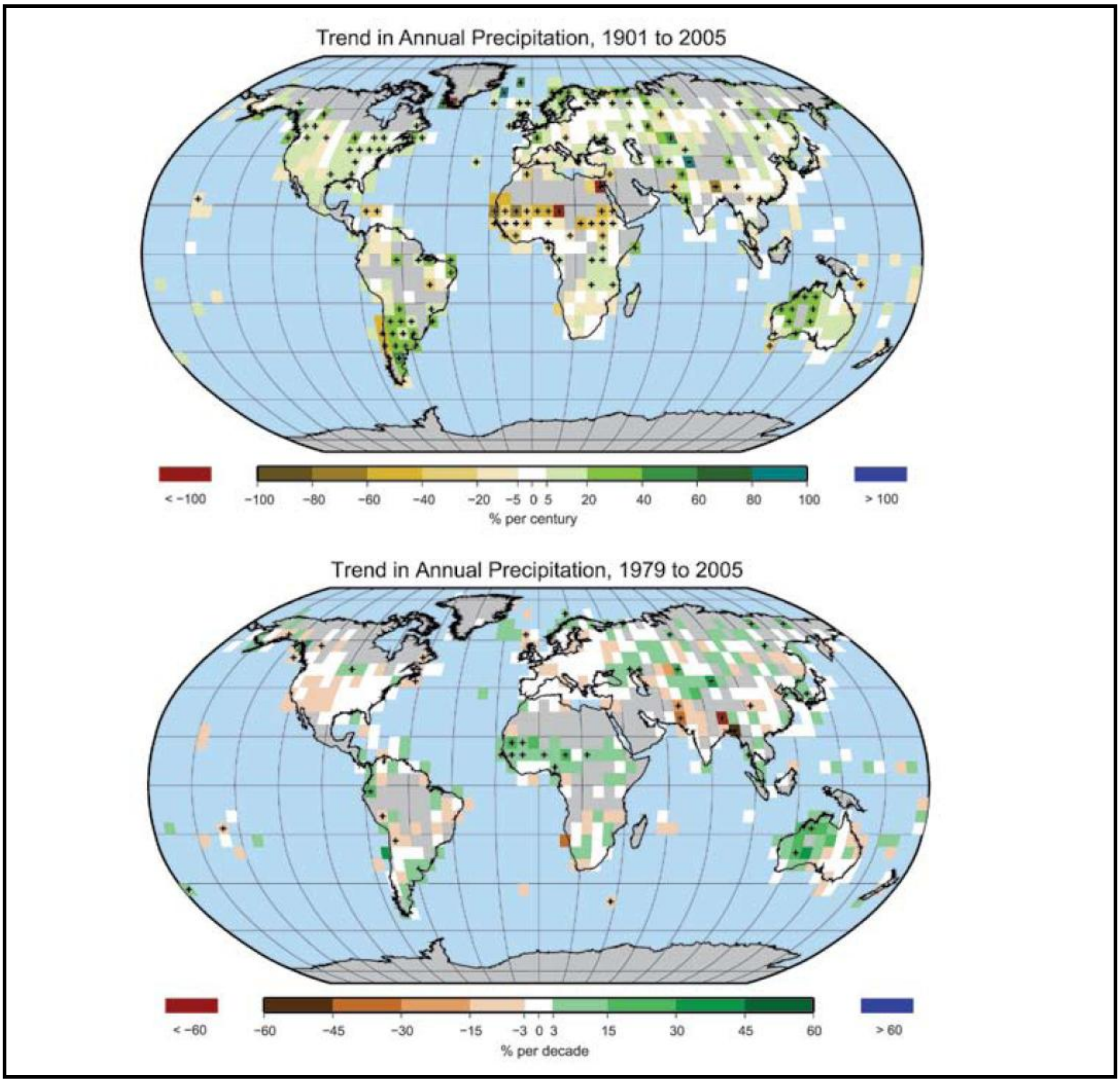

Figure 1: The trend of annual precipitation amounts, from CHCN station data

Approximately, 75% of the freshwater in the world has been stored in the cryosphere on land which is consisting of snow, ice and frozen ground. In most regions of the world, degradation of frozen ground, decreasing of snow covers and glacier occur due to the increase of summer air temperature that these effects can amplify the global sea level rising. The rate of sea level rising has increased during the 19th and 20th centuries. Coastal regions are affected by the sea level rising, but consequences always are not clearly. Increase of global extreme high water levels refers to the mean sea level rise and the variation climate effects (IPCC, 2008).

However, measurements of river discharge have been done by considering indicators for different methods. Some of these indicators are dissimilar statistical test, different record periods, variation in flow regimes due to the human interventions etc (IPCC, 2008).

2.2.2 Projection of changes

Based on continued emissions of the greenhouse gases, the global climate system would likely change during the 21st century and the earth surface temperature will be warmer than the 20th century. The prediction of global warming consequences is associated to many uncertainties, but these consequences will have effects on earth's climate and weather. The development of economy, climate modeling, the emissions of greenhouse gases and the hydrological modeling are a range of reasons which involved to the uncertainties of climate change impacts on water section (IPCC, 2008).

In general, global warming will increase the rates of evaporation; therefore, there will be a higher atmospheric vapor which leads to more precipitation with different patterns in future. Also, the increase of ice melting because of global warming and increases in ocean temperature, will affect the mean sea level to rise during 21st century (IPCC, 2008). All of these causes will amplify the risk of floods in coastal areas and river catchments like London with Thames River, Gothenburg with Göta älv River, etc. As follows, the changes of hydrological cycle during the 21st century will be discussed in details.

The prediction models of climate change forecast precipitation to be increase in tropical regions and at high latitudes areas such as the tropical oceans, the monsoon regimes, eastern Africa and northern part of central Asia in both summer and winter seasons. Also, the reduction will occur at mid-latitudes areas and sub-tropical regions like the Mediterranean area, the Caribbean region and the western coasts of each continent. Figure 2 represents the fifteen-model mean changes in precipitation based on unit of mm/day for the SRES A1B climate change scenario during 2080-2099 relative to 1980-1999, (IPCC, 2008).

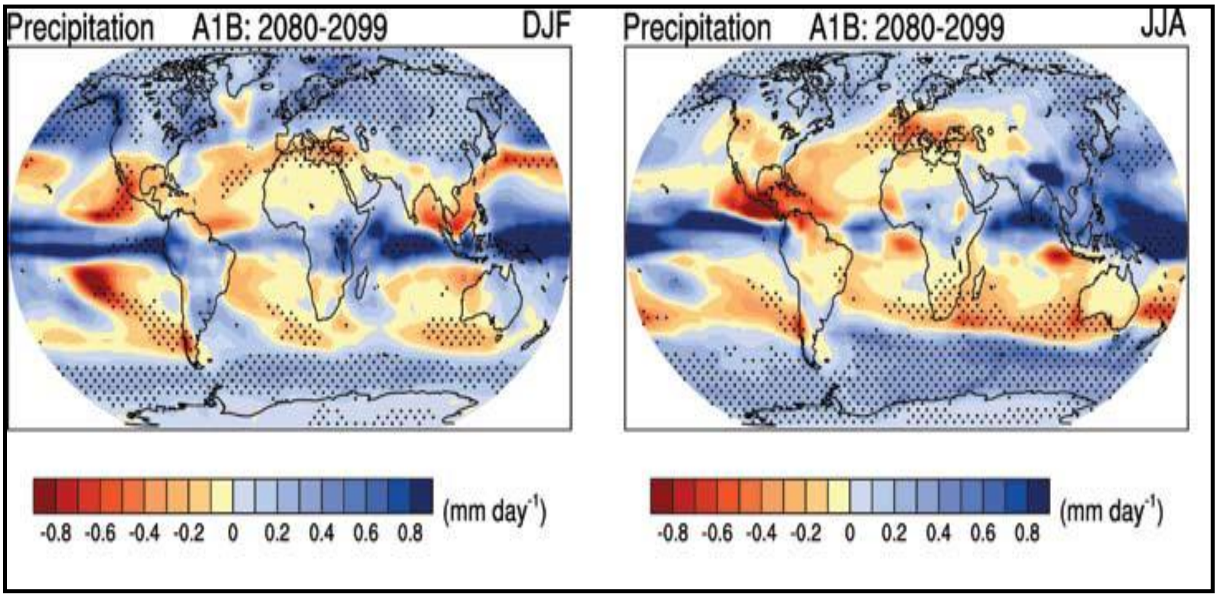

Figure 2: Fifteen-model mean changes in precipitation (unit: mm/day)

The average global evaporation changes are very close to the changes of precipitation at the regional scale because the vapors of water are transported in the atmosphere. The mean annual evaporation will be higher during the 21st century over oceans and high latitude areas due to global warming. Keep in your mind, the water vapor is a greenhouse gas; therefore, it makes available a positive feedback on global warming by its increasing. The percentage of changes in mean evaporation according to the fifteen-model mean changes has been shown in figure 3, (IPCC, 2008).

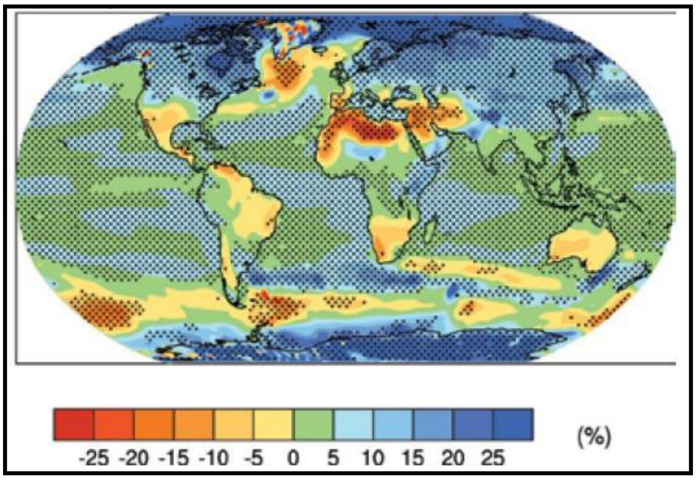

Figure 3: Fifteen-model mean changes in evaporation (%) based on SRES A1B

Also, the frequency of heavy precipitation events in the 21st century will be higher than in the past, and it can happen in tropical and high latitude areas. The risk of droughts can be predicted in mid-continental region in summer season. For example, according to A2 scenario, the increase of extreme drought will be changed from 1% to 30% by 2100. In addition, the risk of intense precipitation and flooding must be projected for future. However, in sub-tropical areas the intense and heavy rainfall which generates high runoff amounts will be combined with longer dry periods at the same time as the increase of evapotranspiration. Thus, Climate models projection for the 21st century represents both the intensity of precipitation and the number of following dry days in many areas. To find out more about the intensity of precipitation and dry days, see figure 4 (IPCC, 2008).

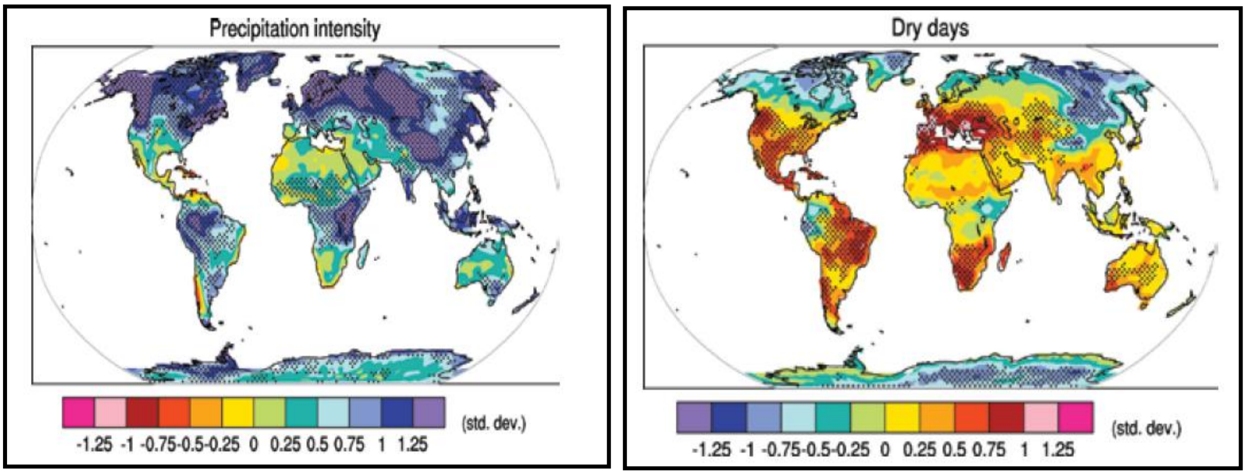

Figure 4: Changes in precipitation intensify and dry days based on A1B (IPCC, 2008)

Lake levels and river flows will be changed during 21st century due to the change of intensity and time of precipitation which can be rain or snow; also, river flow can be affected by changing of evaporation rates. Most of runoff simulations by climate model and hydrological model express in high latitude and wet tropic regions, the runoff will be increased, for example in south-east Asia, but in mid-latitude and dry tropic areas like southern Europe, the reduction of runoff will be expected. Based on global warming, the seasonality of river flows will be increased in winter due to the melting snow, but there is a reduction of that due to the reduced snowmelts and snow cover. However, the rainfall change is more important factor than the change of temperature to predict the future runoff. Changes in the seasonal inflows of rivers, evapotranpiration, and precipitation over many years are the main reasons of lake levels changing. These changes of lake levels sometimes can be about meters by 2100 (IPCC, 2008). Figure 5 represents the changes of annual runoff for 2080-2099 in relation to 1980-1999 for scenario A1B from IPCC.

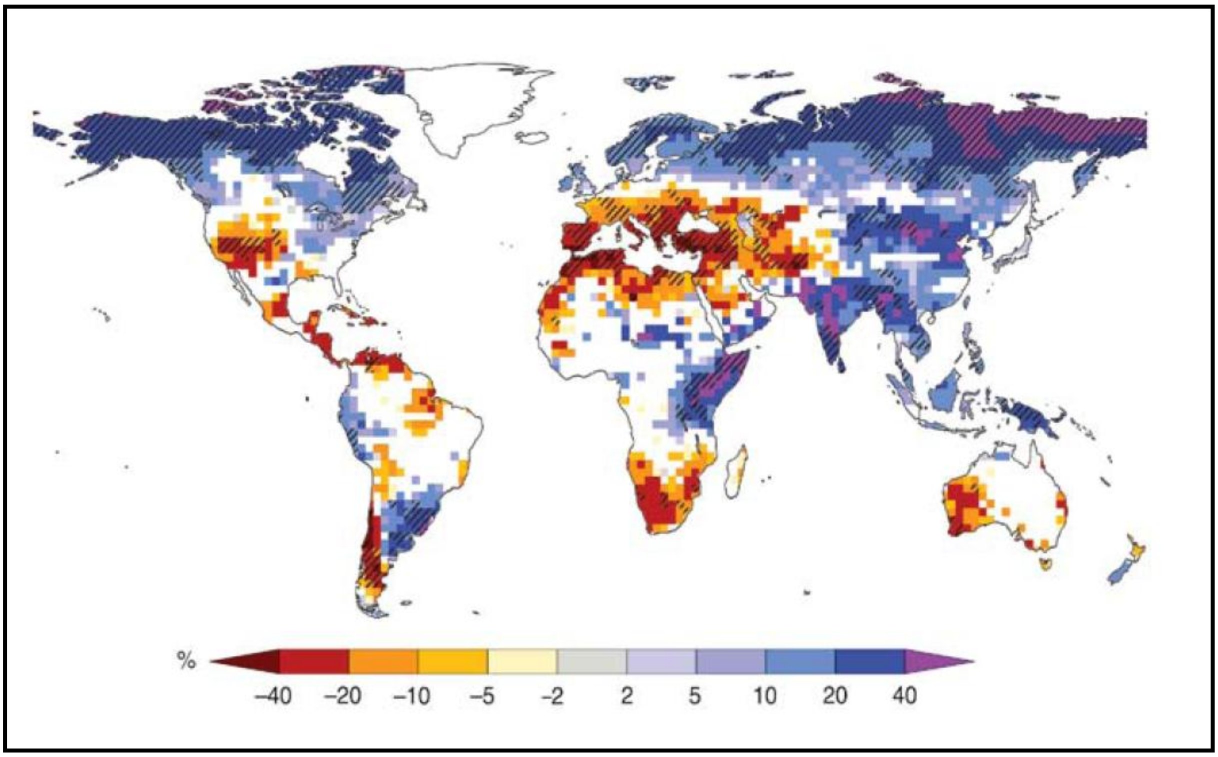

Figure 5: The changes of annual runoff for scenario A1B

2.2.3 Changes of water-related variables in Europe

There are various types of climate in Europe such as Mediterranean, polar, continental, maritime and transitional. Most studies about climate change sensitivity in Europe show there will be more severe climatic conditions in the southern part, e.g. warmer and drier climate. Also, precipitation during summer in the central and Eastern Europe will be decreased due to the higher water stresses in those areas during 21st century (IPCC, 2008).

Based on the observed changes over the 20th century, the mean precipitation during winter seasons in northern Europe will be increased by 2100. In addition, annual runoff in the Atlantic and northern Europe will be greater than before, while reduction of annual runoff is predicted for the Mediterranean, eastern and central Europe in the next hundred years (IPCC, 2008).

Therefore, the risk of flooding will be increased through Europe, and most of areas which are prone to go up in flood frequencies are in Eastern Europe, northern Europe, the Atlantic coast and central Europe, respectively. As mentioned increases in drought frequencies are predicted for southern and south-eastern Europe during the 21st century (IPCC, 2008).

2.3 General impacts of climate change in Sweden

Based on predictions by the UN's Intergovernmental Panel on Climate Change (IPCC), the general impact of climate change in Sweden during the 21st century are as following (The Swedish Commission on Climate and Vulnerability, 2007):

- Increase of temperature in Sweden will be greater than average global warming, and it is in a range of 3 - 5°C with respect to the period 1960-1990. Also, the temperature increase in northern Sweden in winter season may be 7 degrees.
- Precipitation patterns will be changed, and it will be greater than before in summer, winter and spring seasons. While warmer and drier conditions are suggested in southern parts of Sweden.
- Sea level rising by considering ice caps melting in Greenland and Antarctica will be approximately 0.6-1.0 meters in sea bordering Sweden.
- During summer, winter and spring, most parts of Sweden will have an increased number of days of precipitation and more intensive rainfall till 2100.
- Specially, the west of Sweden, such as western Götaland, south-western Svealand and north-western Norrland, will experience runoffs which are larger than in the past.
- The 100 years return high flows will be increased in Sweden western parts, therefore, the risk of flooding in western Sweden will be higher than in other parts of country.

In the next parts, the definition of flood, its characteristics, flood control structures, river basin characteristics and water balance equation will be reviewed because of the increasing of flood risks in the western parts of Sweden during the 21st century.

3 Flood Risk Management

3.1 Flood

Along rivers has been always attracted for civilization due to the guaranteed access to enough water for irrigation of crops, urban and industrial water supplies, later power development and access to the coastal areas. All of these advantages always are in combination of flooding dangers such as economic and traumatic losses. It is very difficult to define the term of flood in general expression, therefore, the causes of floods are used (Wilson, 1990).

3.2 Flood types

There are some types of flooding based on geography condition and flow velocity, and in below a few of them are expressed (floodsite.net)

- Coastal flood – storm surges are generated due to the low air pressure and ocean water driving onto land can be produced by tropical storms. Also, sea waves are reasons of coastal flooding, and can be created by earthquake or volcanoes in the oceans which called tsunami and giant tidal waves. The dominant characteristic of coastal floods is the water level drops and rises with the tide. It may flow into coast at high tide and at low tide it may recede again. Coastal houses and facilities are affected by the water during this type of flooding.
- River flood – Most natural flooding events occur along rivers seasonally when spring rains and melted winter snows are combined to each others. The main reason is overflow of river banks due to quickly filling of river basin. The water is extended for miles on the land in the region of river.
- Flash flood – In areas with steep slopes, collected rain water flows downhill too quickly that causes the water level raises fast in the river bed. This type often occurs suddenly in a river bed that held very little water at first, and it will stop as suddenly as it starts due to the fast speed of water flowing.
- Urban flood – rainfall on an urban area where most of that is paved for different applications, can be result in runoff because rainwater cannot be absorbed into the ground. In fact, the main reason of urban flooding is a lack of drainage in an urban area. This type can have worse losses than other because there are a lot of people in urban area.

3.3 Intensify factors of Floods

According to the flood types, there are many flooding reasons that most of them refer to the hydrological cycle directly or indirectly such as rising sea level, rising lakes level, excessively heavy rainfall and unusually large discharge to the river. In addition, flooding usually occurs in spring and early summer in the cold winter areas like Sweden due to the high rate of snow melting (Ward & Robinson, 2000).

Based on the causes of floods, some factors can modify floods such as stable basin factors, variable basin factors, drainage network factors, channel factors, coastline configuration and the gradient of water depth in offshore. For example, Area of drainage basin as a table basin factor is an important intensify factor because the flood will be greater if the area is larger. It means the flood power or size depends on the area of catchment. The relations among flood types, causes of floods and flood intensify factors are represented in figure 6 (Ward and Robinson, 2000).

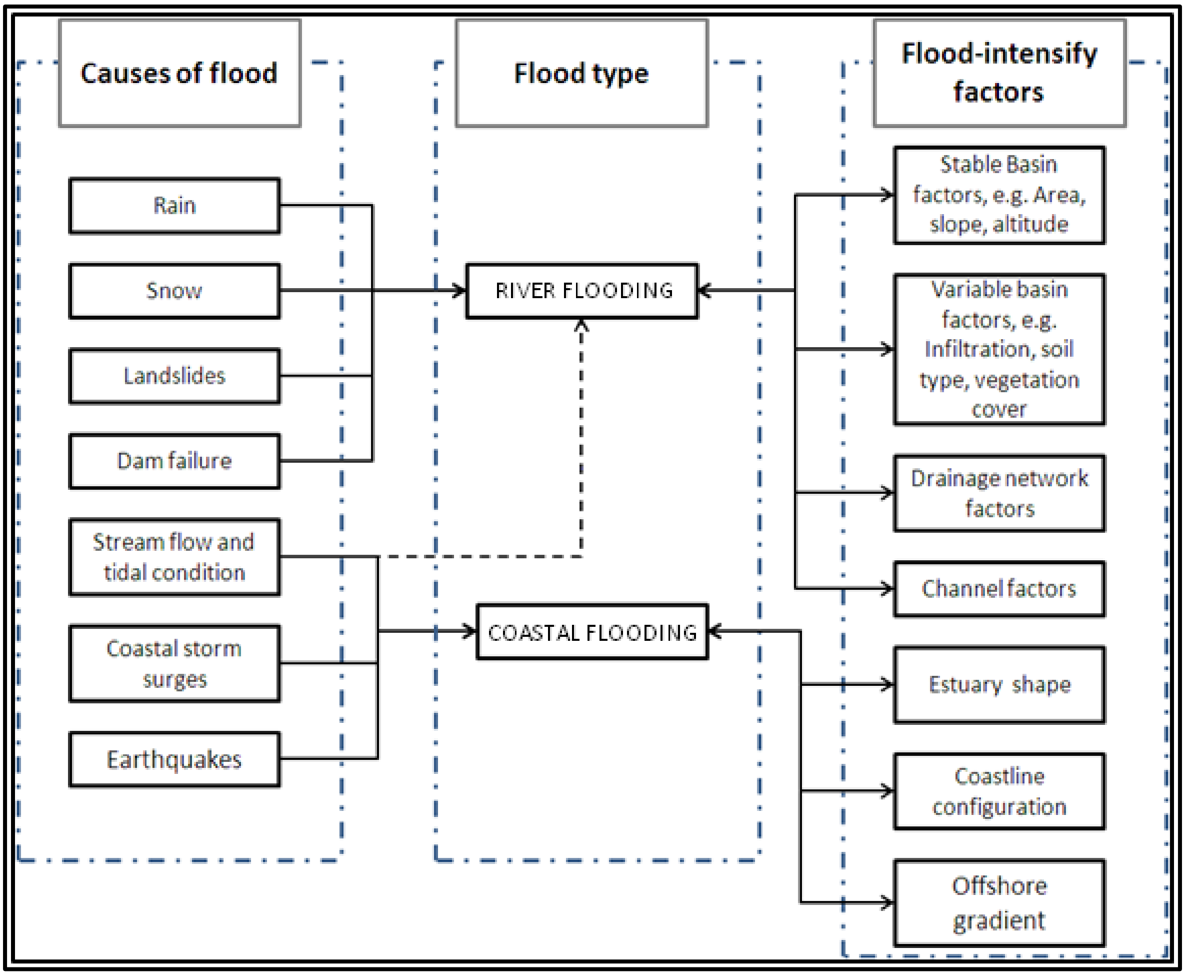

Figure 6: Causes of floods and flood-intensifying factors

3.4 Floodplain and floodway

Based on their nature, floodplains are the flat, low and periodically flooded lands often close to rivers, lakes and oceans, and they depend on both geomorphic and hydrological processes. In addition, the dry zone between levees (a type of flood control structures) is called a river floodway.

The floodplains are usually considered as the focal points for activities like agriculture, commerce and residential development, while the river floodway are the construction and control focus point. The relations among river, its floodway and its floodplain become understandable during and after major flood events because these areas can make complex physical and biological systems that can support different natural resources (Cantrell & Jackson, 2003).

3.5 Flooding hazards

Flood is one of the most costly disasters that cause both property damage and human victims during the 20th century. For example, large floods in China killed about 4 million people in 1931, or the flood on the upper Mississippi River killed only 47 people, but the total economic loss between 15 and 20 billion dollars was estimated by the U.S. Army Corps of Engineers. However, three categories can be defined for hazards associated with flooding such as primary hazards, secondary effects and tertiary effects (Nelson, 2007).

- Primary hazards – this category refers to those which are because of direct contact with the flood waters such as :

- The transportation of large suspended objects, e.g. rocks, cars and houses, due to the higher velocity of water during flooding time.
- Flood waters can affect on the erosion amount of soil, and can destabilize bridges, levees and buildings foundation.
- Everything in human built structures like furniture, walls and floors can be damaged by water due to flooding home.
- Crops, livestock, pets and animals are damaged due to the flooding of farmlands.
- Floods can carry more concentration of garbage, debris and toxic pollutions which can be the reasons of secondary effects as health hazards.

- Secondary effects – Occur due to the primary effects, and the main of those is disruption of services. General secondary effects are as following:
  - Pollution of drinking water can happen, especially, when the flood reaches wastewater treatment plants. In this situation, diseases and health hazards can be caused by floods.
  - Power plants and gas stations can be damaged.
  - Food shortages in underdeveloped countries can occur due to the disruption of transportation systems during floods.
- Tertiary effects (long-term effects)
  - Floods can change the location of river channels, and can develop new channels.
  - Agriculture productivity can be affected due to the deposition of sediments which are carried through floodwaters on farmlands.
  - Job situation can be changed after flooding, some jobs can be lost due to the business destruction, and some job positions can be increased because of rebuild or repair flood damages.
  - The rates of insurance may be increased.
  - Habitats of wildlife can be destroyed.

3.6 Flood control policies

Based on the flood hazards, some policies of flood control in most of the developing countries have been considered to minimize the related impacts. As follows, the most important aspects of these policies are discussed (Tucci, 2006):

- Urban drainage – based on the concept, the drainage of water must be done from urban areas as soon as possible by using pipes and network channels; therefore, the designation of urban drainage can play an important role to minimize flood hazards, especially in developing countries; but the peak flow and the cost of this system of drainage will be increases, and can be appear in the major drainage.
- Floodplain – an uncontrolled urbanization always is the most common debate for flood controlling because the floodplain will be occupied by the population in a progression of years with small flood levels; but during the higher flood levels, damages will be increased and the public administrations have to provide population relief.
- Plan development – A political city division can regulate urban flow control by modules, and it can be developed by sub-basins. The main policies related to the drainage system are as follows:
  - In the major drainage: based on the location, to avoid the impacts of urban drainage to be transferred to downstream of river, hold urban surface for confinement of flood volumes, sediment and trash is the best policy. In fact, instead of garbage and sedi-

ment distribution in channels, conduits or along the river, all of these impacts are saved in some specific places to clean and reduce the maintenance costs.

- In the flood plain – there are two policy categories in this part, structural solutions which are rational only when damages costs are greater than their development, and non-structural measures that have lower costs, but the political implementation of them is associated with some difficulties. Examples of non-structural measures are zoning of flood areas to high and low risk of flooding, forecasting and early-warning systems, and flood proof construction.

3.7 Flood control structures

In the past, flood control has been intended to keep the flood away from people, and it has been done by construction of levees along river channels. Today, based on environmental concerns, economic realities and understanding of hydrological implications of channel systems, some structural solutions need to be investigated as flood control structures.

The designation of these structures involves using the hydrological methods, such as reservoir volume calculation, runoff modeling and water balance equation; also, the hydraulic methods for establishing the profiles of surface water that are related to the different recurrence intervals of floods must be considered as a combination to the hydrological methods (Brooks et al., 1997).

There are some advantages associated with using of these structures that are listed below as (The Solutient Corporation, 2009):

- They can Protect streets and buildings,
- They can stop floods,
- They can be built without any losses for business and home of citizens,
- They are constructed by governments, thus, long-term arrangements and maintenances refer to them, and not to the individuals,
- They can be the best solutions for some areas due to the land limitations.

Four general types of flood control structures are levees, reservoirs, diversions and dredging. These types are reviewed in more details as follow:

1) Levees, Floodwalls and Seawalls: these types raise the stream channel banks to confine water and protect the watercourse property. They are accounted for underground seepage, erosion, large floods and pumping of internal drainage. There are some key consideration in evaluation of levee usage such as:
   - The costs of design, construction and maintenance
   - River accessibility can be affected
   - Surface flows can be drained internally from the levee inside area
   - Development of adverse impacts to wetlands

   The location of levees is along the river or stream edge. A setback Levees are designated to reduce environmental impacts and provide different use benefits. Also, the setback levees inside can be used as open space for recreational goals and accessible location to rivers, see figure 7.

Figure 7: Sacramento River levee, 17 October 2007 (UTC) [2]

Floodwalls are vertical-sided structure with a same performance to the levees, but they occupy less surface area for construction. Steel sheet pile and reinforced concrete are the most common types of material in construction of floodwalls. Figure 8 represents the St. Louis floodwall.

Seawalls, in fact, are retaining walls, and often are built in front of a large lake, ocean or the Gulf. The goal of them is to protect the land erosion against wave action, but the disadvantage of them is their adverse impact on the shore and movement of sand due to the disruption of natural forces, the seawall of Stratford city in USA is shown in figure 9.

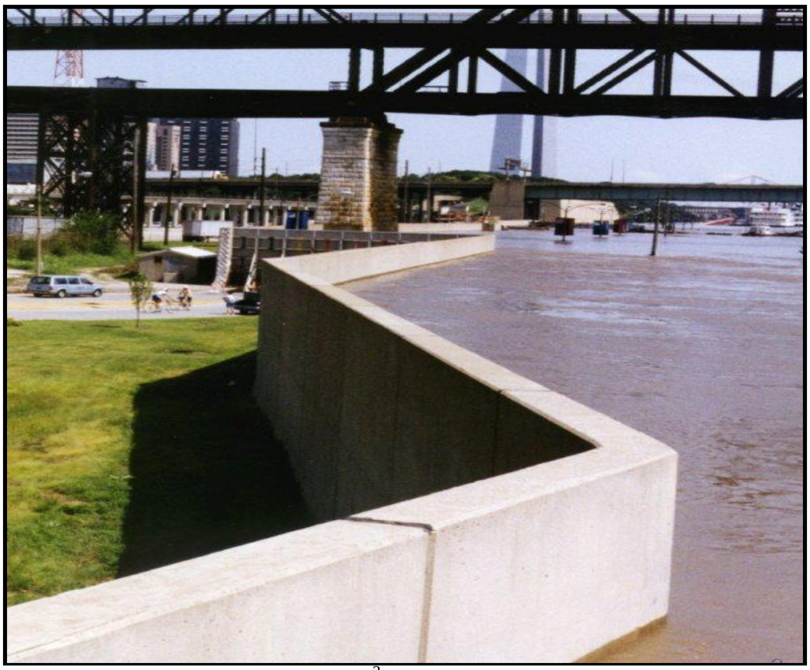

Figure 8: The St. Louis floodwall [3]

[2] Available online on: http://upload.wikimedia.org/wikipedia/commons/6/69/Sacramento_River_Levee.jpg
[3] Available online on: www.mvs.usace.army.mil/pa/floodriskmang.html

Figure 9: the seawall in Stratford city, USA [4]

2) Reservoirs and Detention basins: in fact, floodwaters can be stored temporarily behind dams or in detention basins, and after subsiding of flood the saved water in the reservoir or basin is released or pumped out slowly at the rate which the river downstream can manage. There are two purposes of building flood control reservoirs. At first, protection of goods from existing flood problems is done by large reservoirs. At second, smaller one is to protect property against the impacts of new development. Independently of size, both small and large reservoirs can be natural like valleys or manmade like excavated area to store floodwaters, figure 10 shows an urban detention basin. The evaluation of reservoirs and detentions application needs consider some recommendations like:
   - Deposition of sediment can reduce the reservoir capacity over time.
   - Nitrogen, nutrient, dissolved oxygen, temperature and other related parameters to the water quality can be affected.
   - Their flood preventive ability can fail when water reaches to the higher level than designated reservoir water level.
   - The management and maintenance of them must be constant over time.

Figure 10: An urban detention basin[5]

[4] Available online on: www.townofstratford.com/content/1302/402/625/1100/5066/5106.aspx

[5] Available online on: www. armycycles.com/uploads/pdf/stphmpu2008/mar27/8_Flood_control_4-09.pdf

3) Diversion: floodwaters will be sent to various locations by a new channel which can be surface channels, overflow weirs and tunnels. The surplus floodwaters will be carried to a receiving lake or river by diversions during flood flows. The most important criterion for designing diversion is topography that receiving lake or river must be located relatively close to the flood prone stream and the land must be low in between them. The Coanda diversion structure in Brandywine Creek is illustrated in figure 11.

Figure 11: The Coanda diversion structure [6]

4) Dredging: this type refers to the improvement of conveyance, see figure 12. there are some problems associated with them such as:

   - The cost of dredging is too expensive.
   - The dredging will destroy the developed habitation if the channel has not been distressed for many years.
   - The dredged parts fill back in a few years, and the expense and process will be repeated.

Figure 12: Dredging [7]

[6] Available online on: www.kwoiekcreekhydro.com/uploads/images/pages_images/coanda.JPG
[7] Available online on: www.lakesidemc.com/dredging.html

3.8 Tidal barrage

Tidal barrage is an example of reservoir types, and the goals of them are flood control and surge protection. The design of tidal barrages is always related to, installation and operation of gates because the large spans and heads must be controlled. In fact, they balance the water level between sea and river by using the gates. There are some huge tidal barrages in the world such as Maeslant barrier in Rotterdam (See figure 13), Thames barrier in London, St Petersburg flood protection barrier in Russia, and Venice barrier in Italy (Novak et al., 2001). For more information about Thames barrier in London, check the Thames barrier project pack 2008[8].

Figure 13: The Maeslant barrier in Rotterdam, Netherlands [9]

[8] Available online on: http://www.environment-agency.gov.uk/static/documents/Leisure/Project_Pack.pdf

[9] Available online on: www.privatehollandtours.com/bv01471.jpg

4 Engineering Hydrology

As mentioned before, the design of flood control structures is related to the hydrological methods. Therefore, in this chapter the fundamental parameters of engineering hydrology in relation to this designation are represented in two parts: drainage basin and water balance equation.

4.1 Drainage basin

This part tries to describe the factors which are relative in the amount of water volume that must be controlled by structures, mostly about basin hydrological cycle and its processes. All these process can affect the water level at the flood control structures.

4.1.1 River basin definition

The river basin or catchment is the most common spatial unit in engineering hydrology, and its definition is the land area from which the water flows move into a river and then from the river to the sea. Also, the rainfall at any point of river basin must end up in the same place which is called denominator point; an example of these points can be where the river meets the sea, figure 14 represents a basin area.

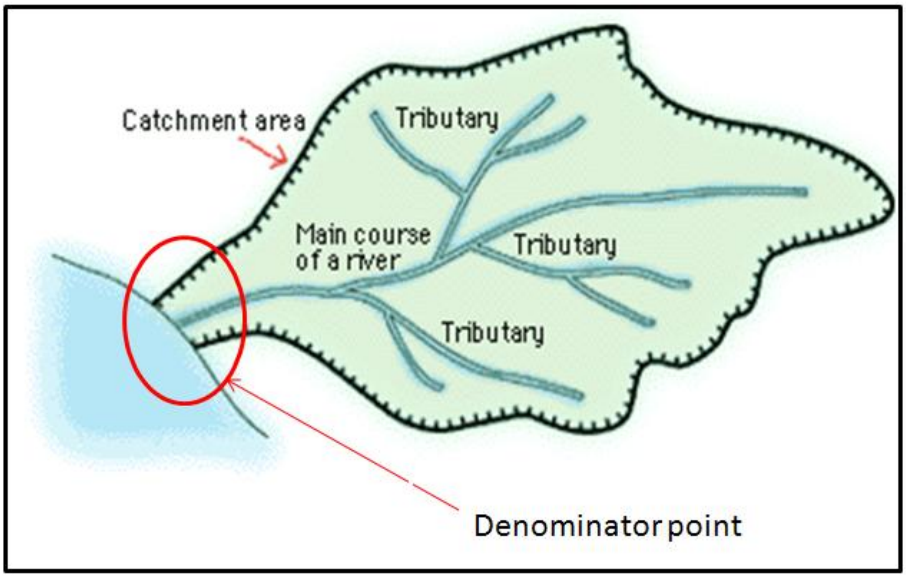

Figure 14: A river basin and dominator point [10]

River basin definition can be expressed in terms of its topography that all water flows downhill to the river, but this assumption is not always correct because sometimes the rainfalls leave the catchment area to another one as groundwater. It is good to know the size of a river basin can be in range from a matter of hectares to millions square kilometers (Davie, 2002).

4.1.2 The basin hydrological cycle

The basin hydrological cycle, shown in figure 15, can be considered as a smaller scale of global hydrological cycle. Precipitation, evaporation and runoff are three processes operating fundamentally, but each of them can be divided into various sub-processes.

Snowfall, rainfall, hail or some mixture of them can be the forms of precipitation. Evaporation is a mixture of water evaporation from rivers or lakes, soil evaporation, evaporation from the surfaces of

[10] Available online on: www.ob.hkd.mlit.go.jp/engilish_data/hp/tisui/yougo/Images/suikei.gif

plants and transpiration from plants. The term of "runoff" includes the liquid movement below and above the earth`s surface. All of these processes are being discussed in details as follows (Davie, 2002).

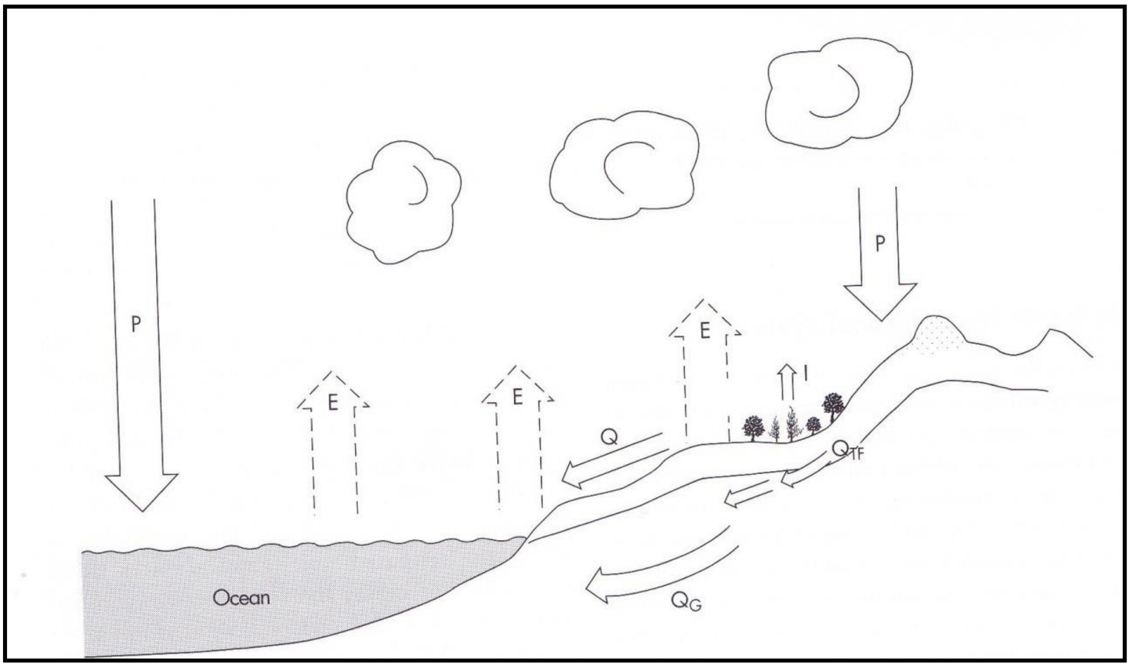

Figure 15: The basin hydrological cycle [11]

4.1.3 Precipitation

In precipitation process the water is released from the atmosphere to the surface of earth. All forms of snowfall, rainfall, hail and sleet are included in term of precipitation. In engineering hydrology the most important input to the river basin area is precipitation.

4.1.3.1 Mechanisms

The formation of precipitation depends on the ability of air to hold water vapor which is affected by temperature. Less water vapor is retained in the cool air than in warm air; thus, when the moist and warm air is cooled the water vapor will increased and eventually will condense to liquid or solid water.

Some static variables affect the distribution of precipitation, such as altitude, aspect and slope which are discussed below (Davie, 2002):

- Altitude – the temperature reduces with altitude, and an air parcel in higher elevation likes to release the vapor of water and make a heavy rainfall.
- Aspect – the main source of rainfall is the arrived weather systems from the west in humid mid-latitudes.
- Slope – the rainfall s is not always vertical, but the effect of slope is ignored in the measurement of precipitation (Davie, 2002).

Hydrologists are interested in analysis of precipitation data such as estimation of average rainfall over an area, determination of spatial pattern and movement of an individual storm, and the occurrence frequency of different magnitude rainfall (Ward & Robinson, 2000).

[11] From (Davie, 2002)

4.1.3.2 Measurements

The amount and time of fallen precipitation is one of main hydrological analyzing aspects. Usually, precipitation is expressed as vertical depth of liquid water, and measured by millimeters or inches, and these measurements are done as a point measurement (at a precise location). "Based on Davie (2002), the measurement is the depth of water that accumulates on the surface if all the rain remained where it had fallen". In fact, all measurement techniques are considered as estimation techniques of precipitation (Davie, 2002).

4.1.3.3 Estimations

The hydrologist uses the fallen precipitation on the large areas like catchments; hence the point measurements of rainfall must be moved to area estimations. Some spatial averaging methods are applied for this movement as statistical techniques such as Thiessens's polygons, hypsometric and isohyetal. All these techniques use Geographical Information Systems (GIS) for estimating, (Davie, 2002).

4.1.4 Evaporation

Evaporation is defined as the process with which any liquid transfers into a gas. In engineering hydrology, water losses from wet surfaces and their conversion to the gas state is called evaporation, and it can be diffused to the atmosphere (Ward & Robinson, 2000).

4.1.4.1 Mechanisms

There are two main aspects in relation to the evaporation process as following:

- The sufficient energy in form of sensible heat, latent heat and soil heat flux must be at evaporating surface
- The diffusion process must be active in the air above the evaporating surface (Ward & Robinson, 2000)

The sun is the main source of energy to transform liquid water into vapor as an available water supply in evaporation process. Also, the atmosphere must be dry enough to receive any water vapor generated. Evaporation occurs when these conditions are satisfied in nature (Davie, 2002).

4.1.4.2 Forms

The evaporation can be in some forms such as open water evaporation, potential evaporation, actual evaporation, transpiration and evapotranspiration which are discussed in more details as follows (Davie, 2002):

- Open water evaporation – is the largest source of evaporation that occurs at the above surface of a water body like lakes, rivers and oceans.
- Potential evaporation – it happens over the surface of lands and when a soil is wet.
- Actual evaporation – it also refers to the surface evaporation and it happens when the amount of available water limits the evaporation below the potential one.
- Transpiration – is the evaporation of water from plants, and occurs as a part of photosynthesis and respiration processes.
- Evapotranspiration – is the combination of actual evaporation from soils and transpiration from plants.

4.1.4.3 Measurements

The amount of evaporation associated with difficulties for measuring of gas concentration in atmosphere. Two categories of measurement are considered in engineering hydrology for such as direct micro-meteorological and indirect measurements. In direct category, there are three methods, the eddy fluctuation, aerodynamic profile and Bowen ratio, also, the evaporation pan method which is based on the water balance techniques, is used in another category (Davie, 2002).

4.1.4.4 Estimations

Based on the mentioned difficulties, the estimation of evaporation has included much effort than actually evaporation measuring. Most of research efforts have been about how the produced models must estimate evaporation. Today, there is another method based on the application of satellite remote sensing in engineering hydrology. Almost all of these methods are in relation to estimation of potential evaporation over a land surface (Davie, 2002).

4.1.5 Runoff

Water reaches to the ground as precipitation and then moves to a channelized stream. This movement of water is included by terms of runoff, and can occur at various velocities and on or below the surface. The runoff moves through a channel towards the oceans, this process is called streamflow or riverflow. The streamflow can be called discharge, too, which is the volume of water plotted against time, and the unit of that in SI is m^3/s. A hydrograph is a continuous record of streamflow, and it is an averaged flow over a time period or a series of samples, for example hourly records (Davie, 2002).

4.1.5.1 Mechanisms

In this part, the various runoff processes in a hillslope scale are described in figure 16, and includes overland flow (Q_o), throughflow (Q_t) and groundwater flow (Q_G). All of these depend on the catchment under study and the rainfall characteristics during a storm. These runoff mechanisms are more explained as following:

- Overland flow (Q_o): is the flow of water that runs over the surface of land before arriving to the stream, and occurs when the rainfall rate is higher than the rate of soil infiltration. In fact, it can be generated where the infiltration capacity of a soil is low such as compacted soil areas (e.g. from movement of vehicles in an agriculture field), roads and paved areas and hydrophobic soils. Also, must be mentioned, there is a partial areas response for any catchment but it is dynamic in space and time.

- Throughflow (Q_t): occurs predominantly in the unsaturated zones of shallow subsurface. The rapid movement of water through the soil matrix can be in relation to existence of macro-pores which are large pores with a diameter greater than 3mm within a soil matrix. Soils cracking, worms burrowing may be the reasons of macro-pores.

- Groundwater flow (Q_G): is the flow of water in saturated zone at deeper subsurface. The soil water moves to the saturated zones from unsaturated states when the addition of a small amount of filtrating rainfall to the zone adjacent to a stream (Davie, 2002).

The runoff mechanisms have less influence in relation to the timing of peak flow than the channel drainage network and the precipitation characteristics of a storm when the catchment scale needs to be considered (Davie, 2002).

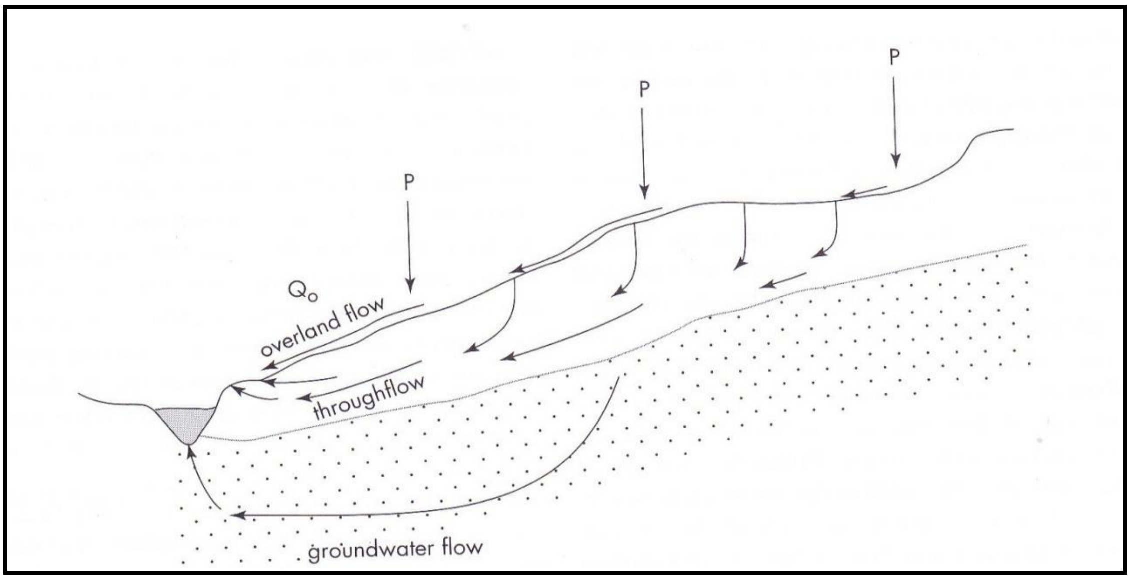

Figure 16: The Hillslope runoff processes [12]

4.1.5.2 Measurements

The measurement techniques of streamflow are expressed in term of hydrometry. There are two main subsections in streamflow measurement: instantaneous and continuous techniques.

- Instantaneous streamflow measurement – two methods of velocity-area and dilution gauging are described for this technique. In the first one, velocity-area method, whereas the discharge unit is m^3/s, it can be rewritten as velocity of stream times to cross-sectional area (m/s times m^2 equals to m^3/s). The second one is based on the tracer will be diluted more when there is a more water in river, hence there is a well connection among the amount of tracer that is naturally in streams, the concentration of tracer put into the river, the concentration of tracer measured downstream after mixing, and the stream discharge.
- Continuous streamflow measurement- includes three techniques of stage discharge relationships, flumes and weirs, and ultrasonic flow gauging.
  - Stages versus discharge relationship: river stage is water level. The relation between water level and discharge can be drawn as a curve so-called rating curve. The river water level will be placed at higher level when there is more discharge into the river.
  - Flumes and weirs: there are two isolations in this technique, one for streamflow velocity, and another one for cross-sectional area. After isolations, the rating curve can describe changes of water levels correspond to the discharge.
  - Ultrasonic flow gauging: this technique measures the stream velocity base on the propagation of sound wave. It measures the time taken for an emitted ultrasonic wave from transmitter to reach a receiver on other side of a river (Davie, 2002).

4.1.5.3 Calculations

There are some methods for calculating runoff such as Rational Method, SCS Method-Peak Runoff, and SCS Method- Runoff Hydrograph. All methods are based on empirical relation among drainage area, rainfall and time of concentration. The Rational Method is the most common one that is used to calculate the peak runoff (Q_P), and is represented as follow:

[12] From (Davie, 2002)

Equation (1):

$$Q_P = Aci$$

Where Q_P is peak runoff in [m^3/s], A is the catchment area in [m^2]; c is the impermeable area factor, and the rainfall intensity is represented by i as [m/s] (Gribbin, 2002).

4.2 Water balance equation

The water balance equation helps to find the water level variation in the space at the flood control structures where can be called reservoir basin. The volume of this reservoir basin is calculated according to the topographic area condition. After calculating the volume of reservoir, the inflow and out flow from the reservoir are very important to balance the water level. All of these steps are describe in more details in this part.

4.2.1 River basin morphometry

The study of the river basin characteristics in physical dimensions, mostly the shape and structure, is known as river basin morphometry that helps to predict the water level and quality in that system during extreme weather conditions. In fact, the river basin is considered as a water reservoir to collect the runoff and other water flows that are as inflow to that (Florida LAKEWATCH, 2001). In figure 17, a lake reservoir is represented.

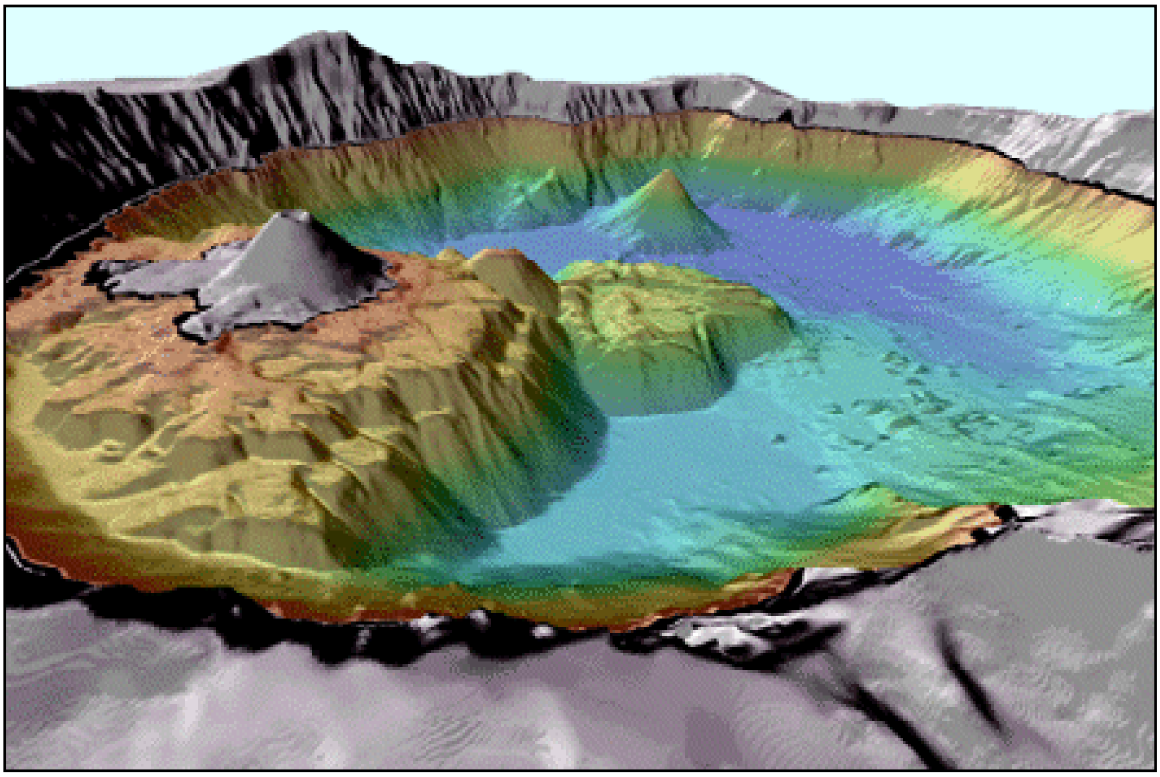

Figure 17: Lake reservoir [13]

4.2.2 River basin bathymetry

A bathymetric map is essentially a topographic map of the river basin bottom that shows contours levels within the river basin. This is used to estimate morphometric parameters, and many of hydrological processes. The trustworthiness of your morphometric data will depend on the precision of the

[13] From (WATER ON THE WEB, 2003)

bathymetric map. Today, the GIS techniques are used to create this type of maps (Florida LAKE-WATCH, 2001). A bathymetric map of an ice lake is shown in figure 18.

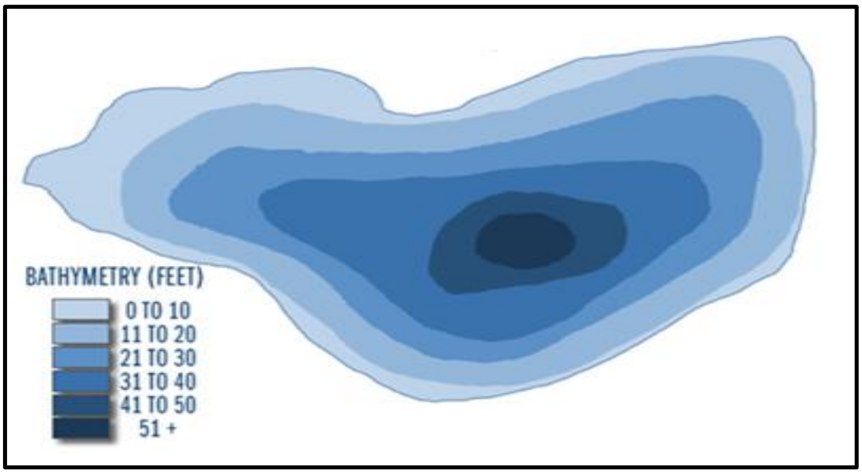

Figure 18: Bathymetric map of a lake basin[14]

4.2.3 River basin volume

The bathymetric map helps to calculate some volumetric characteristics of river basin such as volume, hydraulics retention time, stratum volume and hypsographic curve (graph of depth versus area).

The volume of river basin is called reservoir volume, and the calculation of that refers to the surface area at any contour level and the depth between them as shown in figure 19, which are used in the trapezoidal rule to compute the volume as it is represented in equation 2 in below(Chapra, 1997).

Equation(2):

$$V_{i,i+1} = \left[\frac{A(H_i) + A(H_{i+1})}{2}\right] (H_{i+1} - H_i)$$

Where $V_{i,\, i+1}$ is the volume between H_i and H_{i+1} contour levels; $A(H_i)$ shows the surface area at H_i and $A(H_{i+1})$ is the surface area at H_{i+1} contour level.

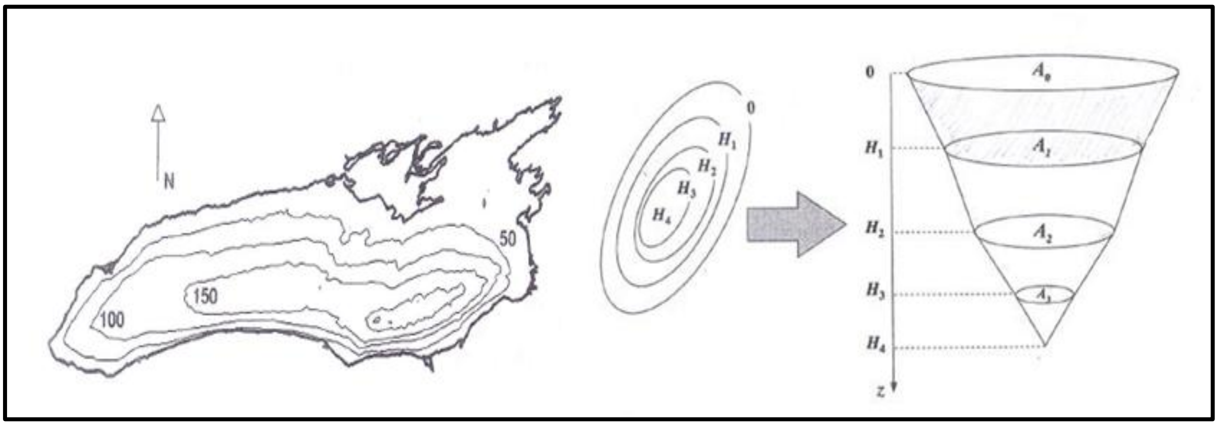

Figure 19: The surface area at any contour level and depth between them [15]

14 From (WATER ON THE WEB, 2003)
15 From (Chapra, 1997)

4.2.4 Gates and valves

A river basin cannot be always closed, and accumulate all inflow waters from catchment area when it is limited by flood control structures. Therefore, the gates or valves are designed for barrages to discharge the additional water from the river basin. In fact, they make the balance of water level in reservoir to prevent flooding condition.

There are two categories of gates, crest gates and high-head gates. The crest gates includes radial gates, sector gates, flap gates, roller gates, fabric gates, and overspill fusegates. While high-pressure gates and high-head valves are described for other category.

Outflow from the gates can be as overflow and underflow. The most common designation of gates is referred to overflow for high-head gate which the outflow is calculated based on the forces of hydrodynamic on them (Novak et al., 2001).

4.2.5 Inflow and outflow

The inflows to reservoir mostly are runoff from precipitation and discharge from other rivers, while the evaporation and gate outflow are considered as the main outflows from a reservoir. All of these processes are mentioned in past parts, but in next part they will be collected to each others to make water level balance in a river basin.

4.2.6 Fundamental water balance equation

Water balance equation is the equation form of hydrological cycle and its processes. In this equation, water is considered as the mass of concern and the hydrological cycle is a close system which there is no mass or energy neither created nor lost within it. This equation is represented in numerous ways, but in equation 3, the fundamental water balance equation expressed.

Equation (3)

$$P + E + \Delta S + Q = 0$$

Where P is precipitation; E is evaporation; ΔS is the change in storage and Q is runoff. The precipitation sometimes is presented by R, too (Davie, 2002).

5 Materials and Method

5.1 Study area

5.1.1 Gothenburg city

Gothenburg is the second largest city in Sweden with 500,000 inhabitants, located at the west coast of Sweden. The history of city refers to the 350 years ago when King Gustav II Adolf found the “Great Letters Patent” to Gothenburg in the year 1621. There are some canals, built in the 17th century, in the city center, but today many of them have been drained and filled in due to increasing traffic.

Also, Gothenburg has the largest and best-equipped port in Scandinavia, currently, and a main part of Swedish exports and imports pass through it. Some of the renowned industries are placed in Gothenburg such as SKF, VOLVO, and Hasselblad. In addition, there are some famous companies in Gothenburg like Saab, Ericsson, Astra Zeneca, Skanska, NCC and Nobel Biocare.

There are many streams, lakes and rivers in Gothenburg. The main river is Göta älv which is a huge river running through Gothenburg, and it has three main tributaries in Gothenburg; Säveån, Mölndalsån and Lärjeån. The water level in Göta älv comes up because of two reasons. Obviously, a large volume of runoff is generated by heavy rainfall during extreme weather and moved into Göta älv. However, in the main river the rain influence on water level is negligible, but important in Mölndalsån, Säveån and Lärjeån. Also, the water level in Göta älv comes up by rising sea level. Therefore, Gothenburg is a prone city to flood (The Sahlgrenska academy, 2008).

Figure 20: Gothenburg city region [16]

[16] Available online on: www.hitta.se

5.1.2 The Göta älv basin

The area of study is the catchment area of Göta älv between Kungälv and the North Sea including the three tributaries of Mölndalsån, Säveån, Lärjeån, and their catchments. Therefore, the basin area starts from the north of Gothenburg to the south of Gothenburg at the entrance point to the North Sea. This area is calculated about 255.7km^2 by GIS software (MapInfo), and the whole of Lärjeån River is located inside, the Mölndalsån River is entered to the area at the Stensjön location, and the Säveån River is considered from the Mellbydalen location towards the Göta älv. This catchment area is represented in the figure 21 by gray color.

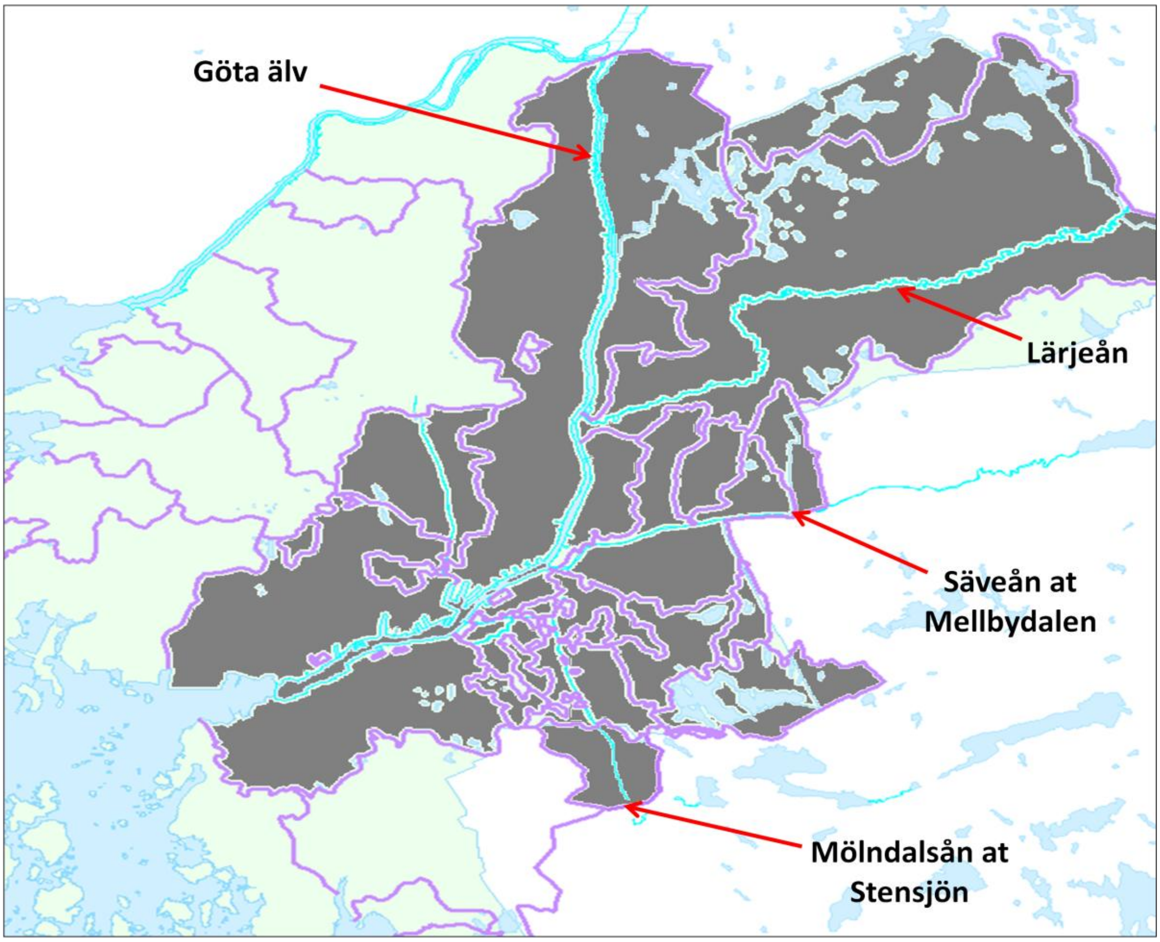

Figure 21: The Göta älv basin represented by gray area (green area is Gothenburg)

For more information about the catchment area, some hydrological information of Göta älv and main tributaries are represented in below.

5.1.2.1 The Göta Älv River

This river drains Vänern lake into Kattegat where is located at the coast of Gothenburg. The whole length of that is 93 km, but Gothenburg watershed includes only the length of 25 km. In below, the main characteristics of Göta älv are expressed briefly (Stadsbyggnadskontoret, 2003).

Priority Class : 1

Mean Flow : 550 m^3/s

Catchment Area : 255.7 km^2 (in study area)

Length : 25 Km (in study area)

Figure 22: The Göta älv River [17]

5.1.2.2 The Lärjeån River

It begins at north of Garbå and empties into Göta älv, and as before, the whole of Lärjeån river is in our study area. The basic information is as following (Stadsbyggnadskontoret, 2003).

Priority Class : 1

Mean Flow : 1.5 m^3/s

Catchment Area : 120 km^2 (in whole of Sweden)

Length : 16 Km

5.1.2.3 The Mölndalsån River

Mölndalsån has its source in the flow of Big and Little Hall Lake in northern Bollebygd and runs through Nedsjö (Nedjön Eastern and Western Nedsjön) in Hindås over to Gothenburg and Mölndal into Säveån at the mouth of Göta River (Stadsbyggnadskontoret, 2003).

Priority Class : 3

Normal Flow : 4 m^3/s

Catchment Area : 270 km^2

Length : 3.5 Km (in study area)

5.1.2.4 The Säveån River

Säveån is a stream in western Sweden, including the source streams. It belongs Göta main basin, and originates out of Lake Sap between Borås and Vårgårda (Stadsbyggnadskontoret, 2003).

Priority Class : 2

Normal Flow : 18 m^3/s

Catchment Area : 1500 km^2 (in whole of Sweden)

Length : 10 Km (in study area)

[17] Available online on: www3.goteborg.se/ekonomi/arsbok02/pics/vovatten_1.jpg

5.1.3 Gothenburg flood history

The Göta älv River is flooded approximately every 10- 15 years, and the most common reasons are no dredging and sea level rising. According to the past, there were two heavy flood events during 2000-2008, and three or four events since 1967 to 2000.

About Mölndalsån and Säveån flooding, the flood events occur in rainy autumn and winter due to the more exploitation of Säveån and Mölndalsån riversides, and it will be increased for future due to the neglecting of dredging. During 2000 to 2008, one heavy flooding happened from Mölndalsån, and since 1900 to 2000 there have been several flooding events. Figure 23 shows the occurred flood from Mölndalsån in October 1967, in figure 24 represent flooding events in Mölndal area on 10^{th} to 14^{th} December 2006.

Figure 23: Flooding from Mölndalsån, October 1967 [18]

Figure 24: Flooding event from Mölndalsån, December 2006, by Rune Feldt[19]

[18] Available online on: http://rune-feldt.se/mdl/index.htm
[19] Available online on: http://rune-feldt.se/mdl/index.htm

5.2 Purpose of study

As mentioned before, the overflowing of Göta älv and rising sea level are the most important factors for flooding in Gothenburg. Therefore, finding a solution to protect the city against flooding is necessary. In addition, this solution must cover the problems associated with today and future extreme weather because of climate changing.

Based on mentioned climate change in the world, precipitation and temperature will be increase in Gothenburg, thus, the risk of flood will be increased during the 21st century. Also, sea level in Gothenburg coast will be raised about +1m according to the IPCC reports by 2100.

The purpose of this study is to examine whether it is possible to apply protective barrage techniques to protect Gothenburg against flooding, and answer to some related questions in two categories such as:

1. Theoretically
   - Is it Possible or impossible in theory?
   - Are there any relevant locations for barrages along the Göta älv?
   - How should the gates be operated?
   - For how long can the barrages be used?

2. Practically
   - How much is the cost of barrages?
   - What are the consequences in the Kungälv area?
   - Is shipping possible in the Göta älv?
   - What happens if sea level rises by +4m in 2200?

5.3 Three Scenarios

In this study, three scenarios are investigated to answer the asked questions in purpose part. All of them are related to the extreme today and in the future based on the IPCC predictions, especially for scenario family A2 and B2.

These scenarios are defined as:

- Scenario I: Today extreme weather
  - It includes the maximum runoff from Göta älv basin and the maximum sea level rising to balance water level according to current weather condition.

- Scenario II: Future extreme weather for 2100 based on A2 scenario family
  - This considers some future factors, which are based on the A2 family scenario of future extreme weather condition, to use in calculation of water balance equation. These factors are future precipitation factor, future temperature increasing, sea level variation factor for future, and an increase of mean sea level by 2100.

- Scenario III: Future extreme weather for 2100 based on B2 scenario family
  - This scenario covers all of future factors that mentioned in scenario II, but based on the B2 family scenario of climate change.

Several available data, assumptions, factors, limitations and methods are used for each one of these scenarios to achieve the purpose. All these proportions are described and discussed in following parts.

5.4 Assumptions

The assumptions in this study are listed as following:

1. The mean water level in Göta älv is at +10m according to the Göteborg Units System, and all results are based on this assumption
2. The precipitation is in rainfall form and is completely generated to runoff; in fact, the whole catchment area is assumed as impermeable area
3. The rainfall data have been measured at Gothenburg center station, but have been used for all of the catchment area
4. Inflow from Mölndalsån and Säveån into the catchment area is assumed as flow measurements at Stenjön and Mellbydalen locations, respectively.
5. The acceptable maximum water level of Göta älv is equal to +11m for today condition
6. The acceptable maximum water level of Göta älv is equal to +12.5m for the 2100 condition

5.5 Available data for this study

The data in relation to rainfall, temperature, inflow of Mölndalsån and Säveån, and sea level variation are listed in below:

1. Hourly rainfall data from January 2005 to May 2009, measured at Gothenburg center station in unit of mm/hr
2. Hourly temperature data from January 2005 to June 2009in unit of °C
3. Daily Inflow of Mölndalsån into the catchment area from January 2005 to December 2008
4. Inflow of Säveån into the catchment area for every 12 hours from 10^{th} January 2006 to 4^{th} May 2009 as unit of m^3/s
5. Hourly sea level from January 2005 to May 2009 as unit of cm
6. Future precipitation factors for A2 and B2 scenario families according to the IPCC reports
7. Future temperature factors for A2 and B2 scenario families according to the IPCC reports
8. Future sea level variation factors for A2 and B2 scenario families according to the IPCC reports
9. The mean sea level rising during the 21th century is accessible from IPCC reports

5.6 Limitations

For this study some limitations are considered that each one can affect on the results. These limitations are:

1. MapInfo is used as GIS software for modeling of elevation (bathymetric map) along the Göta älv, and to calculate the surface area at any contour level
2. MATLAB is used as a programming software to compute runoff and the water level balance equation
3. Based on the available data, the year of 2008 is selected as the reference data for MATLAB programming (only the data from 2006 to 2008 can cover each others, and among these years only 2008 had the highest variation of sea level)[20].

[20] See Appendix I

4. The data of inflow from Mölndalsån and Säveån have been converted to the Hourly data from daily and every 12 hours, respectively, by MATLAB programming because there were not possible to use in original types.
5. The data of Göta älv depth was not available; therefore, for calculation of surface area for each contour level the trapezoidal rule was used.
6. The map represented in MapInfo software were only for the Västra Götaland region, thus, some minor parts of catchment area are estimated by GIS techniques.
7. The year of 2008 was a leap year that in MATLAB program this characteristic has been considered

5.7 Future Factors

The mean sea level will be increased by +1m at maximum level during the 21st century according to IPCC reports, see figure 25. Also, based on Figure 25, the sea level variation factor will be 1.48 by 2100 with respect to the 2008 that is considered as additional value to the sea level.

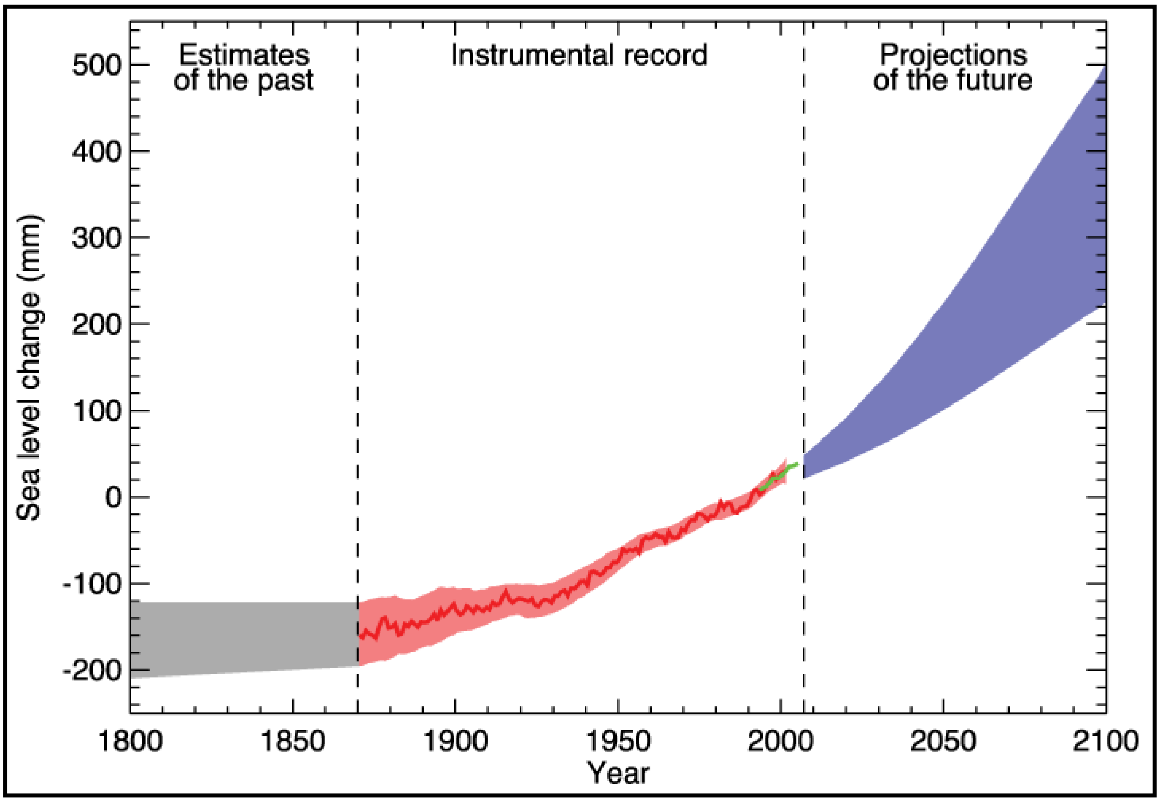

Figure 25: Mean sea level rising during the 21st century based on IPCC

Other future factors are introduced for A2 and B2 climate change scenario families, and they are represented separately for each one based on the Swedish Meteorological and Hydrological Institute (SMHI) as following:

- A2 scenario for 2100
  - Future precipitation factor: the precipitation will be increased with by 15 % with respect to 2008 in Gothenburg area, check figure 26.(it means the future precipitation factor is equal to 1.15)
  - Future temperature increasing: the temperature with respect to 2008 will be added by +3.5°C for 2100 in Gothenburg based on figure 27.

- B2 scenario for 2100
  - Future precipitation factor: the precipitation will be increased with by 10 % with respect to 2008 in Gothenburg (it means the future precipitation factor is equal to 1.1). It is presented in figure 26.
  - Future temperature increasing: the temperature with respect to 2008 will be added by +3°C for 2100 based on B2 scenario, see figure 27.

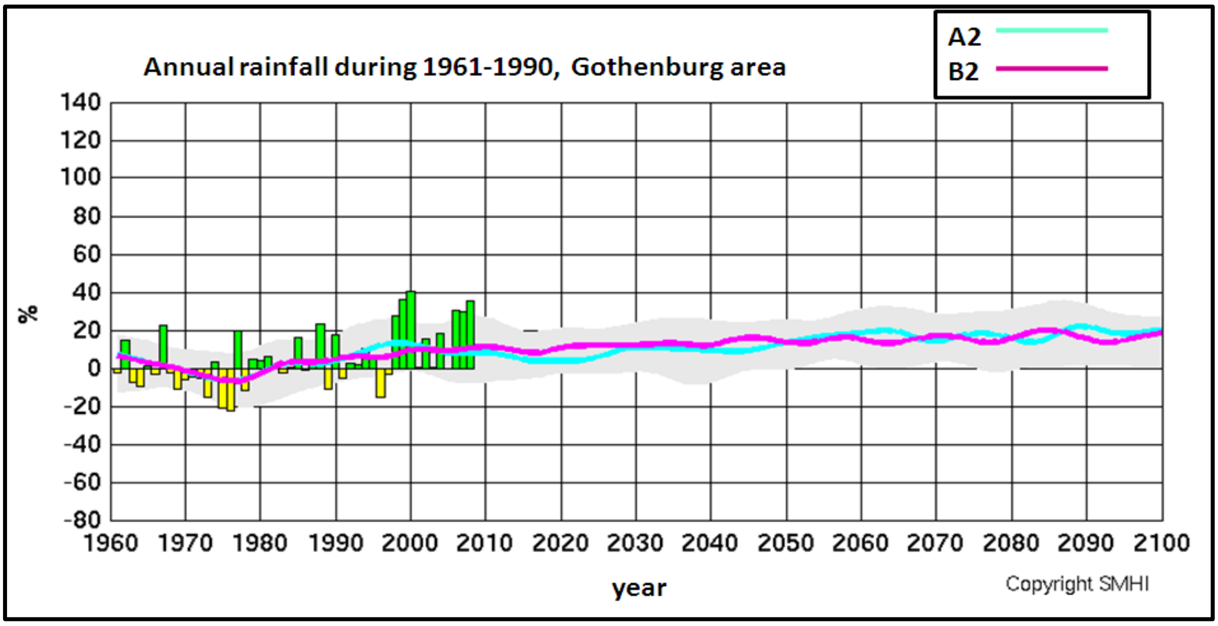

Figure 26: The future precipitation factors for A2 and B2 scenarios (compared to the normal rainfall in period 1960 – 1990, SMHI)

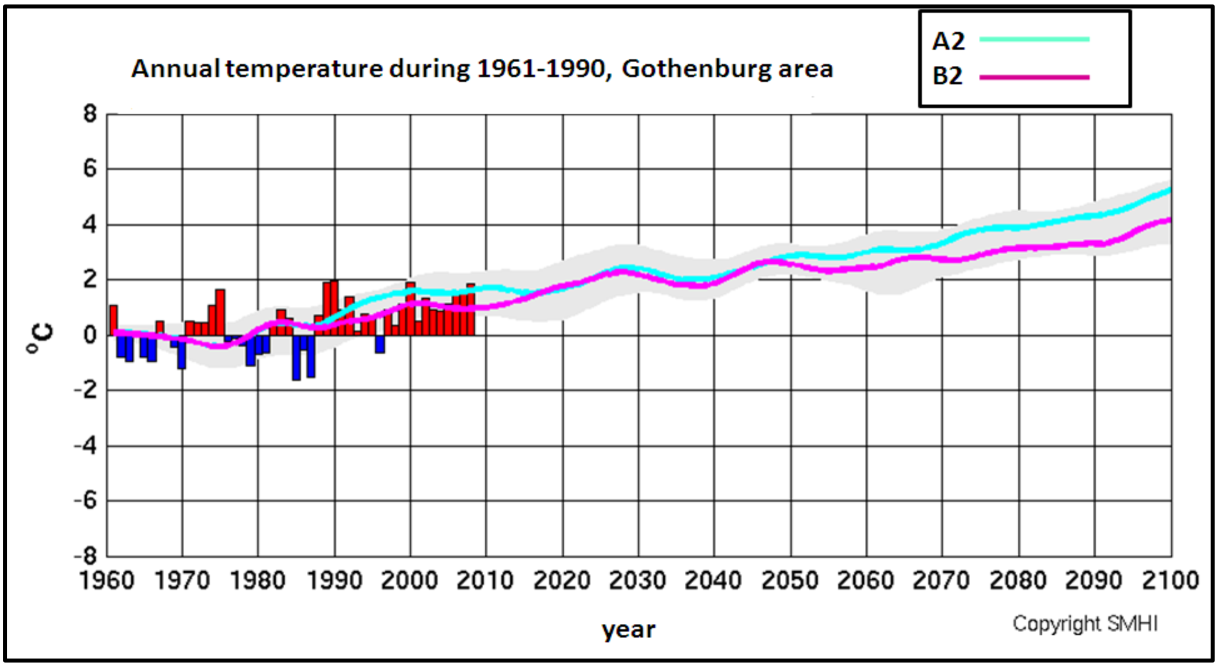

Figure 27: Future temperature factors for A2 and B2 scenarios (compared to the normal rainfall in period 1960 – 1990, SMHI)

5.8 Method steps

5.8.1 Locations of barrages

Three criteria are investigated to find the location of barrages along Göta älv based on how they can affect on reservoir volume, stability of river banks in both sides of the barrages, and outflow of barrage. These criteria are described as follow:

1. Elevation (Topography) – according to the reservoir volume calculation, the highest elevations at both sides of river section provide the maximum reservoir volume. Also, the risk of flooding by rising sea level will be reduced when the barrage had been located at higher elevation due to the running of more rising sea level.

2. Geology – to protect both sides of barrage against settlements and erosion as well as to provide slope stability of soils at there, the geologic investigation is very important. The rocky sides along the river are the best place for barrage construction because the settlements occur where the clay exist.

3. River section- the depth of river is very important for shipping, thus deeper parts of river are interesting to find the location of barrage. In addition, the width of river can affect on the gates of barrage and their outflow based on the gates discharge capacity.

According to these criteria, some sections of Göta älv are suggested for constructing of the barrages, and the best locations are found. There will be two barrages in Göta älv, one at upstream and one at downstream based on specific reason which is the gates of downstream barrage will be closed when the sea level variation is high, thus, the upstream barrage must be closed to divert the normal flow of Göta älv and to prevent rising water level in reservoir.

The bathymetric map along Göta älv is provided by MapInfo (GIS software); also, the Vertical Mapper is used to represent the elevations. This bathymetric map is been shown in figure28, and is made by interpolation of ground levels which their data refer to February 2005. The zone A and B of Figure 28 are represented by figures 29 and 30 in a better resolution. There are uncertainties in this model because the elevation data are not comprehensive. All elevations are considered in Göteborg Units system (the base level is equal to Göta älv water level, +10 m). It means, if elevation of a point in map is +16m, the point has located at +6m above the Göta älv water level (sea level).The location of barrages are suggested by this map according to the topographic criterion. This map will be used to find the reservoir volume in calculation of surface area for each contour level.

5.8.2 Geologic map

As mentioned before, the geologic condition of barrage locations is very important, thus, the geologic map of Gothenburg is represented in Figure 31, as you see the most part of Gothenburg is covered by rocks and clay. The rocky parts are shown as purple parts that are interesting in this study, and the clay is presented by yellow color.

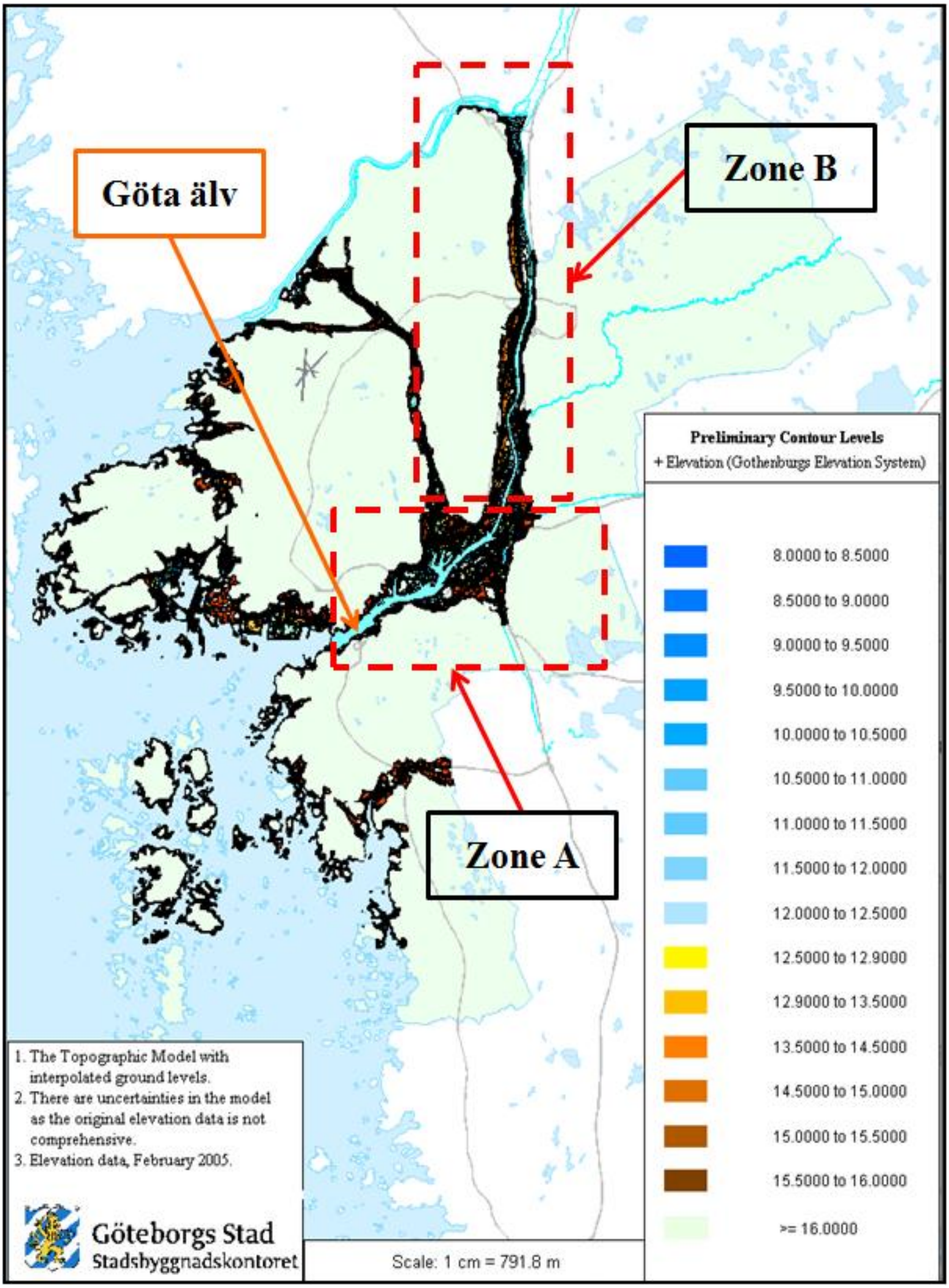

Figure 28: Bathymetric map of Göta älv basin by MapInfo

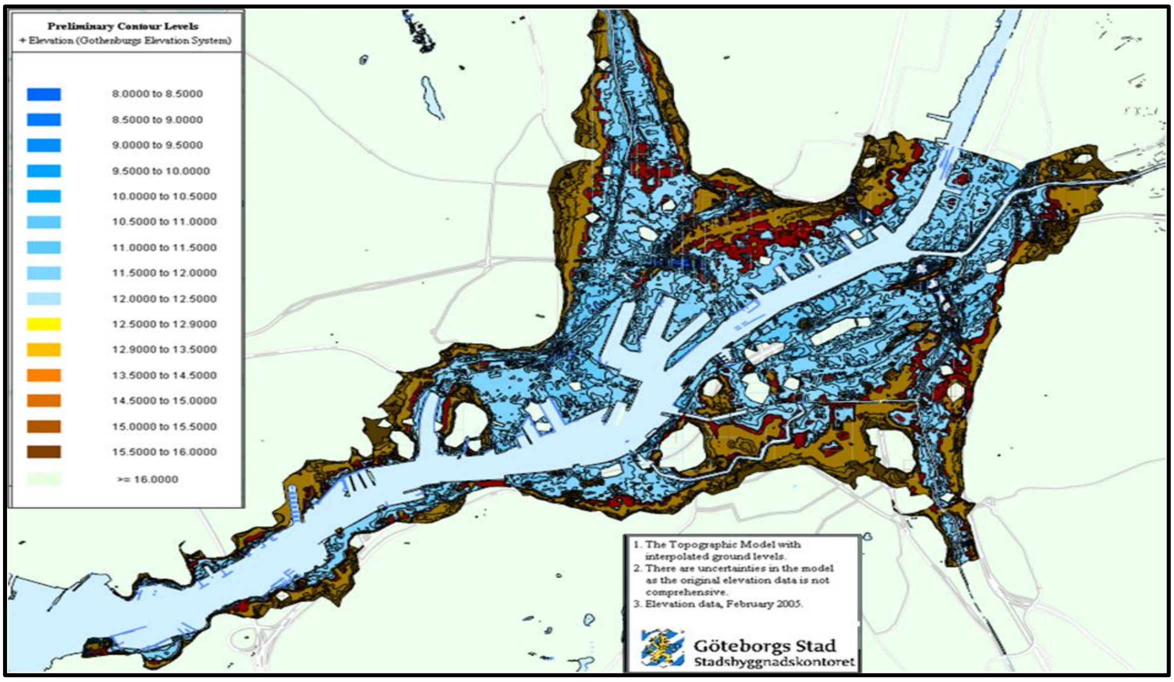

Figure 29: The zone A of bathymetric map for Göta älv basin by MapInfo

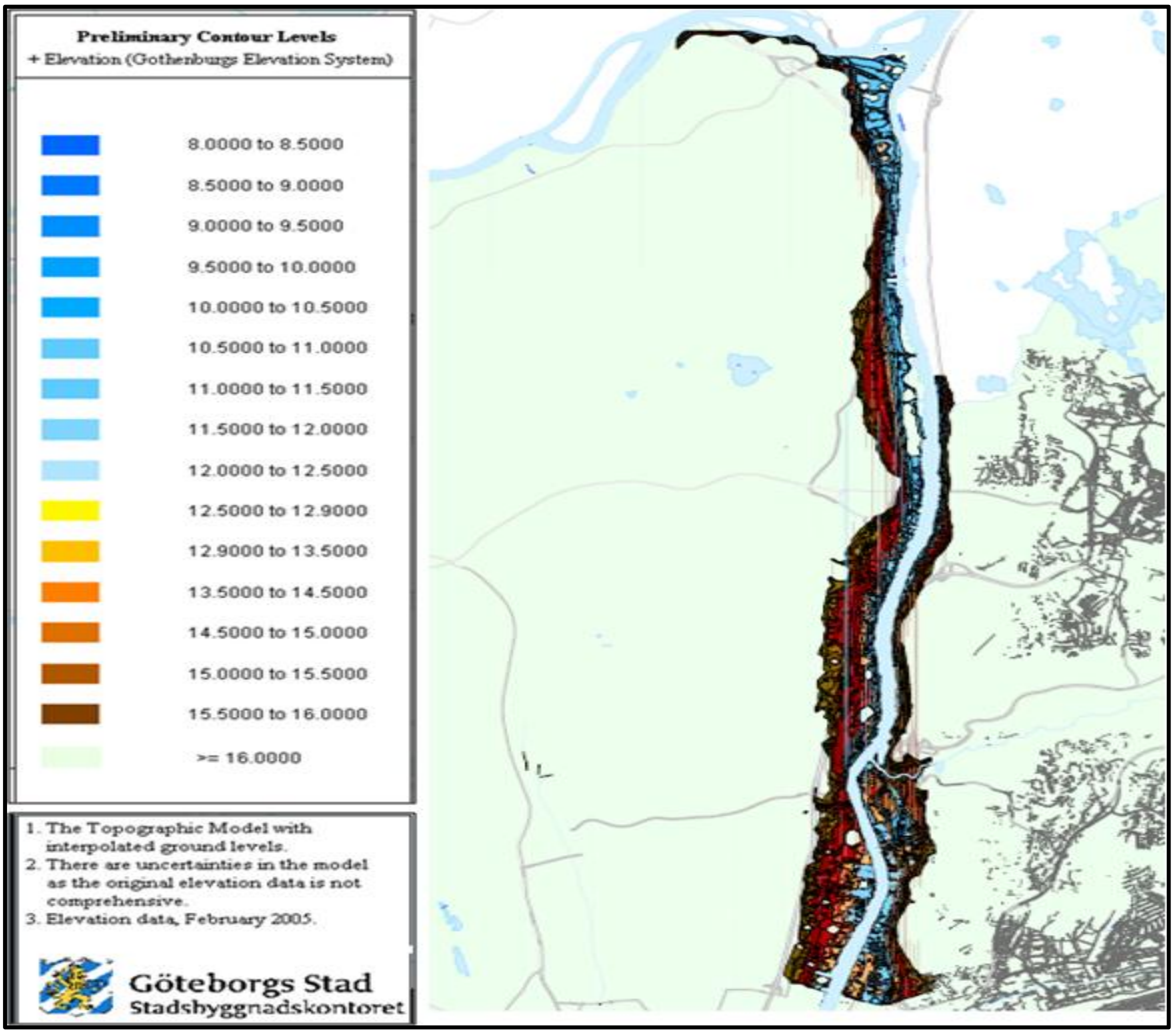

Figure 30: The zone B of bathymetric map for Göta älv basin by MapInfo

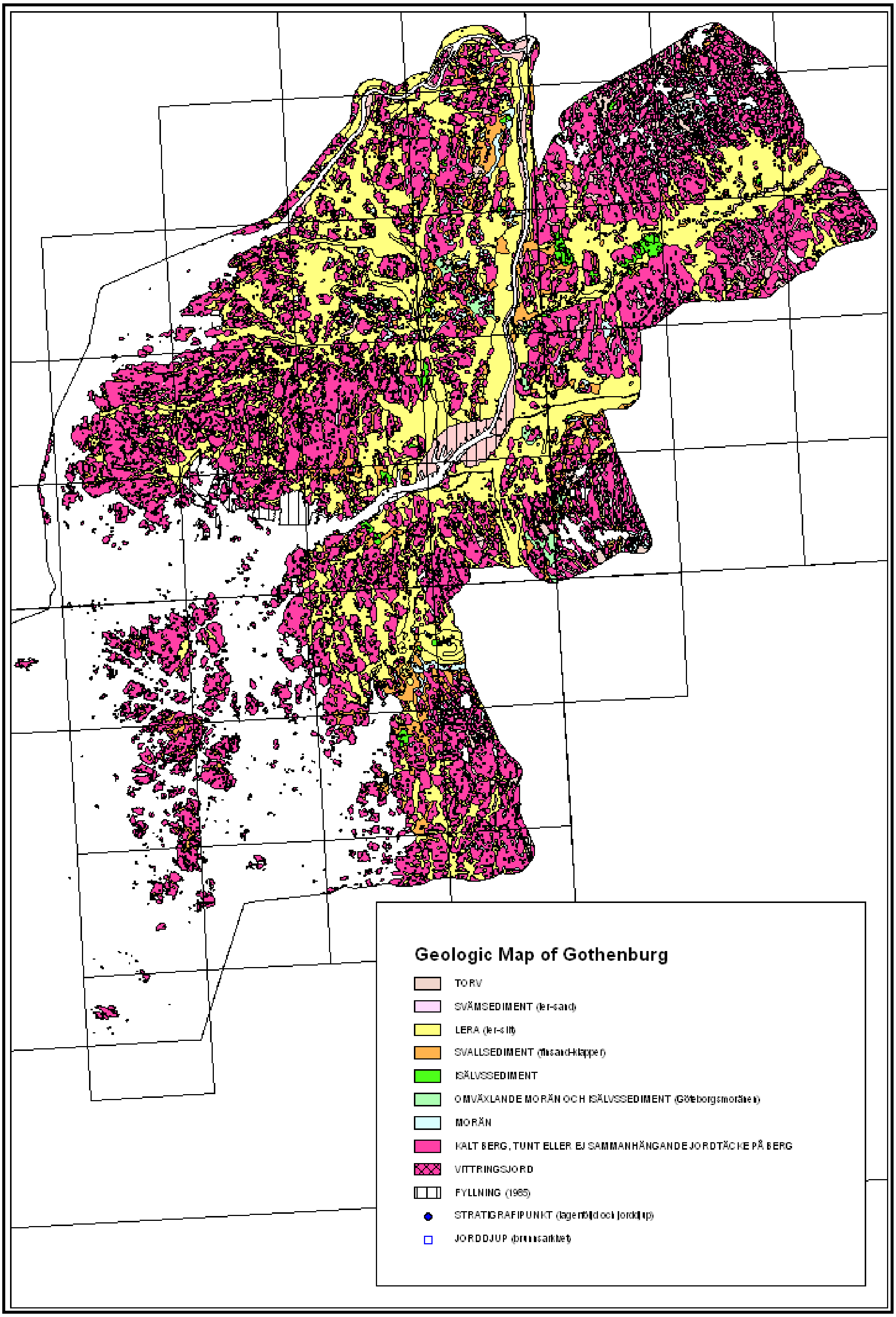

Figure 31: Geologic map of Gothenburg by MapInfo

5.8.3 Reservoir volume calculation

The water level is considered constant between the two barrages, for all three scenarios. To calculate the volume, according to the Section 4.2.3, the surface area of each contour level is computed by MapInfo (GIS software) initially. This computation is done for every 0.5 m contour level distance from +10m to +16m due to the recorded data. All obtained surface areas are shown in table 1 as follow.

Table 1: the surface area for every +0.5 m contour level in Göta älv reservoir

Z [m]	Total Area [10^6 m^2]
+16	27.61
+15.5	26.74
+15	25.21
+14.5	23.80
+14	19.88
+13.5	19.61
+13	17.71
+12.5	14.95
+12	10.80
+11.5	8.00
+11	6.20
+10.5	5.21
+10	5.40

In next step, the MATLAB program (See appendix II) is provided to calculate the reservoir volume based on the trapezoidal rule that mentioned in section 4.2.3. This program calculates the volume of reservoir, preliminary, as table2; then, the reservoir volume is extended to any levels from +10m to +16m by MATLAB that will be represented in result Chapter (Section 6.2).

Table 2: Total reservoir volume of Göta älv

Z [m]	Reservoir Volume [10^6 m^3]	Total reservoir volume [10^6 m^3]
+16	13.60	97.26
+15.5	13.00	83.66
+15	12.26	70.66
+14.5	10.93	58.40
+14	9.87	47.47
+13.5	9.33	37.60
+13	8.16	28.27
+12.5	6.45	20.11
+12	4.70	13.66
+11.5	3.56	8.96
+11	2.85	5.40
+10.5	2.55	2.55
+10	0	0

5.8.4 Water level balance calculation

First, some available data of 2008 such as rainfall, catchment area, temperature, inflows to the catchment area from the Mölndalsån and Säveån rivers are used by MATLAB program for calculating the generated runoff which is released to reservoir. Then the outflow from reservoir is calculated based on the overflow gates. At the end, water balance equation is extended by MATLAB program in general, and the future factors are added to that for estimating future water balance based on the scenarios I and II.

5.8.4.1 Reference data

- **Rainfall (R)** – the data refer to Gothenburg center station, and are shown in figure 32 as below.

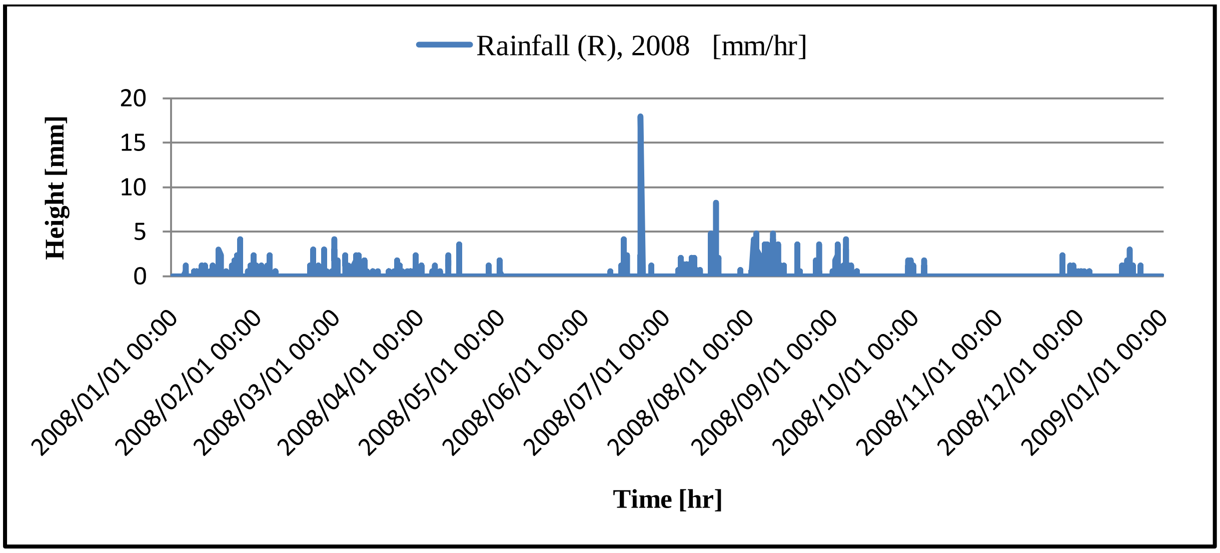

Figure 32: Rainfall data of 2008 as a reference data for MATLAB programming

- **Catchment area (A)** – is equal to 255625940 m^2 as mentioned in section 5.1.2. It is used to calculate the runoff which is produced with respect to rainfall and evaporation rate.
- **Temperature (T)** – is used to calculate the evaporation, and its data is shown in Figure 33 as following:

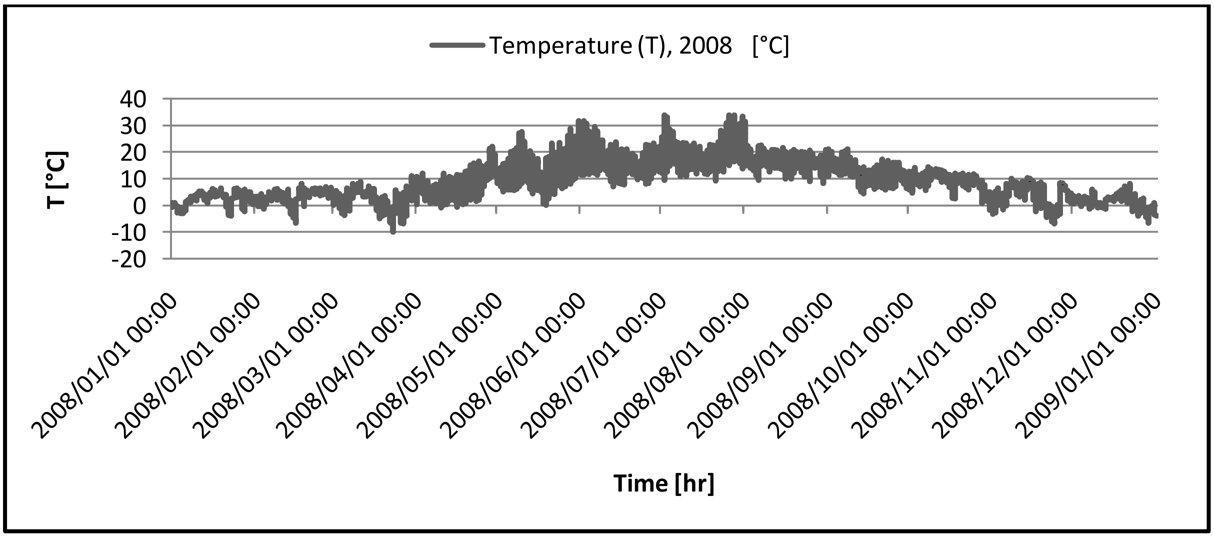

Figure 33: Temperature data of 2008 as a reference data for MATLAB programming

- **Inflow of Säveån (Q_s) –** is added to runoff, and the data of this inflow are for every 12 hours that represented in figure 34. It is extended to hourly value by MATLAB program to be applied in water level balance calculation.

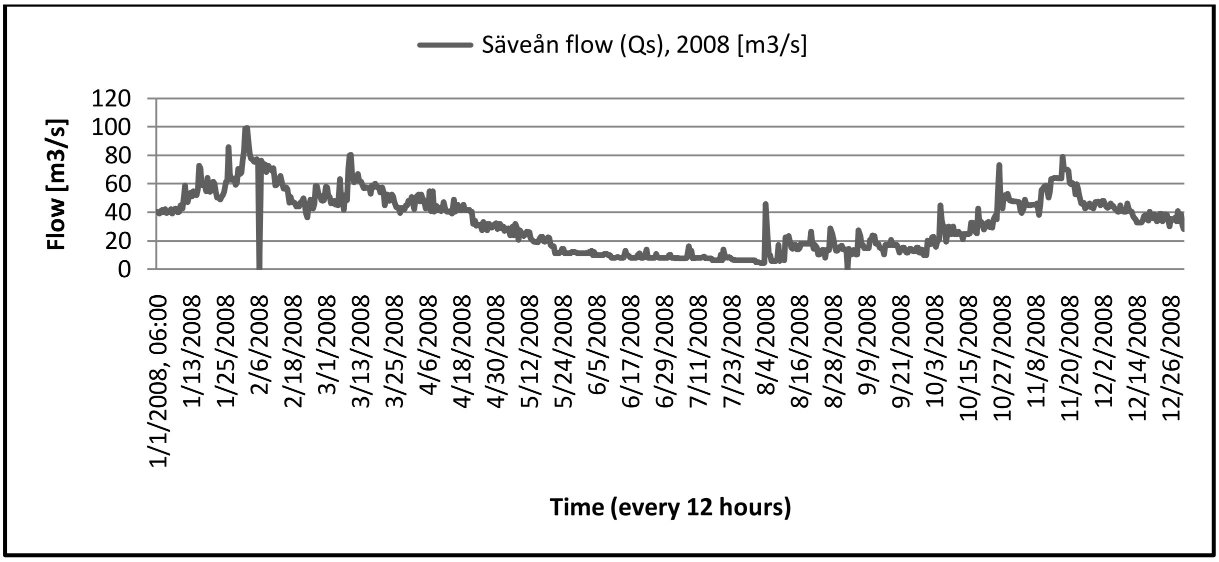

Figure 34: Säveån inflow data of 2008 as a reference data for MATLAB programming

- **Inflow of Mölndalsån (Q_m)** – the flow from Mölndalsån is the another inflow to the catchment area, and figure 35 represents its data as daily measurement in 2008 that is modified to the hourly flow by MATLAB program.

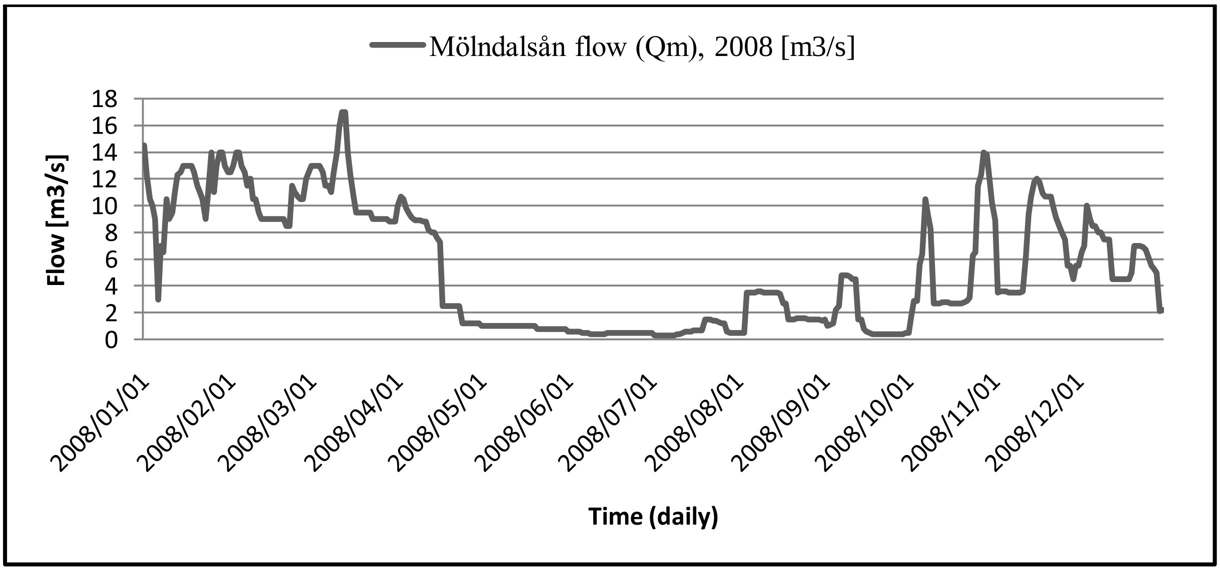

Figure 35: Mölndalsån inflow data of 2008 as a reference data for MATLAB programming

5.8.4.2 Precipitation-runoff calculation

The precipitation runoff is calculated by MATLAB program based on the equation 4 that is in a basic form for this study.

Equation (4):

$$Q_{tot} = (R - E)A + Q_m + Q_s$$

Where Q_{tot} = runoff discharge to reservoir [m^3/hr]

R = rainfall [m/hr]

E = evaporation [m/hr]

A = catchment area [m^2]

Q_m= inflow from Mölndalsån [m^3/hr]

Q_s = inflow from Säveån [m^3/hr]

The evaporation in Sweden is calculated by equation 5 that has been described in below:

Equation (5):

$$E = \frac{221.5 + 29\,T}{365 * 24 * 1000}$$

Where E = evaporation [m/hr] and T = hourly average temperature [°C]

The special precipitation-runoff equation for this study is completed by adding the evaporation and future factors of precipitation and temperature to the equation 4. This equation is represented as following:

Equation (6):

$$Q_{tot} = \left((R * f_1) - \frac{221.5 + 29(T + f_2)}{365 * 24 * 1000}\right)A + Q_m + Q_s$$

In this equation Q_{tot} is calculated in unit of [m^3/hr] due to the available data which are mostly in hourly forms. Also, the f_1 (future precipitation factor) and f_2 (future temperature increasing) are described in below for different scenarios:

- Scenario I - the f_1 =1 and f_2 equal to 0.
- Scenario II - the f_1 is equal to 1.15 and f_2 equals to +3.5 °C for 2100 based on A2 family scenario, as mentioned before in Figure 26 and 27.
- Scenario III - the f_1 is equal to 1.1 and f_2 equals to +3 °C for 2100 based on B2 family scenario, as mentioned before in Figure 26 and 27.

Therefore, the MATLAB program calculates the total discharge from the Göta älv catchment area to the reservoir as hourly discharge for all three scenarios by equation (6) and available reference data. These calculated discharges help to find how long the reservoir take to be filled, at what elevation the water level will be, and how much the gates outflow must be if the sea level is low enough to have the best performance for discharging from reservoir.

An assumption should be considered that very high intensity rain is as same over the whole catchment, and some catchment areas are converted by this assumption in this project to calculate the total runoff.

5.8.4.3 Gates outflow of downstream barrage

The outflow from gates are based on the head between sea level and water level at the barrage, and calculated by the equation (7) which called d'Aubuisson equation (Hamill, 1999).

Equation(7):

$$Q = K_A \, Y_4 \, b \, (2gH_1^* + V_1^2)^{\frac{1}{2}}$$

Where Q = gates outflow [m^3/s], K_A = a value between 0.90 – 1.05, Y_4 = sea level outside the barrage [m] (represented in Figure 36), b = total opening width of river [m] (represented in Figure 37), g = 9.81 [m/s^2], H_1^* = head between water level at the barrage and sea level [m] (represented in Figure 36), and V_1 = the velocity of water inside the barrage [m/s] (represented in Figure 36)

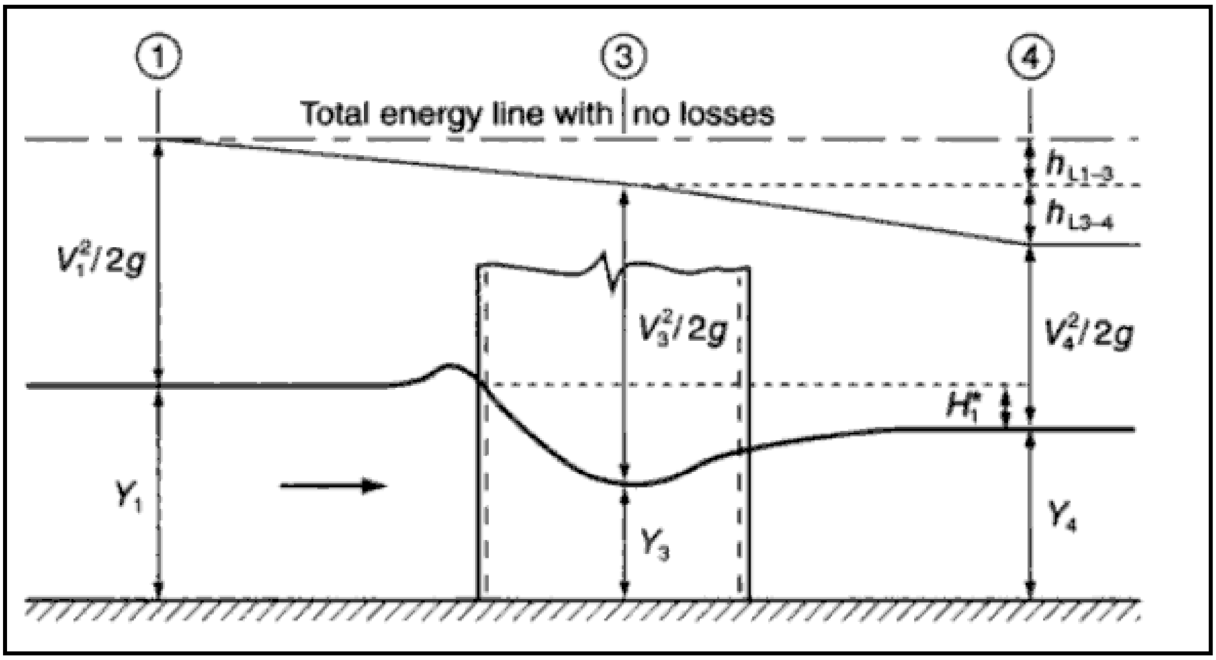

Figure 36: Longitudinal section of barrage location

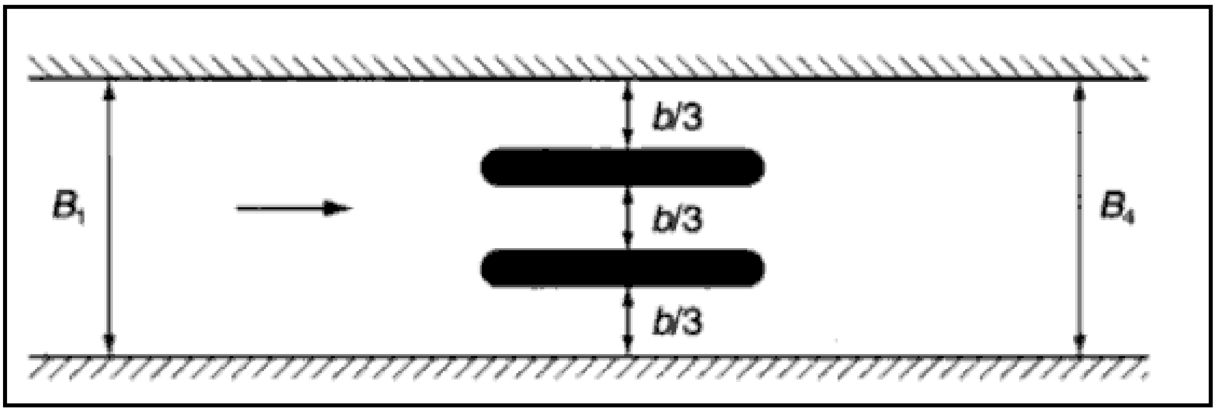

Figure 37: Plan view, representing the total opening width, b

5.8.4.4 Water balance model

At first, the water level in reservoir is calculated according to equation 8 by MATLAB program. Then these water levels and the available data of sea level variations are compared to each other to find out how the gates must be operated to provide the water level balance between the Göta älv and the North Sea.

Equation (8):

$$\frac{dV}{dt} = Q_{tot} = \left((R * f_1) - (\frac{221.5 + 29\ (T + f_2)}{365 * 24 * 1000} \right) A + Q_m + Q_s$$

Where V is the reservoir volume, t is time, and Q_{tot} is the total runoff.

6 Results

6.1 Best location of barrages

6.1.1 Downstream barrage

According to criteria that explained in Section 5.8.1, the best location of downstream barrage is approximately at the entrance of Göta älv to the North Sea where the section of river is between Rya nabbe and Stora billingen area in Gothenburg. This location has been shown in figure 38, and described based on the selection criteria as follow:

- The both side elevations of section are +16m where are the highest elevations along the Göta älv according to the bathymetric map that was illustrated in Figure 28.
- Also, both sides are rocky according to the geologic map, see Figure 31.
- The width of göta älv at this location is 485 m that is computed by MapInfo (GIS software), and can increase the gates outflow from reservoir. The depth is 13 m that can provide shipping through Göta älv and the barrage.

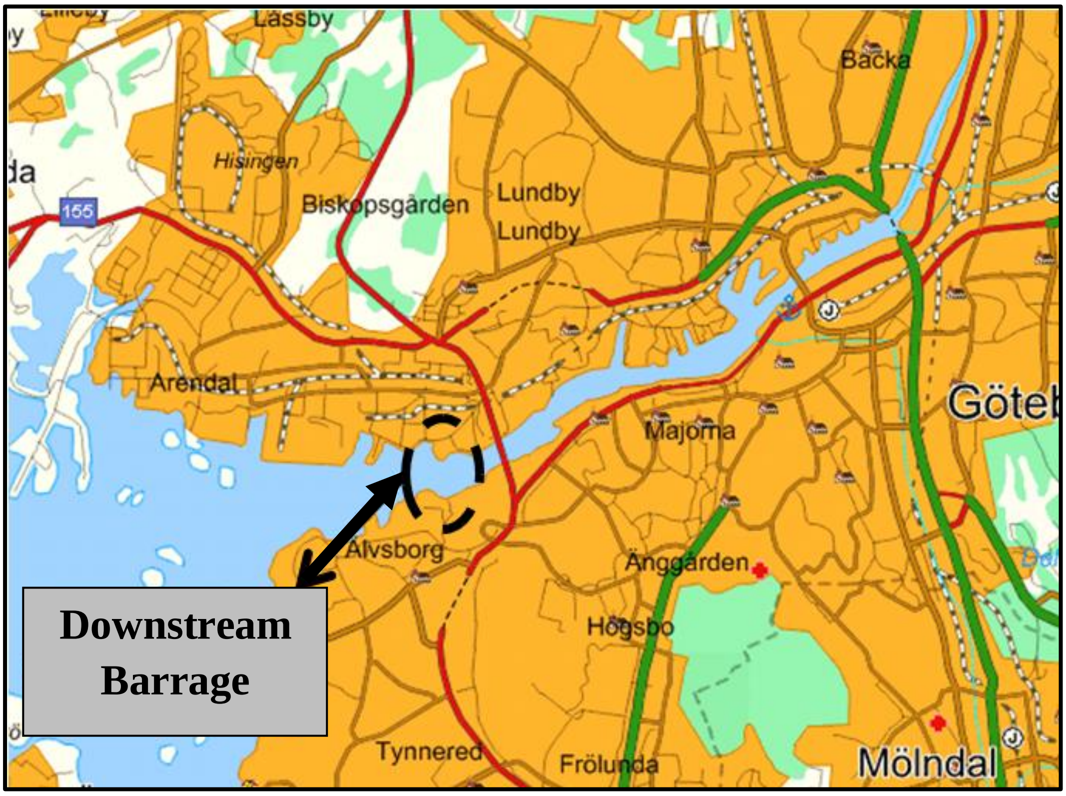

Figure 38: The location of downstream barrage

6.1.2 Upstream barrage

The best location of upstream barrageis suggested at the separation point of main Göta älv into Nordre älv and Göta älv in Gothenburg area. This point has placed exactly at the northern part of Jordfallen where is represented in figure 39.

The elevation in this area is not very high, about +12m, and the rocky parts are poor, but the most important factor to choose this location is shifting of Göta älv normal flow into Nordre älv when the downstream barrage is closed to prevent Gothenburg from sea level rising. It means both barrages will be closed at the same time.

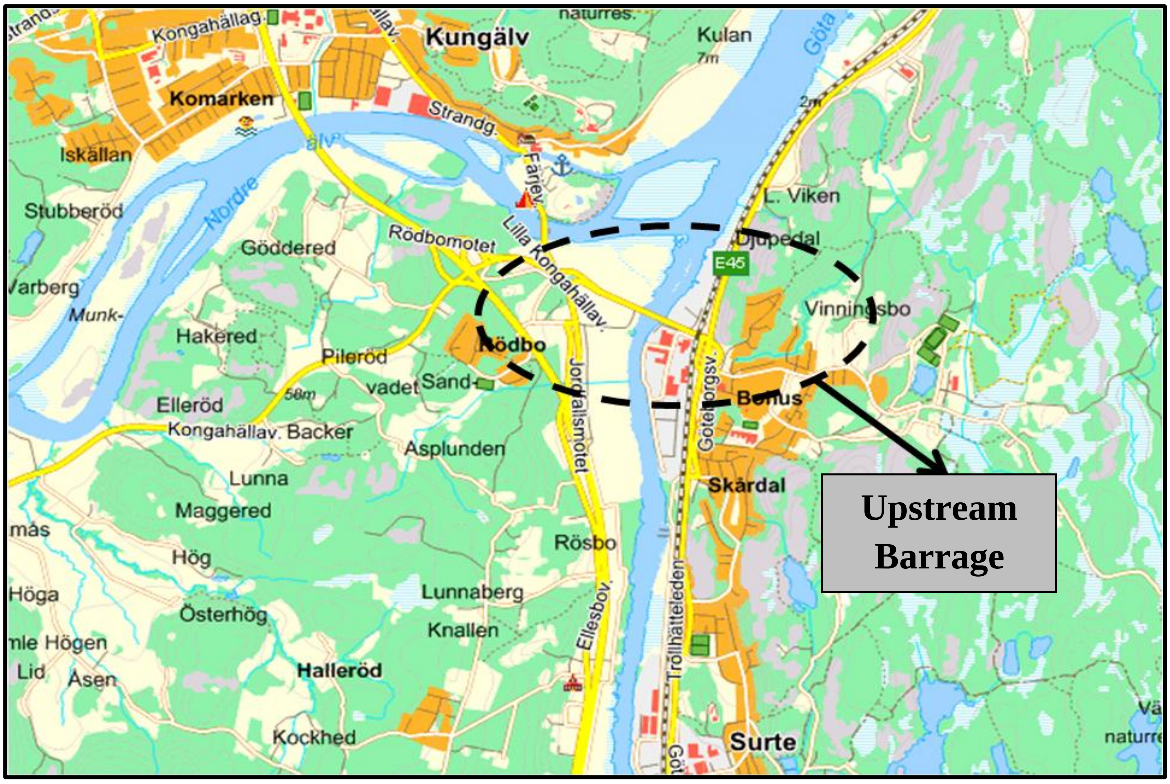

Figure 39: The location of upstream barrage

6.2 Reservoir volume

Based on Section 5.8.3, the reservoir volume between the two barrages is calculated at each contour level from +10m to +16 m by MATLAB program. The result is described in figure 40 in below.

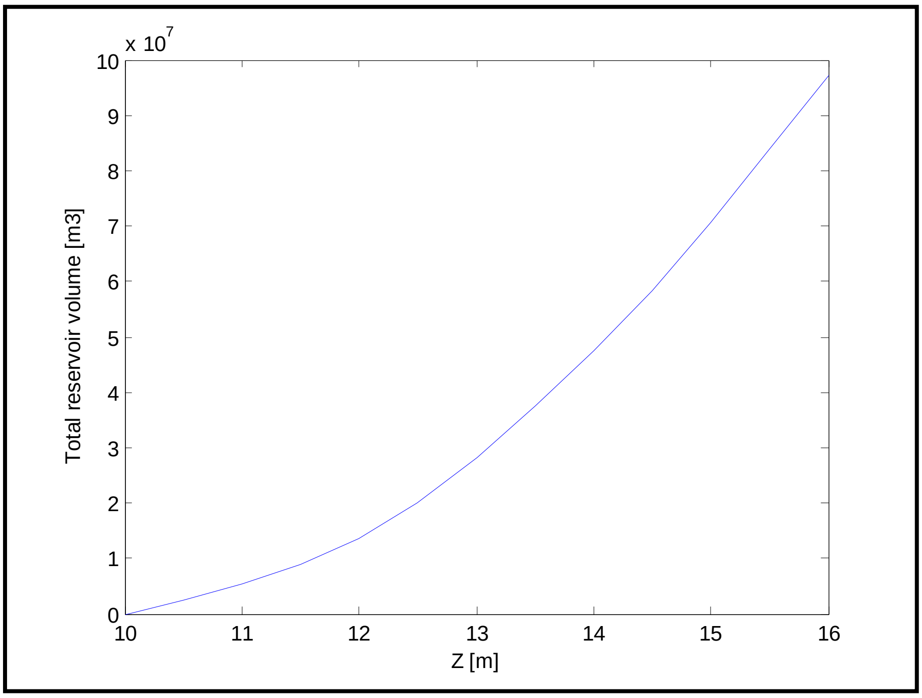

Figure 40: Total reservoir volume at any contour level

6.3 Gates outflow of downstream barrage

The best result for gates outflow from downstream barrage is assumed when six gates are considered in the width of river in location of downstream barrage that is equal to 485m. The width of each gate is assumed 20m, thus the total opening width of river for calculating gates outflow is 360m, see figure 41. The results of gates outflow are described for each scenario as following.

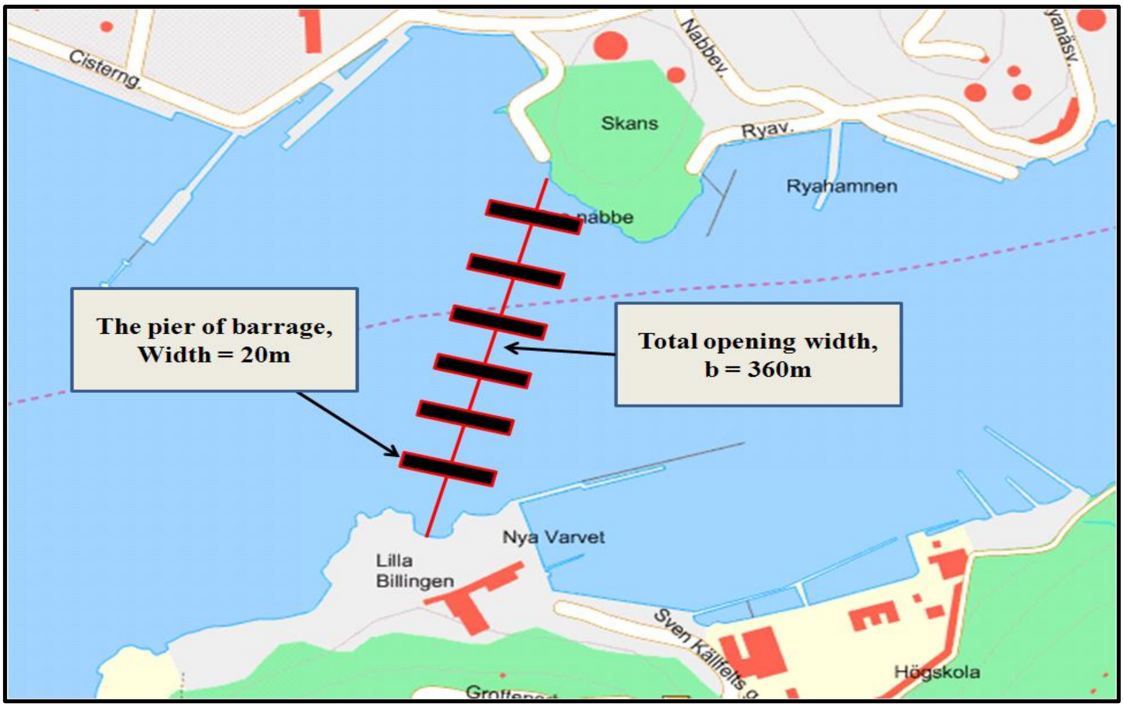

Figure 41: The illustration of gates and total opening width for downstream barrage

6.4 Scenario I

6.4.1 Total runoff

The results of total runoff which is released to the reservoir basin based on scenario I are represented in figure 42 as following. It shows the maximum runoff occurs during June and July mostly.

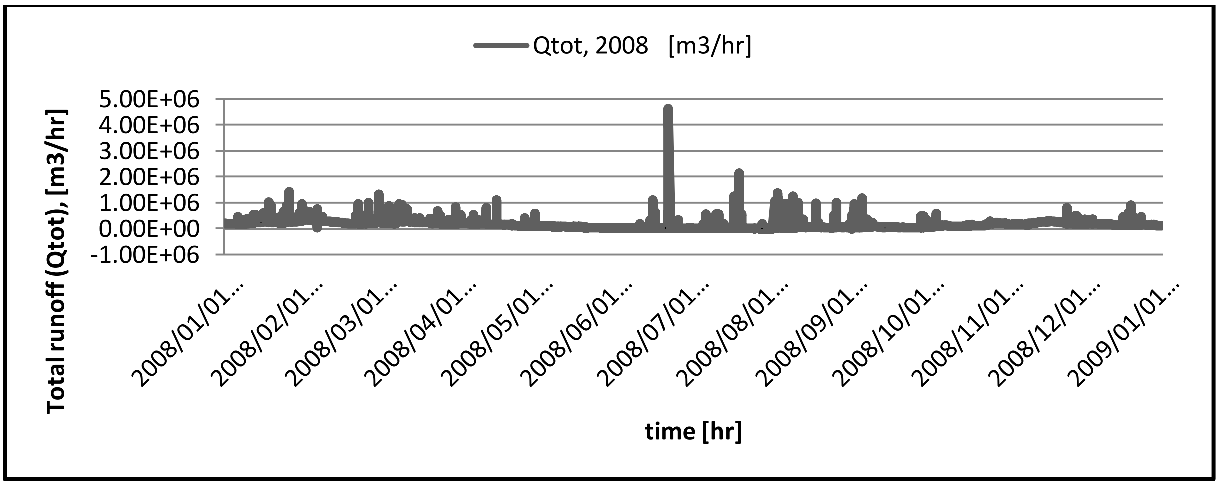

Figure 42:Total runoff into the Göta älv reservoir based on scenario I

6.4.2 Gates outflow

The gates outflow is calculated according to Section 5.8.4.3. Thus, calculating of the water velocity inside the barrage is the first step, and it is based on the minimum of total runoff that computed in previous section, and the sectional area (V = Q/A). Table 3 represents the gates outflow for scenario I.

Table 3: Gates outflow of downstream barrage for scenario I

Sea level, Y_4, [m]	Head, H_1^* [m]	g [m/s^2]	K_A	Total opening width [m]	V_1 [m/s]	Minimum Gate outflow [m^3/s]
0.4	0.10	9.81	1.0	360	0.800	230
0.5	0.20	9.81	1.0	360	0.147	355
0.6	0.30	9.81	1.0	360	0.127	520
0.7	0.40	9.81	1.0	360	0.107	700
0.8	0.50	9.81	1.0	360	0.188	900
0.9	0.60	9.81	1.0	360	0.255	1115

6.4.3 Water level balance

The results of this part are represented in figure 43 which shows the sea level and Göta älv reservoir water level at a same time when both barrages are closed and gates outflow from the downstream barrage is limited according to Table 3 with respect to the sea level when is higher than 0.4 m.

The y coordinate is considered in unit of cm, and the original point is 0 which is equal to +10m in Göteborg units system. Therefore, the acceptable maximum water level in Göta älv will be at +100 cm (or at +1m in Göteborg unit system) that has been shown by a thick arrow in Figure 43. Based on this limitation, sometimes during a year the water level is high than +100 cm that several of them refer to the sea level rising and others refer to the high volume runoff from heavy rainfall. The barrages must manage both of them to support Gothenburg against flooding.

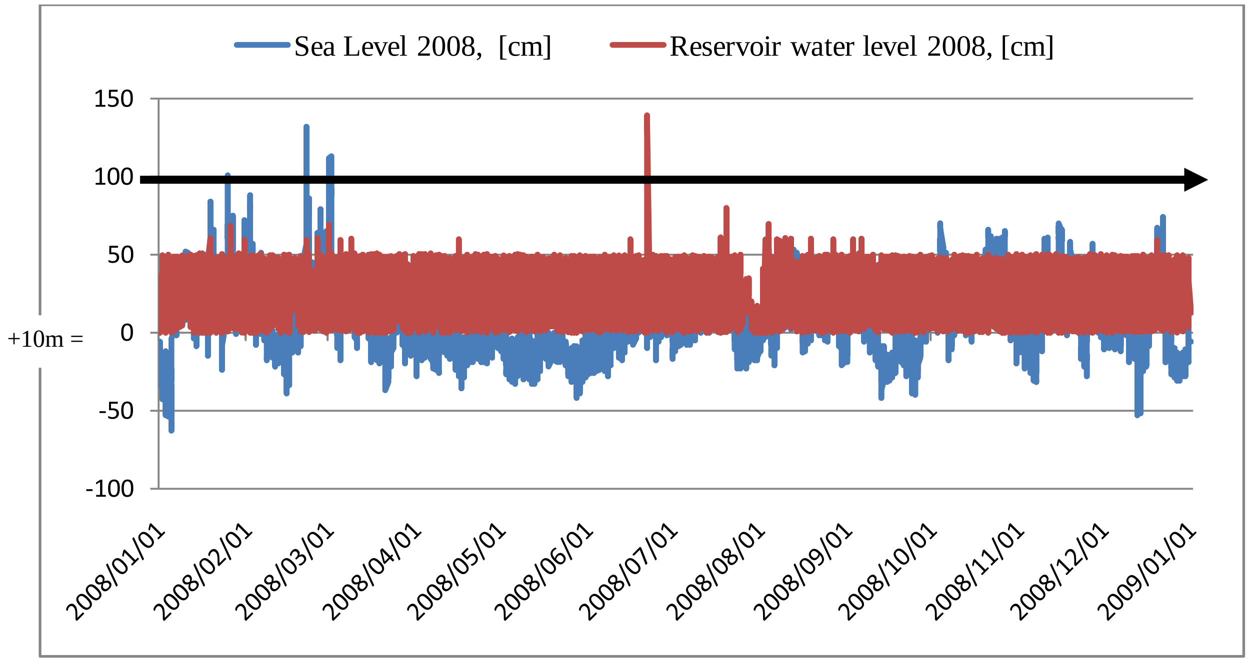

Figure 43: Sea level and reservoir water level at a same time for Scenario I

6.4.4 Barrages operation system

To protect the city against the flooding events from sea level rising mostly in February and March when the rainfall does not any affect on reservoir water level, the barrages can be closed to control sea level, and the upstream barrage must be closed as same time as downstream barrage to control the normal flow of Göta älv which is as a inflow to the reservoir and increases the water level in reservoir. According to the results, the best time period to control these situations is 1 hour because in more time the shifted normal flow of Göta älv is very huge and can cause flooding in the Nordre älv at the northern parts of Gothenburg.

The highest water level because of runoff in Figure 43 is obtained based on the assumption that both barrages are closed, and the limitation of gates outflow is based on Table 3. According to Figure 43, these situations occur during June and July when the sea level is down, thus, to control them the downstream barrage can be opened 30 minutes earlier than the upstream barrage to discharge more water to the North Sea, and increases the reservoir volume.

The results show the composition of both situations does not happen at a same time, and the barrages have managed some situations which are a little similar to that, especially in January and February.

6.5 Scenario II

6.5.1 Total runoff

The results of total runoff in Göta älv reservoir from MATLAB programming are shown the maximum runoff will happen during June in 2100 which is represented in figure 44.

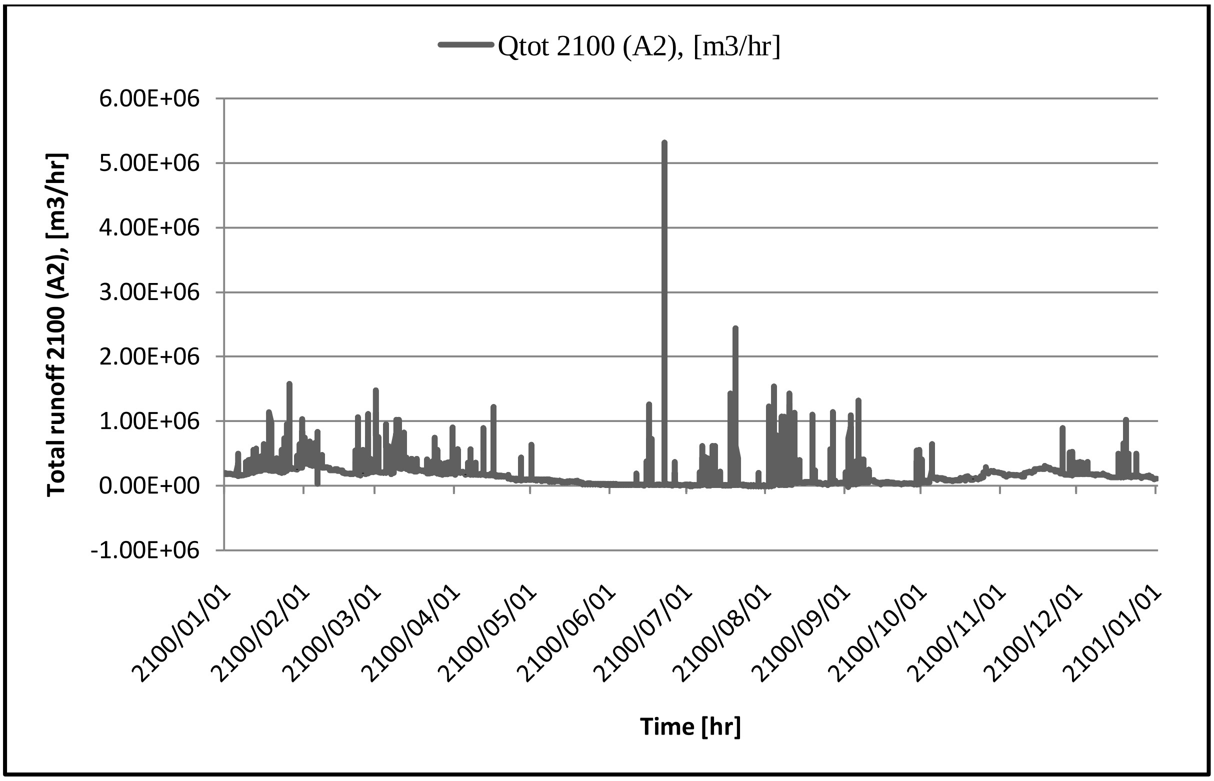

Figure 44: Total runoff into the Göta älv reservoir based on scenario II

6.5.2 Gates outflow

The process is like to Section 6.4.2, and Table 4 represents the gates outflow for scenario II.

Table 4: Gates outflow of downstream barrage for scenario II

Sea level, Y_4, [m]	Head, H_1^* [m]	g [m/s^2]	K_A	Total opening width [m]	V_1 [m/s]	Minimum Gate outflow [m^3/s]
0.5	0.10	9.81	1.0	360	0.044	250
0.6	0.20	9.81	1.0	360	0.033	430
0.7	0.30	9.81	1.0	360	0.023	615
0.8	0.40	9.81	1.0	360	0.200	810
0.9	0.50	9.81	1.0	360	0.075	1050
1.0	0.60	9.81	1.0	360	0.250	1250

6.5.3 Water level balance

The results of MATLAB programming are represented in figure 45, based on the gates outflow limitation from Table 3. As mentioned before, the sea level will be increase by +1 during the 21st century that will be +11m in Göteborg units system and is represented as original level at 0 in figure 40. Also, the acceptable maximum level of water in reservoir will be +12.5 m by 2100, and it has been shown by a thick arrow in figure 45.

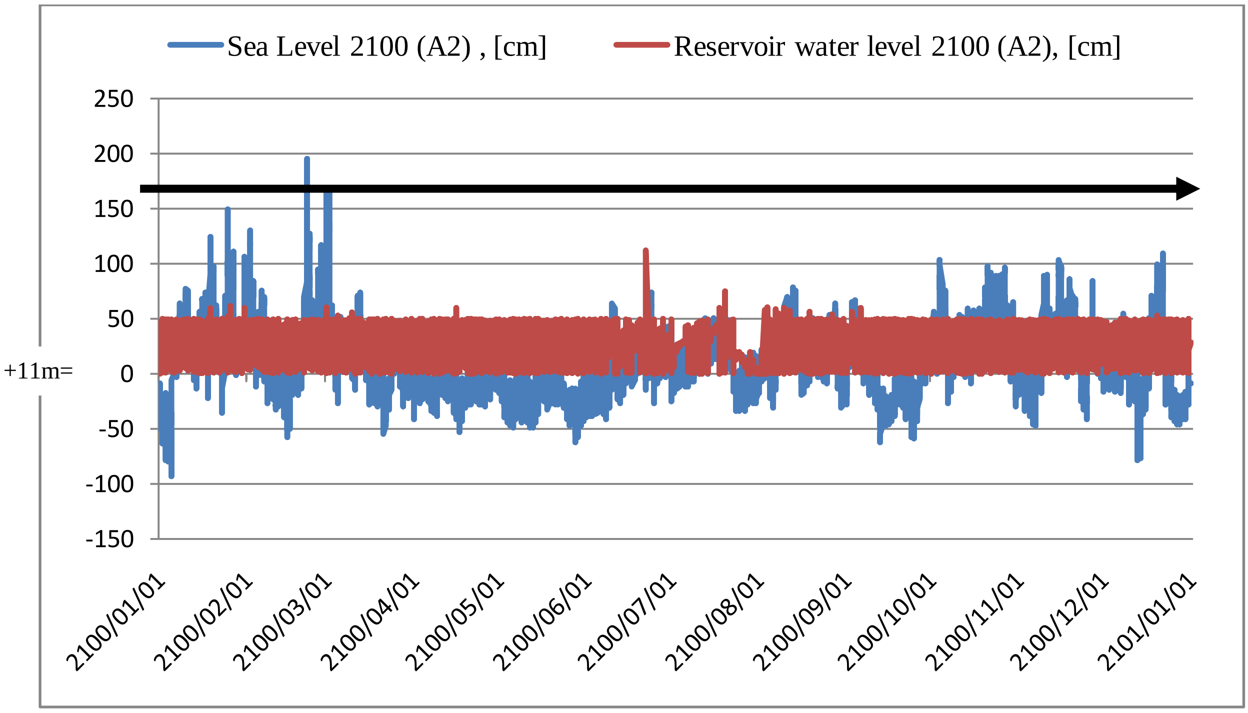

Figure 45: Sea level and reservoir water level at a same time for Scenario II

Based on the results of A2 scenario, the most important factor of flooding in Gothenburg will be the sea level rising during January, February, and March.

6.5.4 Barrages operation system

The barrages must manage only the sea level rising in 2100 because the runoff effects will be managed by them. To control sea level the downstream and upstream barrages can be closed simultaneously and this process must be less than 1 hour. The sea level rising in first three months of a year is very high, thus, the risk of flooding will be higher in these months than others.

6.6 Scenario III

6.6.1 Total runoff

Figure 41 represents of total runoff into the Göta älv reservoir in 2100 and based on B2 scenario of climate change.

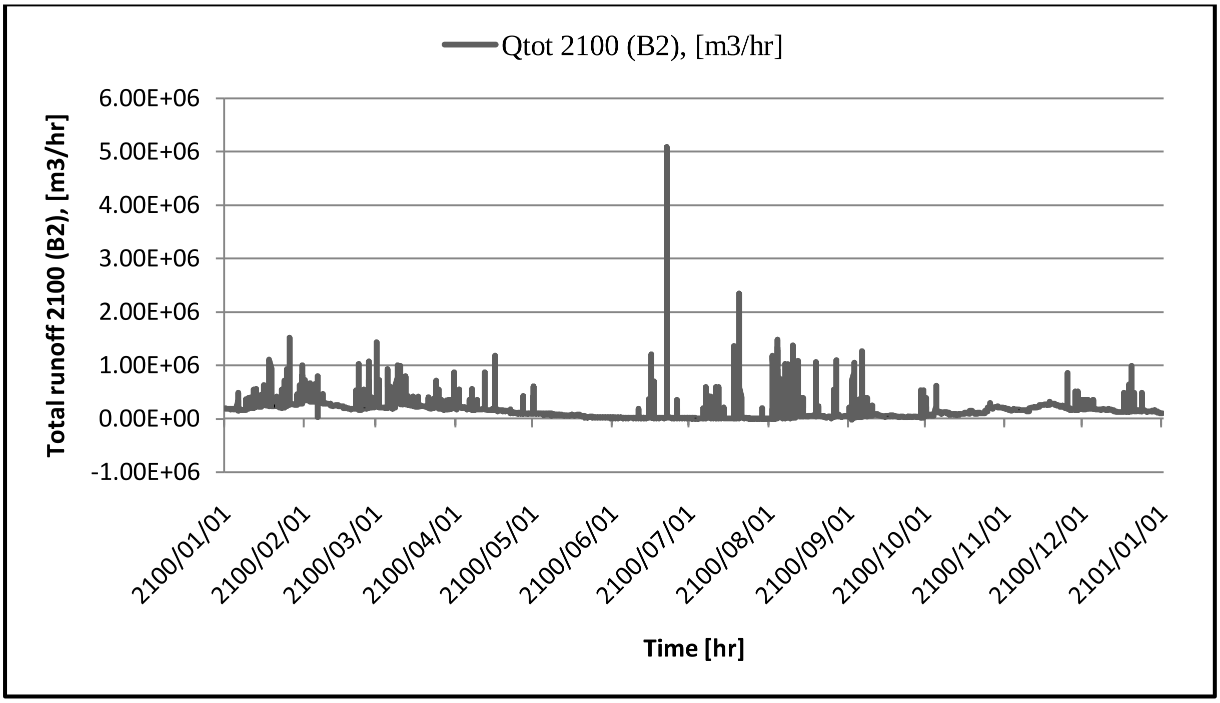

Figure 46: Total runoff into the Göta älv reservoir based on scenario

6.6.2 Gates outflow

It is exactly like Table 3, but for recognizing gates outflow for scenario III, table 5 represented below.

Table 5: Gates outflow of downstream barrage for scenario III

Sea level, Y_4, [m]	Head, H_1^* [m]	g [m/s^2]	K_A	Total opening width [m]	V_1 [m/s]	Minimum Gate outflow [m^3/s]
0.5	0.10	9.81	1.0	360	0.044	250
0.6	0.20	9.81	1.0	360	0.033	430
0.7	0.30	9.81	1.0	360	0.023	615
0.8	0.40	9.81	1.0	360	0.200	810
0.9	0.50	9.81	1.0	360	0.075	1050
1.0	0.60	9.81	1.0	360	0.250	1250

6.6.3 Water balance model

The limitations are same as Section 6.5.3, and the results are represented in figure 47.

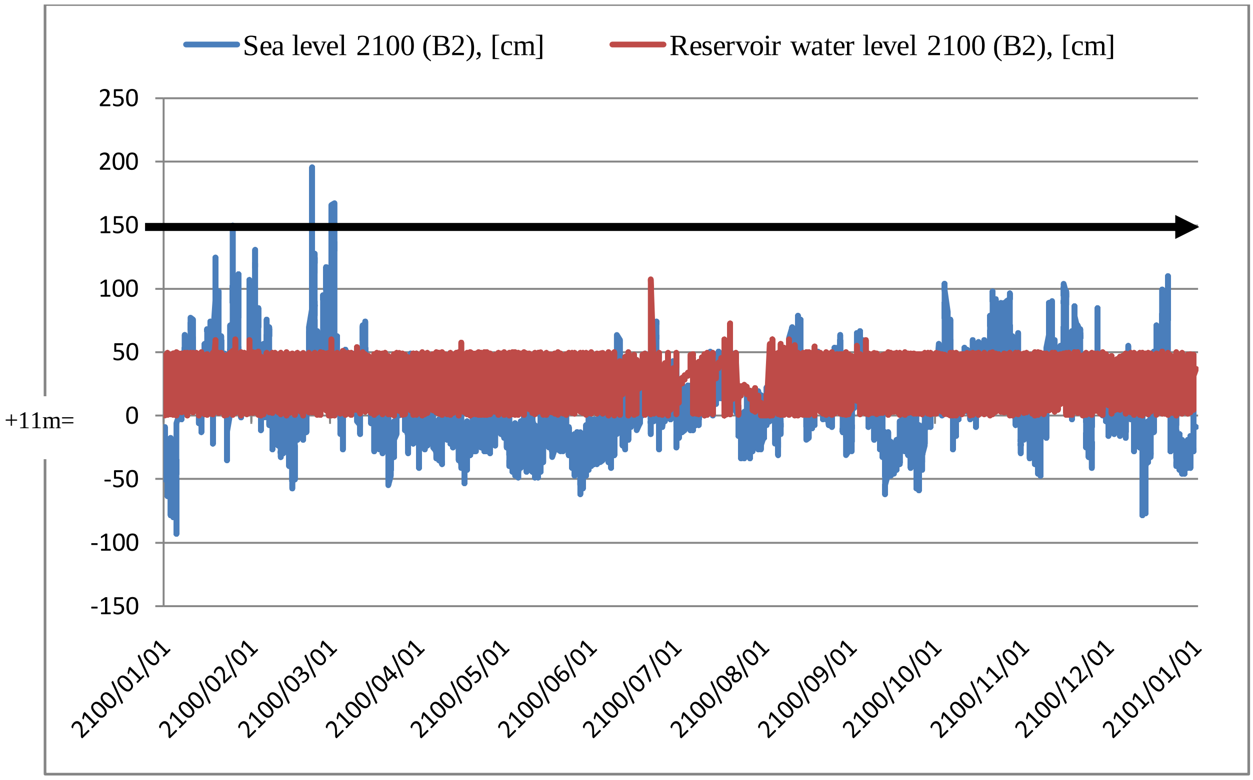

Figure 47: Sea level and reservoir water level at a same time for scenario III

6.6.4 Barrages operation system

The operation of barrages refers to the rising sea level mostly in January, February and March. The barrages will manage them by closing gates downstream and upstream. The risk of flooding in result of runoff is less than sea level rising in future.

7 Discussion

This part tries to answer the questions that are mentioned in Section 5.2, and to give more information about uncertainties of this study.

- Is it possible in theory to protect Gothenburg against floods during the 21st century by protective barrage techniques?
  According to the results that are theoretically, the answer of this question is yes because the barrages could make a balance between sea level and reservoir water level for today and future extreme weather condition.

- Are there any relevant locations for both barrages along the Göta älv?
  The best locations of barrages were described in Section 6.1. The downstream one has located at the ideal place with high elevation, rocky part, and very good width of river. The location of upstream barrage is only suggested at the northern part of Gothenburg to shift the normal flow of Göta älv to the Nordre älv, while the elevation, geology and width of river at there are not as perfect as downstream barrage.

- How the gates must be operated?
  The gates of downstream barrage are calculated based on the head between the sea level, which was predicted by the IPCC reports in time, and the water level at the barrage. Therefore, some limitations for discharging water from reservoir to the North Sea are obtained, check Table 3. Time of closing and opening of gates refers to both of sea level rising and total runoff from rainfall, and whereas the results of this study are based on hourly data, thus the best time is one hour for keeping closed the downstream and upstream barrages when the rising sea level is very high, and keeping open downstream and close the upstream for 30 minutes during heavy rainfall.

- For how long the barrages can be used?
  It depends on a lot of parameters and factors, but based on the limitations, assumptions, available data and future factors of this study, the barrages can manage flooding events during the 21st century.

- Is shipping possible in Göta älv?
  According to the depth and width of Göta älv at downstream barrage location, shipping is possible after balancing of water level. Also, the width of river is limited from 485m to 360 m because of the gates in it, but the width of the two gates is 60m which provide a good width for shipping.

- What are the consequences in Kungälv area?
  This area located at low elevation close to the upstream barrages; therefore it can be flooded when the upstream barrage remains closed for more than an hour because of Göta älv normal flow which is shifted to the Nordre älv River.
  To protect Kungälv against flooding only usage of two barrages is not applicable, and some other flood control structures must be installed there, and the seawall is the best suggestion.

- How large is the cost of barrages construction and how long will it take?

The time and cost of construction depend on many aspects like budget, weather condition, and more, but whereas the downstream barrage is same to Thames barrier in London (check The Thames Barrier Project Pack 2008[21]), the cost is suggested as €1.3 billion and the time is 10 years.

- What happens if sea level rises to by +4m in 2200?
  It is not easy to answer this question because there are a lot of uncertainties about 2200 weather condition, climate change, human activities, and more, but the problem is that if the water level is at +14m in Gothenburg area, with open barrages most parts of city will be flooded at this sea level; if the barrages are closed forever how the city of Gothenburg must manage the runoff.

[21] Available online on: http://www.environment-agency.gov.uk/static/documents/Leisure/Project_Pack.pdf

8 Conclusion

Based on the climate change in the world, most of coastal areas need to be protected against sea level rising to reduce the economic and traumatic losses of flooding events. To achieve this goal, some barrage techniques have been used in several coastal areas like the Thames Barrier in London and the Maesland barrier in Rotterdam. These Barriers have provided an adequate level of protection so far for London and Rotterdam.

This study consists of the predictions of climate change in future and engineering hydrology to examine if it is possible to use same solution as London in the Gothenburg city. Therefore, two aspects of flooding events in the city were considered, first flooding in result of sea level rising during the 21st century, and the second the flooding in result of rainfall runoff with respect to the increasing factor of precipitation and temperature in future. There are many uncertainties in this study because there was not accessibility to the historical data of rainfall, the type of river banks soil, historical data of temperature, the soil infiltration ability in the city, and etc. Thus, the assumptions, limitations and available data were used to have better results from this study.

However, the uncertainties are very important, but the results show that it is possible to use the two barrages for protecting the city during the 21st century, but some other flood control structure must be added to these barrages to make a large defence network as London where there are more than 400 different control structures. According to the results, the sea level rising mostly in January, February, and March can be mitigated by closing the gates of the barrages and the heavy runoff often in June and July can be accommodated by keeping the gates open. This heavy runoff can be generated according to the assumption of rain intensity over whole of Göta älv basin based on Equation 1 which calculates the total runoff as a function of catchment area and rain intensity; this rain intensity has been measured only in the Göteborg center station which has a smaller area than the Göta älv basin, but assumed for the whole of Göta älv basin, therefore, the total runoff has been increased. Based on the results, the barrages represented an adequate protection level when the maximum water level is +11m (in Gothenburg unit system) in today and +12.5m in 2100 condition, but may not be completely effective, and more flood control structures may be required.

This study can be as a first step towards more research and study about using of sea barrage in Gothenburg because to have the best results for managing flooding events in the city by protective barrage techniques, the uncertainties must be removed that it will be possible when the complete data is accessible. Also, the application of sea barrages is a much extended area of study, and it is different for any location. It means various locations have an own situation for investigating the usage of barrages in there.

The most interesting future study is about the 22nd century condition when the mean sea level will be raised by +4m relative to now, and the question is how the gates must be operated? Is it possible to keep open the gates forever or must they be closed forever?

9 Future study

Most important discussion about this study is about the mean sea level by 2200 when it will rise approximately +4m relative to today condition. In fact, the question is what happens in this situation for Gothenburg city, it is flooded or the barrages can protect it against flooding events, the barrages must be closed or opened.

The problem is if the barrages are opened the water level in Göta älv will be raised to +14m, and it causes the flood in the city. If the barrages are closed the runoff cannot be released from the gates to the North Sea unless the water level comes up more than +14m in the reservoir, therefore the city will be flooded again. The future study can be in relation to this problem and suggestion of some solution for that like:

- To review the application of pumping station ,when the gates of barrages are closed, for realizing water form reservoir to the North Sea, this solution can be good but is very expensive.
- To investigate the climate change stopping that is not very good solution because it is not easy to reach this goal without all countries cooperation
- Keep closed the barrages to protect city from mean sea level rising, and construction of some diversion structures to shift the runoff to another pathway for releasing to the North Sea, some suggested location for building dams or other flood control structures are represented in figure 48.
- Application of seawalls along the Göta älv river instead of constructing the barrages, it can be good but the seawalls length will be 50 km with the elevation of 4m, hence it is very expensive and need to be studied more from geotechnical aspects of river banks. Also, the reservoir volume which is obtained by the seawalls is about $5.4*6 = 32.4 *10^6 m^3$ according to Table 2, and it is less than the calculated reservoir by the barrages ($97*10^6 m^3$).
- May be the best solution is moving from the sides of river to the high elevation areas, also change the location of city center to the high elevation parts of city

These and other solutions can be defined for more research in relation to this Master`s thesis.

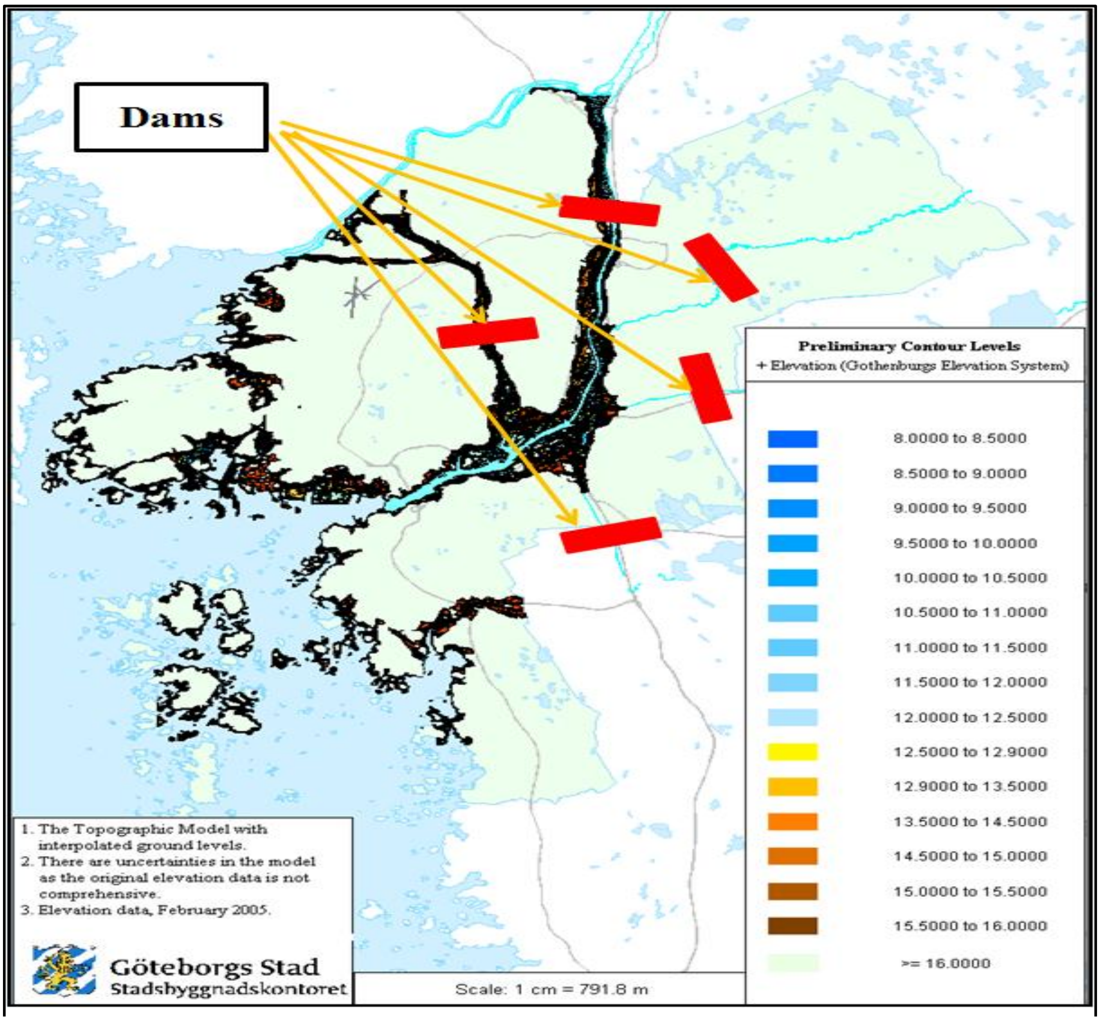

Figure 48: The suggested locations for other flood control structures

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www.floodsite.net

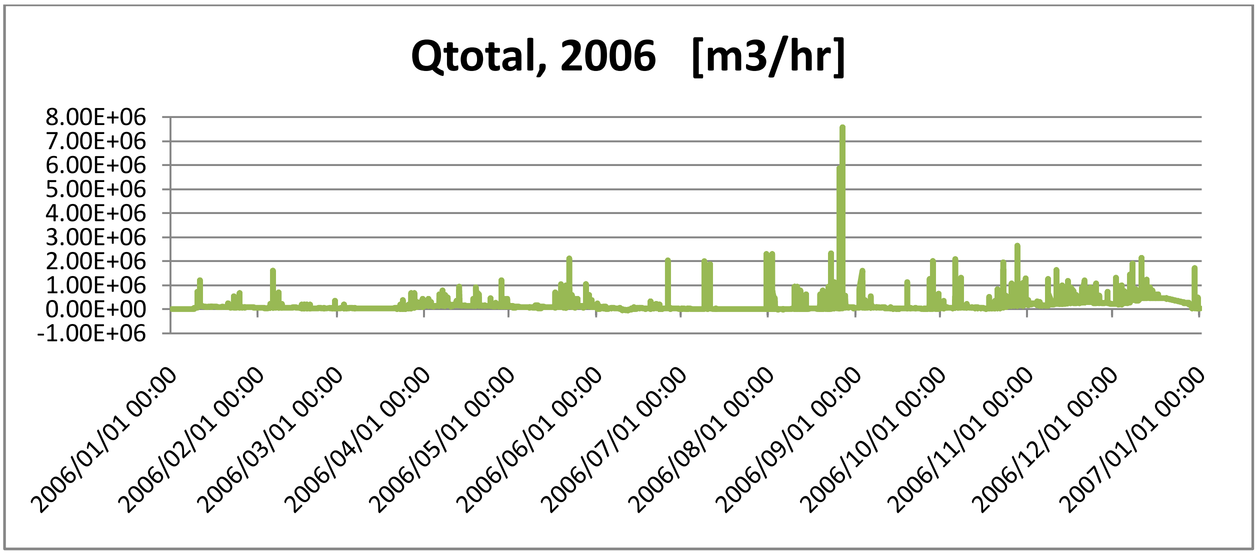
Appendixes

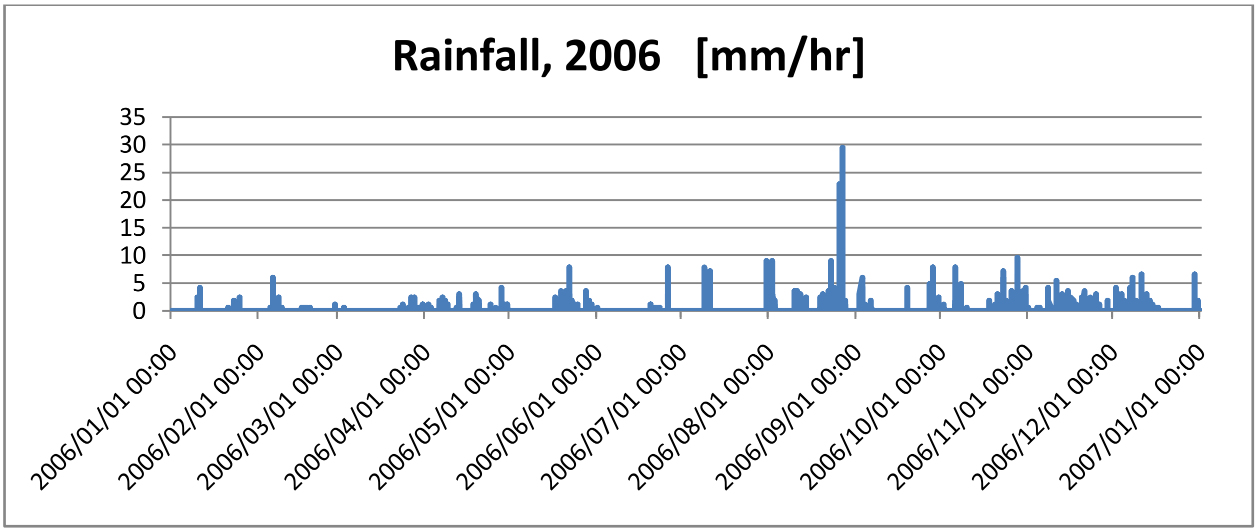
Appendix I – Available data from 2006 to 2008

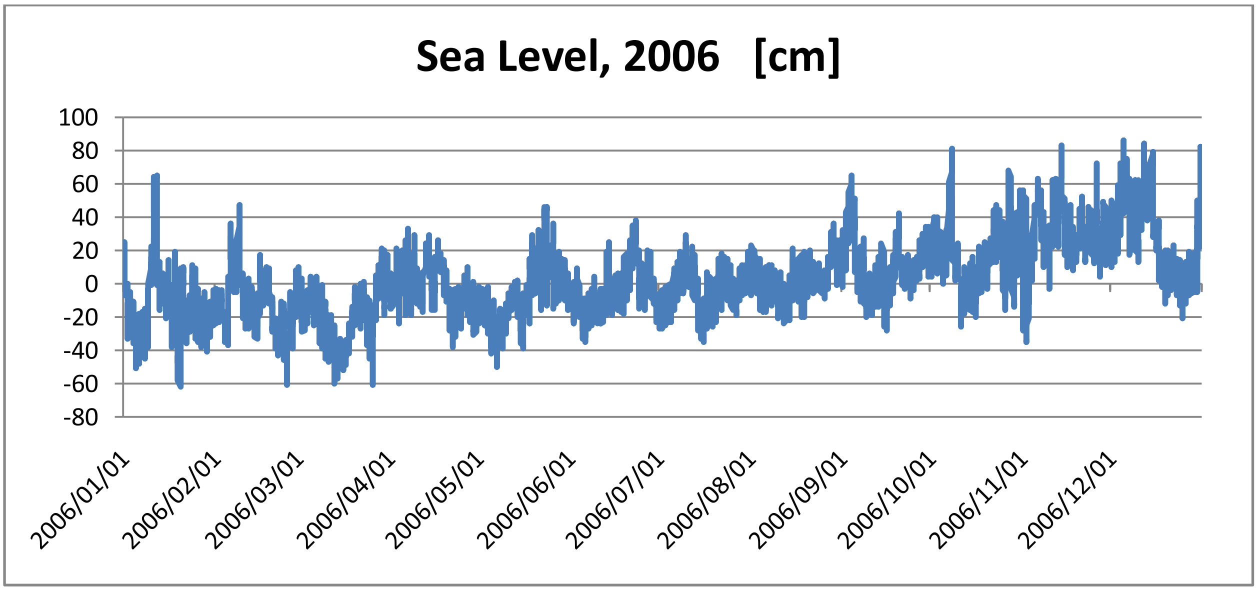
Appendix II – MATLAB program of reference data

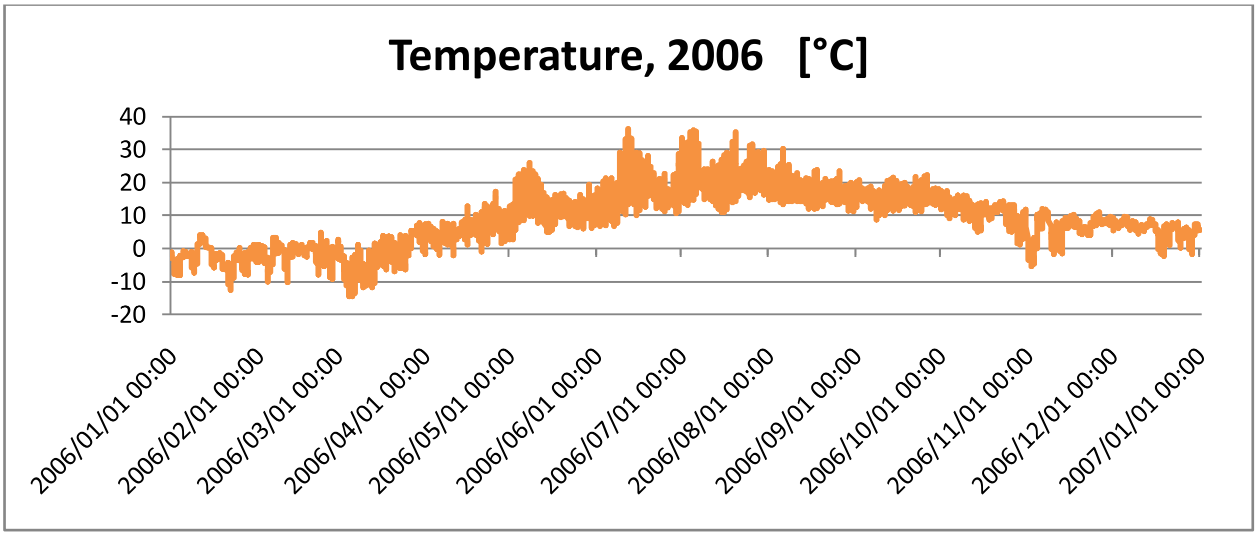
Appendix I – Available data from 2006 to 2008

2006

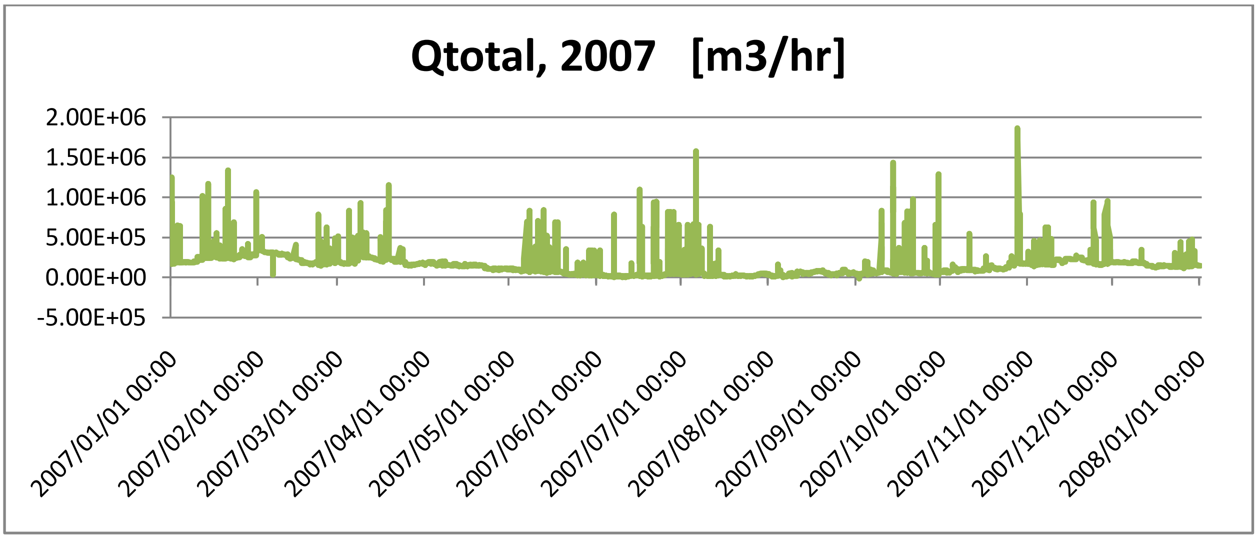


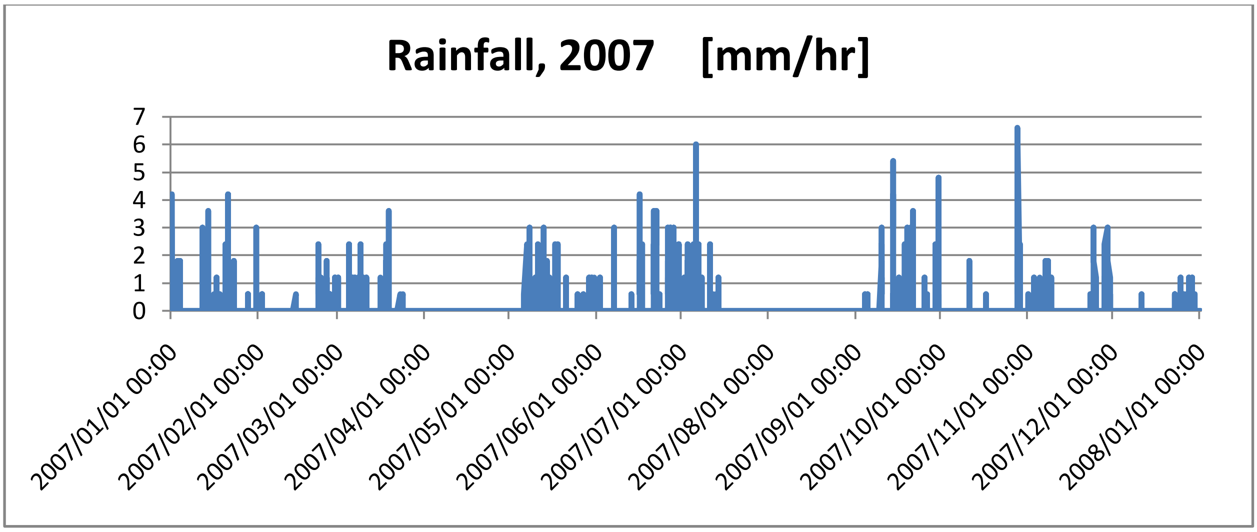


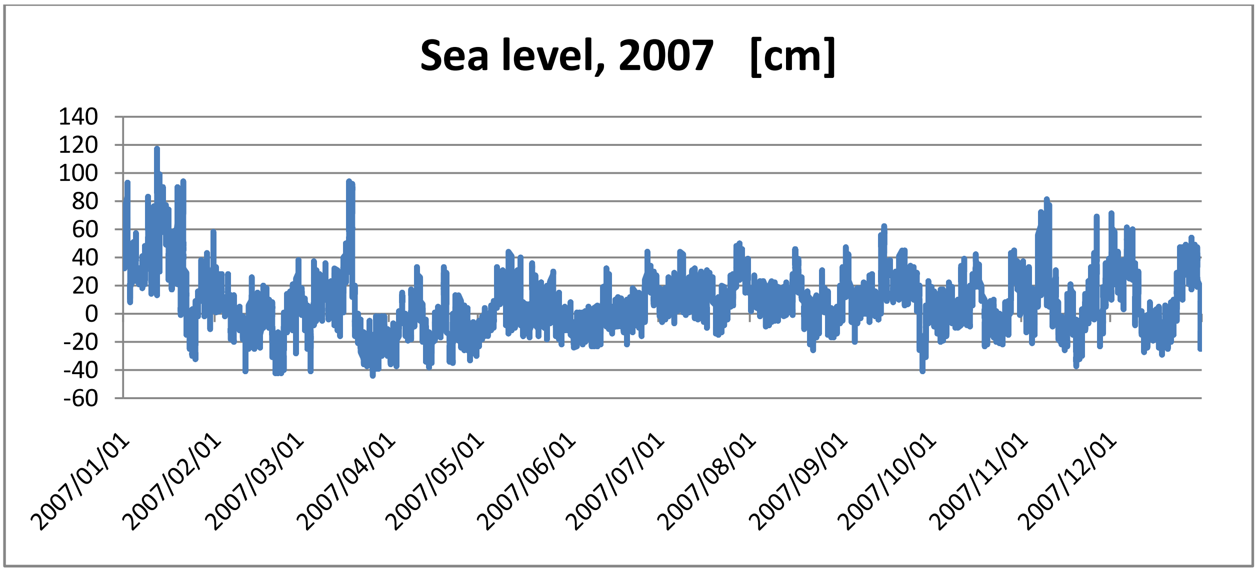



Temperature, 2006 [°C]
40
30
20
10
0
-10
-20
2006/01/01 00:00
2006/02/01 00:00
2006/03/01 00:00
2006/04/01 00:00
2006/05/01 00:00
2006/06/01 00:00
2006/07/01 00:00
2006/08/01 00:00
2006/09/01 00:00
2006/10/01 00:00
2006/11/01 00:00
2006/12/01 00:00
2007/01/01 00:00

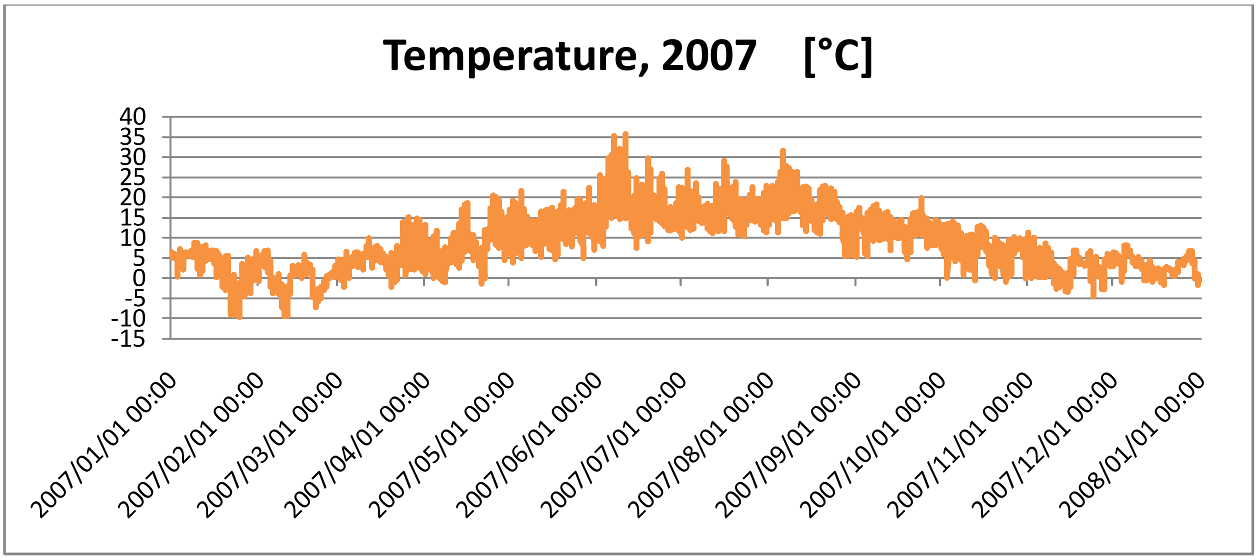
2007


Qtotal, 2007 [m3/hr]
2.00E+06
1.50E+06
1.00E+06
5.00E+05
0.00E+00
-5.00E+05
2007/01/01 00:00
2007/02/01 00:00
2007/03/01 00:00
2007/04/01 00:00
2007/05/01 00:00
2007/06/01 00:00
2007/07/01 00:00
2007/08/01 00:00
2007/09/01 00:00
2007/10/01 00:00
2007/11/01 00:00
2007/12/01 00:00
2008/01/01 00:00


Rainfall, 2007 [mm/hr]
7
6
5
4
3
2
1
0
2007/01/01 00:00
2007/02/01 00:00
2007/03/01 00:00
2007/04/01 00:00
2007/05/01 00:00
2007/06/01 00:00
2007/07/01 00:00
2007/08/01 00:00
2007/09/01 00:00
2007/10/01 00:00
2007/11/01 00:00
2007/12/01 00:00
2008/01/01 00:00

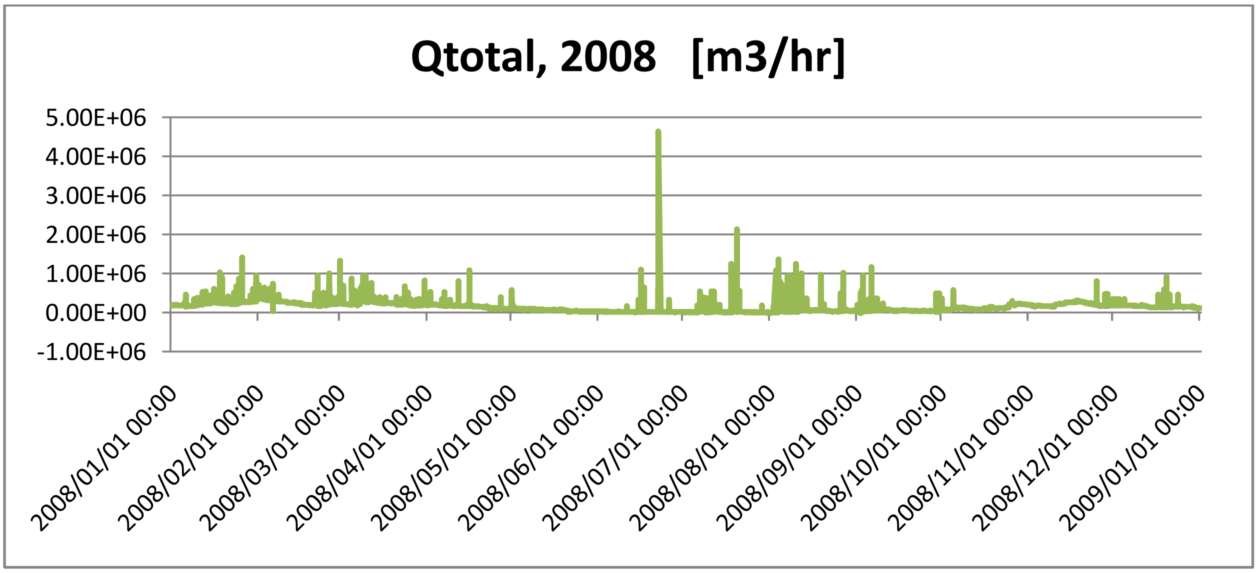


Sea level, 2007 [cm]
140
120
100
80
60
40
20
0
-20
-40
-60
2007/01/01
2007/02/01
2007/03/01
2007/04/01
2007/05/01
2007/06/01
2007/07/01
2007/08/01
2007/09/01
2007/10/01
2007/11/01
2007/12/01

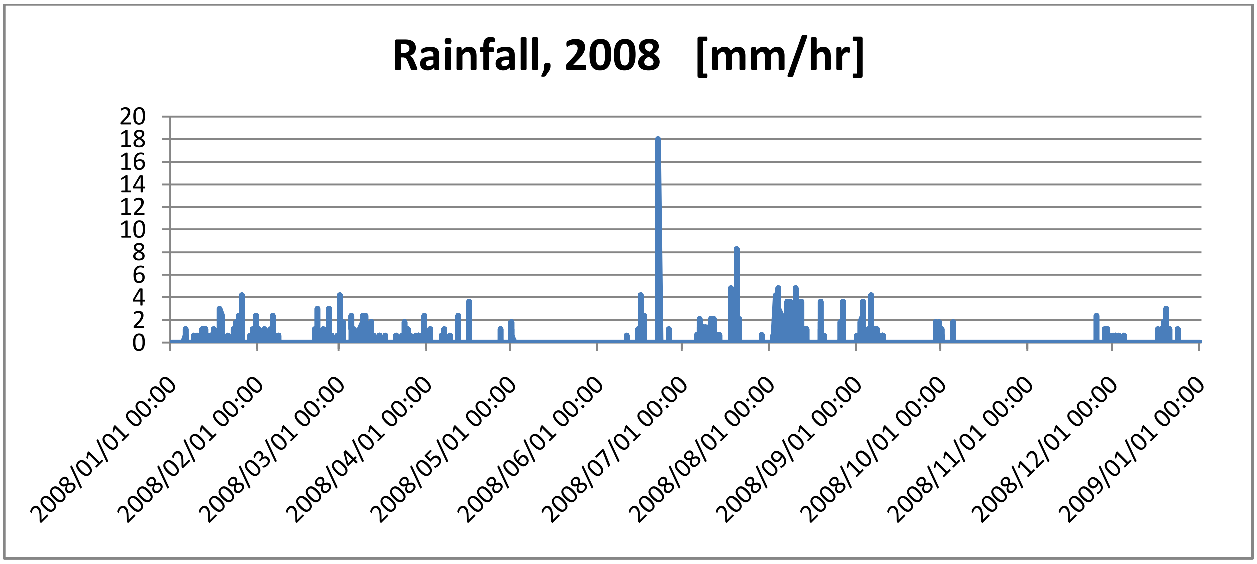


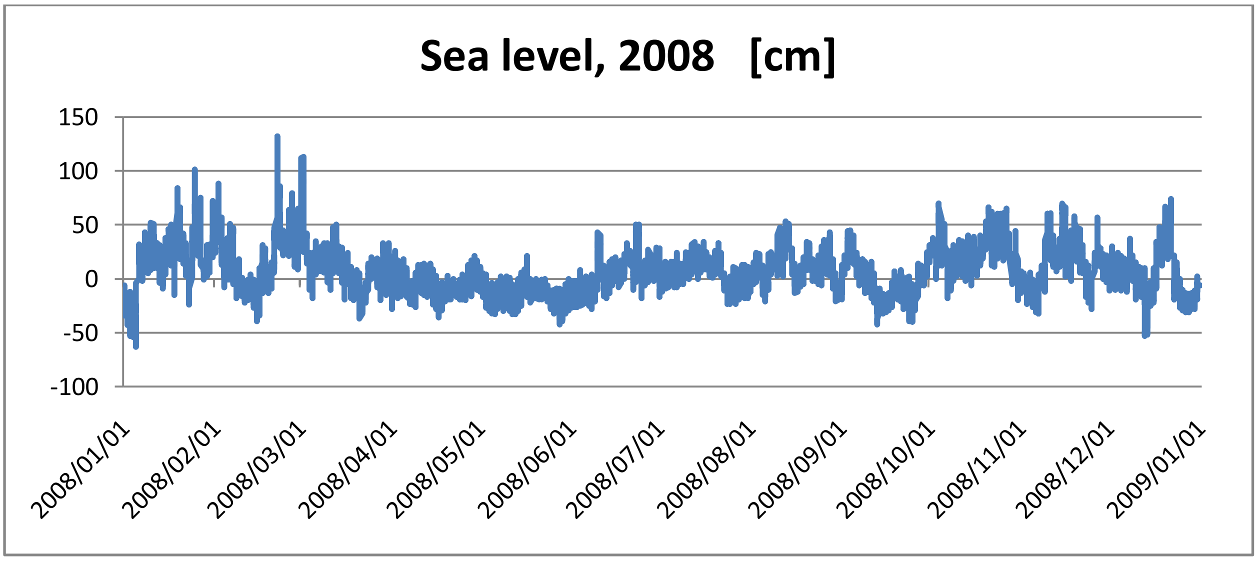
Temperature, 2007 [°C]
40
35
30
25
20
15
10
5
0
-5
-10
-15
2007/01/01 00:00
2007/02/01 00:00
2007/03/01 00:00
2007/04/01 00:00
2007/05/01 00:00
2007/06/01 00:00
2007/07/01 00:00
2007/08/01 00:00
2007/09/01 00:00
2007/10/01 00:00
2007/11/01 00:00
2007/12/01 00:00
2008/01/01 00:00

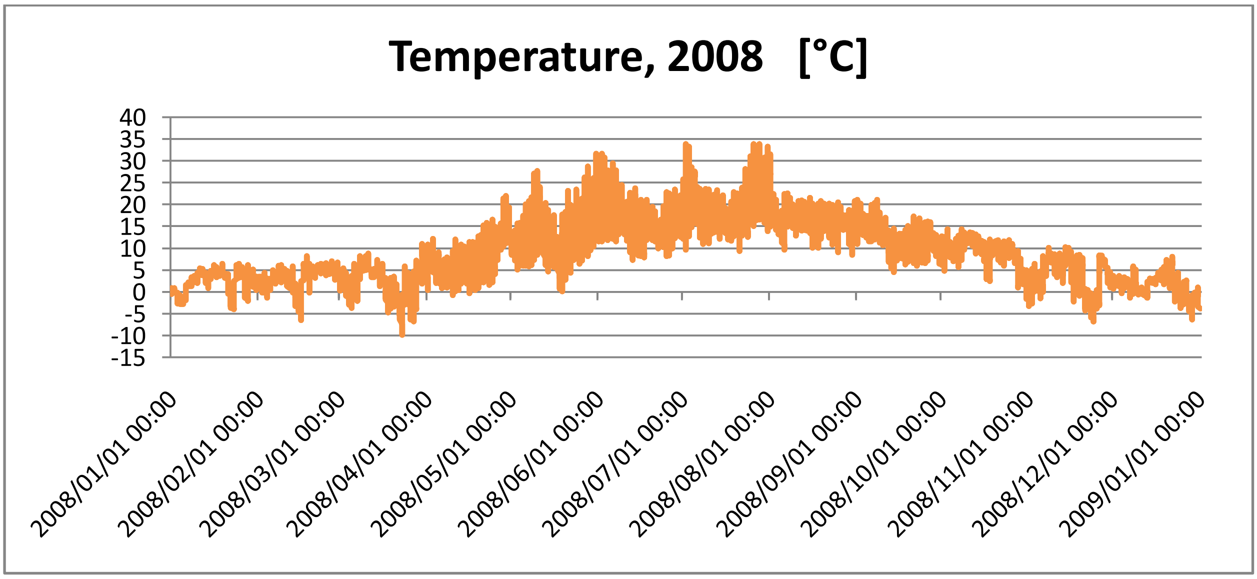
2008



Qtotal, 2008 [m3/hr]
5.00E+06
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
-1.00E+06
2008/01/01 00:00
2008/02/01 00:00
2008/03/01 00:00
2008/04/01 00:00
2008/05/01 00:00
2008/06/01 00:00
2008/07/01 00:00
2008/08/01 00:00
2008/09/01 00:00
2008/10/01 00:00
2008/11/01 00:00
2008/12/01 00:00
2009/01/01 00:00


Rainfall, 2008 [mm/hr]
20
18
16
14
12
10
8
6
4
2
0
2008/01/01 00:00
2008/02/01 00:00
2008/03/01 00:00
2008/04/01 00:00
2008/05/01 00:00
2008/06/01 00:00
2008/07/01 00:00
2008/08/01 00:00
2008/09/01 00:00
2008/10/01 00:00
2008/11/01 00:00
2008/12/01 00:00
2009/01/01 00:00


Sea level, 2008 [cm]
150
100
50
0
-50
-100
2008/01/01
2008/02/01
2008/03/01
2008/04/01
2008/05/01
2008/06/01
2008/07/01
2008/08/01
2008/09/01
2008/10/01
2008/11/01
2008/12/01
2009/01/01


Temperature, 2008 [°C]
40
35
30
25
20
15
10
5
0
-5
-10
-15
2008/01/01 00:00
2008/02/01 00:00
2008/03/01 00:00
2008/04/01 00:00
2008/05/01 00:00
2008/06/01 00:00
2008/07/01 00:00
2008/08/01 00:00
2008/09/01 00:00
2008/10/01 00:00
2008/11/01 00:00
2008/12/01 00:00
2009/01/01 00:00

Appendix VI – MATLAB program of reference data (2008)

```
clear all
close all
format long

leapyear  = 1;
Temp_factor  = 1;
Rain_factor  = 1;
Qs_factor    = 1;
Qm_factor    = 1;

Area        = 255625940;
h0          = 10;

countfile = input('enter the input file number: ');
inputfile = ['data' num2str(countfile) '.txt'];
inputdata = load(inputfile)
z = inputdata(:,1);
A = inputdata(:,2);
[Nstep b] = size(z);
EXIT = 0;
while (EXIT == 0)
   disp('functions : '),
   disp('1. Total Volume ');
   disp('2. Partial Volume ');
   disp('3. Step Volume ');
   disp('4. Accumulating Volume ');
   disp('5. Extrapolation ');
   disp('6. Save new data ');
   disp('100. Exit');
   Func = input('what do you want to do? ');
   switch Func
```

```
case 1
   TotalVolume = trapz(z,A)
case 2
   level1 = input('Enter level 1 : ');
   level2 = input('Enter level 2 : ');

   if (level1 > level2)
      quit
   end
   tolerance1 = abs (z(1,1)-level1);
   tolerance2 = abs (z(1,1)-level2);
   Step1 = 1;
   Step2 = 1;
   for iStep=1:Nstep
      if ( abs(z(iStep,1)-level1) < tolerance1 )
         Step1 = iStep;
      end
      if ( abs(z(iStep,1)-level2) < tolerance2 )
         Step2 = iStep;
      end
   end

   Volume = trapz(z(Step1:Step2,1),A(Step1:Step2,1))


case 3

   for iStep=1:Nstep-1
      V(iStep)=trapz(z(iStep:iStep+1,1),A(iStep:iStep+1,1));
   end

    plot(z(1:end-1,1),V)

case 4
```

```
        Vol(1)=0;
        for iStep=2:Nstep
            Vol(iStep)=Vol(iStep-1)+trapz(z(iStep-1:iStep,1),A(iStep-1:iStep,1));
            Vol
        end
        plot(z,Vol);

    case 5
        distance = input('At which distance you want the area? ');
        Area = A(end,1)+(distance-z(end,1))*(A(end-1,1)-A(end,1))/(z(end-1,1)-z(end,1))
        z(end+1,1)=distance;
        A(end+1,1)=Area;
        Nstep=Nstep+1;

    case 6
        outfile = ['data' num2str(countfile+1) '.txt'];
        outputdata(:,1)=z(:,1);
        outputdata(:,2)=A(:,1);
        save outfile -ascii outputdata

    case 100
        EXIT = 1;
  end
end

Rain     = load('References/R_ref.txt');
Qs       = load('References/Qs_ref.txt');
Qm       = load('References/Qm_ref.txt');
Temp     = load('References/T_ref.txt');
Date     = load('References/Date_ref.txt');

Date(end,1) = 12;
Date(end,2) = 31;
Date(end,3) = 2008;
```

```
Date_leap = Date;

Rain_leap = Rain;

Temp_leap = Temp;



for i=1:732

   for j=1:12

       Qs_leap((i-1)*12+j)=((Qs(i+1)-Qs(i))/12)*j+Qs(i);

   end

end


for j=-12:-1

       Qm_leap(13+j)=((Qm(2)-Qm(1))/24)*j+Qm(1);

end


for i=1:365

   for j=1:24

       Qm_leap(12+(i-1)*24+j)=((Qm(i+1)-Qm(i))/24)*(j-1)+Qm(i);

   end

end


for j=1:12

       Qm_leap(24*365+12+j)=((Qm(end)-Qm(end-1))/24)*(j-1)+Qm(end-1);

end


Qm_leap = Qm_leap';

Qs_leap = Qs_leap';


Rain_ord(1:59*24)   = Rain_leap(1:59*24);

Temp_ord(1:59*24)   = Temp_leap(1:59*24);

Qs_ord(1:59*24)     = Qs_leap(1:59*24);

Qm_ord(1:59*24)     = Qm_leap(1:59*24);

Date_ord(1:59*24,:) = Date_leap(1:59*24,:);
```

```
Rain_ord(59*24+1:8760)   = Rain_leap(60*24+1:end);

Temp_ord(59*24+1:8760)   = Temp_leap(60*24+1:end);

Qs_ord(59*24+1:8760)     = Qs_leap(60*24+1:end);

Qm_ord(59*24+1:8760)     = Qm_leap(60*24+1:end);

Date_ord(59*24+1:8760,:) = Date_leap(60*24+1:end,:);


if (leapyear == 1)

   Q_tot = Rain_leap*Rain_factor/1000*Area - (221.5+(29*(Temp_leap + 0)))/(366*24*1000)*Area +
Qs_leap*Qs_factor*3600 + Qm_leap*Qm_factor*3600;

else

   Q_tot = Rain_ord*Rain_factor/1000*Area - (221.5+29*Temp_ord*Temp_factor)/(365*24*1000)*Area +
Qs_ord*Qs_factor*3600 + Qm_ord*Qm_factor*3600;

end


zbar(1)=z(1,1);

for iStep=2:Nstep

   zbar(iStep)=(z(iStep-1,1)+z(iStep,1))/2;

end

zbar(Nstep+1)=z(end,1);


V1(1)=V(1);

for i=2:12

   V1(i)=(V(i)+V(i-1))/2;

end

V1(13)=V(12);


dvdz(1)=(V1(2)-V1(1))/(z(2)-z(1));

for iStep=2:Nstep

   dvdz(iStep)=(V1(iStep)-V1(iStep-1))/(z(iStep)-z(iStep-1));

end

dvdz(Nstep+1)=dvdz(Nstep);


h(1)=h0;

for i=1:8784-1
```

```
    alaki = h(i);
    for ss=1:100
    if (alaki<=11)
        Qgate = 0;
    elseif (alaki>10.5 && alaki<=10.6)
        Qgate = 230 * 3600;
    elseif (alaki>10.6 && alaki<=10.7)
        Qgate = 355 *3600;
    elseif (alaki>10.7 && alaki<=10.8)
        Qgate = 520 * 3600;
    elseif (alaki>10.8 && alaki<=10.9)
        Qgate = 700 * 3600;
    elseif (alaki>10.9 && alaki<=11)
        Qgate = 900 * 3600;
    elseif (alaki>11)
        Qgate = 1115 * 3600;



    end
    for ii=1:Nstep
        if (alaki<=zbar(ii+1)) && (alaki>=zbar(ii))
            dvdzatzz = dvdz(ii);
        end
    end

    dzdtalaki=(Q_tot(i)-Qgate)/dvdzatzz/100;
    alaki =  alaki + dzdtalaki;
    alaki = max(alaki,10);
    end
    h(i+1) = alaki;

end
```

```
h=h';

plot(Q_tot)

plot(h)

save -ascii Qtotal.dat Q_tot
save -ascii height.dat h
```