WATER RESOURCES MANAGEMENT & HYDROCLIMATIC DATA ANALYSIS IN TRANSBOUNDARY RIVER BASINS UNDER THE INFLUENCE OF CLIMATE VARIABILITY & WATER ABSTRACTION: NILE RIVER BASIN

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DECLARATION

I declare that the analysis and findings in this thesis was carried out by me. This work has been published in a peer-reviewed journal "Assessment of Upstream Human Intervention Coupled with Climate Change Impact for a Transboundary River Flow Regime: Nile River Basin" and published in Journal of Water Resources Management and has not been previously submitted either in part or full for any other award than the degree of Doctor of Philosophy in Civil Engineering at University of Salford

ABSTRACT

Water is a vital component for developing nations, as it is important for human consumption and domestic use, irrigation, and industry. The freshwater availability for each country should be known or estimated to sustainably manage its available supply, or its share of available water in case of transboundary basins during the subsequent years. The freshwater availability in the present and the future is governed by two factors: the effects of climate change or climate variability and the effects of human induced factors. The climate change can be sensed from the increase or decrease of precipitation, increase in temperatures, and increased prevalence of heat waves, drought events and the degree of severity of the drought events in some areas and increase in floods in other areas. The human induced factors can be witnessed in the change of land use, damming the rivers and excessive water obstruction and withdrawal.

The sustainable management of the available water resources is essential for future generations and environmental resources, especially with the present and possible future challenges in terms of increase in demand due to population growth and possible changes in precipitation. The application of water resources management practices is more difficult to achieve in transboundary river basins. Sustainable management could be achieved by assessing the utilization of the water at a transboundary scale besides studying the possible impacts of climate change and applying mitigation measures to avoid water scarcity in downstream countries.

The problems facing transboundary river basins are very complicated and there is a need to study the problems occurring due to the human interventions and climate

change or climate variability, which will give a solid ground to determine how much the river flow is being affected qualitatively and/or quantitively and try to find suitable effective solutions for each of them.

In this thesis the case of the Nile river basin will be representative of several shared river basins. The Nile river basin is third biggest river basin in the world and the second largest basin in Africa after the Congo basin in terms of area. It is shared between eleven countries and covers about 10% of African land.

This thesis aims to present an analytical framework to determine how the river discharge has been affected by the influence of both climate variability and human induced factors. The findings from this thesis can support better understanding of the changes occurring in river discharge due to coupled impact of climate variability and river damming. The study of the changes occurring in the river discharge due to climate variability and human intervention can lead to better planning for sustainable management practices of water resources in transboundary river basins especially in arid and semi-arid regions.

River flows have different fluctuations in river discharge as a result of the influence of the change in climate and human influence. The main aim of this research is to measure how the climate variability and human intervention affect the river flow either as an increase or a decrease in river discharge. The change in river discharge occurs based on the degree of intervention and the climatic conditions. Thus, the relation between the degree of human intervention and climate variability to the river discharge could or might help in taking the optimum procedure in the sustainable management of water resources, and help in negotiations between riparian countries to reach to a suitable treaty saving the rights of both upstream countries and downstream countries, and establish effective measure(s) to mitigate the water scarcity crises.

The objectives are to analyze the river discharge reaching the downstream countries in the past, and how the human induced factors and climate variability in terms of changes in trend and the occurrence of drought events affected the river discharge.

This has been addressed by assessing climate variability in the study area. The research includes the studying and choosing of the best metrological dataset for the areas with scarce meteorological datasets. The analyses of precipitation data obtained from the Global Precipitation Climatology Centre (GPCC) and detecting if there is a trend, Parametric and non-parametric tests are applied to the metrological data as the precipitation and temperature, in addition, the drought indices are calculated for the different time windows. and subsequently calculating drought events in the main basins impacting on the downstream flow.

Then river discharge data are analyzed using different hydraulic indices at key stations in the downstream country and measuring the alterations occurring in the flow. The degree of alteration is a function of the number of civil engineering projects being in operation and classified by time windows; pre-alteration is between 1900 and 1925, while the alteration period is between 1933 and 2012. The alteration period was classified into three periods based on the degree of alteration.

The research includes analyzing the records of river discharge reaching Egypt for 112 years. The total record of discharge (112 years) will be divided to time-windows based on the degree of interventions, statistical analysis is applied to the discharge of each time window, the alteration in discharge is compared between the different time windows. Finally, the investigation of the water usage in the upstream countries through existing structures and consumptive use of water.

The different time windows in the study was between 1900 and 1925, 1933 and 1963, 1964 and 1999, and between 2000 and 2012. It was found that the highest period with the discharge alteration was the last period, and this period had the strongest drought events then came the period 1964—1999.

The precipitation patterns had a decrease in the last two periods (1964—1999) and (2000—2012). The high alteration and strong drought events affected the river discharge in these two periods compared to the original period between 1900 and 1925. The results showed that there was no significant change in trends of the precipitation in the Nile basin and the major flow contributor sub-basins. There was a noticeable decline in trend at the two key river discharge stations (Dongola and Tamaniat stations).

The increased drought events affected the precipitation pattern in this period. The influence of the human induced factors and how they can control the river discharge increased with the degree of intervention, especially in periods with low precipitation and river flow.

The findings revealed that there are changes in the river flow regime caused by both changes in the rainfall pattern in addition to the regulation in the upstream countries. There is a direct relationship between the interventions in the upstream countries and changes in the flow regime especially when coupled with drought events. By increasing the water usage upstream, there is an increase in the alteration of the flow downstream. The years between 2000 and 2012 were linked to the highest alterations between the modified years.

The proposed framework is a step forward in filling the gap in knowledge by analyzing how the river discharge react climate variability coupled with human intervention in large river transboundary basins.

The water resources future strategic plan could be built based on the river discharge situation and how the river discharge is proportional to the variability in climate and human intervention.

Chapter one: Introduction

1.1 Background

Fresh water is vital for living and in the development of nations. In order to maintain fresh water for the future generations, it should be sustainably managed. Managing the water resources for countries sharing transboundary river basins is more complicated and competitive than national water resources management. The complexity is mainly due to the difference in interests between the riparian countries. Each country has its own strategic and development plans; without putting in consideration the plans of other countries sharing the river basin. The upstream country needs to store or get use of most of the flowing river water in their territories, thus they start constructing different projects aiming for the maximum use of the available water. What influences their actions is the increase in demand as a result of population change and national development plans, in addition to the impacts of climate change that have already happened and will happen in the future.

The study of the transboundary basins is important due to the portion of land these basins cover and the population living within. The transboundary basins cover almost half the land surface, more than one third the world's total population lives there and accommodates about 60% of world's river flow (UN & INBO, 2015).

The number of countries sharing the same basin differs, with the largest number of countries sharing a basin being 17 in Danube river basin in Europe; in the second place in terms of countries sharing the same basin comes 5 basins shared between 9 and 11 countries and the Nile basin is one of them shared between 11 countries.

There are 19 basins shared by 5 or more riparian countries (Sallam, 2014). The greater the number the countries sharing the basin the more complicated the situation is due to the increase in different interests and conflicts.

Figure 1-1 Africa’s Transboundary River basins after (Wolf et al., 1999)

There are 263 transboundary river basins worldwide (Sallam, 2014), with about 20 percent of these international basins in Africa (Figure 1-1).

The complexity of managing water resources for downstream countries in transboundary basins arises when most of the river flow or water resource originates outside the borders. This situation puts the water availability under the mercy of the climate variability and the mitigation measures and plans of the upstream countries.

Figure 1-2 shows that the climate change is one of nine factors affecting the negotiations between the transboundary basin and considered as a barrier for implementing a sustainable water resources management practices in transboundary basins.

The climate change affects the sustainability of water resources management in transboundary basins as they have influence on the local strategic plan for each riparian country and encourage building abstraction structures.

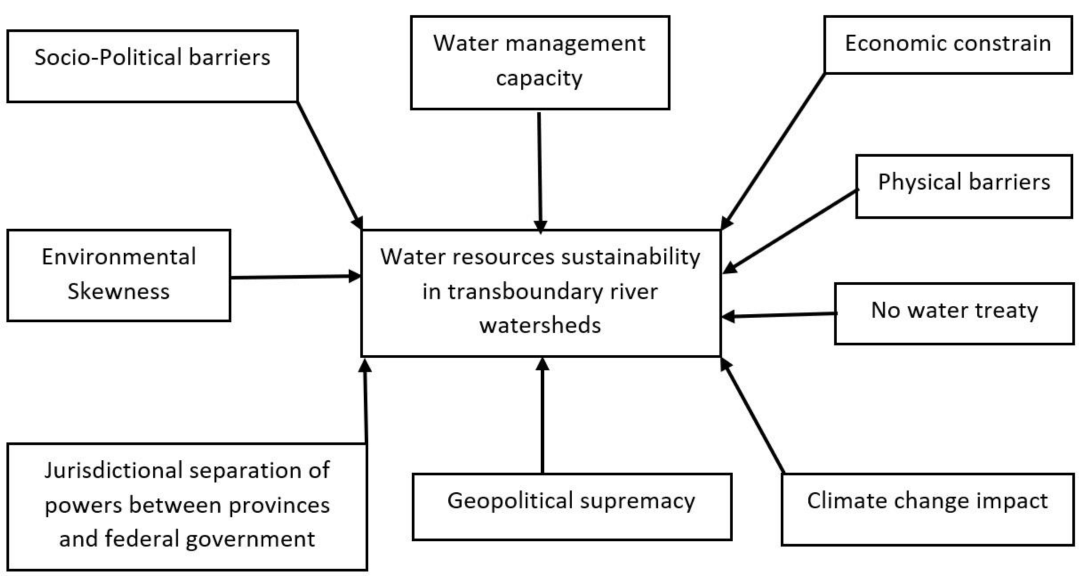


Figure 1-2: Driving forces affecting water resources sustainability in transboundary river watersheds. (After:(Al-Faraj and Scholz 2014))

The sustainability of water resources management in transboundary basins is affected by 9 factors (Al-Faraj & Scholz, 2014b). One of the factors that has influence on the other factors is the impact of climate change and how it can alter the precipitation and temperature. As a result of the climate change other factors will be affected and others will appear due to the interest of riparian countries to build structures on the river flow based on the water management policy of each riparian country. Due to the previous factors, implementation of water treaties between riparian countries will face difficulties and refuses from riparian countries.

The difficulty of reaching a treaty satisfying all the riparian countries, demands will appear also due to the location of the riparian countries either are downstream or upstream countries and the political strength of the countries, and if there are political conflicts between the riparian countries.

The climate change also causes changes on the environment in terms of the change in water quantity and quality, the mitigation of the effect of climate change on the environment needs the intervention of water management institutes which might be limited by some operating rules in some countries (Arnell & Charlton, 2009).

The construction of physical structures as dams can help in the process of mitigation of climate change effects but its construction is depending on the economic capability and constrains of some governments if the physical structures are costly. The construction of structures also can have negative effect on other riparian countries.

Some countries have more than 90% of their water resources originating from outside of their borders; for example, Egypt is one of the riparian countries and the last downstream country of the Nile basin. Also, Mauritania is sharing the Senegal river basin with Genia, Mali and Senegal, and Botswana (Chikozho, 2014).

One of the main contributors in a river discharge is the climate especially precipitation and temperature and the shifts that happen in the climate will eventually and directly affects the amount of a river discharge either with increase or decrease. The changes in the climate and the increased drought episodes lead to more conflicts between the riparian countries sharing the same basin or even different sectors in the same country due to the fear of water scarcity or decrease in water supply and not meeting the present or future demands (La Jeunesse et al., 2016).

The water resources could be affected due the changes in the precipitation, temperature and other meteorological factors such as the humidity, wind speed and even soil moisture, the effect could be felt in the droughts or floods phenomena with increased frequencies and/or magnitude that directly affects the water resources on both short and long terms (Olmstead, 2014).

Miller and Yates (2006) underlined that future climate change could influence municipal, industrial and irrigation demands, and proposed that an increase of about 1.1 ℃ would cause an increase of approximately 5% in average per capita municipal use, additionally, irrigation the main cause of water demand will increase due to the increase of the drought severity as a result of drought events.

Africa is facing problems with water resources and about a quarter of Africa population which is almost 300 million are facing water stress (UNEP, 2010). The climate change will add pressure on the water resources supply in case there is a decrease in precipitation, the availability of the resource and its accessibility, and increase in population will increase the demand in different sectors of water usage (Bates et al., 2008). Due to the current situation and the possible future scenarios of climate change the countries sharing the same basin should discuss how to mitigate these challenges and unite and produce basin wide sustainable management techniques.

1.2 Problem Statement

The world's renewable and suitable water resources availability is 43,802 Km^3/year, Africa share from the world total fresh renewable water is 3,931 Km^3/year which is approximately only 9% of the world fresh water, while the highest share is for Asia and South America, then comes North America and Europe (Table 1-1). The percentage of the share of each region does not give an accurate indication of the situation of water shortage in these regions.

Table 1-1 comparison of each country share of available world's fresh water after: (UNEP 2010)

Country/Region	Volume/year (Km^3)	%age of world freshwater	Per capita (m^3/year)
World	43802	100	6498
Africa	3931	9	4008
Asia	12393	28.3	3037
South America	12380	28.3	32165
Central America & Caribbean	781	1.8	9645
North America	6887	15.7	15166
Oceania	892	2	32366
Europe	6548	14.9	8941

The per capita annual availability of water gives a real image of the water availability in these regions. Africa is the second lowest continent after Asia in volume per capita per year value with only 4008 m^3/capita/year which is below the average world per capita share. (UNEP, 2010).

Fresh water is essential for the survival and development of countries as it is used for municipal, industrial, and agriculture purposes. For each country to achieve its target in development, it needs to secure its demands of water during the present as well as the future days.

The security of water demand could be achieved by sustainable water resources management, but riparian countries sharing the same river basin face difficulties in applying such practices due to the different interests between riparian countries sharing the same river basin.

Each country seeks its requirements of water without caring for the other riparian countries. The problem facing the downstream countries occurs when the freshwater is obstructed and withdrawn from the source of river flow in the upstream countries. The abstraction of freshwater is caused by excessive consumption of water in addition to the construction of dams and water exploitation projects.

Climate change impacts increase the stress between the riparian countries in the transboundary river basins due to the possible decrease in precipitation and increase of temperature and drought. During the previous 100 years (1900—2000) most regions of Africa had increase in near surface temperature with an average of 0.5 ^{o}C, except for central Africa there was no change. It is expected that there will be rapid increase in average temperature in Africa than the rest of the world. Concerning the precipitation in the last century no significant trend could be found and for the future projection, the Northern, Sahel and Southern part of Africa are expected to have decrease in precipitation and for the Central and Eastern Africa an increase is predicted in the future.

The water resources in the Eastern Africa is expected to be affected by climate change and reduced flows are expected to be detected due to high temperature and increased evapotranspiration and upstream development for irrigation and hydropower (Niang et al., 2015).

There are many knowledge gaps and a real need to assess the water exploitation and the effect of droughts as a representative of climate variability at transboundary scale and adaptation of current and possible future changes at a transboundary river basin scale.

There are three factors that contribute to the application of sustainable water management in transboundary river basins:

a) Scale of development in upstream countries,

b) The transboundary scale,

c) Scale of development in downstream countries.

1.2.1 Upstream Nations Development Scale

River flow reaching or entering the downstream countries is highly dependent on the extent of climate change at the river origins, and the good will of the upstream countries in case there is no treaty in allowing the flow to the downstream countries. Some upstream riparian countries, such as Iran, think they have the right to use every drop of all the water even originated in the country boundaries or passing through it without considering the interests of the other riparian countries (Al-Faraj & Scholz, 2014b). The river discharge is affected by the damming and water abstraction projects like irrigation projects and hydropower projects in the upstream countries. A study for measuring the changes occurred in Mekong basin river discharge for a period of 44 years, concluded that there was significant changes in the river discharge as a result of the hydropower operations (Räsänen et al., 2017). The effect of these projects is not steady from the date of operation and it will change with time depending on the climate condition; in addition, it will exacerbate when additional water abstraction projects are constructed in the future to cover the population and different sectors demand.

1.2.2 Transboundary Scale

Sustainable water management on the transboundary river basins scale depends on the agreement between the riparian countries on the rights or share of fresh water for each country of the basin. Egypt plans water consumption every year based on its right in water based on the agreement of 1959 that states the right of Egypt of 55.5 billion cubic meters (Swain, 2011b). The difficulty of applying sustainable basin management practices is due to the lack of agreement among riparian countries and the shallowness of understanding the influence of current, mid and long-term water abstraction especially when coupled with climate change. The case of the Euphrates-Tigris witnessed a lot of complication in negotiation and conflicts between the riparian countries, each country planned its water use separately without reaching an agreement with the other riparian countries. The conflicts and negotiations started from the beginning of the 20th century which caused a delay in implementing a basin wide water resources planning (El-Fadel et al., 2002; Kibaroğlu, 2017).

It is very important to exchange the data transparently among the riparian countries to provide accurate study of the changes in flow quantity and quality, in addition to data as pollution, quality of the ecosystem should be provided before the construction of large projects (Ganoulis et al., 2011).Efficient climate change and water scarcity adaptation depend on sharing the historical and present hydro-meteorological and river discharge data at transboundary level.

1.2.3 Downstream Nations Development Scale

As a result of the previous two points the downstream countries are the lower hand in international river basins which make it subject to water scarcity and insufficient water supply more than upstream countries. The upstream country can take more water scarcity mitigation measures than the downstream as they are facing one problem, which is the shifts in the climate change only, and the downstream countries will be exposed to the impacts of both upstream exploitation projects and/or climate change or both combined, which might lead to water scarcity in water quantity and/or quality. The Nile basin is a good example of the importance and complexity of the problem. The northern part of the Nile basin (Main Nile basin) shared between Egypt and Sudan is highly dependent on the runoff from three sub-basins of the eastern Nile basin (Blue Nile basin, Atbarah basin, and Sobat basin) (Peden et al., 2013). Figure (1-3) shows the Nile basin and Nile sub-basins, and the contribution of the eastern basins in the Main Nile river flow. The Blue basin is shared between Ethiopia and Sudan with a contribution of 59% of the Main Nile flow, the Atbarah basin is shared between Eritrea and Sudan with contribution of 13%, and the Sobat basin is shared between Ethiopia and Sudan with a contribution of 14% (Peden et al., 2013). Any change in the Blue Nile river or other main contributor basins flow is due to either climate change or human induced factors that directly affect the flow at the Main Nile basin. This effect will lead to water scarcity in the countries of Sudan and the greatest effect will be in the Egyptian river flow (Arjoon et al., 2014).

In order to build a coherent basin wide management strategy, the current situation of the river discharge should be clear for all sectors and countries contributing to the strategic management plan.

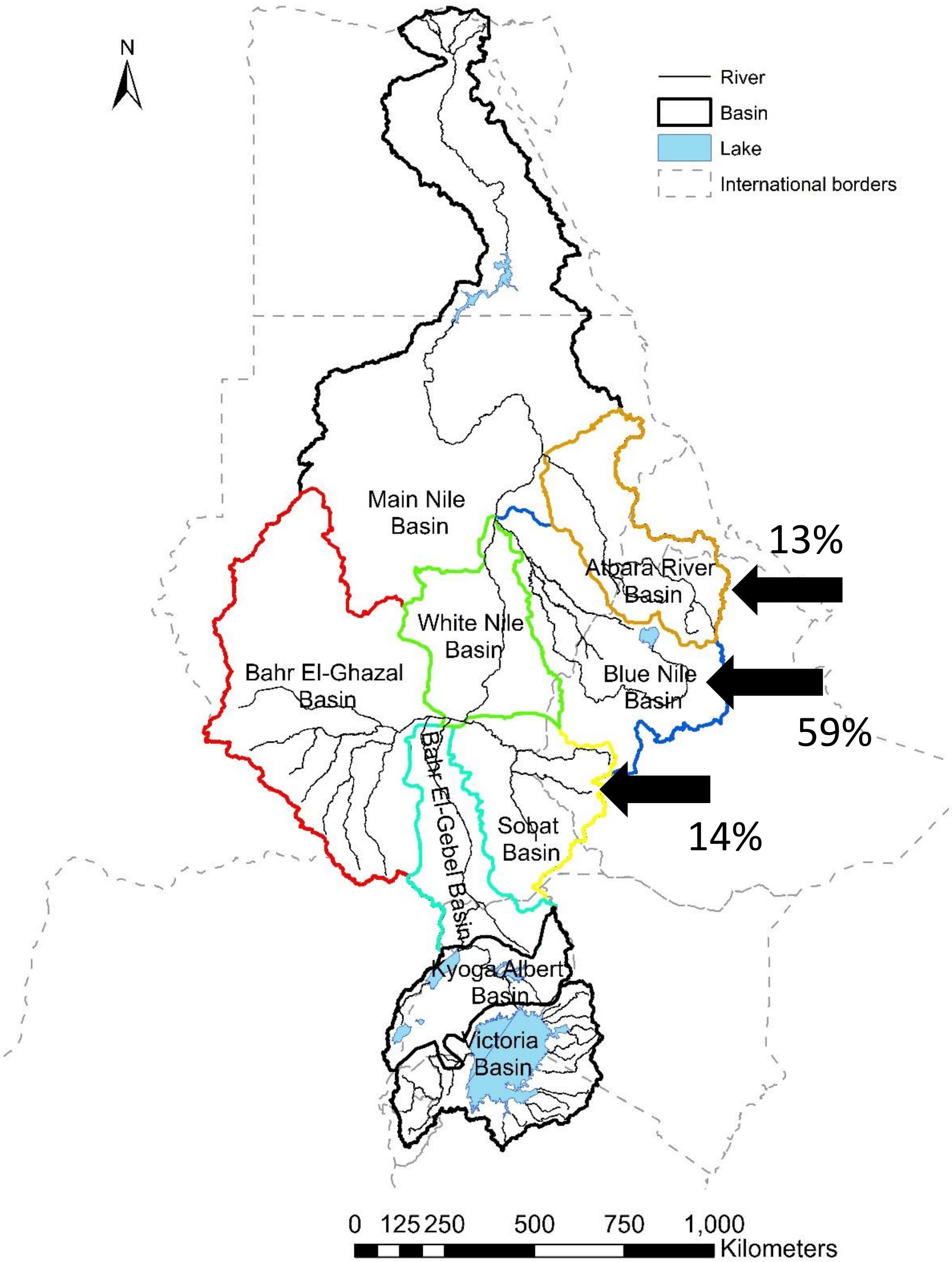


Figure 1-3 the division of the Nile River basin to Sub-basins (after: NBI, 2012)

The reasons led to the current river discharge situation in terms of climate variability and human interventions should be investigated and how the level of alteration in either or both terms affected the river discharge.

Based on the present situation of the river flow regime and the possible changes that might happen as decrease in river discharge and increase in water pollution as a result of climate change and human intervention, the countries and stakeholders sharing the same basin should set their goals and strategic plans based on this view (Global Water Partnership and International Network of Basin Organization, 2009).

This research investigates and evaluate the upstream water storage projects, and climate variability in form of changes in precipitation trends, and drought events, and how they have effect on river discharge reaching the downstream countries in transboundary river basins.

The complicated problem facing shared basins needs a representative case study watershed to assess the problem. Previously Furat and Miklas in 2014 studied the Diyala river basin shared between Iraq and Iran.

In this research the Nile basin will be the case study, the Nile basin is one of many other shared river basins in Africa as Senegal and in Asia as Euphrates. The riparian countries start to exploit projects to secure their demands of fresh water and to obtain the maximum use of the water passing through their border and the downstream countries are the countries suffering shortage in the supply to cover the different demand sectors.

Lately there was a concern in Egypt regarding the construction of a large dam in Ethiopia near its borders with Sudan. The concern in Egypt and its government led to conflict between Egypt and Ethiopia in the negotiation's stages on the storage amount, the years of filling and the operation of the dam in the future and specially in drought events. The main reason that led the Egyptians to be concerned about Ethiopia constructing a mega project (the Renaissance dam), was because that Ethiopia as an upstream country and the main contributor in the Nile river flow started constructing the Project without negotiating or reaching a treaty with Egypt that states Egypt annual share of Nile river discharge and the operation of the dam to secure its demands (El Bastawesy et al., 2015; Mulat & Moges, 2014).

The threats facing the river flow causing a decrease in the river discharge in transboundary river basin as climate variability should be mitigated using the help off all riparian countries sharing the river basin. The riparian countries should build a cohesive basin wide strategic plan to help in mitigation of climate variability that might help in maintaining the most precious resource.

Understanding the alteration in the river discharge due to climate variability and human induced factors for different countries and sectors could help in building a robust sustainable water resources management plan in transboundary basins.

The findings or the output of this research are expected to be a distinctive contribution to knowledge of sustainable management of water resources in shared river basins and especially in the Nile basin.

The Nile basin covers an area of 3 million Km^2 and is shared between 11 countries (Sallam, 2014). The Nile has different flow origins as the Lake Victoria in Tanzania in the south of the Nile basin, but the country with the highest contribution is Ethiopia.

The rain in Ethiopia highlands feeds three main tributaries; the Blue Nile river, the Atbarah river, and the Sobat river, on the other hand Egypt is the lowest country contributing to the river flow. Egypt is the downstream country and is the last country the river Nile is flowing through before it reaches the Mediterranean Sea.

The riparian countries are seeking economic growth through: a) increasing their hydroelectric production; b) increasing the agricultural area even rain fed and/or irrigated; c) securing their needs of water for domestic and industrial use. Some water obstructing structures are in operation with different interests from irrigation to hydropower generation while others are still in the building process and will operate in the near future (Awulachew et al., 2007; Block et al., 2007; Peden et al., 2013).

The assessment of the current and past situation of the effect of climate change and human intervention on the river discharge, could help in the insight of better future and minimize as much as possible the effect of the catastrophe that might happen because of both. The thesis answers four questions:

1. What factors affect discharge reaching downstream countries?
2. How much is the effect of the variability in climate and drought on the river discharge?
3. What are the effects of the climate variability coupled with human intervention on the river discharge?
4. What is the relation between the number and size of water abstraction projects and degree of alteration and the river discharge?

1.3 Aims and Objectives

The results and conclusions of this research give a good guide to develop or adapt representative measure(s) or technique(s) for sustainable water resources management that help in the mitigation of the possible future basin wide water scarcity and for downstream countries particularly:

The main research question is how the river discharge flowing to the downstream countries in transboundary river basins is affected by the climate variability specially when coupled with human intervention.

The answer to this question might help in determining the effective practices either in water demand reduction or increasing the supply or finding new sources of freshwater resources. The nature of the discharge reaching the downstream countries will be addressed from the past years and how it is affected either artificially or by climate variability effects or both combined.

There is a need to find a framework to help in analyzing the previous factors contributing in the alteration of river discharge. A framework for assessing how the development in the upstream countries influence increased with time and the impacts of the climate variability specially when both are combined.

The proposed framework might help in choosing the most suitable and effective measure to mitigate the water scarcity.

The main aim of the research is to construct a solid ground methodology and framework, that could help in better understanding of the present condition of the river discharge and how it is affected by climate variability, drought events and human induced factors; this methodology can support the implementation of appropriate water resources management practices and the choice of the most effective water shortage or scarcity mitigation measure in the downstream countries. The stakeholder decision will be based on the understanding of the changes occurring in the river discharge because the influence of climate change, drought events severity and frequency, and human intervention and might occur in the future. The aim of the research will be achieved through the following objectives:

Objective 1: To introduce a methodology for finding metrological data sets in scarce data areas and use it in measuring climate variability studies and drought events.

Objective 2: To evaluate the impact of climate variability and droughts on river discharge in Pre-dammed flow conditions and in intervened flow conditions.

Objective 3: To analyze the river discharge, and to assess the changes in the river discharge according to the degree of human intervention.

The achievement of the aim and objectives will answer the following questions and sub-questions:

1) Is the data reliable for the assessment of the climate variability in the study area?
2) How the river discharge is affected by the climate variability?
   2.1) What factors affect discharge reaching downstream countries?
   2.2) How much is the effect of the variability in climate and drought on the river discharge?
3) Does the human intervention have an influence on the river discharge and does the degree of intervention differs?
   3.1) What are the effects of the climate variability coupled with human intervention on the river discharge?
   3.2) what is the relation between the number and size of water abstraction projects and degree of alteration in the river discharge?

The aim and objectives answering the main research question as explained in the following chart.

Research Question

The main research question is how the river discharge flowing to the downstream countries in transboundary river basins is affected by the climate variability specially when coupled with human intervention.

Research Aim

To construct a solid ground methodology and framework, that might help to better understanding the situation of the present condition of the river discharge and how it is affected by climate variability, drought events and human induced factors

Question 1

Is the data reliable for the assessment of the climate variability in the study area?

Objective 1

To introduce a methodology for finding metrological data sets in scarce data areas and use it in measuring climate change studies and drought events.

Question 2

How the river discharge is affected by the climate variability?

Objective 2

To evaluate the impact of climate variability and droughts in unaltered flow conditions and in intervened flow conditions.

Question 3

Does the human intervention have an influence on the river discharge and does the degree of intervention differs?

Objective 3

To analyze the river discharge, and to assess the changes in the river discharge according to the degree of human intervention.

Figure 1-4 relation between research question(s) and research aim and objectives

1.4 Importance of Study

Based on the problem statement, there is a knowledge gap in the effect of climate variability in transboundary basins and specially when coupled with human intervention. The findings of this research can help in the sustainable water resources management of fresh water in the transboundary river basins, especially with respect to water availability to downstream countries and the mitigation of droughts and water scarcity.

the findings of this research also might help stakeholders to quantify, determine and understand the impacts of the upstream exploitation coupled with climate change in order to make backup plans to minimize the expected impact of the crises.

The study of the Nile basin could be considered as a representative of many of transboundary river basins suffering from the same situation. The findings and conclusions are expected to form a distinctive contribution to the knowledge of sustainable water resources management at transboundary scale.

The methodology and the findings of the research could contribute to better water resources management and planning for future water consumption and use. The methodology provides an assessment of the main controlling factors of the river discharge, the climate variability, and the human intervention.

According to the results and findings from the methodology and analysis, the downstream countries can assess and expect the water availability to re-arrange the water resources management plan to cope with the situation of the river discharge. The assessment of the river discharge situation can help in the negotiations of the technical operation of water structures and use along the river discharge between riparian countries and different sectors.

The solution can be either to find new water supply sources or to minimize the water demand.

1.5 Structure of Thesis

This study consists of six main chapters. Chapter 1 contains the background, problem statement, research questions, aim and objectives, importance of the study and the structure of the thesis. Chapter 2 recounts previous research work on:

- Water resources management and obstacles facing the application of water management practices.
- Water scarcity and drought.
- Effect of Climate change on the river flow through floods and droughts.
- Human induced factors and their effect on river flow regime.
- Measuring the changes in the rainfall, temperature patterns using trend analysis.
- Indicators to measure the climate change and indicators to measure the influence of the man-made projects on the downstream countries.
- Summary of the literature and the lessons learned and how the literature helped in formulating the methodology.

The description of the study area and the main contributor sub-basins in the river flow can be found in Chapter 3, in addition to the description of the methodology used while studying the problem to achieve the objectives and the aim of the research. The chapter discusses the following items:

- The data required to implement the research.

- The description of the study area and the complexity of the situation in the Nile basin; Presentation of the data collected, and the water abstraction projects in the basin.
- Choosing the appropriate climate data for scarce data areas.
- Adapted methods for assessing climate variability using parametric and non-parametric trends.
- Method used for assessing the drought events in the study area.
- Method used for assessing the effect of climate variability and human intervention on the river discharge and which objective they fulfil.

Chapter 4 is the results of the study and how climate variability and human intervention factors contributed to changes in river runoff.

The chapter starts by showing if there was a change in the precipitation trends using parametric and non-parametric methods for the different main sub-basins of the Nile basin. Discussing the drought events and the classification of the drought severity for each time-window. The number of drought events on monthly and annual scale within each time-window and the number of stations witnessed drought and their distribution in the main sub-basins.

The changes in the precipitation pattern between the different time-windows and how they are related to the changes in the discharge pattern of the same time-windows for the key stations.

Assessing the effect of both water exploitation and climate variability and drought event on the river discharge reaching downstream countries at the transboundary level.

The discussion if the results are covered in Chapter 5. In this chapter the explanation the results and their effects of are discussed in addition to comparison with some of the previous research.

The conclusions are covered in Chapter 6.

Chapter two: Literature Review

2.1 Introduction

Water is not a product being traded but is a natural resource that must be managed wisely for present and future needs and protected from any interventions threatening its quality and quantity (Luderitz, 2004). Fresh water is essential for human health and the development of countries, even though the fresh water content of the world's water available doesn't exceed 3% of the total world's water content, out of which only 0.3% is available as surface flow (Forare, 2009). The freshwater resources are not distributed equally between the different countries; many countries share the same river basin with different ratios in fresh water allocation, some countries are upstream which have the control in the river flow of the basin, while other countries are downstream countries, and have no control on the river flow reaching its boarders.

There are 263 basins worldwide with different number of countries sharing the same basin, with different levels of conflicts between these countries on sharing the basin water resources. These basins convey about 60% of the global fresh water and serving more than one third the world's population (Sallam, 2014).

Every country is seeking to satisfy its demand of the freshwater resources from the available water supply. The demand is not steady, it changes with time depending on the chaneges in population and the level of development, neither the supply is steady it might be subjected to decrease because of climate changes and what it can do in the hydrologic cycle for example, decrease in precipitation and increase in temperature and evaporation. The decrease in the available water resources and the increase in the demands may increase the tension and conflicts between countries or even between competing sectoral users in the same country (Uitto & Duda, 2002). Any change in the natural climate conditions, as decrease in precipitation is considered a threat to the social, economic and environmental lively hood (UNEP, 2010).

The number of countries sharing the same basin increases the conflicts on the share of each of the transboundary countries on the available water resources. Danube river is one of the transboundary basins and shared by 17 riparian countries, and any decrease in the freshwater resources either due to climate change or human intervention for any of these countries especially the downstream countries, will lead to a conflict between these countries. Based on this possibility of the climate change in a report of the Intergovernmental Panel on Climate Change (IPCC) 2013 in Danube river zone, (Stolz et al., 2018) predicted the possible climate change impact on the Danube river basin. The results showed that all portions of Danube will be affected with water shortage but with different scales, which eventually will lead to a conflict on shares of water resources between riparian countries.

Asia also has transboundary basins, based on (Bernauer & Siegfried, 2012) the climate change has its physical effects which can be seen in the changes in the rainfall and temperature, as well as political and social effects as a result of conflicts between parties on the fresh resource. The conflicts become more complicated as the countries are poor and suffering from complicated internal politics.

The Mekong river is one of the transboundary basins in Asia and shared by 6 countries. Many studies have been covering the possible changes in climate in Mekong basin, the results were promising in both wet and dry seasons with increase in the flow. The main problem in the Mekong basin is the increase in the dams construction. Since 1965 till

2018 more than 80 dams have been constructed beside the possible increase in the water withdrawal for the irrigated land, the main consumer of water (Hecht et al., 2019).

The Nile river basin is one of the biggest international basins in Africa and worldwide and is highly populated, as its population is over 200 million people with a ratio almost 25% of Africa's population (UNEP, 2010). Adenan and Noorani (2013) Highlighted that the population growth and economic development in an area is accompanied with an increase in the freshwater demand to satisfy the needs.

From the this section, it is concluded that there will be a high competition generally on water as the freshwater resource might become rare to find as a result to the climate change and the increase in demand due to increase in population and temperature. The conflict on water is going to be highly noticed in transboundary countries sharing the same resource.

2.2 Sustainable water resources management in transboundary scale

Minimization of the conflicts that are possible in the future for freshwater accessibility, will be achieved through agreement between the riparian countries and applying basin wide practices. The world's fresh water resources are limited which make them under continuous pressure from man-made actions and natural or environmental change such as desertification, urbanization, and economic growth (Harlin & Morrison, 2009). The possible challenges facing countries in sustaining the natural resource raise the concern to manage the available water resources sustainably.

Water resources sustainability is defined as “the capability to provide water for the needs of people and ecosystems without impairing capabilities for continuing to meet future needs” (Wurbs, 2014, p. 1).

Lenton et al. (2009, p. 5) defined the water resources management as it is “The development of infra structure, the allocation of the resource, the implementation of the incentives for its efficient use, its protection, as well as the financing of all these activities”.

It was also noted that unless sustainable management practices applied to water resources, broader development goals will not be achieved (Lenton et al. 2009).

Sustainable water resources management is an important procedure to achieve sustainable development for countries and nations. Sustainable development is satisfying the requirements of the present while keeping all the ecological, environmental, and hydrological integrity and without affecting the ability of the future generation meeting their own needs (Ramakrishna, 2004).

Water resources management practices are considered, planned and applied for the benefit of multi-users. The benefit is that each party receives the required demand of the freshwater and to minimize the effect of extreme climatic events (Al-Faraj & Scholz, 2014b).

AL Radif (1999) highlighted some of the water problems that should be considered in the water resources management plans, which are: a) the uneven distribution of the precipitation, b) the impact of world population growth on water resources where the demand of water increases either domestic, agricultural, or industrial but the water resources supply is the same, c) water scarcity which is due to unsustainable water management practices, and d) the climate change which increased the severity of floods and droughts.

The previous problems concluded by AL Radif can be mitigated or adapted by applying sustainable water resources management. There are some obstacles preventing or delaying the application of the sustainable water resources management especially in transboundary basins, some of these challenges are: a) the population increase, global population increased around 1.7 billion between years 1992 and 2012 in addition to population density and demography, b) As a result of the increase in population there is a sharp increase in the demand of water to supply the need of food and energy, c) competition between different water users and different sectors; d) climate change, and e) Upstream users intervention from groundwater mining, pollution and water abstraction led to the reduction of water availability in many areas (UNEP, 2012).

The upstream sectors or countries intervention in a shared basin is a major challenge water resources manager must consider. The increased demand on water in different sectors as domestic, irrigation, and hydropower resulted in high competition on the water resources between riparian countries and different users in the same country (Masih et al., 2009). The effect of climate change and the increased water abstraction and consumption and the increased water storage, caused a water shortage in some countries of west Africa. The water shortage increased the conflicts and tension between the riparian countries (Thomas, 2008).

The human intervention and construction of water abstraction projects on the rivers to satisfy the increasing demand of fresh water in irrigation, domestic, and industrial use have risen the concern to understand and estimate the impact of these interventions and projects on the hydrologic regime of the riverine systems between different sectors using water and especially in transboundary rivers. The hydrologic regime of a river is the magnitude, timing, frequency, duration and rates of runoff (Poff et al., 1997).

The achievement of the optimum sustainable water resources management in transboundary river basins, depends on understanding how the climate change and human intervention affected or caused changes in the natural flow regime (Al-Faraj & Scholz, 2014b).

The application of water resources management is very essential for countries suffering high levels of population growth and, in the meantime, seeking economic growth. The situation is more complicated and harder to manage when these countries are downstream countries.

Egypt in the Nile basin is a good example of the dependence of the downstream riparian countries on the Transboundary River flow. Egypt is more than 90% dependent on the Nile flow, the lack of a basin water management between the riparian countries might affect the runoff reaching Egypt or downstream countries in other transboundary basins (Selby & Hoffmann, 2014).

The main problem facing the sustainability of the water resources on transboundary scale is the absence of the water treaty or agreement and if there is any agreement between the riparian countries, a significant weakness can be found such as underestimation of the future impacts and the absence of strong framework between riparian countries for coordination and collaboration (Al-Faraj & Scholz, 2014b).The agreements between countries on shared waters promoted peace, security and economic growth for the whole region (Brels et al., 2008). History assures that the challenges presented at transboundary waters were solved by cooperation and not conflict and fighting over the available water resources. The number of international water treaties or agreements achieved is more than 300 agreement while the conflicts were only 37 cases (Harlin & Morrison, 2009).

There are different types of frameworks to achieve agreement between different parties (Ramakrishna, 2004), the used framework in the Yamuna river basin is the water resources accounting framework, the water resources accounting framework uses the regional water quality and quantity management.

One of the main challenges facing the water resources management is population which is reflected in the increase of water consumption directly as in domestic use or indirectly as in irrigation and industry. The population is a strong threat and difficult to control and the rates of population increase are not promising for maintaining each person annual usage of fresh water.

The climate change is one of the factors that is not controllable and difficult to predict, the only action nations and governments can take, is just mitigate its effect. The factors caused by climate change, are the change in the distribution of precipitation and the changes that might occur in the future either increase or decrease, the changes in temperature and drought events. The third problem facing water resources engineer is the human intervention in the upstream and the conflicts between water users.

The previous reasons are more dangerous and more complicated in transboundary water, where each country wants to secure its use of water due to increase in population and the increase of water usage in different sectors. That security for each country is achieved through the construction of mega projects in the upstream countries without thinking of the downstream country needs (Calvi et al., 2019).

The lack of collaboration between the riparian countries and the mismanagement of water resources under the influence of climate change and human intervention in transboundary basins may have dramatic impacts. The Aral Sea is a good example of the effect of excessive expansion in irrigation land without following a sustainable management plan. The Aral Sea lake was considered the 4th world largest lake in surface area until the 1960s. the area was then decreased gradually to be 60,200 km^2 in the 1971 instead of 67,499 km^2, in 1976 there was a further decrease until it became 55,700 km^2. The decrease was continuous until it shrunk to 6,990 km^2 in 2014 (Micklin, 2016).

The excess human intervention in the Aral Sea was in the form of irrigation expansion. The irrigable land increased from 4.5 million ha in 1960 to more than 140% by the 1990s in addition to the cultivating desert land that requires excess water. The second form of human intervention was the construction of dams. More than 80 reservoirs were constructed with different purposes and the water withdrawal jumped from 64.7 km^3/year in 1960 to 107 km^3/year in 2006 (FAO, 2012). The excess water consumption was due to the change in climate hotter rainless summer and snowless winter forced farmers to change crops to more water thirsty crops, which led to more water consumption (FAO, 2012).

There are different examples of drying wetlands and lakes at different climatic conditions as the Chapala lake in Mexico, Lake Chilwa and Lake Chad in Africa (Okpara et al., 2016). The lessons learnt were ignoring the sustainable management practices especially in transboundary basins can lead to a catastrophe harming all the riparian countries and stakeholders.

The riverine ecosystem should be protected through integrating policy and science to make river management more sustainable. The riverine system has been affected due to the impacts of climate change and human needs that resulted in more dam construction and more changes in the land scape. River management should pay more attention for the protection and restoration of aquatic environments. There are different principles for sustainable river restoration such as restoration strategies across spatial scales, process oriented versus static approaches, setting goals and benchmarks for river restoration and Socio-political forces that restore river basins (Schmutz & Sendzimir, 2018).

In conclusion of the previous discussed literature, treaties between upstream and downstream countries related with the abstraction projects design should be done to sustainably manage the water resources and all the countries takes its own rights of the water available.

It is hard to find and implement water resources management between riparian countries although it is highly required as it will be reflected in preventing the start of conflicts and tensions between countries with different interests on the available water resources. An agreement should be achieved fulfilling all the requirements or most of them between the riparian countries, the upstream countries should consider the needs of the downstream countries and plan their development according to the benefit of both upstream and downstream countries.

To provide better future for the coming generations, the present water resources must be managed sustainably. The sustainable development generally is highly correlated with sustainable water resources management.

2.3 Water Scarcity and drought

The world is suffering from the increase in both water quality and quantity scarcity. The main contributor to the increase of the water scarcity is the increase in the demand for fresh water due to the increase in the global population (Uitto & Duda, 2002).

According to Uitto and Duda (2002) there will be scarcity as long as there is a growth in population and even if the climate conditions are the same. Accordingly, any changes occur to the normal climatic condition will dramatically lead to additional stress on the water scarcity, one of the images of climate change is the drought events. Drought is not a physical destructive natural hazard like earthquakes, but drought can affect large regions and causing impacts on different aspects economically, environmentally, and socially. Drought is also considered the number one natural hazard in terms of directly affecting people (Hayes et al., 2004; Sheffield & Wood, 2008), although drought is a result climate variation and is a natural disaster but the effects of drought can be exacerbated due to unhealthy man habits and intervention (Sheffield & Wood, 2008).

At present days and the last decades and due to global warming that is considered a reason of climate change the drought phenomena became more frequent and more severe (IPCC, 2013). There are factors helping in expecting more severe and frequent drought events as the increasing demand accompanied with the population growth and the expected climate change alterations in increasing temperature and decrease in precipitation (Al-Faraj et al., 2014). Drought severity is measured based its frequency and duration any increase in droughts severity will affect the hydrological cycle, which will eventually affect the runoff and discharge of rivers. For these reasons, it is important to expect and estimate the future drought impacts caused by severe droughts due to climate change (Al-Faraj et al., 2014; Nam et al., 2015).

Based on the discussed literature in this section, drought is a phenomenon that will occur according to a nature cycle, and it will exacerbate with the climate change in areas expected to have low precipitation and high temperature in the future. This phenomenon can't be stopped but it can be mitigated through making early warning and prediction of upcoming drought events.

2.4 Climatic and non-climatic drivers

2.4.1 Climate change and its effect on river flow

Climate change has direct and indirect effects on the riverine ecosystem. The direct effect can be felt in the alterations in the hydrological cycle and increased water temperature, while the indirect effects can be seen in the change of land use and using water as a source of renewable energy. The climate change can lead to increased drought frequency, reduced run-off from snow, earlier spring warming, increased water use for irrigation, changed river discharge due to dams construction and increase of water pollutants, which will lead to freshwater biodiversity loss (Pletterbauer et al., 2018).

Climate change is not affecting a certain area of the globe without the other area, but it has a global effect on the hydrologic cycle at an unsteady rate, which increases the challenges and the complexity of facing the variability of rainfall, droughts and flooding. The future projection predicts that nearly 1.8 billion people will be facing water scarcity by the year 2025, and about two-third of the world's population will be facing water stress (Harlin & Morrison, 2009). In the present time almost half of the world population suffer of water scarcity for at least a month per year. This percentage is expected to increase to reach almost two-third of the population. The most affected population will be in Africa and Asia (Boretti & Rosa, 2019).

Some of the processes of hydrological cycle especially the precipitation and evapotranspiration processes will be affected by the climate change and the global warming, any decrease in the precipitation and increase temperature will change in the nature of the runoff and increase the evapotranspiration, that is why there is an urgent need for water resources managers, stakeholders, and decision makers to sustainably manage the water resources for maintaining the ecological functions of water ecosystems (Brels et al., 2008). The climate change has effect on different components of the water cycle as precipitation and evapotranspiration. The precipitation did not have homogeneous changes for the entire globe. The location and the period of study affected the changes in precipitation results, some portions of the globe experienced increase in precipitation, while other witnessed decrease in precipitation. The rise in temperature caused a significant rise in the evapotranspiration of the globe. The combination of change in precipitation and rise in temperature led to increase of flooding events in some portions with increased precipitation and increased drought events in other portions. Africa had the highest drought events than the rest of the world from the 60s till now (Dagbegnon et al., 2016).

The number of areas or zones facing the water stress is growing and the climate change will cause an increase in that number due to the high variance in water resources accessibility and severe frequencies or intensities of floods or droughts events (UN-Water, 2008). Desertification and land degradation are increased under the influence of climate change affecting about 500 million people in 2015. The most significant regions suffering desertification are the Sahara region, North and middle east of Africa and the Middle East (Shukla et al., 2019).

On the transboundary scale it is expected that climate change might add pressure on water resources either in water availability or in water quality or both. Climate change will increase the risk from flash floods and droughts (UN-Water, 2008).

Global warming is caused due to the increase in the concentrations of greenhouse gasses, IPCC, 2007 stated that four main greenhouse gases concentration increased due to human activities, these gases are: carbon dioxide (CO_2) as shown in (Figure 2-1), methane (CH_4), nitrous oxide (N_2O) and the halocarbons (Stocker et al., 2013).

Other factors also contribute in the global warming is the concentration of volcanic aerosols in the atmosphere; the Sun's ever-increasing solar energy output; and cyclical changes in Earth's orbit are natural influencers on Earth's climate (Rafferty, 2011).

The global warming can be observed in the changes in surface temperature, changes in ocean characteristics, sea level rise, melting of snow and ice, changes in precipitation, increase in water vapour, and the increase in the number of warm days (Rafferty, 2011).

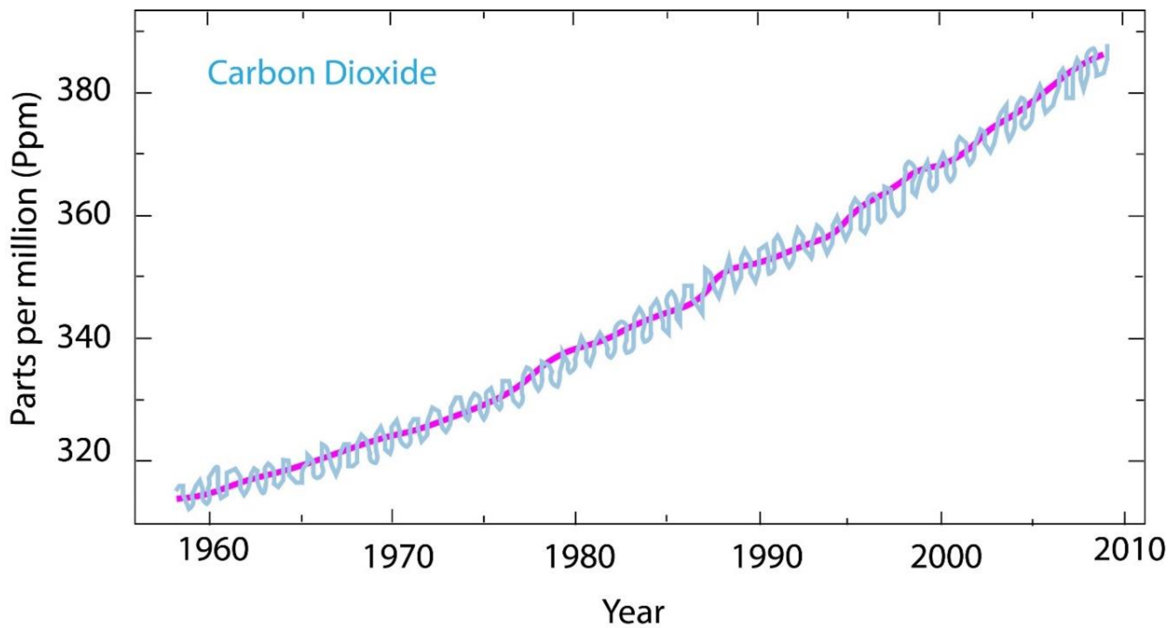


Figure 2-1 Carbon dioxide concentration from 1958 to 2009 (after: (IPCC, 2013; Richardson et al., 2009))

The Earth is getting warmer based on direct thermometer for 150 years (Silver, 2008). During the 20th century there was an increase in the earth's temperature by approximately 0.6 ± 0.2 °C (IPCC, 2001). The increase in the average temperature for period 2003—2012 was 0.78 °C when compared to temperature between 1850—1900 (Stocker et al., 2013).

In addition to the change in temperature, there was changes in the precipitation patterns and the precipitation patterns change globally between increase in regions and decrease in others. Some regions experienced increase in precipitation, while other parts suffered from droughts. An increase in drought events were observed since 1970s. Figure (2-2) shows the distribution of the precipitation and the alteration happened in the 20th century. The green circle is an indication if there is no change or increase in the precipitation trends, while the orange color is an indication of decrease in the precipitation trends. The larger the circle the larger the alteration. The worst alteration occurred was in two locations, the Sahara region in Africa, all the region suffered decrease in precipitation trends with different values. The second worst area was the west-southern part of Latin America also suffered a decrease in precipitation trends between 30 and 50%. Europe have some regions suffered a decrease in precipitation trends but with no more than 20%, while most of Europe had increase in precipitation trends reaching 40%. The best precipitation trends occurred in Northern America and Australia reaching maximum of 40% increase in Australia and 50% for Northern America. In 2005 Amazon and parts of Asia and Africa suffered from increased drought intensity (IPCC, 2007).

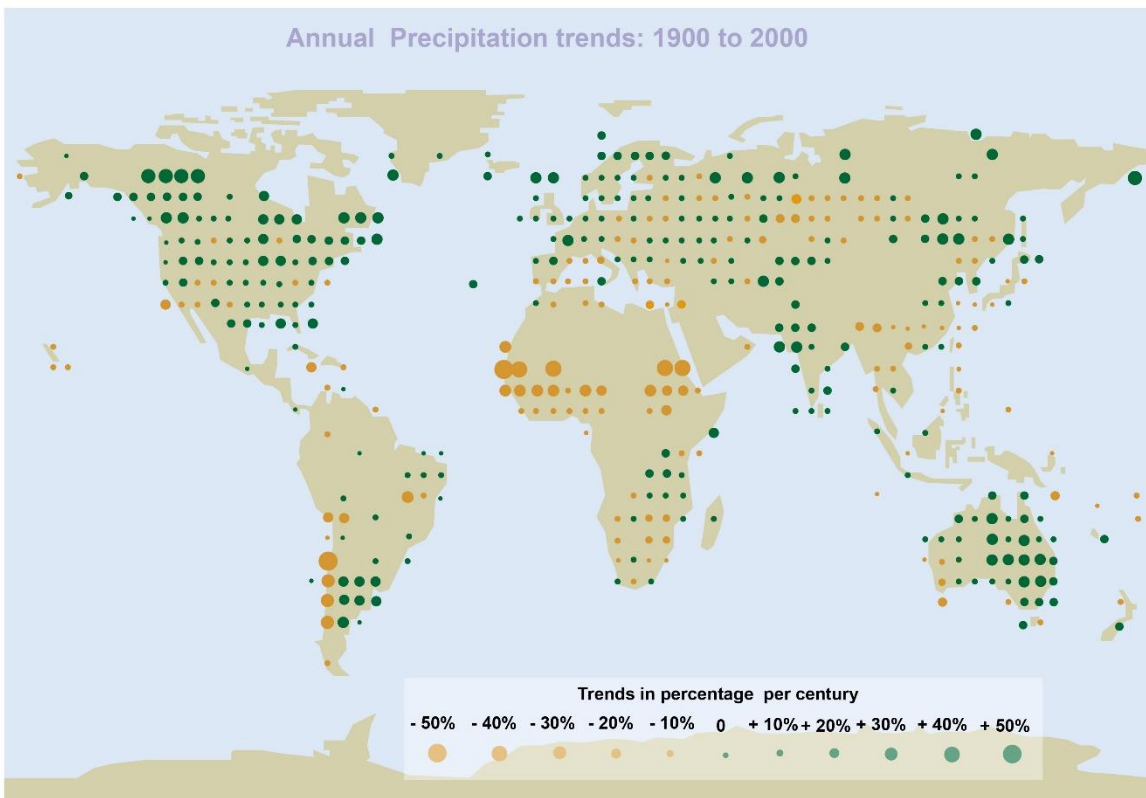


Figure 2-2 Annual precipitation trends between 1900 and 2000, (after: (IPCC 2007))

One of the forms of climate change is heat waves. Europe suffered in summer 2003 heat waves with high temperature and more than one day. February the 4th 2004 was a remarkable date in England, the temperature on that date reached 12.5 °C in central

England which was the highest early February temperature since records began in 1772. The month of February was also the occasion of a severe heat wave for different parts, in Brisbane, North Australia, where there were 29 sudden deaths in one night (Smith, 2005). The period between 1954 to 2015 was assessed in terms of heat waves intensity that led to death of people and crop wilting. The most severe heat waves was observed from 2003 to 2015 with 60% of the total events for the whole study period (Russo et al., 2015).

From the collected literature about the climate change there are different factors causing the changes in climate and there are proofs of the changes in climate. The changes in climate are not controllable and the factors forcing the climate to change can't be stopped immediately since it started with the industrial revolution, and even if it stopped it is not clear how the climate is going to react to that action. There is an urgent need to mitigate the climate change impacts on the water resources sector until the human forces leading to climate change are controllable.

Al-Faraj and Scholz in 2014 schematized the adaptation options to climate change (Figure 2-3) as the climate change is one of the factors affecting policies and actions between the riparian countries in a transboundary river basin (Figure 1-2) (Al-Faraj & Scholz, 2014b).

As a mitigation measure for the climate change in water resources, Al-Faraj gave a good guide to follow in both supply and demand sides. The supply side has seven practices, the seven practices cover different options for countries suffering water shortage. Some of the options are difficult to apply for downstream countries and require the contribution of the upstream countries as the inter-basin water transfer and the increase of water storage. Another solution is the desalination of sea water, the problem of this solution appears when some countries do not have coasts to use the sea-water desalination method.

The third measure proposed by Al-Faraj was the increase of storage capacity, this method is affective but for the upstream countries which control the runoff of the hydrologic cycle, while the downstream countries have a limited share of water and cant increase its share without treaties.

Al-Faraj proposed different methods depending on the nature of each country to mitigate the climate change, some methods depend on the economic constrains of each country, while other methods require high technology and depends on the precipitation nature of the region.

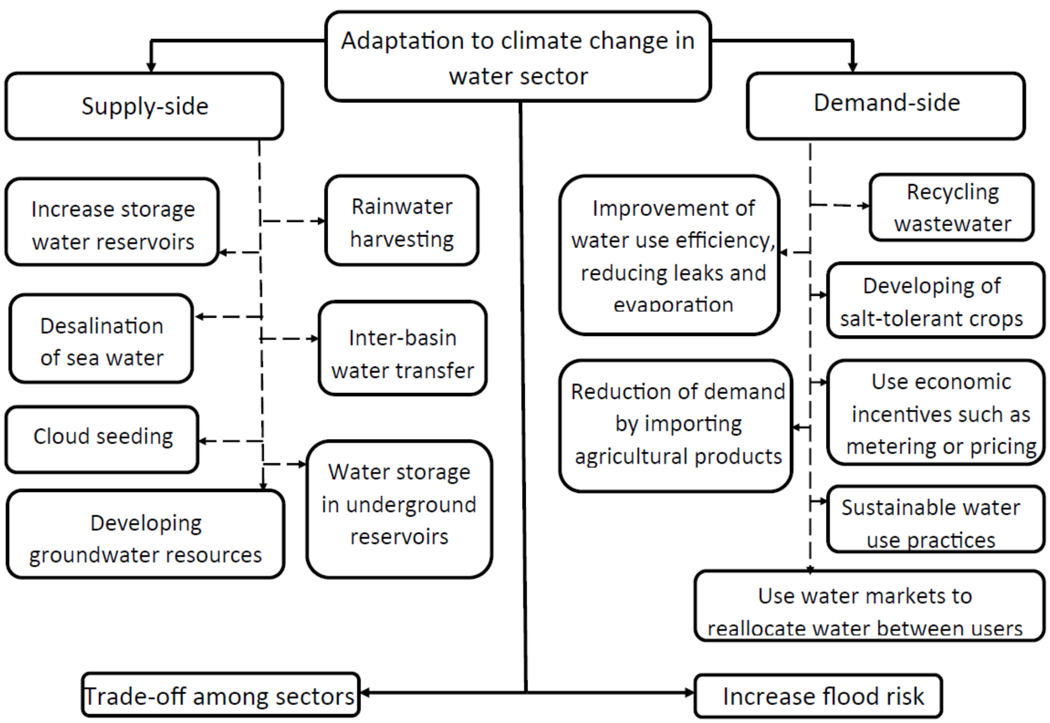


Figure 2-3 Options for adaptation to climate change. (After:(Al-Faraj and Scholz 2014))

According to Figure (2-3), Al-Faraj discussed the mitigation of the climate change in water resources from the demand-side as well as the supply side. The demand side has seven methods to mitigate the climate change. All the options depend on country level management and mostly related to the irrigation, the main consumer of water, as the improvement of water efficiency, water recycling, importing agricultural products and developing salt tolerant crops and other economic practices.

The climate change is considered a major threat for developing countries, due to the poor adaptation measures in these countries. The problem of climate change in these countries is exacerbated, because they depend on the water resources in their economy which is based on irrigation(Melkonyan, 2015).

It is not important what is the reason of climate change either caused due to natural climatic cycles or human induced activities or both combined, any shift in the climate have a huge impact on the hydrologic cycle. It is important to predict river flow for a convenient water resources management and proper distribution between water users or between countries in transboundary basins (Adenan & Noorani, 2013).

Sharif et al in 2010, attempted to link extreme flow measures with large scale climate indices; the data analysis included extreme changes in timing and magnitude of flow events and the responsible of these changes was the climate change (Sharif et al., 2010).

Thodsen (2007), helped in the prediction of the climate change and its effect on the river flow. The method used was a regional climatic model and based on the IPCC scenarios and the predicted changes in the precipitation, modelling the discharge using a rainfall/runoff model.

2.4.2 non climatic drivers

Large-scale modifications have occurred in the natural flow conditions of many rivers worldwide. The modifications in the form of human intervention can be seen in the construction of dams, river diversion, changes in land use, and groundwater pumping (Poff et al., 1997). These activities resulted in changes in the flow regimes as discharge reduction, besides adversely affecting the ecological functioning of water ecosystems (Chimtengo et al., 2014).

Some studies discussed the influence of both climate change or variability and the human intervention on the river flow regime. Perez et al (2019), analyzed the stream flow time series at the Inn and Adige catchment to assess the changes in the river discharge due to natural and human induced factors. The human induced factors as the structures construction and the changes in the water management policies and practices. The results showed that the human intervention which is the dam construction and the hydropower plants had higher effect on the river discharge than the natural variations.

A study was performed on the Mekong basin in Asia to measure the impacts of both climate change and dam development, specially, with the rising in demands in food security and energy. The problem was that the mitigation of the increased demands due to population growth, was the construction of dams, and in addition the climate change had led to changes in the flow regime. The factor with the greater impact on the flow regime and affects the security was the decrease in precipitation. What was interesting is that the dam development had a negative influence on the river flow regime but, it also might be used to minimize the impact of the climate change in some portions of the transboundary basin (Yang et al., 2019). What Yang et al achieved in this research gives an indication that the water resources management on transboundary scale might have the solution for water scarcity in some portions of transboundary basins.

Chen et al (2016) applied a study on the Yangtze river in China. The study aimed to measure the changes in the trends of the precipitation, Temperature as a response for the change in climate and the trends of river discharge due to changes in climate and also human intervention, especially after the construction of three large dams. The results of the research showed that the main contributor in the changes of the river discharge was the human intervention and not the climate change. The precipitation was not affected by the change in climate, the increased construction of the structures on the river especially, for the hydroelectric purpose had the higher influence for the changes in discharge. The changes were increase in discharge for some months and decrease in other months. The reason for these changes was the storage and release of water for the operation of the hydroelectric dams.

Chimtengo et al (2014), analyzed the Rivirivi river flow behavior in natural and altered periods, before and after water allocation practices and construction of dams and used water quantity indicators. In order to implement this study more than one index was used, from these indices the high flow index and the median flow index. The results of the study showed the annual river flow changed between the pre- and post-alteration period, the zero flow has increased. The change in the land cover and urbanization caused increase in the high flow between the two periods. The authors also recommended to consider management techniques to meet the water demands.

According to the previous research mentioned in this section the river flow regime or discharge is affected due to the influence of climate change, human intervention with different purposes or both combined. Some studies showed changes in river discharge either by increase or decrease to satisfy the human demands. What was interesting is that the human intervention can contribute to the water resources management of the transboundary basin.

The previous research discussed in this section are exciting for the study of the impacts of climate variability and human induced factors on different basins with different conditions and the react of the river discharge due to the effects of both climate variability and human intervention.

2.5 Trend Analysis

The precipitation is the main factor of the hydrologic cycle, any change in the precipitation has the highest impact on the rest of the cycle. The changes in the precipitation in a region in a river basin as an example is caused by the changes in climate (Onyutha et al., 2016). The decrease in precipitation will affect dramatically the supply of fresh water for a certain region, the decrease in rainfall intensity and frequency is a sign of change in climate, Syafrina et al (2015), were interested in measuring the changes in the rainfall events using hourly rainfall data and the tools used for analysis were parametric and spatial trend analysis. The year was divided into four rainfall seasons, and the parametric method used was linear regression beside the Ordinary kriging as a spatial pattern trend tool. What was found was increase in the trend of rainfall with different degrees.

The trend of metrological and hydrological data can be measured by many and different number of methods and based on the data distribution type. The data normally distributed can be tested using parametric tests, one of the ease to use methods for measuring the trend for normally distributed data is the linear regression method. The data which are not distributed normally can be analyzed using nonparametric tests, the most common method used by researchers is the Mann-Kendall test (Tabari & Hosseinzadeh Talaee, 2011).

Different methods are used to measure the changes in trends parametric and non-parametric. Even the parametric test is more powerful but the most used by hydrologic researchers is the non-parametric tests (Ahmad et al., 2015), the wide spread test by the researchers is the Mann-Kendall test used by (Longobardi & Villani, 2010; Mohammed et al., 2017; Xia et al., 2012; Yang et al., 2012). The Mann-Kendall test has some statistical advantages compared to parametric tests which encourages researchers to use this test for checking the trend in hydrological and meteorological data, these advantages are: 1) Ignoring the distribution of the data either normal or not; 2) The statistical measure used while comparing the data is the median and not the mean; 3) No data transformation is required; 4) Greater power for skewed distribution (Duhan & Pandey, 2013).

The Mann-Kendall test was presented by Mann in the mid-fifties of the 20^{th} century. The test aimed to measure the skewness of variables against time. The test was then modified by Kendall in 1975 to be the Mann-Kendall test (Longobardi & Villani, 2010).

Trend Analysis for precipitation data in Serbia has been applied using parametric method (linear regression) and nonparametric method using Mann-Kendall for a period of 30 years. The study was applied for different time scales; monthly, seasonally, and annually. The monthly trend varied between increase in some months while decrease in others, for the seasonal scale an increase in the winter and autumn, and no trend has been detected on the annual scale (Gocic & Trajkovic, 2013).

The Mann-Kendall test was also used beside a Sen trend test (a new proposed method) by (Ay & Kisi, 2015) to investigate the trend of monthly data at six different locations in Turkey. Due to the accuracy of the Mann-Kendall test results, the results of the Mann-Kendall test in this study was used to check the accuracy of the results from the new method. The trend differed from one location to another and the difference also was in the increasing and decreasing trends.

Onyutha (2016) conducted a comparison between two methods of trend tests the Mann-Kendall and the Cumulative Rank Difference (CRD), and there was a high correlation and agreement between the two methods.

The interest in studying the hydrological or meteorological trends and change with time as a result of climate change differed from a researcher to another depending on the aim of their research. Tabari and Talaee (2011), analyzed the trend in one variable of climate, which was the air temperature, the study covered both maximum and minimum temperatures and the time scales covered annual, seasonal and monthly scales. The aim of the research was to detect the influence of the CO_2 and other gases causing climate change and how they affect the regional climate. The research concluded that there was an increasing trend in both the minimum and maximum temperatures for the arid and semi-arid regions.

Duhan and Pandey (2013), were concerned for the water available for irrigation and how it may affect the economy related to the change in precipitation. Thus, they studied the spatial and temporal variability of the precipitation in India. The method used in this study were the application of some statistical indices beside the Mann-Kendall test. The results showed that not all the stations studied had the same attitude by increase or decrease for the total years of study but generally the summer season had increase in precipitation, while, there was decrease in winter which will affect the rice production.

Mohamed et al (2017), studied how the climate change might affect the water resources and the river flow. The factors that was assessed for the trend analysis in the study was the precipitation and it was found there was a decline or decreasing trend in the amount of precipitation per year. The study used both linear regression and Mann-Kendal test. What should have been also subjected to study is the change in temperature trend, but the researchers studied the temperature through the frequency, duration and strength of drought events.

2.6 Drought Categories and Indices

Drought is water shortage for a certain period due to the effect of change in climate nature and this lack of water is affecting the environment (Kallis, 2008; D Tigkas, 2008; Dimitris Tigkas et al., 2012). Drought has destructive impact on the agricultural, and environmental ecosystems and its influences even reaches the socioeconomic eosystem (Al-Qinna et al., 2011). Due to the increased magnitude and frequencies of drought more people are being affected by the severity of drought than any other natural hazard (Dimitris Tigkas et al., 2012). The best way that might help in being prepared for drought events and apply measure plans, is to study the drought in terms of severity, duration and special distribution (Kallis, 2008). These drought impacts can be reduced or mitigated through assessing and forecasting drought behaviour (Al-Qinna et al., 2011).

Droughts affect many sectors of water users and considered as a threat to people's lives, and it doesn't occur in a certain climatic zone. The main contributor in drought is the reduction in the amount of precipitation for a certain period it could be for a short time as days or long periods as season or a year. Drought depends on: intensity of rainfall, number of rainy days, any shifts in the raining time of a year or a season specially the delay on a season of plant growth period, and spatial distribution of rain; Hydro environmental factors, such as soil and storage (Kallis, 2008). The drought also can be felt in its hydrological form when it affects the river flow and the storage in lakes and reservoirs (Dimitris Tigkas et al., 2012).

The occurrence of drought is related to some other factors beside the precipitation as: changes in temperature; high winds; changes in relative humidity; distribution of the rainy day in a season. Drought also can be identified by different characteristics like intensity, magnitude, duration, and spatial extent. Due to the complex nature of the drought in terms of causes and characteristics, it is difficult to produce a universal drought index to measure and assess the drought. In order to overcome the problem of assessing the drought there are different indices developed to analyze and monitor drought (Zehtabian et al., 2013). The choice of drought index is dependent on the climatic data availability and the ability of the index to detect spatial and temporal variation during the event (Morid et al., 2006).

There are different drought indices, the Standardized Precipitation Index (SPI) is one of the most common meteorological indices due to its low data requirements. The SPI is used for drought analysis based on temporal scales of six, twelve and twenty-four months, and the SPI showed greater results when was used to assess time scales more than 12 months.

The SPI was developed by McKee in 1993 to overcome a major problem in the Percent of Normal index. The Percent of Normal index was computed through the division of the precipitation by the mean precipitation of 30 years and multiplying by 100%. The inaccuracy of the Percent of Normal index was the use of the mean precipitation instead of the median. The Percent of Normal index disadvantage was solved by the introduction of the SPI. The SPI depends on the long-term precipitation data. This data is arranged using Gamma distribution then transformed to normal distribution. The positive value means greater than median precipitation, while negative values indicates less than median precipitation (Bordi & Sutera, 2007).

Another index is the Reconnaissance Drought Index (RDI), which was introduced in a study comparing between the analyses of the SPI and RDI based on data of different Climatic Zones, it was concluded that RDI requires more analytical data such as the calculation of the evapotranspiration compared with the SPI (Zehtabian et al., 2013).

Nam et al in 2015 tried to answer the question how drought is affected by the change in climate in terms of the drought duration and severity. The estimation of the temporal trends of future was undertaken using three drought indices: SPI, Standardized

Precipitation Evapotranspiration Index (SPEI), and Self Calibrating Palmer Drought Severity Index (SC-PDSI). The data used was the observed meteorological data and the projected climate change scenarios (2011-2100). The study showed that the impacts and severity were increased with time in each of the four indices (Nam et al., 2015).

Shahabfar et al (2012), decided to use a new method to estimate the drought using remote sensed data instead of metrological data for semi-arid regions methods. The methods used were the Perpendicular Drought Index (PDI) and Modified Perpendicular Drought Index (MPDI). The results of the study showed that the remote sensed data are reliable and the used indices in drought monitoring and estimation and the advantage of remote sensed data was the large spatial coverage.

Morid et al (2006), compared between seven drought indices they include the percent of normal (PN), the SPI, the deciles index (DI), the China- Z (CZI), the modified CZI (MCZI), the Z-Score and the effective drought index (EDI). The conclusion of the study was that not all the drought indices were identical, some of the indices were not realistic as the DI, while other cannot be relayed on as the Percent of Normal. And finally, the authors recommended the mixing of the rainfall-based indices with the remote sensed indices for future studies.

Jain et al (2015), Decided to compare between six drought indices, the used drought indices were: SPI, EDI, statistical Z-Score, CZI, Rainfall Departure (RD), Rainfall Decile based Drought Index (RDDI) in terms of region and climatic condition limitation. The conclusion of the study was that Effective Drought Index EDI is more realistic than other drought indices in the historical drought analysis. The study also concluded that EDI is suitable to be used in drought monitoring and assessment in semi-arid and dry sub-humid areas that were used in the study. The recommendation of this drought index is because the realistic identification of the drought severity.

Vicente-Serrano et al (2015), compared between of four drought indices which were Palmer Drought Severity Index (PDSI), the RDI, the SPEI and the Standardized Palmer Drought Index (SPDI) in terms of sensitivity to precipitation and evapotranspiration for different regions of the world. The conclusion showed that all the indices are sensitive to the variation of the precipitation and evapotranspiration. The RDI shows a strong limitation in the variation in the magnitude of precipitation and evapotranspiration which means it is not useful in drought analysis and monitoring for climate change scenarios. The SPDI showed sensitivity to precipitation much more that the PDSI. The PDSI is not suitable for use in arid and semi-arid regions, the sensitivity to variance in precipitation is much higher than the evapotranspiration. In semiarid regions, the SPEI showed equal sensitivity to Precipitation and evapotranspiration.

AL-Faraj et al (2015), used historical data for 30 years to assess and determine the drought events occurred in the Dyala basin in Iraq during these years. The study was conducted using two drought indices the SPI and RDI and the results indicated that there were alterations caused by the climate change impact in the study area.

Tigkas (2008), used RDI for the identification of the drought episodes, and the assessment of their severity for four drought regions in Greece. The study found that drought with more sever events have occurred during the past 50 years, and in some areas the duration exceeded a year time. Two drought scenarios were generated for the future (2050 – 2080) the optimistic scenario with no changes, while the second scenario showed an increase from 51% up to 85% in the percentage of drought years.

The SPI was used by (Al-Qinna et al., 2011) in the Hashemite Kingdom of Jordan using long-term rainfall data and the study concluded that by the passing of time the drought became more severe. Tigkas et al in 2012, used the RDI for the forecasting of the meteorological drought and the Stream Drought Index (SDI) for the hydrological drought. The authors implimented this study to prove the importance of the early warning to drought and how the stakeholder can take the right precautions or the suitable mitigation measures to reduce the effect of this crises (Dimitris Tigkas et al., 2012).

Based on the discussed literature, many drought indices have been used by researchers. There was no generic index that can satisfy all the researcher demands. In order to help in choosing the best index to use in the analysis based on the data required, and the advantages and disadvantages of the different indices, a summary was developed from the discussed literature and can be found in the Table (2-1).

Table 2-1 summary of different drought indices.

Serial	Drought Index	Data required	Remarks
1	Standardized Precipitation Index (SPI)	Rainfall	Long term data of at least 30 years is required to compute SPI, it does not allow missing data. High efficiency and estimate intensity and duration of drought.
2	Standardized Precipitation Evapotranspiration Index (SPEI)	Rainfall, temperature, and Evapotranspiration	Suited for studies on the effect of global warming on drought severity
3	Palmer Drought Severity Index (PDSI)	Rainfall, and temperature	disadvantage: uses empirical equations based on few locations.

Serial	Drought Index	Data required	Remarks
4	Self-Calibrating Palmer Drought Severity Index (SC-PDSI)	Rainfall, and temperature	Calibrates the PDSI with data appropriate for each location
5	Standardized Palmer Drought Index (SPDI)	precipitation, moisture supply, runoff, and evaporation	mixture of the supply and demand concept of the PDSI while having the statistical nature of the SPI and SPEI
6	Perpendicular Drought Index (PDI)	infra-red bands of remotely sensed data, and soil moisture	performing well for early stages of vegetation growth
7	Modified Perpendicular Drought Index (MPDI)	infra-red bands of remotely sensed data, and soil moisture	same as PDI but also consider vegetation growth.
8	percent of normal (PN)	Rainfall	one of the most straightforward measures of rainfall deviation from its long-term mean
9	deciles index (DI)	Monthly rainfall	very sensitive, which leads to unrealistically high temporal and spatial variations in wet conditions and the variations being more pronounced during summer
10	China- Z (CZI)	Rainfall	suggested that because of simplicity in calculating drought severity at monthly time step using CZI, it can be preferred over SPI, where rainfall data are often incomplete
11	modified CZI (MCZI)	Rainfall	not suitable with large range of precipitation between the stations
12	Statistical Z-Score	Rainfall	good as SPI and can be calculated on multiple time steps. It can also accommodate missing values in the data series like CZI
13	Effective Drought Index (EDI)	Rainfall	The EDI and SPI use similar classification of drought severity.
14	Rainfall Departure (RD)	Rainfall	It is a straightforward method
15	Rainfall Decile based Drought Index (RDDI)	Rainfall	advantage simplicity in its computation, disadvantages high possibility of error
16	Reconnaissance Drought Index (RDI)	Rainfall, temperature, and evapotranspiration	gives no valid values when evapotranspiration is equal to 0, which is very common in cold regions in winter

Serial	Drought Index	Data required	Remarks
17	streamflow drought index (SDI)	monthly streamflow volumes	used for forecasting annual hydrological drought severity

In most of the studies measuring the drought indices depended mainly on the precipitation data or rainfall deficiency, stream flow, and temperature in calculating the drought. There is a strong relation between the effect of climate change as in precipitation where the runoff is a part of the precipitation in the hydrologic cycle and the drought events.

Due to the importance to measure the changes in the precipitation as an indication of drought events and the data availability the accuracy of the index, the SPI is the index used in this study.

2.7 Hydrologic anomaly

The river flow is one of the main contributors of the water supply for countries and in some cases is considered the major contributor as the case for Egypt in the Nile basin, Egypt is more than 90% dependent on the river flow (Selby & Hoffmann, 2014).

Any changes in the river flow as a representative of the supply side, will cause re-arrangement of the water strategic planes and in some cases causes water scarcity.

In this section the anomaly or the changes of the river flow will be discussed for different case studies and tools used to measure the alteration.

Due to the importance of the river flow and its prediction in the future, many researchers used different research methods and approaches some of these methods are: Gene-expression programming, fuzzy logic, hydrodynamic modeling, autoregressive integrated moving average autoregressive integrated moving average (ARIMA), artificial neural network (ANN), support vector machine (SVM) , and support vector machine smallest power (LSSVM) are some approaches have been used in Malaysia (Adenan & Noorani, 2013).

In this section the changes occurred in the river discharge will be discussed and the factors that contributed to these changes.

Upstream hydraulic structures and enormous water abstraction schemes have adversely impacted multiple downstream water uses and considerably modified the flow regime in the downstream state of Iraq (Al-Faraj & Scholz, 2014). The man-made intervention has a bad influence on the water availability despite the level or size of intervention, especially during the dry or non-rainy periods. The river flow alteration ranged from 220.5% to 242.3% (Al-Faraj & Scholz, 2014). Dam operations have had significant impact on the natural flow regimes in most of the world large rivers (Lu, Li, Kummu, Padawangi, & Wang, 2014). Excessive upstream irrigation abstractions for rice irrigation had severely reduced flows in the downstream (Mwakalila, 2008).

Since the opening of the Sidi Salem dam on the watercourse of the Medjerda in 1981, an alarming narrowing of the riverbed in the lower valley has been observed. This geo-morphological change is attributed to different factors ranking from the reduction in the discharge flows (Zahar, Ghorbel, & Albergel, 2008).

The Indicators of Hydrological Alteration (IHA) is a method for assessing the degree of hydrologic alteration related to human effect in the ecosystem. The assessment is based on analyzing the available hydrologic data either from measurement points (e.g. streamflow gauges) or from model generated data (Richter, Baumgartner, Powell, & Braun, 1996). The IHA software program was originally developed by The Nature Conservancy in the 1990s to quickly process daily hydrologic records to enable characterization of natural water conditions and facilitate evaluations of human-induced changes to flow regimes. This program, available at no cost from TNC, has been used by scientists and water managers in river basins throughout the United States (U.S.) and worldwide (Mathews & Richter, 2007). The program was designed to calculate the values of 33 hydrologic parameters that characterize the intra and inter-annual variability in water conditions, including the magnitude, frequency, duration, timing and rate of change of flows or water levels (Richter, Baumgartner, Powell, & Braun, 1996).

Two primary criteria were used in selecting the original suite of 33 hydrologic parameters: their ecological relevance; and their ability to reflect human-induced changes in flow regimes across a broad range of influences including dam operations, water diversions, ground-water pumping, and landscape (catchment) modification (Mathews & Richter, 2007)

The natural flow regime in Mekong River Southeast Asia, is changing due to the recent hydropower development of many large dams in both mainstream and tributaries. The Indicators of Hydrological Alteration (IHA) was used to examine the impacts of dam operation on water discharge. They found that the water discharge was obviously lower in the dry and marginally lower in wet seasons in the post-dam period (1992 - 2010) than in the pre-dam period (1960 – 1991) (Lu, Li, Kummu, Padawangi, & Wang, 2014).

The increasing water consumption in the upstream rainfed areas of the Karkheh basin, Iran and their impacts on the downstream river discharge was simulated using the semi-distributed SWAT model. Three scenarios were tested at subbasin and basin levels: converting rain-fed areas to irrigation agriculture (S1), improving soil water availability through rainwater harvesting (S2), and a combination of both (S3). The results of these scenarios were compared against the baseline period 1988–2000. The basin scale impact of the tested scenarios suggested a decline in mean annual flows of about 10%, 4% and 14% in the case of S1, S2 and S3, respectively (Masih, Maskey, Uhlenbrook, & Smakhtin, 2011).

In 2014 AL-Faraj and Scholz studied the effects of man-made projects in the upstream besides the drought incidents and their effect on the downstream flow regimes. The assessment was done using Indicators of Hydrologic Alteration (IHA software version 7.1) and climate variability. They concluded that the human-related activities coupled with the impact of drought have considerably modified the flow regime and therefore reduced the flow volume available for the downstream state (Al-Faraj & Scholz, 2014).

In 2009 the hydrological alteration was analyzed using three methods: the range of variability approach (RVA), wavelet transform analysis (WT), and a combination of the two. The data used in the study was daily streamflow record, and record of instantaneous measurements with time step of 15 min. they concluded WT is the ideal tool to identify the main scales of variability and their variation in time due to flow regime, while RVA is intuitive but not suitable for separating the different causes of alteration and identifying the most impacted scales of variability (Zolezzi, Bellin, Bruno, Maiolini, & Sivigilia, 2009).

The hydrologic impact of a diversion weir in Taiwan was investigated the using the RVA and evaluated thirty-two hydrologic parameters addressing the magnitude, timing, frequency, duration and rate of change before and after construction of the weir. They concluded that the Construction and operation of the diversion weir, with the aim of providing water resources for municipal, industrial, and agricultural purposes, will cause considerable hydrologic alterations. With the RVA, the effects on the hydrologic regime of the weir construction can be assessed, and the targets for river management can be established (Shiau & WU, 2004).

The hydraulic alterations were evaluated by using the RVA and employing thirty-three hydrologic parameters and these parameters were based on magnitude, timing, frequency, duration and rate of change. They found that the construction and operation of the TGD, aiming to control flood and generate electricity, have inevitably caused significantly hydrological alterations, which severely change the balance of natural flow regime (Jiang, Ban, Wang, & Cai, 2014).

The measure of the changes and the anomaly of the river flow teased the curiosity of the researchers to study these changes. In this section the research in the past years was discussed in terms of methods used, data required and the advantages and disadvantages of these methods. The discussion in this section can be concluded in Table (2-2).

Table 2-2 summary of different river flow anomaly analysis tools.

Serial	Author	Year of Publication	Method used	Data required	Remarks
1	Richter, Baumgartner, Powell, & Braun	1996	Indicators of Hydrological Alteration (IHA)	The assessment is based on analyzing the available hydrologic data either from measurement points (e.g. streamflow gauges) or from model generated data	The method compares the hydrology of a reference ‘unaltered’ regime to an ‘altered’ paradigm. This model consists of 33 hydrologic measures that are grouped into five major categories: (i) magnitude,(ii) magnitude and duration of annual extreme conditions, (iii) timing of annual extreme conditions, (iv) frequency and duration of high and low pulses, and (v) rate and frequency of changes in conditions
	Mathews & Richter	2007			
	Al-Faraj & Scholz	2014			
	Lu, Li, Kummu, Padawangi, & Wang	2014			
2	Masih, Maskey, Uhlenbrook, & Smakhtin	2011	Soil Water Assessment Tool (SWAT) model	Digital Elevation Model (DEM), land use and soil maps and climatic data, besides information on soil characteristics and land use management practices.	

2.7 Chapter Summary

The literature review chapter discusses different topics starting with the importance of the water resources management and especially in transboundary scale and how it can help in decreasing the conflicts between riparian countries and help the countries and different sectors mitigate the crises of climate change and other human induced factors.

After introducing the importance of the water resources management and how it can help in mitigating crises such as water scarcity, it was worthy to discuss the water scarcity and drought problems affecting different portions and how they can affect countries.

Since the drought is exacerbated by the influence of climate change in some portions of the globe it was worthy to discuss the causes of the climate change and how they affect the hydrologic cycle and eventually the river flow. The river flow is not only affected by the climate variability or change but is also affected by the human induced factors such as dam construction with its different purposes and the water abstraction projects as irrigation and industrial demands. Different causes lead to changes in river flow and the vulnerability of the river flow to climatic and non-climatic drivers made it important to study the relation between the changes in climate or the changes in the trends of the precipitation and temperature and how it can affect the changes in the river flow. The changes in the river flow are also affected by the drought events in terms of severity and duration, the strong influence of the drought on the river discharge should be measured. Many drought indices have been discussed and compared to choose the most suitable index to use based on the data availability and the case study condition.

After assessing the main drivers causing the changes in the river flow or the flow anomaly, the flow anomaly should be measured and how it was affected either due to climatic or non-climatic drivers.

The discussed literature helped in planning and formulating the methodology. The methodology will discuss climate variability in the Nile basin and especially in the eastern Nile basin. The climate variability will be assessed in terms of the changes in trends of precipitation and temperature and how these changes affected the river discharge patterns. After the assessing of trend analysis, the drought in the past century will be assessed using the SPI and how the river discharge was affected with the severity of the drought events. Finally, the anomaly of the river discharge will be assessed based on the climate variability and the degree of human intervention on the river flow. Hopefully the proposed methodology will help in better understanding of the situation in this area and help in negotiations between riparian countries.

Chapter Three: Methodology

3.1 Introduction

The investigation and the assessment of some key factors, including but not limited to, the human induced structures in the upstream, hydro-climatic conditions, and the data availability and accessibility is very important and critical.

Due to the importance of the investigation of the effect of the climate variability and the human intervention on the river discharge, there is a need to develop a technical framework that might help in preparing the suitable or appropriate mitigation measure, and whether the adaptive action will be effective or not under the presence of both upstream development projects and climate change needs,

The proposed methodology will help in achieving the reach objectives and aims to:

1. Identify the data needed to undertake the analysis.
2. Data collection and management to discuss the data availability and the data completion.
3. Upstream structures year of operation in order to analyze the changes in discharge before and after the construction.
4. Analysis of the meteorological data in terms of precipitation, evaporation, and potential evapotranspiration to understand the previous history and help in the determining the possible impacts of climate change.
5. Analysis of the discharge before and after the presence of the structures to separate the changes in discharge either due to climate changes or due to upstream development.

Figure 3-1 is a mapping between the objectives and how they can be achieved through the proposed methodology.

Research Aim

To construct a solid ground methodology and framework, that might help to better understand the situation of the present condition of the river discharge and how it is affected by climate variability, drought events and human induced factors.

1. Identify the data needed to undertake the analysis.

3. Data collection and management to discuss the data availability and the data completion.

Objective 1

To introduce a methodology for finding metrological data sets in scarce data areas and use it in measuring climate change studies and drought events.

2. Upstream structures year of operation in order to analyze the changes in flow before and after the construction.

4. Analysis of the meteorological data in terms of precipitation, Evaporation, and potential evapotranspiration to understand the previous history and help in the determining the possible impacts of climate change.

Objective 2

To evaluate the impact of climate change and droughts in unaltered flow conditions and in intervened flow conditions.

5. Analysis of the flow before and after the presence of the structures to separate the changes in flow either due to climate changes or due to upstream development.

Objective 3

To analyze the flow regime, and to assess the changes in the flow regime according to the degree of human intervention.

Figure 3-1 Mapping between the objectives and the proposed methodology.

3.2 Description of the Study area

Figure 3-2 shows the entire Nile Basin which is one of the shared river basins. It is shared between 11 riparian countries. The Nile is the longest river in the world at about 6700 km. It extends over an extremely wide band of latitude, from 4°S to 31°N and a longitude, from 24°E to 40°E, with a total catchment area of nearly 3,400,000 km^2 (Multsch et al., 2017; Onyutha et al., 2016; Sutcliffe & Parks, 1999). The Nile basin covers one tenth of the area of Africa, the Nile river originates from Lake Victoria starting the journey of the White Nile and moving north until it joins the Blue Nile river at Sudan forming the Main Nile River, the Blue Nile River is originated in the Ethiopian highlands. The last tributary joining the Main Nile is the Atbara river from Ethiopia and Eritrea (Pacini & Harper, 2016).

The flow rate at the origins of the Nile river south is almost constant for the 12 months of the year with flow rate around 1000 m^3/sec., then the Bahr el Gebeil river is formed. The Bahr el Gebeil suffers a large loss in the amount of flow, almost 50% of the flow in addition to the added rainfall are lost due to evaporation and transpiration, to result in an outflow from the Bahr El Gebeil of approximately 500 m^3/sec. The White Nile is formed by the joining the flow from Bahr El Gebeil and Bahr El Ghazal west then joining the contribution of the Sobat river east.

The drainage area of the Sobat basin is half that of Bahr El Gebel with an area of 225,000 km^2, even though, it contributes with 400 m^3/sec, while Bahr El Gebel shares with a negligible amount of 2 m^3/sec (Di Baldassarre et al., 2011).

The flow regime in the study area is highly dependent on the rainfall, the Blue Nile drains a major part of the western Ethiopian highlands, the river flow is in the Blue

Nile is concentrated in a short period due to the single rainy period. The Atbara River drains the north part of the Ethiopian highlands with a runoff season shorter than the Blue Nile and is dry most of the year (Sutcliffe & Parks, 1999).

The Blue Nile river flows from Lake Tana and consists of 13 tributaries with a catchment area of 176,000 km^2 in Ethiopia and 135,548 km^2 in Sudan. The rainfall varies between 1000 mm/year, and 1400 and 1800 mm/year and in some parts more than 2000 mm/year to less than 200 mm/year in the Sudan and near the junction between the Blue Nile and the White Nile (McCartney & Menker Girma, 2012). Approximately 3 quarters of the rainfall occur in the summer season between June and September (McCartney & Menker Girma, 2012). The daily mean temperature in the Ethiopian highlands ranges from 15 to 18 ℃ and as the attitude decreases towards the Sudan border the temperature increases to 30 ℃ in addition the evaporation is around 2500 mm/year (Block et al., 2007).

Egypt is considered one of the 11 riparian countries sharing the Nile basin (Figure 3-2). Egypt’s water resources are the Nile River with a contribution of 55.5 Billion Cubic Meters (BCM) /year based on the “Nile Water Agreement 1959” (Ashok Swain, 1997). The Blue Nile contributes approximately 60 to 70% of the total flow at Aswan (Upper Egypt) and an important river basin to the Eastern Nile countries (Mulat & Moges, 2014). Ethiopia, with 12% of the drainage basin, generates 86% of the river year-round flow (Melesse, Abtew, & Setegn, 2014). The total contribution of the Ethiopian highlands to the Main Nile river flow is 86%, divided to 59% from the Blue Nile, 14% and 13 % from Sobat and Atbara rivers respectively (Peden et al., 2013).

From the previous literature, most of the projects were constructed in the 4 basins the Blue Nile, Atbara river, Sobat river and the Main Nile as shown in Figure (3-2). It is important to study the changes in the rainfall in these 3 basins beside the Main Nile basin.

The Nile basin countries have predominantly agricultural economies, therefore the highest sector withdrawing water in the Nile basin is the irrigational sector, especially with increasing population, the withdrawal of water for agricultural purpose in Egypt and Ethiopia is 75% of the total water withdrawal for these countries, while this percentage increases to more than 90% in Sudan (Mason, 2004). In year 2010, the 3 countries depending on the Blue Nile flow were Ethiopia (where the Blue Nile originates), the Sudan and Egypt. The three countries consuming water from the Blue Nile had an irrigation potential with 2220,000, 2750,000, and 4420,000 ha respectively (Swain, 2011a).

The water treaty in the Nile basin or specially in the Eastern Nile basin was between Egypt and Sudan starting from year 1929 giving Egypt the use a minimum of 48 billion cubic meters per year (BCM/year). Since 1704 until the 2000's the Egyptian and Ethiopian parties suffered from conflicts, and no treaties was reached (El-Fadel et al., 2003).

The agreement between the two countries, Sudan and Egypt changed in 1959, the agreement was done after further study of annual flow and some political changes. The agreement stated and based on the annual flow reaching both Sudan and Egypt that Egypt's share from the 84 BCM/year is 55.5 BCM/year and 18.5 BCM/year for Sudan, while the rest are considered losses. Since the 80's the conflicts rose between the three riparian countries due to the increase in the agricultural and water demands to satisfy the growing population needs (Swain, 2011a).

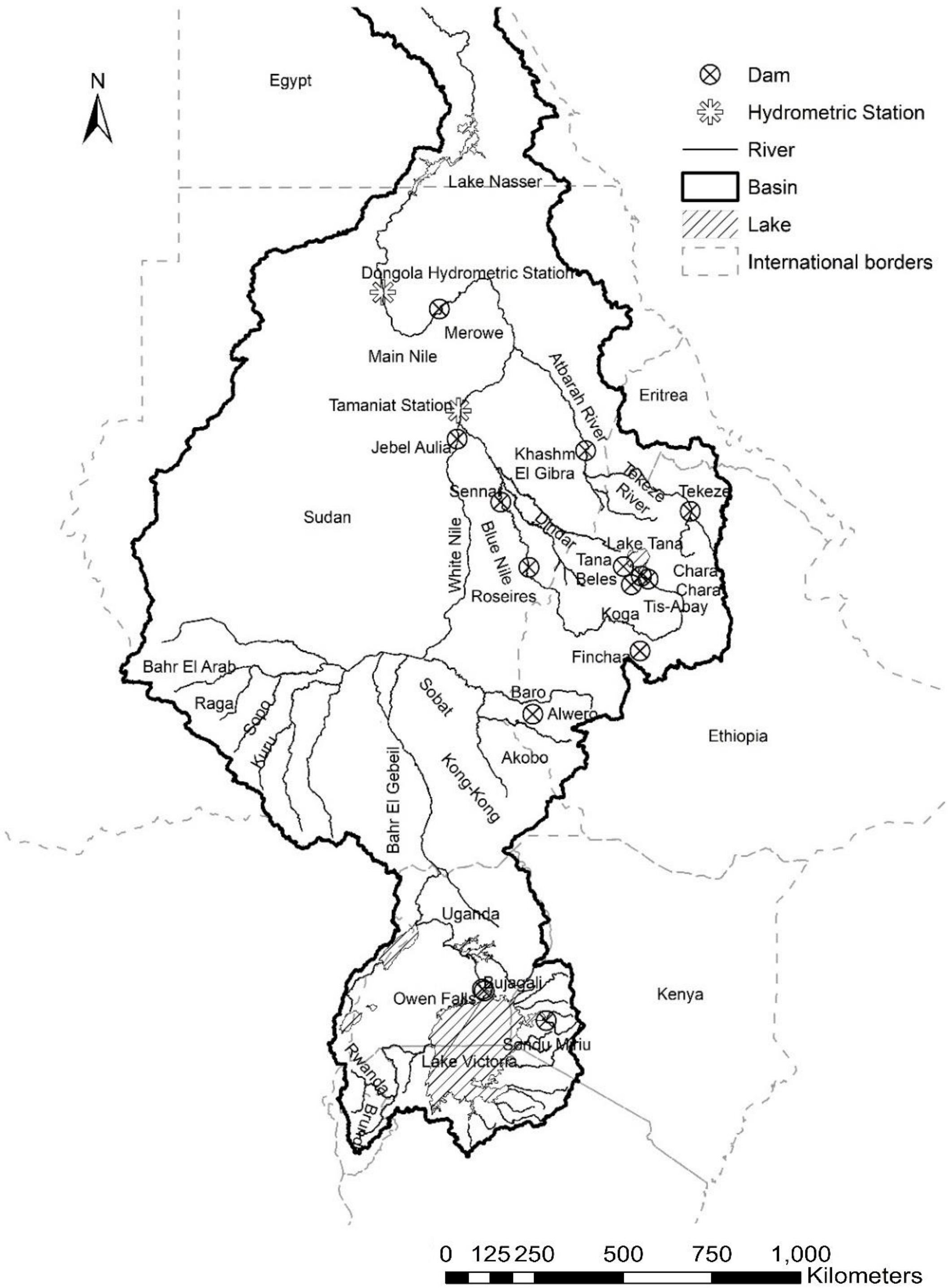


Figure 3-2 The Study Area Showing the Dams constructed and the Dongola and Tamaniat hydrometric stations

3.3 Data required

In order to make a proper analysis and attain the objectives and achieve the research aim, the following data will be required:

1. Hydrological data as monthly river discharge for more than one hydrometric station.
2. Metrological data as precipitation and temperature.
3. Existing dams; the purpose of construction (either for irrigation, or hydropower generation) and the storage capacity of the reservoirs.

3.4 Data Collection and Management

To address the study problem and based on the literature previously discussed, the following data will be required:

The river discharge data: The importance of the river discharge data in the study is that it will be used in the measurement of the alterations in the discharge from climate changes and human induced effects. In addition, it will help in the separation between the alteration in the discharge due to climate change or development in the upstream. The type of time series which is critical in this study is the monthly discharge.

The monthly discharge was collected for two stations the Dongola station and the Tamaniat station. It was intended to use more hydrometric stations but due to the discontinuity of the data at the other hydrometric stations the Dongola and Tamaniat stations were used in this study. The location of the Dongola and Tamaniat stations helped in overcoming the problem of number of stations used in the study.

The Dongola Station has been chosen due to its location and that it will give the best indication of the alterations in discharge before reaching Egypt. The Tamainat station was chosen as its location is directly downstream of the major sub-basins contributing to the river discharge, as presented in Figure 3-2.

The Dongola station is the optimum station because it is the last station in the downstream of the Nile river before water is stored in Lake Nasser and is located at the North of Sudan and gives a very good indication of the amount of water reaching Lake Nasser in southern Egypt.

To address the aim of this study appropriately, a long time series of 107 years of monthly discharge records: 1900–2012 (data from 1928–1932 cannot be acquired) was analyzed. The collected data was observed at two key discharge sites: The first station (the Dongola station) is in the northern area of Sudan (upstream of Lake Nasser); and the second station (the Tamaniat station) is just downstream the junction between the Blue Nile and the White Nile and the beginning of the Main Nile.

The Dongola station can assess the discharge coming from the three main basins contributing in the river discharge, the Blue Nile basin, the Atbarah basin and the Sobat basin, while Tamaniat assess the discharge from only 2 basins: the Blue Nile and Sobat.

The data were obtained from the Egyptian Ministry of Water Resources and Irrigation. However, data from 2013–2017 could not be acquired as these data sets were collected from databases of the “The Nile Basin” released by the Egyptian Ministry of Water Resources and Irrigation, which are only accessible every five years. The river discharge data collected cover both pre- and post-impact flow regime conditions.

Metrological data: Precipitation and temperature data were also analyzed in this study. The former is the main parameter driving river discharge.

Changes in precipitation through the period of study were also analyzed to determine their impact on the river discharge, and study if the changes in the river discharge are due to climate change or anthropogenic activities or both.

The collection of climatic data was challenging. The data collected for the land-based stations were scarce in terms of number of stations covering the study area. Furthermore, some stations were not operational for the entire study period. Data were collected from more than one source to assess and cross-check the accuracy of information.

Measurement data for the Nile basin were incomplete. In the periodicals of the Egyptian Ministry of Water Resources and Irrigation, monthly measurement data of the Nile basin were not distributed sufficiently to implement the study. In Egypt, there are 98 stations distributed all over the country, but only 49 are still operational. Sudan had 131 stations of which only 31 are still working. Ethiopia is considered the main reason of the river flow and the country with the highest rainfall records, has only one station in Addis Ababa. The data available from the periodicals are poor in terms of number of stations to build a reliable study.

The Nile Basin Initiative (2018) provides incomplete annual Nile data, which are sub-basin-based and not country-based. Moreover, the Main Nile basin is linked to only readings from 10 stations, while the Blue Nile basin has annual readings for only 11 stations. There is also a challenge of non-continuity of the station readings for the study period. Furthermore, the Food and Agriculture Organization of the United Nations (FAO) provides monthly data via their Faoclime tool, which was used for cross-checking purposes as well.

Furthermore, to overcome the challenge of relatively sparse data availability in this research, more than one source of processed data has been used the Global Precipitation Climatology Centre (GPCC) and Climate Forecasting System Reanalysis (CFSR), and a comparison and validation exercise has been undertaken between the collected land-based data, the (GPCC) and the (CFSR).

Three main types of precipitation data sets are used in water resources management plans in case there are scarce surface gauging data. The first type is based on surface gauging data as the GPCC, the second type is based on satellite data, and finally the third type which is based on both surface and satellite data. The data with the highest accuracy is the first type and the errors or uncertainties in this method is due to the quality control in the collected gauge data (Kotsuki & Tanaka, 2013).

The GPCC was founded under the calling of the World Meteorological Organization (WMO) in 1989. The purpose was the construction of a reliable network of land-based precipitation data for hydrological and energy budget purposes (Becker et al., 2013; Schamm et al., 2014; Schneider et al., 2014). The GPCC gridded data are based on the collection of the global land-based data. According to the estimation of the WMO, there are more than 400,000 precipitation gauge stations are in operation globally, from this huge number of stations only 7000 stations were exchanging data and for the purpose of the GPCC project monthly data for 40,000 have been and are being collected, the data is then transformed to grid data sets by interpolation to cover the globe with different spatial resolution (Rubel & Rudolf, 2005). The first version was released in December 2011 with data collected from 67,200 stations (Schneider et al., 2017).

The collection of the data continued, and another version was produced in 2015 using the data from 2011, but 7900 stations were added (Schneider et al. 2016, 2017). Various data collection versions have been published in the meantime. In this study, version 7 with the longest period of coverage was used.

The GPCC data is collected from the ground station raw data. The errors in the raw data still have its effect on the GPCC data when used in analysis. The uncertainty caused by the gauge or ground station error can be estimated by (±1.2 %) of the station reading (Schneider et al., 2014).

The accuracy and reliability of the gridded data-sets collected from ground station data as the GPCC depends on number, spatial distribution and quality of observational stations (Dinku, 2019).

The hydrological data source can be land station (gauge reading), satellite estimates and reanalysis data. The reanalysis system is the combination of the irregular data either satellite or ground based data with physical and dynamical models to generate a grid estimate of the hydrological condition (Sun et al., 2018). CFSR is based on a fully coupled ocean-land-atmosphere model and uses numerical weather prediction techniques to assimilate and predict atmospheric states (Saha et al., 2010; Sun et al., 2018). The CFSR data covers period of 35 years from 1979 to 2014 with a spatial resolution of 0.3^o x 0.3^o, the CFSR data was used previously in water resources research (Fuka et al., 2014; Mohammed et al., 2017; Mohammed & Scholz, 2017).

The GPCC stations have a spatial resolution of 0.5^o x 0.5^o but covering a longer period from 1901 to 2013, due to this resolution the number of stations in the study area were 1040 stations (Fig. 3-4), less by 1457 stations than the CFSR data (Fig. 3-3).

In order to choose the dataset to produce a reliable research, both processed data sets (GPCC and CFSR) consistency tests were compared with the available land stations (gauge readings) from the periodicals.

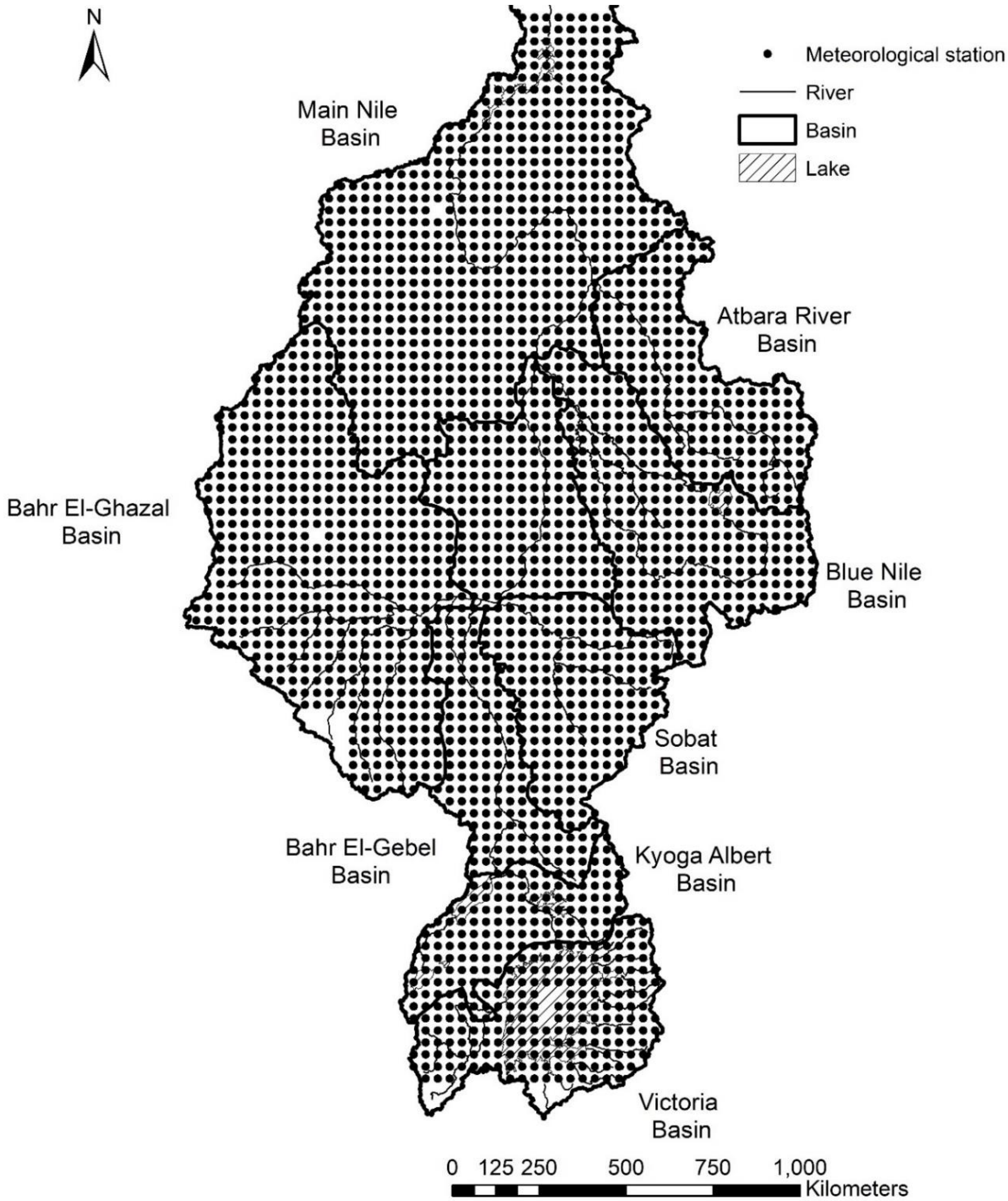


Figure 3-3 Location of the CFSR meteorological stations in the Nile Basin

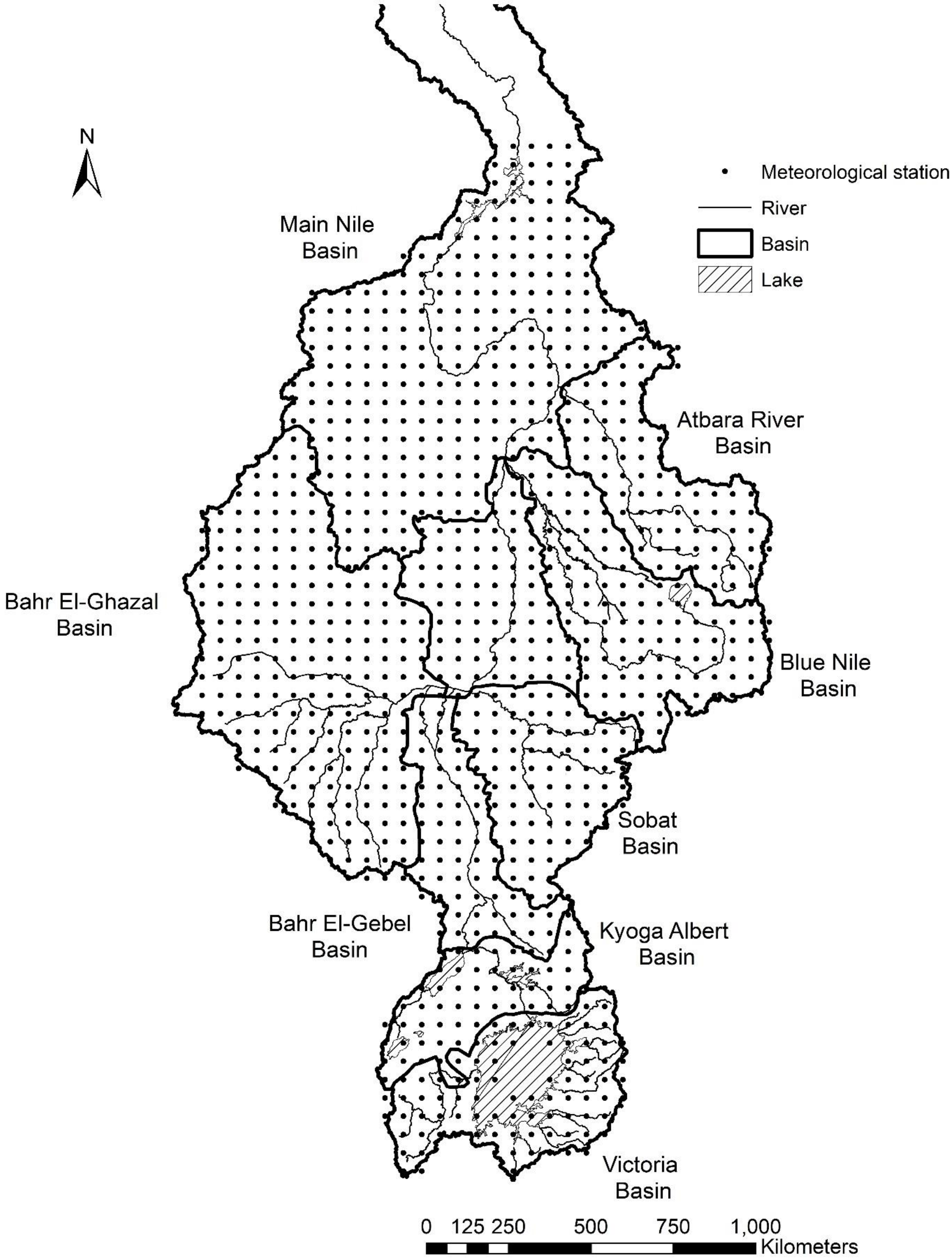


Figure 3-4 Location of the GPCC meteorological stations in the Nile Basin

The calculation of the study area sub-basins precipitation values was performed using the Thiessen network according to equation (1). The ArcGIS 10.4 tool was used to estimate the area of the Thiessen network polygons as shown in (Fig. 3-5)

$$P_{av} = \frac{\sum_{i=1}^{n} a_i \times P_i}{\sum_{i=1}^{n} a_i} \quad (1)$$

Where P_{av} is the mean value of the basin precipitation (mm), P_i is the value of the precipitation (mm) at the station in the basin and a_i is the meteorological station area (km^2), and n is the number of meteorological station areas.

It is crucial to assess the correlation between the precipitation data sets from the GPCC and the land-based data and between the CFSR and the land-based stations.

Table, 3-1 and 3-2 present the correlation between the precipitation land-based stations and the GPCC and CFSR, respectively, and Fig 3-6 shows the location of the land-based stations and the GPCC stations, while Table 3-3 shows the correlation between the temperature land-based stations and CFSR and Fig. 3-7 shows the location of the land-based stations and the CFSR stations.

Table 3-1 Consistency between the Precipitation data of the gauge stations from the periodicals and GPCC data

Meteorological variable	Station ID	Mean (mm/year)	Standard Deviation (mm/year)	Max (mm/year)	Min (mm/year)	Correlation Coefficient
Precipitation	Abu-Hamed	12.66	20.52	139	0	
	96	13.28	19.75	122.87	0.86	0.99
	114	15.88	20.77	138.49	0.51	0.97
	95	13.82	20.34	129.86	0.66	0.99
	Khartoum	144.59	75.12	415.5	4.4	
	282	153.79	67.63	342.24	15	0.83
	258	127.42	70.72	369.48	5.65	0.91
	259	140.72	70.68	386.14	7.82	0.92

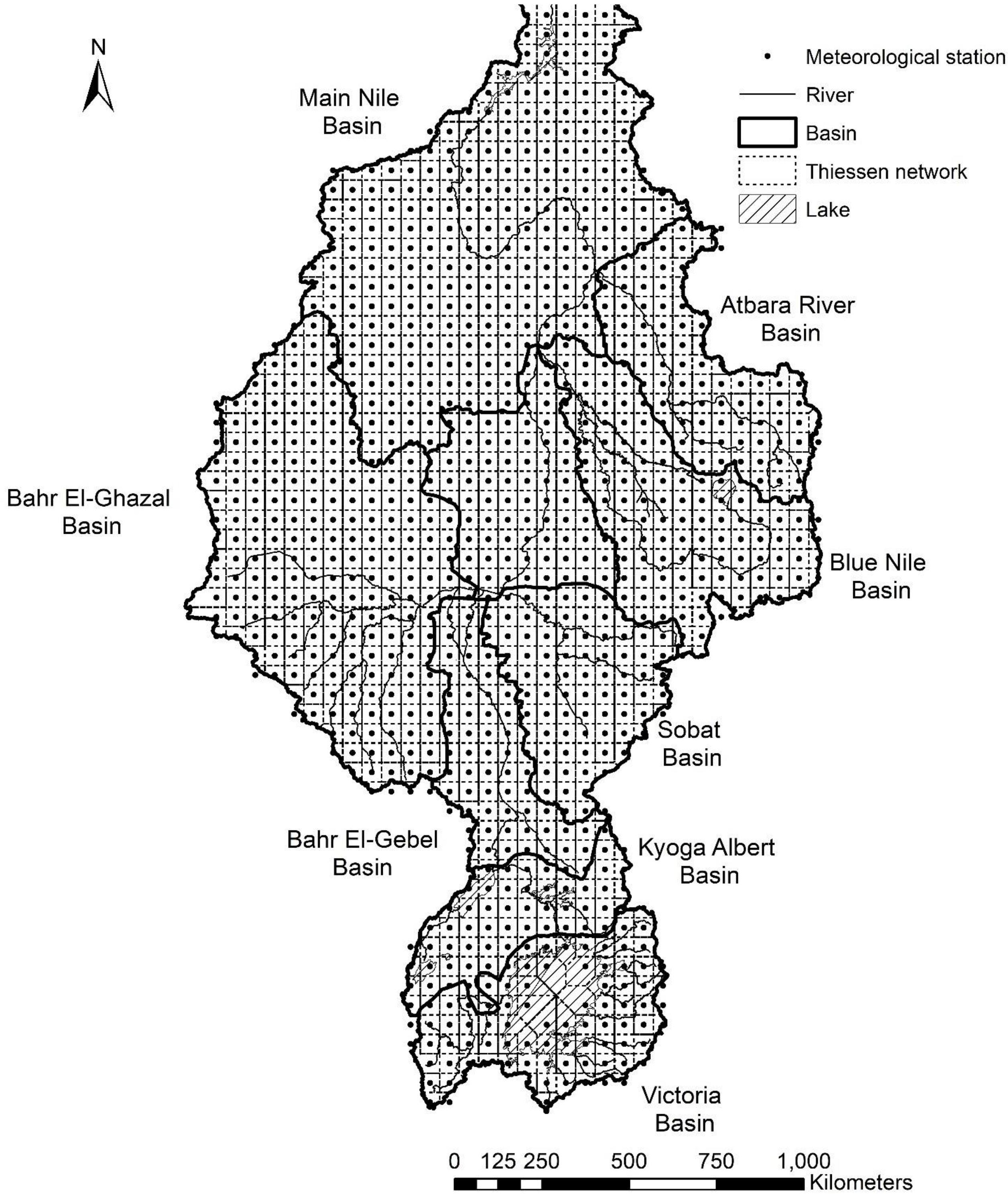


Figure 3-5 Application of the Thiessen network.

As observed from Tables 3-1 and 3-2 there is a stronger correlation between the land-based data and the GPCC stations for precipitation, and Table 3-3 shows the strong correlation between CFSR stations for temperature. The correlation coefficient is a statistical measure to indicate if there is a strong relation between two variables. As the correlation coefficient is equal to one it means there is a strong relation between these variables and no relation when it is equal to zero.

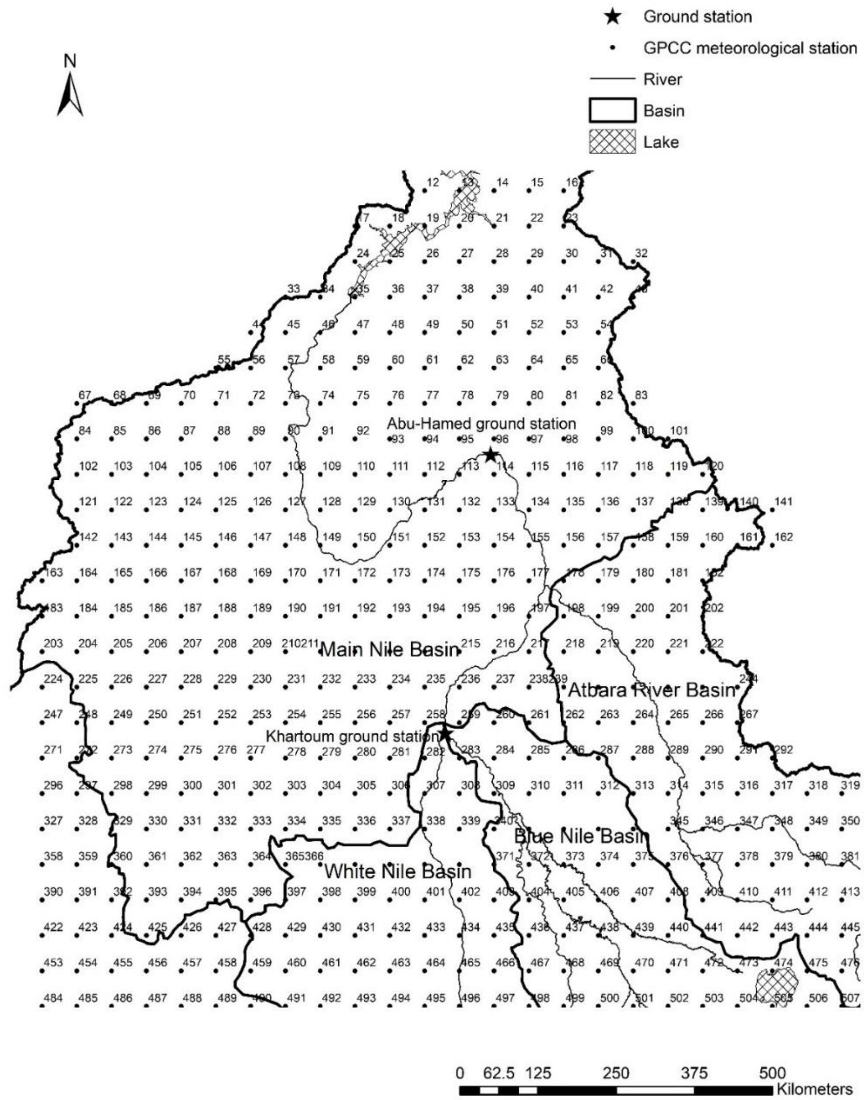


Figure 3-6 Location of the GPCC meteorological stations and the ground stations

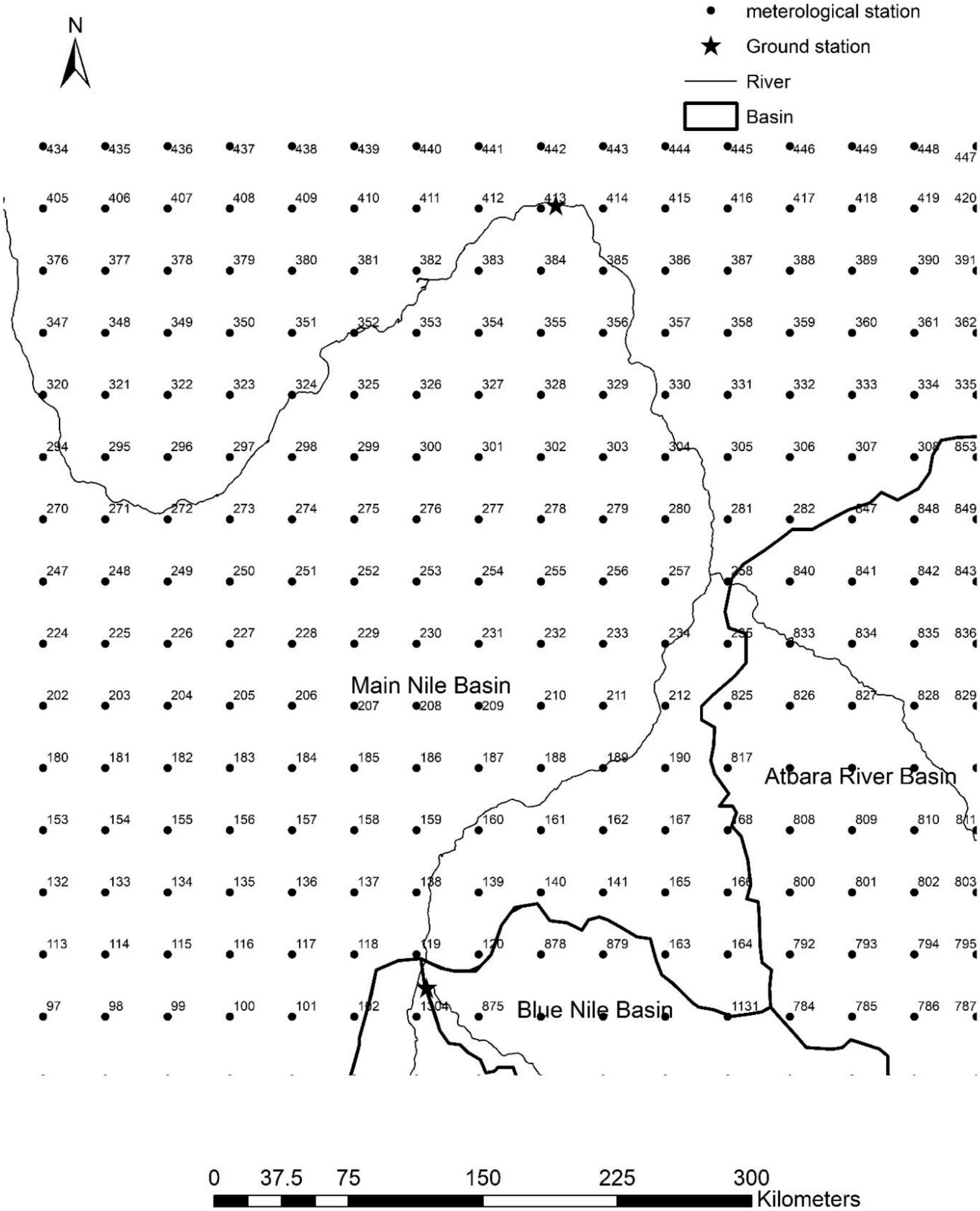


Figure 3-7 Location of the CFSR meteorological stations and the ground stations

Table 3-2 Consistency between the Precipitation data of the gauge station from periodicals and (CFSR) data

Meteorological variable	Station ID	Mean (mm/year)	Standard Deviation (mm/year)	Max (mm/year)	Min (mm/year)	Correlation Coefficient
Precipitation	Abu-Hamed	7.68	8.13	35.8	0	
	413	8.47	11.47	51.80	0.09	0.11
	414	11	16.63	81.08	0.31	0.08
	Khartoum	118.27	76.11	415.5	4.4	
	1304	134.6	109.1	481.06	8.65	0.36
	119	121.66	102.57	382.79	5.03	0.39

Table 3-3 Consistency between the temperature data of the gauge stations from periodicals and (CFSR) data

Meteorological variable		Station ID	Mean (ºC)	Standard Deviation (ºC)	Max (ºC)	Min (ºC)	Correlation Coefficient
Temperature	Maximum	Abu-Hamed	37.17	5.62	44.3	22.4	
		413	35.46	6.22	43.08	19.94	0.99
		414	35.7	6.14	43.24	20.18	0.99
		Khartoum	37.14	3.75	42.8	25.7	
		1304	37.74	4.1	45.08	25.29	0.96
		119	37.76	4.3	44.97	24.75	0.97
	Minimum	Abu-Hamed	21.18	5.64	28.9	8.6	
		413	17.25	5.44	25.65	4.8	0.99
		414	17.38	5.33	25.7	5.2	0.98
		Khartoum	23.11	4.47	29	11.8	
		1304	20.21	4.8	27	8.65	0.95
		119	19.7	4.97	27.1	8	0.95

Hydraulic structures: collecting data on existing and under construction dams and storage capacities and the dates of operation is important to assess the degree of human intervention and the how the river discharge is affected. The upstream segments of the Nile River and its tributaries have been notably dammed in the upstream riparian countries (Peden et al., 2013). There is also a further development plan to increase the number of water control and water diversion facilities (Peden et al., 2013).

The damming of the Nile River in the upstream riparian countries started in 1925. The Sennar Dam was constructed for the purposes of irrigation and hydroelectricity generation with a storage capacity of 0.93 Bm^3. Since its construction, Sudan and other upstream countries have built further dams and hydraulic structures for multi-purpose usages. A giant dam is currently being constructed in Ethiopia but further negotiations between riparian countries (Ethiopia, Sudan and Egypt) regarding its operation and storage volume regime are still on-going.

Due to the increase in interest of upstream countries to construct further dams on the Nile River, a deeper understanding of how they impact the river discharge of downstream countries is required to avoid transboundary conflicts. Table 3-1 shows the timelines during which the Nile river and its tributaries were subjected to major human intervention in the countries located upstream of Egypt. The data were collected from the Food and Agriculture Organization and have been described, previously (Sutcliffe and Parks 1999; Peden et al., 2013; McCartney and Menker Girma 2012).

Table 3-4 Damming of the Nile River and its tributaries between 1900 and 2012 (sources: Sutcliffe and Parks 1999; Peden et al., 2013; McCartney and Menker Girma 2012).

Country	Dam name	River	Year	Storage (Bm^3)	Use	Latitude (°)	Longitude (°)
Sudan	Sennar	Blue Nile	1925	0.93	Irrigation and hydroelectricity	13.547	33.635
Sudan	Jebel Aulia	White Nile	1937	3.5	Irrigation and hydroelectricity	15.239	32.465
Ethiopia	Tis-Abay	Lake Tana	1953/2001	River flow	Hydroelectricity	11.483	37.583
Uganda	Owen Falls	White Nile	1954	215	Irrigation and hydroelectricity	0.445	33.187
Sudan	Khashm El Gibra	Atbara	1964	1.3	Irrigation and hydroelectricity	14.925	35.908
Sudan	Roseires	Blue Nile	1966	3	Irrigation and hydroelectricity	11.798	34.388
Ethiopia	Finchaa	Fincha	1971	2.395	Irrigation and hydroelectricity	9.558	37.366
Ethiopia	Alwero	Alwero	1995	0.075	Irrigation	7.860	34.493
Ethiopia	CharaChara	Blue Nile	2000	9.1	Regulation of Lake Tana outflow	11.565	37.403
Kenya	SonduMiriu	Victoria	2007		Hydroelectricity	-0.346	34.852
Sudan	Merowe	Main Nile	2009	12.5	Hydroelectricity	18.721	31.986
Ethiopia	Tekeze	Atbara	2009	3	Hydroelectricity	13.300	38.710
Ethiopia	Koga	Blue Nile	2008/2010	0.083	Irrigation	11.333	37.133
Ethiopia	Tana Beles	Blue Nile	2011	Average annual 2.424	Transfer of water from Lake Tana to the Beles Catchment	11.819	36.918
Uganda	Bujagali	White Nile	2011	0.75	Hydroelectricity	0.497	33.139

3.5 Methods

The purpose of this section is to discuss the methods used to fulfill the aims of the research. The first objective of the research, as shown in Figure (3-1), which is "to introduce a methodology for finding meteorological data sets in scarce data areas and use it in measuring climate variability studies and drought events" is achieved through the data collection and process used to choose the optimum data set for the research. The second and third objectives which are "to evaluate the impact of climate variability and droughts in unaltered flow conditions and altered flow conditions" and "to analyze the river discharge, and to assess the changes in the discharge according to the degree of human intervention”, respectively will be achieved by using the introduced methods in this section.

The second objective will be achieved by classifying the study period into different time windows based on the degree of alteration form the data collection of the structures on the Nile river and year of operation discussed in Table 3-4, in addition to the trend analysis of the meteorological data and river discharge data and the analysis of the drought events.

The third objective will be achieved through the assessment of the hydraulic alteration under the influence of the climate variability and based on the degree of alteration.

This research is proposed to answer how is the river discharge is affected by variability in temperature and precipitation especially when coupled with the human intervention and dam construction in the upstream countries.

The answer is either, the river discharge is affected by climate variability and water abstraction in the upstream, or affected by the climate variability only and not the human intervention, or affected by the human intervention and not the climate variability, or neither affected by the climate variability nor the human intervention.

The previous studies in the literature discussed how the flow regime is affected by both factors. Some studies discussed the climate variability only while other were concerned about the human intervention and the climate variability.

Based on the previous research there is a direct relation between the climate variability and the river discharge, and there was a noticeable change in the flow regime based on the intervention in the upstream.

The methodology proposed will help in answering the question if there is a relation between climate variability, human intervention, and river discharge.

According to the UNEP the eastern part of the Nile basin will experience a decrease in precipitation which should directly affect the river discharge. The trend analysis will be applied to the precipitation and river discharge data. It is expected that there will be a decrease in the precipitation and so will be a decrease in the river discharge value.

In the literature it was discussed how drought events can have a huge impact on river discharge. In this research drought events severity and intensity were invistigated and how they can affect the river discharge. It is expected that drought will have a steady rate, or a certain pattern based on the climatic condition. The river discharge will be affected if there is an increase in the severity and/or intensity of drought events.

The damming of the river flow is expected to have negative impact on the river discharge and there will be an inverse relation between the number of dams in the upstream and the river discharge flowing to the downstream.

3.5.1 Trend Analysis of Climatic and Discharge Data

One of the objectives of this research is to detect the changes that occurred in a long series of hydro-climatologic data "to evaluate the impact of climate variability and droughts in unaltered flow conditions and altered flow conditions", therefore it is important to investigate if there is or there is not a trend in the data. There are different tests such as parametric and non-parametric tests (Duhan et al., 2013). In this research the linear regression representing the parametric test and the Mann-Kendall (M-K) non-parametric test was adapted to detect the trend in the data.

The linear regression method was adapted in this study to investigate the relation between the precipitation and river discharge variables and the time.

The trend is observed as a rising and positive slope which means increasing trend or dropping and negative slope indicating a decreasing trend. The M-K test advantage is that it can be used in detecting both linear and nonlinear trends. The M-K test was applied in the research using XLSTAT and MATLAB 2015 at significance level of 5%.

3.5.2 Drought and Climate variability

The drought has direct impact on the river flow and river discharge, the drought impact depends on the severity and the duration of the drought as discussed in the literature review. The study of the drought severity will help in achieving the second objective of the present study and how the river discharge is affected by the drought events through the period of the study.

In this research the historical drought events were investigated using the Standardized Precipitation Index (SPI). The SPI will be applied for all the study period on monthly and annually scale that represents intermediate and long-term index, and for the three main contributor sub-basins of the Nile basin (Blue Nile, Atbarah and Sobat basins) and for each station within. The SPI was categorized into four periods of the total study period. The classification was based on the degree of alteration to measure the effect of climate variability with the human induced factors on the river discharge. The four periods were as follows: 1901 – 1925, 1933 – 1963, 1964 – 1999 and 2000 – 2012.

The SPI uses a single parameter which is the precipitation and was widely used by researchers in the past years (Palchaudhuri & Biswas, 2013; Svoboda et al., 2006; Yaseen K. AL-Timimi, 2013).

The SPI is categorized from extremely wet when the value is greater than 2.0 to extremely dry when it is less than -2.0, and for the rest of the values were as follows: when the value is between ($1.5 \leq SPI < 2.0$) is considered very wet, moderately wet ($1.0 \leq SPI < 1.5$), near normal ($-1.0 \leq SPI < 1.0$), moderately dry ($-1.50 < SPI \leq -1.00$) and finally, severely dry ($-2.00 < SPI \leq -1.50$) (Zarch et al., 2011). DrinC software was used to calculate the SPI.

3.5.3 Assessment of Hydraulic Alteration

In this study, a set of hydrologic indices was used to determine the degree of alteration in the pre-damming discharge. The indices are: (a) the annual mean flow, (b) monthly and annual medians, and (c) magnitudes of annual extreme conditions such as the 10th, 25th, 75th and 90th percentiles. The study considers the monthly discharge data between 1900 and 2012 at the Dongola hydrometric station in Sudan. In 1925, the first dam in the upstream countries of the Nile River was constructed in Sudan. The period from 1900–2012 is divided into two-time windows: Pre-damming (1900–1925) and post-damming (1933–2012). The post damming period has also been divided into sub-groups based on the degree of human-induced alteration.

The post-damming period has been divided into three-time windows: (a) 1933–1963, (b) 1964–1999, and (c) 2000–2012. The division considers the number of dams constructed over the entire post-damming period, with a minimum of four dams in a period. In this research, a methodology proposed by Al-Faraj and Scholz (2014) has been adopted, the methodology divides the discharge record to time windows based on the degree of alteration and applying hydrologic indices to identify the alteration in pre-damming flow regime due to the combined influence of climate and upstream damming activities.

This method helps in further understanding of the cumulative impact of induced forces and climate change through years. This research adopts the studying of the cumulative impacts of human induced factors and the climate variability seen in changes of precipitation in these periods and drought events occurred.

Flow Duration Curves (FDC) method was applied on the study for the different time intervals at both stations. The FDC is useful in showing the characteristics of the flow (Sugiyama et al., 2003), it can summarize the changes occurred in the flow at a certain location of a catchment (Best et al., 2003; Verma et al., 2016).

Flow duration curve analysis is a technique that gives a good indication of the regime in a river or streams in terms of flood events and minimum flow (Smakhtin, 2001), which encourages the researchers to use this technique in the analysis of the stream flow (Welderufael, & Woyessa, 2010).

A research in 2009 was done in order to help decision makers in Iran to reach a sustainable water development in semi-arid region by analyzing surface water flow. The analysis was done using daily stream flow data recorded at 7 stations. The research used 5 river flow analysis methods and one of the methods used was Flow Duration Curve (FDC) analysis. The FDC was used in the research to check the water availability for the required project, which was either hydropower or irrigation (Masih et al., 2009). According to (Das Gupta, 2008) the flow duration curve (FDC) analysis is the use of historical data to determine the probability of the river discharge exceeding a certain value for a percentage of time.

In this research, the FDC was applied for the different time windows to monitor the changes in the low flows that occurred most of the time and the less frequent higher flows.

Chapter Four: Results

In this chapter the results of the methods used to fulfil the objectives will be discussed. The results in this chapter will start from the trend analysis in the precipitation, temperature, and river discharge. Then going through the influence of the drought and measuring the SPI in each time window of the study period and how the river discharge was affected by the drought events. The changes in the in meteorological data and the river discharge pattern in the different time windows will also be presented and whether, there is a relation or a correlation between the meteorological data pattern and the river discharge pattern. Finally, discussing the alteration in the river discharge in the pre- and post-alteration period and how the degree of the intervention affected the river discharge will be presented in a separate chapter.

4.1 Trend Analysis

In this section the changes occurred in metrological data and river discharge along with time will be analyzed whether there is a change with time (increasing or decreasing trend) or only fluctuation at certain period and then returned to normal or constant conditions. The fulfilment of this investigation will support in the achievement of the second objective: to evaluate the impact of climate variability and droughts on river discharge in Pre-dammed flow conditions and in intervened flow conditions.

After studying the correlation between the datasets and choosing the GPCC data for precipitation and the CFSR data for the temperature data in this research, trend analysis has been applied. Both parametric and non-parametric trends have been used in this research.

The trend analysis was applied for both precipitation and temperature data using the stations distributed in the whole basin. The GPCC stations were used for precipitation, and the CFSR for Temperature.

The river discharge at the two key locations Dongola and Tamaniat hydrometric stations were also analyzed using parametric and non-parametric tests.

Table 4-1 and Figure 4-1 shows the Trend analysis for the 9 sub-basins of the Nile basin, and the number of stations in each sub-basin. Trend analysis was applied for each station of the 1040 using the Mann-Kendall test beside the precipitation of the whole basin calculated using Theisen polygon method. It is observed from Table 4-1 that 7 sub-basins out of 9 had insignificant change, and only 200 stations less than 20% of the total number of stations had a P-value less than 0.05. This small percentage means that most of the stations has almost constant precipitation and there is not a decreasing or increasing trend.

Table 4-1 Trend analysis for the Precipitation of the Nile sub-basins

Basin	No. of stations	No. of stations with P-value >0.05	No. of stations with P-value <0.05	Whole basin P-value	Whole basin linear trend (Slope)
Main Nile	289	217	72	0.007	-7.00E-05
Atbarah	80	65	15	0.304	-0.0001
Blue Nile	120	90	30	0.401	-0.0002
Sobat	79	62	17	0.417	-0.0001
White Nile	75	62	13	0.342	-9.00E-05
Bahr EL-Ghazal	210	205	5	0.566	-5.00E-05
Bahr El-Gebel	57	57	0	0.576	-8.00E-05
Kyoga	52	42	10	0.612	6.00E-05
Victoria	78	40	38	0.007	0.0003
Total	1040	840	200		

Figure 4-1 shows the location and the distribution of the stations with and without trend. The concentration of stations with trend at the Atbarah and Blue Nile Basins were near the exit and not at the highland the location of the highest annual precipitation location.

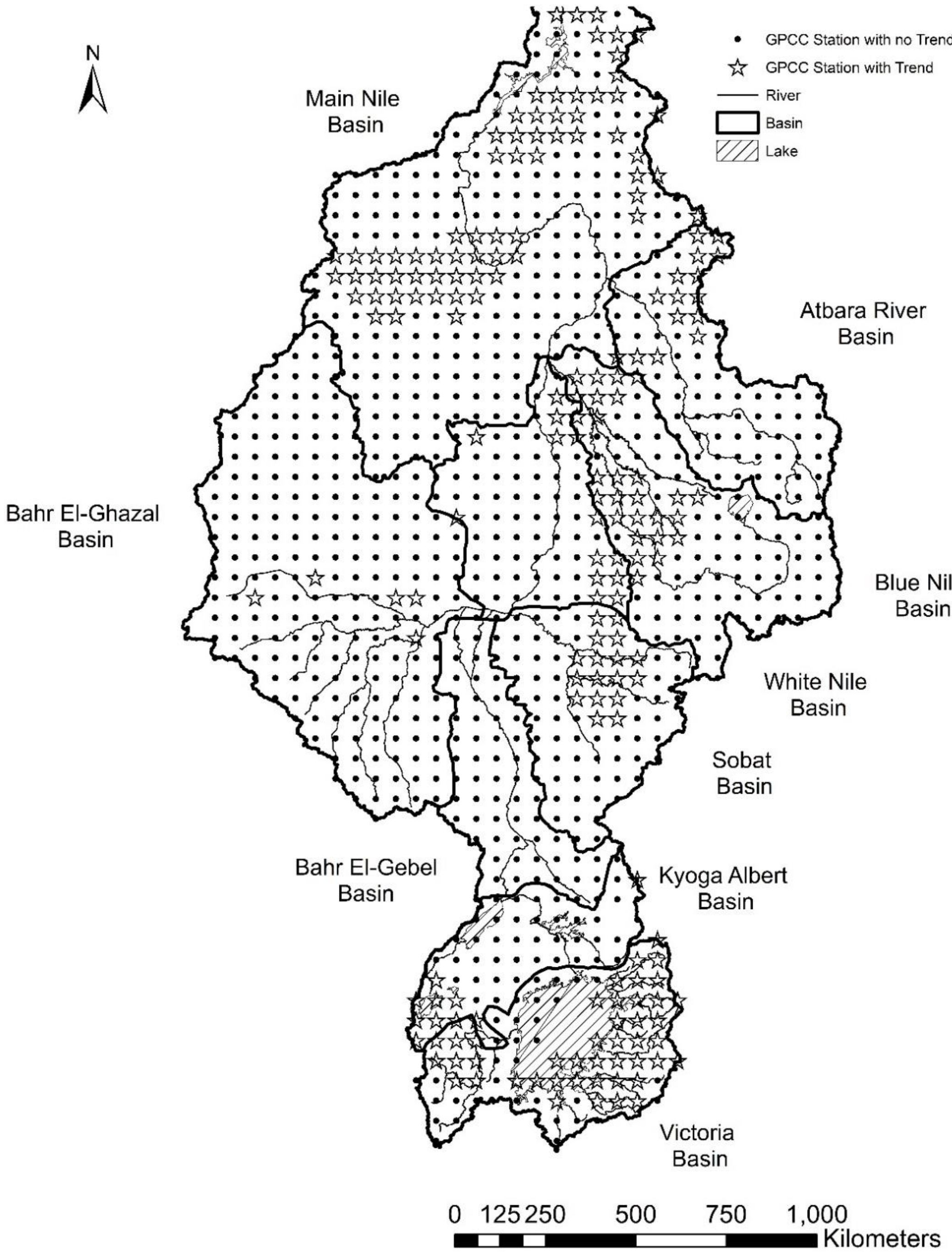


Figure 4-1 stations with and without trend in the Nile basin

The main contributor basins of the Main Nile river discharge reaching Egypt (Blue Nile, Sobat and Atbara) had 279 stations of the 1040 stations of the whole basin. The 297 stations were classified to stations with trend and other without, 217 stations of the 297 stations had no trend with a P-value greater than 0.05, and only 62 stations had a P-value less than 0.05. A decreasing linear trend was observed in 7 sub-basins, but it was observed that either there is an increasing or decreasing trend in the precipitation of the sub-basins, it has a very small value.

By taking a closer look at the stations in the three main basins generating the Main Nile discharge (Figure 4-2), it was found that the stations in the Ethiopian highlands with the highest precipitation contribution in the highland of the basin had no trend. The stations with the lower precipitation contribution and located in the lowlands of the basin and near the exit suffered a decreasing trend in the values of precipitation.

The 30 stations with a trend of the Blue Nile basin was one quarter the total number of the stations in the basin and was not located in a critical location in the basin, even though, the contribution of the area containing the stations of the Blue Nile basin to the total precipitation of the basin was calculated (Appendix 2, Table 8-1).

The total contribution of the stations with a trend ranged from 2 % of the total precipitation in January to 20.16 % in October. For the rainy season, the contribution was 17.55 %, 19.39%, and 19.27 % in July, August and in September, respectively. The low contribution of the stations with trend in the Blue Nile basin had no effect of the total trend of the whole basin.

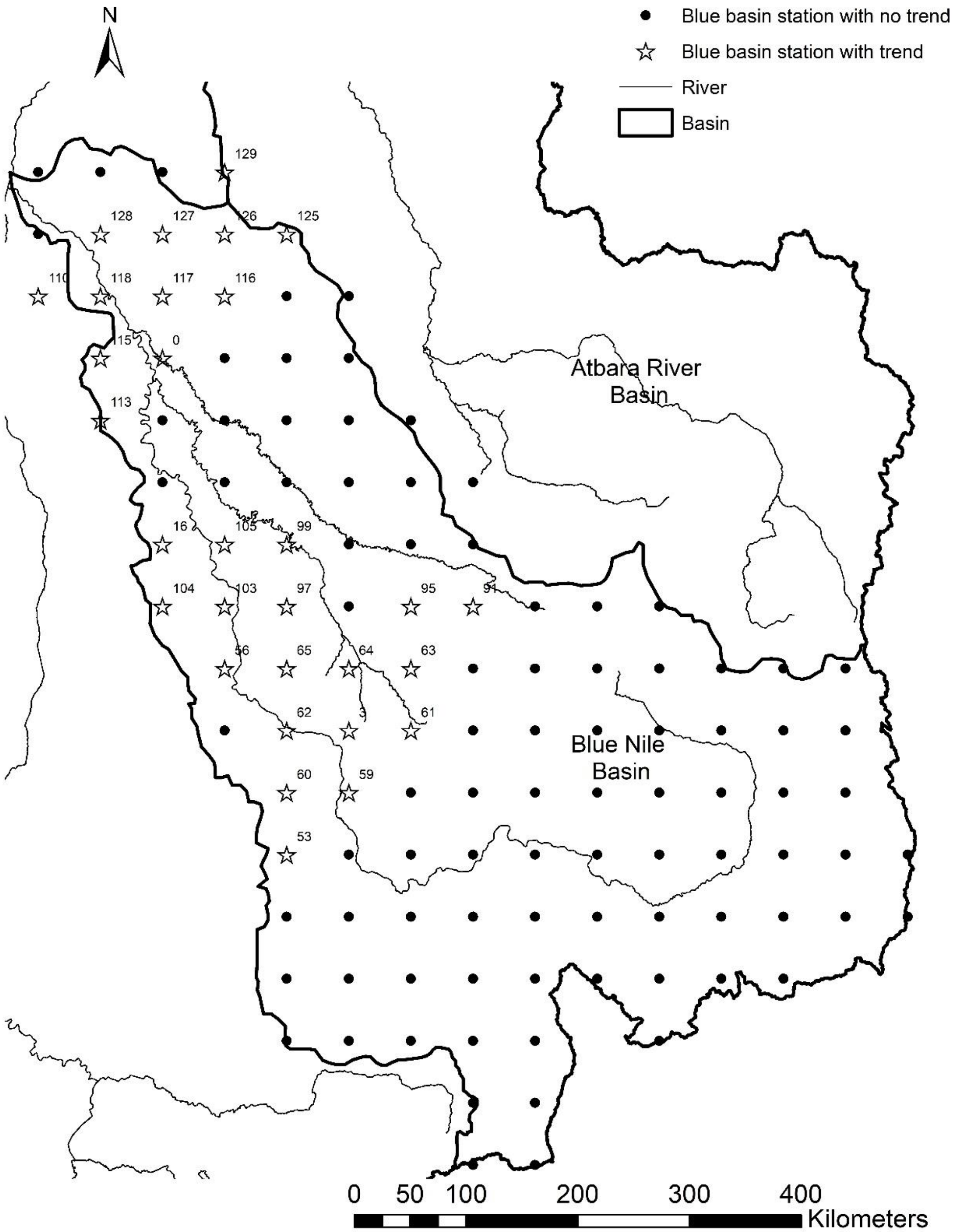


Figure 4-2 Blue Nile basin stations with and without trend.

The location of the stations with trend in the Atbara basin were closer to the outlet of the basin than the Ethiopian highlands (Appendix 2, Fig. 8-3). The location of the stations and the number of stations that do not exceed 20 % of the number of stations in the Atbara basin, gives an indication that the changes in precipitation trend for these few stations would not affect the total precipitation of the basin.

Although the location and number of stations gave a good indication of the effect of stations with trend on the whole basin, the contribution of these station in the basin precipitation was analyzed (Appendix 2, Table 8-2).

The contribution of the 15 stations in the whole basin precipitation ranged from 0.92 % in March to 10.28 % in December. For the month in the wet period the contribution was 3.79 %, 5.48 % and 4.25 % in July, August and September, respectively.

The stations that had trend in the Sobat basin were near the highlands or the beginning of the river discharge unlike the situation of Atbarah basin. The number of stations with a trend was still small compared to the total number of stations in the basin with 22 % of the total number (Appendix 2, Figure 8-2)).

In this case it was important to study the contribution of these stations to the total precipitation of the basin. The percentage ranged from 21.9 % in February to 27 % in July as seen in (Appendix 2, Table 8-3). The percentage for the wet months were 27 %, 26.9 % and 26.4 % in July, August and September, respectively.

The trend analysis for the whole precipitation record gave a good indication how the climate changed in the 112 years of precipitation. It was crucial to analyze the trend in precipitation for each month, in order to trace the change that will occur in the river discharge as a result of changes in precipitation.

The months of the three main basins contributing to the river discharge (Blue Nile, Atbarah, and Sobat basins) were analyzed in terms of both linear and nonparametric trend (Table 4-2). It was observed that the number of stations and even the stations that had a trend were not constant for the months that had a trend.

Table 4-2 Monthly trend for the three main sub-basins

Basin	Atbarah				Blue Nile				Sobat			
	No. of station with P-value >0.05	No. of station with P-value <0.05	Whole basin P-value	Linear Trend (slope)	No. of station with P-value >0.05	No. of station with P-value <0.05	Whole basin P-value	Linear Trend (slope)	No. of station with P-value >0.05	No. of station with P-value <0.05	Whole basin P-value	Linear Trend (slope)
Jan	52	28	0.653	0.00001	87	33	0.149	0.00002	73	7	0.903	0.00008
Feb	50	30	0.008	-0.00004	64	56	0.014	-0.0002	32	48	0.0156	-0.0002
Mar	71	9	0.852	0.00002	93	27	0.689	-0.00009	54	26	0.168	-0.0003
Apr	71	9	0.99	0.00003	100	20	0.741	0.00004	80	0	0.583	-0.0002
May	76	4	0.23	-0.00009	95	25	0.22	-0.0004	59	21	0.032	-0.0007
Jun	53	27	0.034	-0.0003	76	44	0.077	-0.0004	54	26	0.049	-0.0005
Jul	72	8	0.117	-0.0004	83	37	0.027	-0.0005	78	2	0.236	0.0004
Aug	33	47	0.005	-0.0007	80	40	0.005	-0.0006	69	11	0.237	-0.0003
Sep	59	21	0.0326	-0.0004	71	49	0.039	-0.0007	74	6	0.899	-0.0002
Oct	72	8	0.452	-0.00002	103	13	0.99	0.0002	80	0	0.806	0.0002
Nov	70	10	0.821	0.00002	97	23	0.431	-0.00007	78	2	0.919	-0.00002
Dec	65	15	0.171	0.000005	99	21	0.93	0.00002	71	9	0.693	0.00002

The trend analysis showed that the months with a decreasing precipitation trend were as follows: for Blue Nile basin months February, July, August, and September; then for Atbarah basin months February, June, August, and September; finally, Sobat basin months February, May, and June. Although, there was a non-parametric trend detected in critical months of the discharge (August and September), the linear trend showed a very low rate of decrease.

The number of stations in Atbara basin that showed a trend in the month of February were 30 out of 80 but had enough influence to affect the trend of the whole basin. The distribution of these stations in (Appendix 2, Fig. 8-3), showed that 13 stations of the

30 stations with a trend were in the Ethiopian highlands. The month of June compared to February showed a decrease in the number of stations with a trend to be 27 instead of 30. The location of some stations also was different than that of February, but still the critical area at the Ethiopian highland was affected with changes in precipitation (Appendix 2, Fig. 8-4).

The month of August was the third month to witness a change in precipitation for Atbarah basin. The number of stations with a trend was the largest among the four months with a trend, with 50 stations out of 80 had showed changes in precipitation. The number of stations was enough to influence the change in the precipitation of the whole basin, even though, it was observed in (Appendix 2, Fig. 8-5) that almost half the critical stations were located at the source of the flow of the river.

The last month that had a trend for Atbarah basin was September. The number of stations with a trend decreased to be only 21 of the 80 stations distributed in the basin. By referring to (Appendix 2, Fig. 8-6) it was observed that 15 of the 21 stations were located at the source of the flow that resulted in the change of the whole basin precipitation in September.

For all the months that suffered a decreasing trend in the precipitation for the Atbarah basin there was a critical area that showed the trend which is at the source of the river flow. The main concern is that the recorded changes will encourage the construction of water storage structures in order to store as much water as possible to secure the needs of the future, which eventually lead to the river discharge decrease reaching the downstream countries.

The month with trend in the Blue Nile basin was February, and the three months of the wet period were July, August, and September. From Table 4-2 the number of stations with trend for the month of February were 56 stations out of 120, the highest ratio of stations among the other months. Appendix 2, Fig. (8-7) shows the spatial distribution of these stations in the Blue Nile basin, most of the stations with trend are concentrated in the middle part of the basin and around 15 of them are in the Ethiopian highlands.

The month of July had 37 stations out of 120 with a decreasing trend, the number of stations with a trend decreased by 34% compared to February. The stations presented in (Appendix 2, Fig. 8-8) were not concentrated in a special zone but were distributed through the basin. The Ethiopian highland had 12 stations out of the 37 stations with a trend.

The stations with a trend in August increased again to be one third of the stations, 40 out of 120 stations had trend. A total of 12 of the stations with trend were in the Ethiopian highlands and the rest were in the middle of the basin (Appendix 2, Fig. 8-9).

The month of September had 49 stations with trend out of 120 stations. The stations with trend were not concentrated in one place, 15 of them are at the Ethiopian highland, while the rest are distributed between the middle of the basin and the outlet of the basin at Khartoum (Appendix 2, Fig. 8-10).

The zones showed a decreasing trend will encourage stake holders in this area to think about storing water through building reservoirs and dams and change the reservoir operation for existing dams.

The Sobat basin had months with a non-parametric decrease as February, May, and June (Table 4-2). Appendix 2, Figs. 8-11, 8-12 and 8-13, show the distribution of the stations in the Sobat basin.

More than half of the stations in the month of February had a decreasing trend, where 48 out of 80 stations had a significant trend. 28 of the 48 stations are in the northern part of the basin, near the Ethiopian highlands and at the origins of the river flow (Appendix 2, Fig. 8-11).

The number of stations with trend decreased compared to the number of stations with a trend in February to be 21 and 26, in the months of May and June, respectively. The distribution of the stations for the month of May is shown in Appendix 2, Fig. 8-12, 16 out of the 21 stations with trend were in the northern part of the basin and the origins of the river flow.

The location of the stations with trend for the month of June were concentrated at the northern part of the basin, all the 26 stations were at the origins of the river flow.

In order to determine how the changes in trend can affect the total discharge volume, the contribution of precipitation of each month percentage of the annual flow was calculated, and the months with the higher contribution in the flow for the three basins are August, July, and September, respectively (Table 4-3).

Table 4-3 Contribution of the monthly precipitation for the three main basins.

Basin	Jan (%age of mean annual flow)	Feb (%age of mean annual flow)	Mar (%age of mean annual flow)	Apr (%age of mean annual flow)	May (%age of mean annual flow)	Jun (%age of mean annual flow)	Jul (%age of mean annual flow)	Aug (%age of mean annual flow)	Sep (%age of mean annual flow)	Oct (%age of mean annual flow)	Nov (%age of mean annual flow)	Dec (%age of mean annual flow)
Atbarah	0.3	0.5	1.5	3.2	6.3	11.5	27.9	30.1	13.0	4.0	1.2	0.5
Blue Nile	0.5	1.0	2.3	3.6	8.6	14.2	22.8	23.7	15.2	5.9	1.6	0.6
Sobat	1.3	1.6	4.2	7.8	12.3	12.9	15.2	16.0	13.2	9.2	4.4	2.0

The common month between the three basins that had a decreasing trend was February. February is considered one of the dry months in the three basins, according to Table 4-3 the contribution of the precipitation for the month of February was 0.5%, 1% and 1.6% for the Atbarah, Blue Nile and Sobat Basins respectively.

February is one of the dry months, and continuous decrease in rainfall will lead to more decrease of discharge in the dry period. Since the three main contributor basins had decreasing trend, then less discharge will occur in the dry period.

The Atbarah basin had 4 months with a decreasing trend, one of them is in a dry period and the other three are the wet period of the year, the contribution of these months in the basin precipitation were 0.5%, 11.5%, 30% and 13% for months February, June, August and September, respectively, giving a total of 55% of the basin precipitation with a decreasing trend.

The Blue Nile basin had 4 months with a trend, the contribution of these months in the annual precipitation of the basin is as follows: 1%, 22.8%, 23.7% and 15.2% for months of February, July, August and September, respectively, giving a total of 63% of the total basin annual precipitation.

Sobat basin had 3 months with trend, but unlike the Atbarah and Blue Nile basins, 2 months with trends were not in the wet period. The contribution of the months with trend for the Sobat basin is as follows: 1.6%, 12.3% and 12.9% on months February, May and June, respectively, with a total of 27% of the annual precipitation of Sobat basin.

The months with the highest contribution in the river flow from the Blue Nile basin are had a decreasing trend, this situation is also for the Atbarah basin but unlike the situation of Sobat basin.

The change in the precipitation trend will eventually affect the river dishcarge and future planning of the upstream country, that will lead to the change of river flow regime for downstream countries.

The trend analysis was applied for the temperature at the three main basins. The trend analysis yielded that there was a trend for the maximum temperature in two of the three basins, the Blue Nile basin and the Atbarah basin with a p-value of 0.008 and 0.003, respectively.

As there was a change in the precipitation trends that is considered the main factor of the stream flow, the river discharge at the two observation stations (Dongola and Tamaniat) had to be analyzed. The analyses have been applied for both monthly and annually flows, Table 4-4 presents the linear and Mann-Kendall test and Figures 4-3 and 4-4 show the linear trend for these stations.

The non-parametric test p-value were less than 0.00001 for Dongola basin, and 0.0018 for Tamaniat station. There was an annually and monthly significant trend for both Dongola and Tamaniat stations except for March and August for Dongola station and February. March, July, and August for Tamaniat station.

Table 4-4 Monthly trend for the two stations

Station	Dongola		Tamaniat	
	Linear trend (slope)	P-value	Linear trend (slope)	P-value
Jan	-16.239	<0.0001	-7.4599	0.008
Feb	-6.9355	<0.0001	-2.9241	0.3744
Mar	-2.0223	0.4414	2.9053	0.1112
Apr	10.985	<0.0001	18.498	<0.0001
May	16.089	<0.0001	17.169	<0.0001
Jun	11.401	<0.0001	7.5206	0.0287
Jul	15.643	0.0029	-1.2754	0.46
Aug	-6.8444	0.5845	-6.2649	0.2463
Sep	-76.412	<0.0001	-53.452	<0.0001
Oct	-95.393	<0.0001	-65.13	<0.0001
Nov	-43.213	<0.0001	-26.293	<0.0001
Dec	-26.471	<0.0001	-16.461	<0.0001
Annual	-220.15	<0.0001	-133.17	0.0018

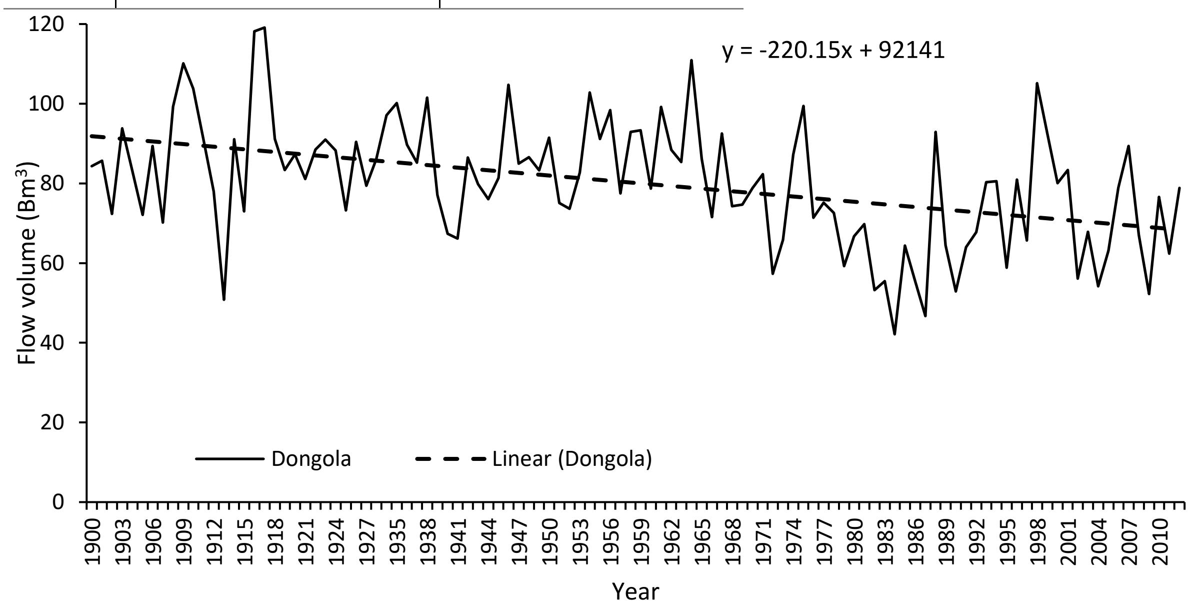


Figure 4-3 Linear trend for the Dongola hydrometric station.

For months July and September there was a decreasing trend in both precipitation and river flow. However, for August there was a decreasing trend in precipitation, while for river discharge there was a very small decrease in linear trend and no trend in non-parametric tests.

This finding could be due to two reasons, either the decrease occurred in precipitation had low impact on the river discharge, and/or the consumption of the fresh water in the upstream was low compared to the river discharge.

The results showed a mild decreasing trend or no trend in the precipitation when applying the parametric or the non-parametric tests. The results are somehow agreeing with the hypotheses of the decreasing precipitation in the Eastern Nile basin.

What was agreeing with the hypotheses is the decreasing trend of the river discharge on both parametric and non-parametric tests.

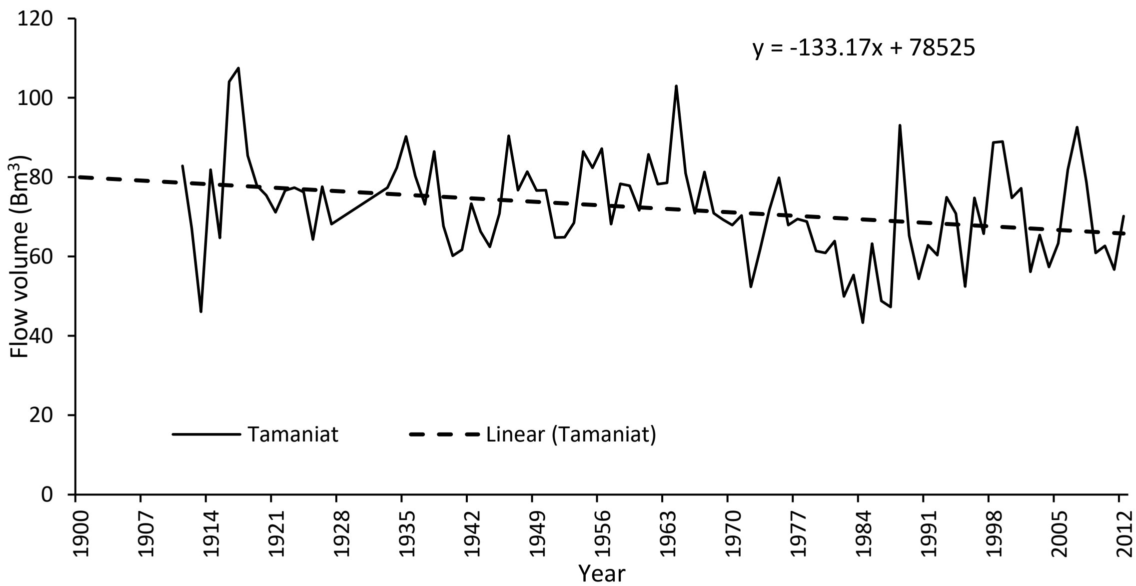


Figure 4-4 linear trend for the Tamaniat hydrometric station.

4.2 Drought Indices

Assessing the drought events and number of occurrences of severe droughts is part of the fulfilment of the second objective: to evaluate the impact of climate variability and droughts on river discharge in Pre-dammed flow conditions and in intervened flow conditions.

In order to detect the drought events in the study basin, the SPI was calculated using the precipitation data at the three main basins contributing to the Main Nile river flow (Blue Nile, Atbarah and Sobat basins). The drought event from the literature collected is the decrease in the amount of rainfall than the normal rainfall in a certain period and for a certain period. The severity of the drought is the degree of dryness of this period and the amount of decrease in the rainfall.

The SPI was computed monthly and annually as an intermediate long-term drought index. Tables 4-5, 4-6 and 4-7 present classification of the SPI either it is normal condition, Moderate dry, or severe dry and their percentages for each period of the time window for the three main basins.

4.2.1. Drought events in the Blue Nile basin

The drought events increased and became more severe over time, the Blue Nile basin is the major contributor in the river flow, in the first-time window between (1901 and 1925) only one year was a severe dry period. Each month had at least one severe drought event, while February was the only month with no severe drought events, on the contrary was the rainy seasons, as the month of September recorded the highest number of severe drought events. August, the highest contributor in precipitation, had 2 severe drought events, then came July as the third highest contributor with one event. The moderate dry event occurred in one year of the first-time window, the number of moderate dry events was more than the severe dry events on the monthly scale. The highest number of events occurred in January with 5 times which is 20% of the period between 1901 and 1925. The rest of the months were between 0 and 3 events, concerning the highest months in precipitation contribution, the highest month with moderate drought events was July with 3 events which were 12% of the period. The months of August and September had 1 and 0 events, respectively.

The precipitation condition for period between 1933 and 1963 was better than the period between 1901 and 1925.

The severe drought events occurred only one year and the highest month with severe drought was April with 3 events that represent 10% of the records. The wet period had one severe drought events for July and August and zero events for September.

There were no moderate dry events between 1933 and 1963 on the annual scale. The highest month with moderate dry events was January with 7 events which were 23% of the January records for this period. The wet period had only 4 months with moderate dry events, 2 of them were in July and one for both August and September.

Table 4-5 shows how the drought events changed from time window to another and was not constant in each time window, that can help in finding a relation between the changes occurred in the river discharge and climate variability in terms of drought events. The table is divided into two parts, the first part is number, and degree of drought events occurred for each month in each time window.

The second part is the percentage of occurrence of the drought event in the time window. It can be observed that for the four time windows all of the months had most of the precipitation in normal conditions, as can be seen in the number of events and percentage, for example the month of July in period 1901—1925 had 18 years with near normal precipitation conditions for the month of July, 3 years with moderate dry conditions and 1 year with severe dry drought and the rest of years in the period are considered wet conditions.

Some months had the same characteristics for the whole period, for the month of August in period 2000—2012 all the precipitation events for the 13 years were near normal conditions.

Table 4-5 Drought events in the Blue Nile basin and its %age of the precipitation period.

	1901-1925			1933-1963			1964-1999			2000-2012		
	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry
Jan	14	5	2	18	7	2	27	4	0	9	3	0
Feb	17	1	0	20	3	2	22	4	5	7	3	2
Mar	16	3	1	23	2	2	24	2	2	10	0	2
Apr	20	1	2	18	4	3	26	3	4	10	0	0
May	18	0	2	25	1	0	29	0	3	7	1	3
Jun	18	2	1	23	1	1	27	2	4	9	0	2
Jul	18	3	1	20	2	1	22	4	5	8	3	1
Aug	16	1	2	21	1	0	25	6	4	13	0	0
Sep	16	0	3	21	1	1	27	3	4	12	1	0
Oct	19	2	1	23	3	1	18	6	2	8	2	1
Nov	19	1	1	21	1	2	23	6	1	11	1	0
Dec	18	2	1	22	3	0	22	5	4	9	0	2
Year	17	1	1	22	0	1	21	8	5	7	5	1
% of drought events to the whole period												
Jan	56	20	8	58	23	6	75	11	0	69	23	0
Feb	68	4	0	65	10	6	61	11	14	54	23	15
Mar	64	12	4	74	6	6	67	6	6	77	0	15
Apr	80	4	8	58	13	10	72	8	11	77	0	0
May	72	0	8	81	3	0	81	0	8	54	8	23
Jun	72	8	4	74	3	3	75	6	11	69	0	15
Jul	72	12	4	65	6	3	61	11	14	62	23	8
Aug	64	4	8	68	3	0	69	17	11	100	0	0
Sep	64	0	12	68	3	3	75	8	11	92	8	0
Oct	76	8	4	74	10	3	50	17	6	62	15	8
Nov	76	4	4	68	3	6	64	17	3	85	8	0
Dec	72	8	4	71	10	0	61	14	11	69	0	15
Year	68	4	4	71	0	3	58	22	14	54	38	8

The worst drought events took place in the period between 1964 and 1999. On yearly scale, 5 years were marked as severe drought years with 14% of the period, even on the monthly scale, months of February and July had 5 events and other 5 months with 4 events.

The wet months had 13 severe dry events, 4 times for the months of August and September each and 5 times for the month of July.

The highest record of moderately dry events was between years 1964 and 1999 with 8 events covering 22% of the years in this period. The months with the highest moderate drought events were August, October and November with 6 events. The wet period had 13 moderate dry events 6 of them were in August and 4 were in July and 3 in September.

The 14% of the severe drought events on annual scale between 1964 and 1999 decreased to be 8% between years 2000 and 2012. Seven months between years 2000 and 2012 had severe dry droughts, May was the month with highest events by witnessing 3 events. The wet period had only one severe drought event and it was in August.

The highest percentage of moderate drought events happened between years 2000 and 2012 with 38% of the years in this period. The months with the highest moderate drought events were January, February and July with 3 events for each month. The rest of the wet period in August and September had one event in September.

The strongest drought events occurred in the 3rd and 4th time-window with 36% of years suffered drought between years 1964 and 1999 and 46% of years between 2000 and 2012. The period between 1901 and 1925 had 92% of precipitation between near normal and wet condition, this percentage was not the best. Years between 1933 and 1963 had 97% of its precipitation between wet and near normal. The percentage decreased to 64% between 1964 and 1999 and the worst was between 2000 and 2012 which was 54%.

4.2.2. Drought events in the Atbara basin

The normal period in Atbara basin between years 1901 and 1925 did not suffer severe dry events on the annual scale, on the monthly scale there were 4 months suffered severe drought 2 of them were in the wet period on July and September (Table 4-6). The moderate dry events for the same period happened in 2 years, the highest month with number of moderate drought events was April. The moderate drought events took place in the wet period for 4 times, 2 of them were in September. 92% of the years did not suffer drought events, 72% were considered near normal and 20% were wet years. For the 2nd time-window between 1933 and 1963, the annual severe drought events were the same as the pre-damming flow condition with zero events. The moderate drought events were better than the pre-damming flow condition with only one moderate dry event. On the monthly scale February, witnessed the highest severe drought events with 3 events, and July was the only month in the wet period with a severe drought and it occurred once. The moderate dry events increased on the monthly scale than the natural condition, November was the highest with 6 times, then January with 5 times. The wet period suffered 8 events, 2 of them were in September and the rest were shared between July and August, equally.

The precipitation condition got worse between years 1964 and 1999, the severe drought increased from zero events to be 14% of the record, the monthly scale also increased to range from 1 event on May to 6 events on January, the wet period suffered 11 events 4 times in July and September, each, and 3 times in August.

There was also an increase in the moderate drought events, 5 years witnessed moderate drought events through the period between 1964 and 1999.

The month with the more frequent events was August with 8 times, the second highest record in the wet season was September with 7 events and finally July with 5 records. The last period between 2000 and 2012 had a smaller number of years with severe drought, even though, it had the highest percentage with 15%, the same observation was on the months of August and September.

Table 4-6 Drought events in the Atbarah basin and its %age of the precipitation period.

	1901-1925			1933-1963			1964-1999			2000-2012		
	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry
Jan	23	0	0	24	5	0	20	2	6	7	1	2
Feb	16	2	0	20	1	3	24	4	3	6	3	3
Mar	25	0	0	23	2	2	22	2	4	9	1	2
Apr	20	3	1	24	2	0	25	3	4	9	0	3
May	20	1	0	21	3	1	22	6	1	9	1	2
Jun	17	1	1	26	1	1	25	4	3	8	3	0
Jul	20	1	1	18	3	1	21	5	4	10	2	0
Aug	18	1	0	22	3	0	20	8	3	11	0	2
Sep	17	2	1	22	2	0	20	7	4	9	0	2
Oct	18	2	0	27	3	1	27	2	4	10	2	0
Nov	20	2	0	16	6	1	26	3	2	10	1	0
Dec	20	1	0	24	2	0	18	5	4	9	0	1
Year	18	2	0	20	1	0	21	5	5	8	3	2
% of **drought events to the whole period**												
Jan	92	0	0	77	16	0	56	6	17	54	8	15
Feb	64	8	0	65	3	10	67	11	8	46	23	23
Mar	100	0	0	74	6	6	61	6	11	69	8	15
Apr	80	12	4	77	6	0	69	8	11	69	0	23
May	80	4	0	68	10	3	61	17	3	69	8	15
Jun	68	4	4	84	3	3	69	11	8	62	23	0
Jul	80	4	4	58	10	3	58	14	11	77	15	0
Aug	72	4	0	71	10	0	56	22	8	85	0	15
Sep	68	8	4	71	6	0	56	19	11	69	0	15
Oct	72	8	0	87	10	3	75	6	11	77	15	0
Nov	80	8	0	52	19	3	72	8	6	77	8	0
Dec	80	4	0	77	6	0	50	14	11	69	0	8
Year	72	8	0	65	3	0	58	14	14	62	23	15

The moderate dry events occurrence increased also in percentage to be 23% on annual scale. The wet season had only 2 events on the month of July and the highest months with moderate drought events were June and February with 3 events each.

4.2.3. Drought events in Sobat basin

There were drought events in the Sobat basin for all the time-windows. The normal condition between 1901 and 1925 had only 1 year marked as a severe drought, and 3 years as a moderate drought (Table 4-7). The highest number of months with severe drought were July and August with 4 times each. The rest of the month had between zero and only 1 severe drought event. The highest with moderate drought events was September with 5 events, then came June with 4 events.

The period with the best condition for the Sobat basin was between 1933 and 1963 on annual scale, there was no severe drought and only one year marked as a moderate dry condition. 6 months had severe drought events, the highest in the number of events was September with 3 events, then came June, July, October and November each with 2 events.

August was the only month in the wet season to suffer moderate drought with 2 times, and the highest month in number of moderate droughts was January with 4 times.

The precipitation situation became slightly difficult between years 1964 and 1999 more than 1st and 2nd time windows. There were 2 severe drought and 3 moderate drought events on annual scale. The monthly wet season severe drought was better than the 1st and 2nd time window with only 2 events in August. In the rest of the months there was an increase in the severe drought events and the highest was 5 events in February. The wet season had 7 moderate drought events 4 of them were in September.

Dramatic changes were observed in the 4th time window between 2000 and 2012. 69% of the years were noticed as drought years, 4 out of 13 years are moderate dry years and 5 years were severe drought. The wet season had 5 months as severe dry and 5 months as moderate dry events.

Table 4-7 Drought events in the Sobat basin and its %age of the precipitation period.

	1901-1925			1933-1963			1964-1999			2000-2012		
	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry	Near Normal	Moderate Dry	Severe Dry
Jan	23	2	0	23	4	0	18	5	4	5	1	3
Feb	22	0	0	21	2	1	23	4	5	5	2	5
Mar	17	3	1	23	1	0	23	6	1	7	2	3
Apr	22	0	1	26	2	0	25	4	3	9	0	3
May	18	2	1	25	1	0	27	2	2	7	2	4
Jun	13	4	1	22	3	2	28	3	1	8	2	2
Jul	18	2	4	21	0	2	27	1	0	9	3	1
Aug	16	1	4	23	2	0	26	2	2	10	1	2
Sep	14	5	1	22	0	3	28	4	0	9	1	2
Oct	19	3	1	22	3	2	22	4	2	7	2	2
Nov	17	3	1	21	3	2	26	5	1	9	1	0
Dec	21	2	0	24	0	0	17	8	4	10	1	1
Year	15	3	1	25	1	0	22	3	2	4	4	5
% of **drought events to the whole period**												
Jan	92	8	0	74	13	0	50	14	11	38	8	23
Feb	88	0	0	68	6	3	64	11	14	38	15	38
Mar	68	12	4	74	3	0	64	17	3	54	15	23
Apr	88	0	4	84	6	0	69	11	8	69	0	23
May	72	8	4	81	3	0	75	6	6	54	15	31
Jun	52	16	4	71	10	6	78	8	3	62	15	15
Jul	72	8	16	68	0	6	75	3	0	69	23	8
Aug	64	4	16	74	6	0	72	6	6	77	8	15
Sep	56	20	4	71	0	10	78	11	0	69	8	15
Oct	76	12	4	71	10	6	61	11	6	54	15	15
Nov	68	12	4	68	10	6	72	14	3	69	8	0
Dec	22	0	1	26	2	0	25	4	3	9	0	3
Year	60	12	4	81	3	0	61	8	6	31	31	38

The worst period was between 2000 and 2012 where 69% of the years suffered drought. The last 32 years suffered severe drought events. The drought events affected the river discharge volumes in the last two time windows (1964—1999) and (2000—2012). The number of the moderate dry and sever dry years for the Blue Nile basin were 23 years 15 of them were starting from 1980.

The precipitation drought events have been calculated at the three major basins for the different time periods. It was observed how the changes in the drought events occurred on annual and monthly scales, and how the drought events became more severe.

It was important to identify how the changes in drought events and the change in trends affected the precipitation pattern in the basins for the different time-windows.

To understand the behaviour of the stations within the basin, examples of the 3 basins Blue Nile, Atbarah and Sobat with different drought conditions severe drought, moderate drought and near normal condition are presented in Appendix 2, Figs. 8-14 to 8-22.

Appendix 2, Fig. 8-14 shows the distribution of the Blue Nile basin station when near normal conditions occurred in 1980. Year 1980 is considered as a near normal condition, this year contained all the classifications of drought from wet conditions to severe dry conditions. 18 stations were wet stations concentrated in the middle of the basin, 4 stations were moderate dry drought condition but distributed through the basin, 4 stations were severe dry stations and were also distributed through the basin, the near normal condition was the most common between the 120 stations of the Blue Nile basin in 1980 with 94 stations.

Year 1984 was the worst year in drought within the whole record of study for the Blue Nile basin. Appendix 2, Fig. 8-15 presents the stations and drought condition in year 1984. Only one station was in wet condition, 35 stations were near normal conditions, 15 stations were moderate dry, the rest of the 69 stations were in severe dry condition. Year 1997 was a moderate dry year in the Blue Nile basin. Year 1997 was unlike years 1980 and 1984, it did not witness any wet station. 12 of the stations were severe dry stations but distributed in the basin, 17 stations were moderate dry and were also distributed in the basin, the rest of the 120 stations were near normal conditions.

There were also changes in the drought and precipitation of the Atbara basin, there were months and years considered wet, near normal, moderate dry and severe dry with the 112 years record.

Appendix 2, Fig. 8-17 shows an example of a moderate dry year, year 1970 in Atbara basin had 3 classifications of drought in its stations. 12 of the 80 stations were considered severe dry stations, few of the stations were in the northern area of the basin but the majority were at the south of the station where the flow originates. 7 of the stations were moderate dry stations and had the same distribution as the severe dry stations. The rest of the stations were near normal stations, the stations were distributed in all portions of the basin.

Year 1984 was one of the toughest years with severe drought not on the Blue Nile basin only, but also on the Atbara basin. Appendix 2, Fig. 8-18 presents the categories of the stations on this year, more than half of the stations suffered severe drought, 59 stations covering all the basin and specially at the origins of the flow suffered severe drought. Then, 11 stations were classified as near normal, finally 10 stations were moderate drought.

Year 1980 was representative of the near normal condition in the Atbara basin. Appendix 2, Fig. 8-19 shows the stations of Atbara basin year 1980 and their classifications. The stations in Atbara basin witnessed all sorts of drought, 9 stations were categorized by severe drought and located at the northern part of the basin, 9 stations were moderate dry 5 of them were near the severe drought stations, while the other 4 were at the southern area of the basin. 16 stations were noticed to be wet and were located at the middle part of the Atbara basin, the majority and more than half of the stations were near normal stations.

Sobat basin was same as the Atbarah and Blue Nile basins and had different episodes of climate within the 112 years. Appendix 2, Fig. 8-20 is an example a near normal year in the Sobat basin, year 1991 had the precipitation in all the stations of the basin categorized as a near normal.

Year 2002 was a representative of a moderate dry year for the Sobat basin. Appendix 2, Fig. 8-21 presents the stations of the Sobat basin and their categories. There was a mix between different sorts of drought in year 2002, 17 stations were suffering severe drought of which 8 were at the outlet of the basin and the rest were at the origins of the flow. 13 stations were considered as moderate dry stations of which 5 were at the outlet of the basin and the 8 were at the river flow origins. The rest of the 80 stations were near normal stations and were distributed through all the basin.

Year 2010 is a good example of severe drought year in the Sobat basin. As seen in Appendix 2 (Fig. 8-22) a range of different climate conditions were found, with one wet station and 10 stations showing moderate drought. The most effective stations were the severe dry stations, which were located at the origins of the flow at the north eastern part of the basin, and they shared by 35 stations of the 80 stations of the basin. The rest of the stations were near normal stations.

From the maps representing the different drought conditions there were no certain pattern followed, some cases of all the stations within the basin had the same drought category, other cases such as severe drought years were some stations considered wet. The number and location of the stations and their categories had the upper hand in determining the type of the drought of the year.

The results were not agreeing to the hypotheses, the hypotheses of the research assumed that the drought events will have a certain repetitive pattern. The drought events became tougher with time which has a strong effect on the river discharge.

4.3 Changes in rainfall and temperature pattern

Assessing the rainfall and temperature pattern is part of the fulfilment of the second objective: to evaluate the impact of climate variability and droughts on river discharge in Pre-dammed flow conditions and in intervened flow conditions.

The precipitation is neither seasonally nor annually steady (Figs. 4-5, 4-6, 4-7 and 4-8). As precipitation is the main source of river runoff, there is a direct relationship between climate variability from the perspective of precipitation and river flow. Precipitation irregularities were the only main constrain affecting the change in pre-damming flow conditions between 1900–1925. The other study periods (1933–1963, 1964–1999 and 2000–2012) were characterized by changes to discharge due to changes in precipitation and human intervention in comparison to the pre-damming flow period between 1901 and 1925. The main four sub-basins (Blue Nile, Sobat, Atbarah, and Main Nile) experienced changes in the mean precipitation patterns.

4.3.1 Precipitation pattern in the Blue Nile basin

The Blue Nile, which is considered as the major contributor to discharge, shows changes in rainfall patterns. For example, between the mean rainfall from 1901–1925, and the long-term rainfall between 1901–2012, there was a decrease in the mean rainfall from 1118 mm/year to 1105 mm/year, representing about 1.2%.

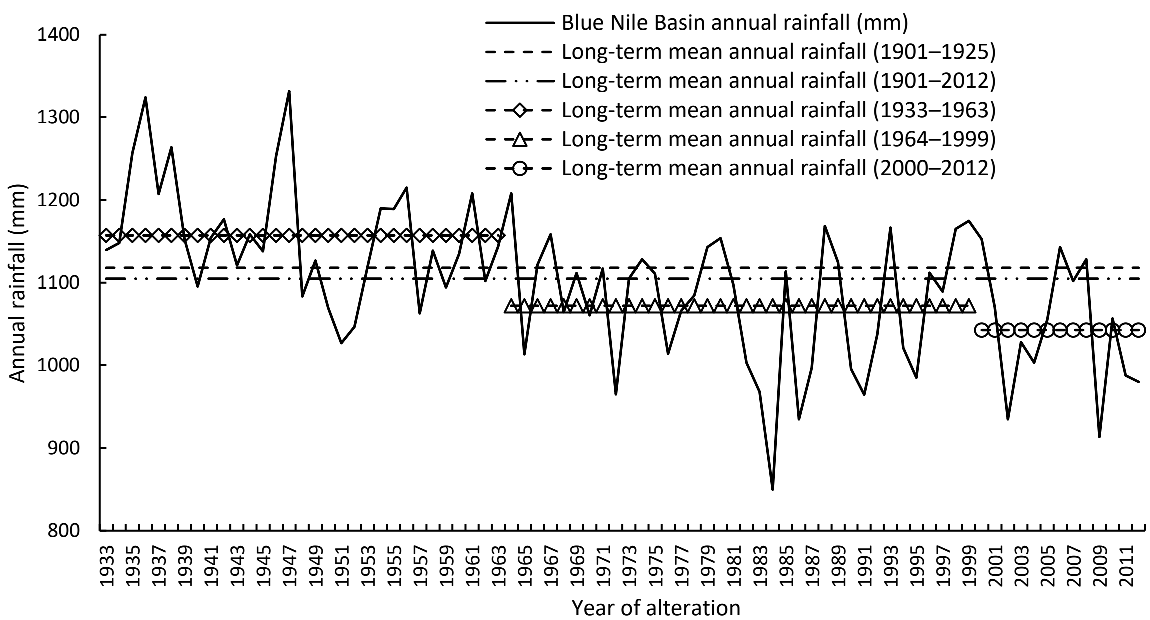


Figure 4-5 Mean annual Precipitation of the Blue Nile basin.

The only period that showed an increase in the mean precipitation is between 1933 and 1963 with annual mean precipitation 1158 mm/year, there was an increase of 3.5% in rainfall between 1901–1925 and 1933–1963. For the periods 1964–1999 and 2000–2012, there was a decrease by 4.1% and 6.7%, respectively as seen in (Figure 4-5).

The changes in the mean annual rainfall for the different time-windows confirm that the changes happened in the drought events of the same periods and the percentage of the drought events in the whole period. The minimum values of the annul precipitation started in the 80's due to the increase in severe dry and moderate dry events.

4.3.2 Precipitation pattern in the Atbara basin

The situation in the Atbara basin was like that of the Blue basin (Figure 4-6). The value of mean annual precipitation for the natural condition period was 542 mm/year and was greater than the whole study period between 1901 and 2012 which was 526 mm/year, the decrease in the mean annual precipitation between the two time-windows was 3%.

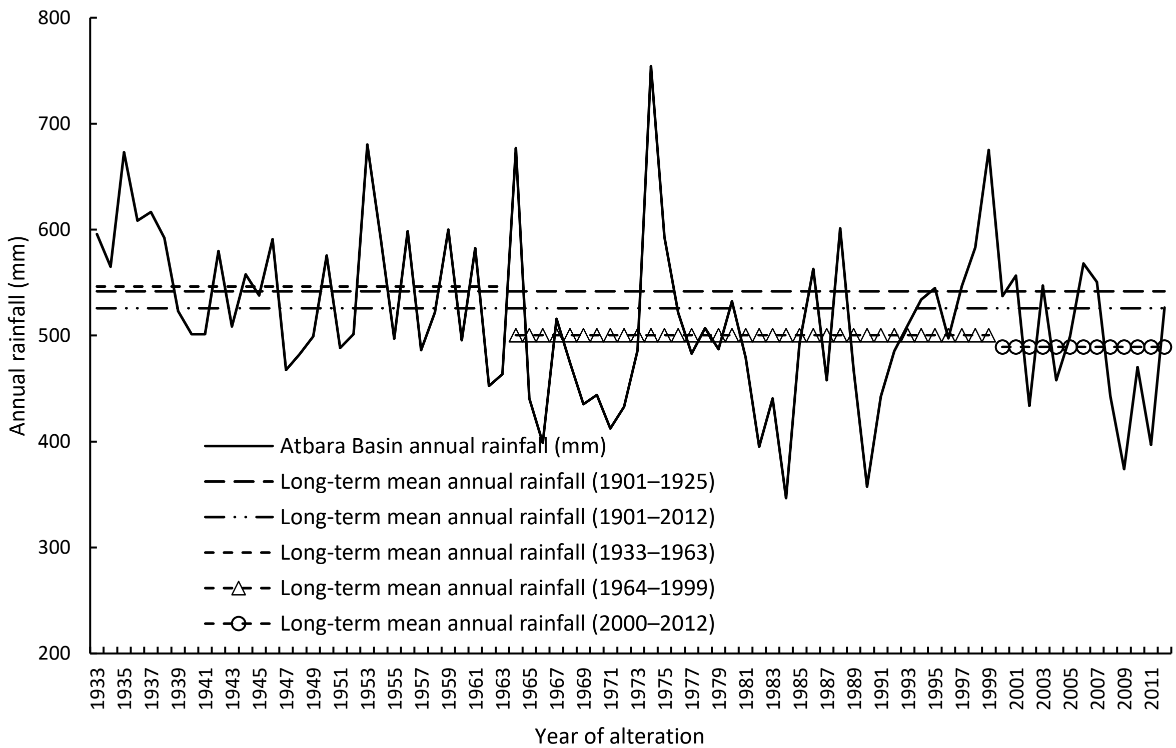


Figure 4-6 Mean annual Precipitation of the Atbara basin.

The period between 1933 and 1963 showed a slight increase by 0.8% more than the mean precipitation of pre-damming flow condition to be 546 mm. this increase is a reflection of the drought condition discussed previously.

The periods with the higher alteration had a noticeable decrease in the mean annual rainfall. Periods between 1964 and 1999 and between 2000 and 2012 witnessed a mean annual rainfall with 500 mm and 489 mm, respectively.

The drought events in the study period was familiar to the changes in the mean annual rainfall. The drought events for the periods between 1964 and 1999 had drought events in 28% of years and this percentage increased in the last time-window between 2000 and 2012 to be 38% of years.

4.3.3 Precipitation pattern in the Sobat basin

The mean annual rainfall in the Sobat basin for the normal condition period was 1097 mm/year. The following period between 1933 and 1963 had greatest mean annual rainfall between all the time periods, the mean annual rainfall for this period was 1159 mm/year which was greater than the normal period by almost 6% and greater than the worst condition which was found between 2000 and 2012 by 16%.

What was different between rainfall in Sobat basin and the other 2 main contributer basins (Blue Nile and Atbarah basins) is that all the periods had a mean annual rainfall value greater than the normal period. The period between 1964 and 1999 had a mean annual rainfall 1118 mm/year and the long term mean annual rainfall between 1901 and 2012 was 1111 mm/year, except for the period between 2000 and 2012 the mean annual rainfall was 999 mm as shown in (Figure 4-7).

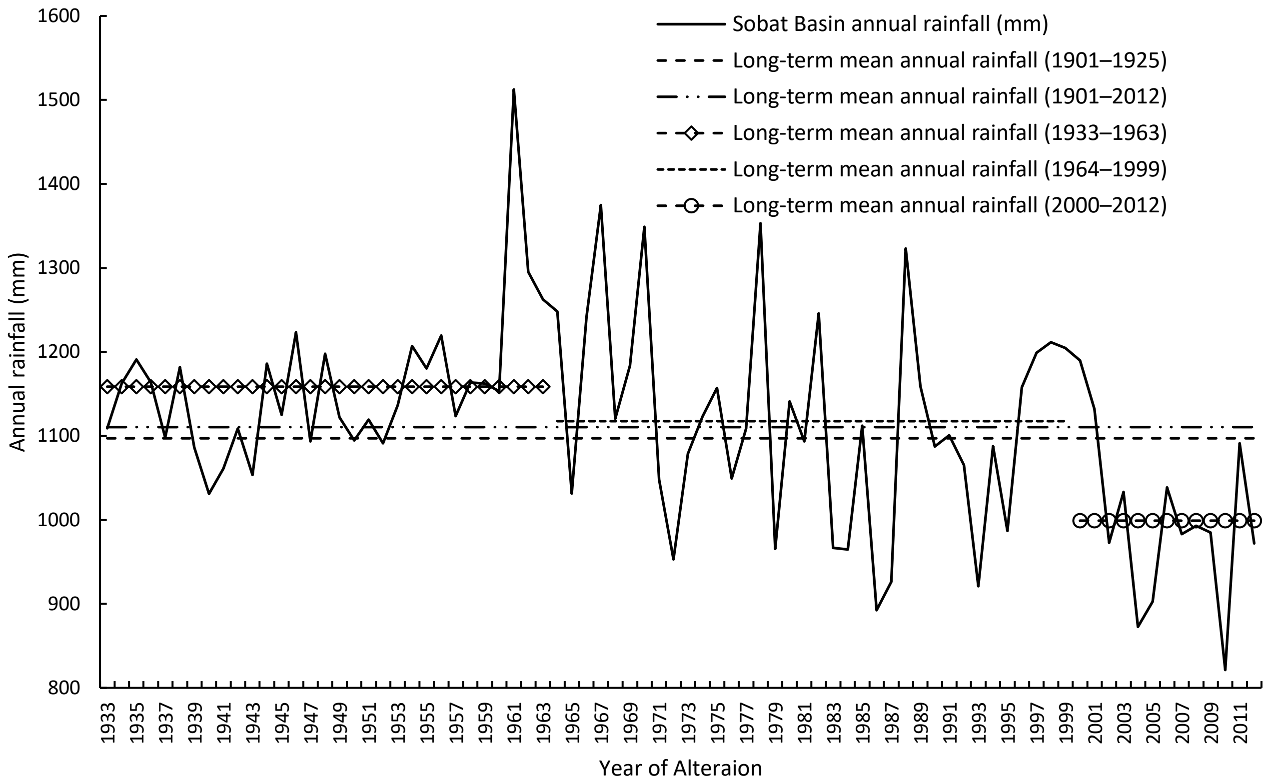


Figure 4-7 Mean annual Precipitation of the Sobat basin.

4.3.4 Precipitation pattern in the Main Nile basin

Figure 4-8 shows the mean annual rainfall for the different time windows of the Main Nile basin. The first observation is that rainfall in Main Nile did not exceed the 100 mm/year in any of the time-windows, this observation gives indication how the precipitation of Main Nile is not considered as a major contributor to the river flow due to its poor precipitation relatively to the Blue Nile, Atbarah and Sobat basins.

The natural condition period had a mean annual rainfall 91 mm/year, then the successive period had a minor increase with 1 mm/year to be 92 mm/year. After this slight increase there was a drop in the period between 1964 and 1999 by around 30% to be 65 mm/year.

The period between 2000 and 2012 mean rainfall rose again by 4 mm/year to 69 mm/year. The decrease in the 3rd and 4th affected the long-term mean annual rainfall for the whole study period between 1901 and 2012 to be 80 mm/year lower than 1st and 2nd time-windows.

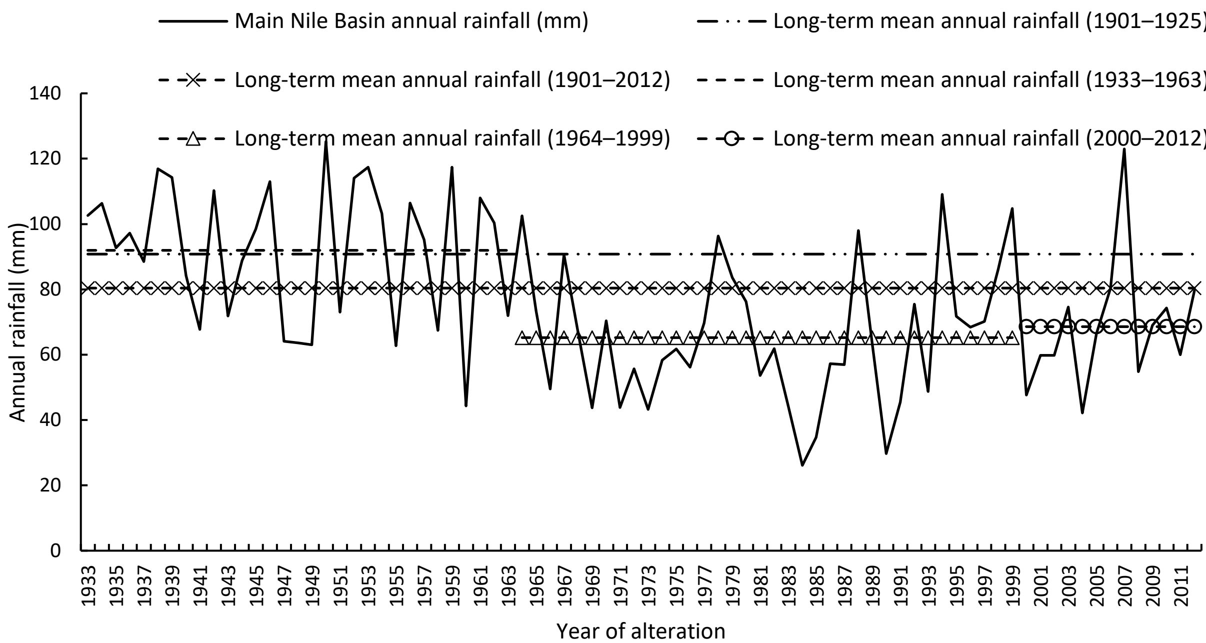


Figure 4-8 Mean annual Precipitation of the Main Nile basin.

The rate of change for the rainfall patterns between the periods 1901–1925 and 1901–2012 was different compared to the rate of change in discharge at Dongla station for these two time periods. Changes in rainfall for the sub-basins Blue Nile, Sobat, and Atbarah were -1.2%, 1.2%, and -3.0%, respectively. These changes in rainfall and the contribution of the sub-basins to the river discharge led to a decrease in the discharge by 2.8%, while the observed changes in discharge at Dongola station indicated a decrease by 7.7%. For the changes in rainfall between the periods 1901–1925 and 1933–1963, the Blue Nile, Sobat, and Atbarah sub-basin average rainfalls increased by 3.50%, 5.60%, and 0.85%, these increases in the rainfall patterns of the three sub-basins should led to an increase in the amount of discharge at Dongola station. However, the contrary was the case, and a decrease in discharge by 1.2% was noted. This shows that there must be another reason such as human intervention for the decrease of the amount of discharge.

The temperature was monitored for 34 years only. The 34 years was divided into two-time windows from 1979 to 1999 and from 2000 to 2012. No extreme changes or events in the values of the maximum and minimum temperature. The mean maximum temperature for the first period at the Blue Nile was 31.12 ℃ and between 2000 and 2012 increased to be 32.34 ℃. The mean temperature at Atbara basin increased from 34.2 ℃ to 35.3 ℃. Atbara basin also witnessed a decrease in the mean maximum values by 0.33 ℃.

The decrease in the precipitation pattern agreed with the previous studies and the hypotheses that there will be decrease in precipitation and increase in temperature through the study period.

The results also agreed with the hypotheses of the expected effect of the drought events. Less precipitation pattern was found in the periods with more drought events.

4.4 Pre-and Post- Alteration of River Discharge

Assessing the alteration of in the river discharge at the two key locations is for the fulfilment of the third objective: to analyze the river discharge, and to assess the changes in the river discharge according to the degree of human intervention.

4.4.1. Altered and unaltered mean annual discharge ratio

The total discharge volume of the whole period (1900–2012) of investigation for Dongola station was between 328.5 m^3/s and 12,307 m^3/s. The minimum discharge was observed in May 1922 and the maximum value was recorded on September 1998. While for the Tamaniat station the minimum discharge occurred was 366.5 m^3/sec and was for April 1922, and the maximum value was 9,484 m^3/sec for September 1917.

The long-term mean discharge volume for the unaltered period at Dongola between the years 1900–1925 was 87.8 Bm^3/year and for Tamaniat for Period (1911–1925) was 77.3 Bm^3/year. Table 4-8 and Appendix 2, Table 8-4 show the discharge, annual volume, and the percentage of change from the unaltered mean annual discharge volume, for both Dongola and Tamaniat stations, respectively, for each year of post alteration.

The anomalies of the river discharge at Dongola station ranged from a decrease of 48% observed in 1984 to increase in the river discharge with 126% in 1964. By looking deeper in each period, it was found that the period between 1933 and 1963 had anomaly ranged from 75% in year 1941 to 120% in year 1946, and the number of year the discharge was exceeding the long term unaltered mean discharge was 13 years in the time window (1933—1963), almost 45% of the period had excess water than that of the normal condition.

As the human intervention increased and the drought episodes increased in the second and third period of alteration, the alteration in the discharge increased. The anomaly in the discharge for the period between 1964 and 1999 ranged from 48% in year 1984 to 126% in year 1964. Although, the period between 1964 and 1999 had the highest percentage of increase in the discharge volume, 82% of its annual discharge was below the mean annual discharge for the normal condition. The reason year 1984 had the lowest percentage of discharge volume is due to the severe drought occurred in this period and specially that year, and this problem would have been exacerbated if it was accompanied with water consumption from the river flow.

Table 4-8 Anomaly of the annual mean discharge for the altered period to the long-term annual discharge for the unaltered discharge at Dongola

Water year	Discharge (m^3/s)	Discharge volume (Bm^3)	% to the long-term mean annual discharge volume (1900–1925)	Water year	Discharge (m^3/s)	Discharge volume (Bm^3)	% to the long-term mean annual discharge volume (1900–1925)
1933	2769.29	86.14	98.11	1973	2115.74	65.81	74.96
1934	3121.53	97.09	110.59	1974	2804.78	87.24	99.37
1935	3326.00	103.45	117.84	1975	3196.37	99.42	113.24
1936	2883.1	89.68	102.15	1976	2295.14	71.39	81.31
1937	2738.81	85.19	97.03	1977	2415.9	75.14	85.59
1938	3265.05	101.56	115.68	1978	2332.95	72.56	82.65
1939	2477.24	77.05	87.77	1979	1903.55	59.21	67.44
1940	2164.74	67.33	76.69	1980	2144.29	66.70	75.97
1941	2126.16	66.13	75.33	1981	2242.67	69.76	79.46
1942	2780.48	86.48	98.51	1982	1709.88	53.18	60.58
1943	2567.13	79.85	90.95	1983	1783.18	55.46	63.18
1944	2445.6	76.07	86.65	1984	1354.55	42.13	47.99
1945	2616.51	81.38	92.70	1985	2071.37	64.43	73.39
1946	3367.28	104.74	119.30	1986	1782.79	55.45	63.16
1947	2731.87	84.97	96.79	1987	1501.93	46.72	53.21
1948	2782.79	86.56	98.59	1988	2988.43	92.95	105.88
1949	2677.47	83.28	94.86	1989	2072.15	64.45	73.41
1950	2941.36	91.49	104.21	1990	1700.23	52.88	60.24
1951	2414.74	75.11	85.55	1991	2057.10	63.98	72.88
1952	2366.13	73.60	83.83	1992	2178.63	67.76	77.19
1953	2658.56	82.69	94.19	1993	2581.40	80.29	91.46
1954	3306.71	102.85	117.15	1994	2589.51	80.54	91.74
1955	2930.17	91.14	103.81	1995	1891.98	58.85	67.03
1956	3163.97	98.41	112.10	1996	2602.62	80.95	92.21
1957	2491.13	77.48	88.26	1997	2112.27	65.70	74.84
1958	2987.27	92.92	105.84	1998	3381.56	105.18	119.81
1959	3001.54	93.36	106.34	1999	2973.38	92.48	105.34
1960	2529.32	78.67	89.61	2000	2572.92	80.03	91.16
1961	3189.81	99.22	113.01	2001	2679.40	83.34	94.93
1962	2842.98	88.43	100.72	2002	1804.40	56.12	63.93
1963	2744.6	85.37	97.24	2003	2180.94	67.84	77.27
1964	3565.59	110.90	126.33	2004	1740.74	54.14	61.67
1965	2770.45	86.17	98.15	2005	2029.71	63.13	71.91
1966	2299.77	71.53	81.48	2006	2537.81	78.94	89.91
1967	2973.77	92.50	105.36	2007	2873.07	89.36	101.79
1968	2388.89	74.30	84.64	2008	2155.86	67.06	76.38
1969	2400.46	74.66	85.05	2009	1680.56	52.27	59.54
1970	2535.49	78.86	89.83	2010	2462.58	76.60	87.25
1971	2645.45	82.28	93.73	2011	2004.24	62.34	71.01
1972	1842.21	57.30	65.27	2012	2534.34	78.83	89.79

The 4th time window between 2000 and 2012 the discharge condition became more critical, the percentage of the discharge in this period ranged from 60% in year 2009 to 102% in year 2007. Year 2007 was the only in this period that the percentage exceeds 100% of the pre-damming flow condition, the ratio of the years below the mean annual discharge volume of the pre-damming flow condition increased between years 2000 and 2012 to be 92% instead of 82% in the 3rd time-window.

The annual discharge at the Tamaniat station was not steady, there were changes between the annual discharge and the mean annual discharge for the normal condition period. The period between 1933 and 1964 had a minimum value of 60 Bm^3 year 1940 with a decrease of 78% of the long-term mean annual pre-damming flow, and the maximum discharge was in 1946 with anomaly of 117%. The number of years with increased anomaly in this period was 15 years which 50% of the discharge was in this period.

Period between 1964 and 1999 had 29 years with anomaly less than the long-term mean annual discharge for the natural period. The anomaly in this period ranged between a minimum value of 43 Bm^3 that occurred in 1984 with anomaly 56% and 103 Bm^3 in year 1964 with anomaly 133 %. The last time window had 10 years out of 13 years with anomaly less than 100% and the maximum anomaly was 120% the scarcest year was 2002 with a volume of 56 Bm^3.

Figure 4-9 shows the annual discharge volume for the natural condition period compared to the mean annual discharge volume for the different time-windows of altered flow.

It was observed that there was a difference between the precipitation trends for the main contributors of river discharge (Figures 4-5, 4-6, and 4-7) and the river discharge at Dongola station (Figure 4-9).

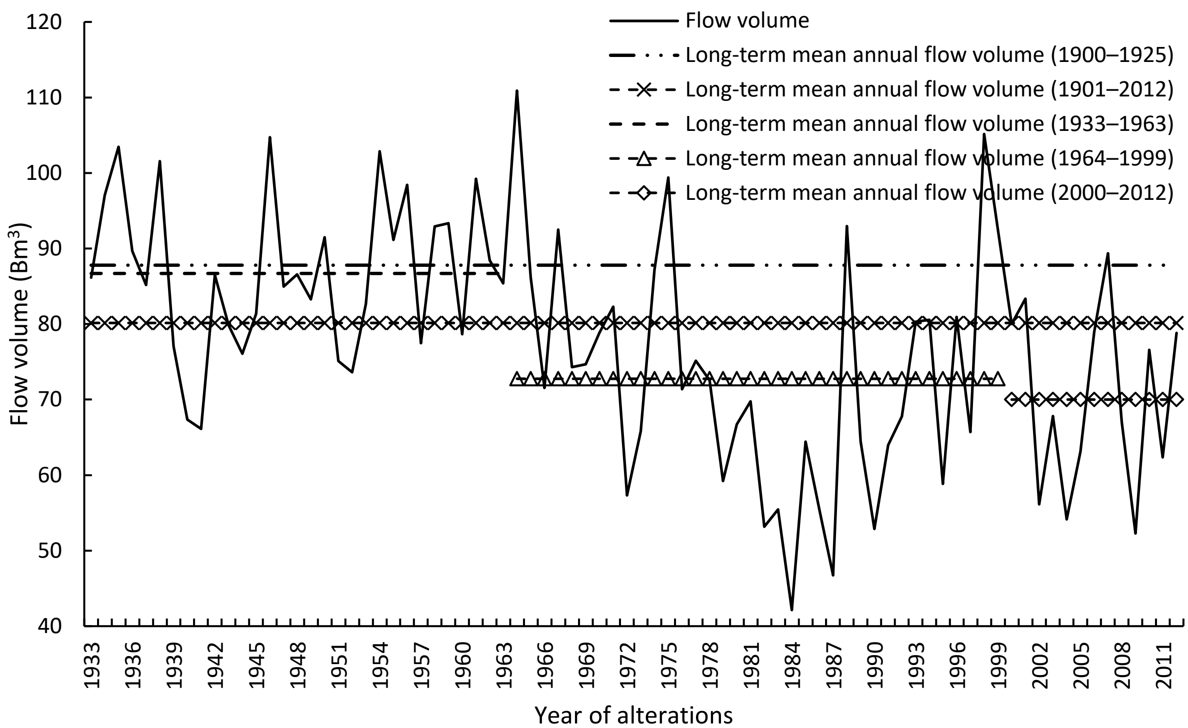


Figure 4-9 Annual deviation of altered discharge to long-term unaltered discharge at Dongola station.

The long-term mean annual discharge for the natural condition at Dongola station had the highest value with 88 Bm^3/year, by comparing the Dongola discharge in the natural condition with rainfall on the same period in the 3 main contributor sub-basins it was not the highest value between all the time-windows.

In the second position is the mean annual discharge for the period between 1933 and 1964 with 87 Bm^3/year, Although the rainfall for the same period was the highest between all the periods for the 3 main sub-basins.

The following alteration periods between 1964–1999 had a mean annual discharge with 73 Bm^3, the rainfall for the same period was also in the 3rd place.

The period between 2000–2012 had also a long-term mean value less than the long-term mean value in the normal condition with a record of 70 Bm^3, which was consistent with the precipitation patterns for the same period.

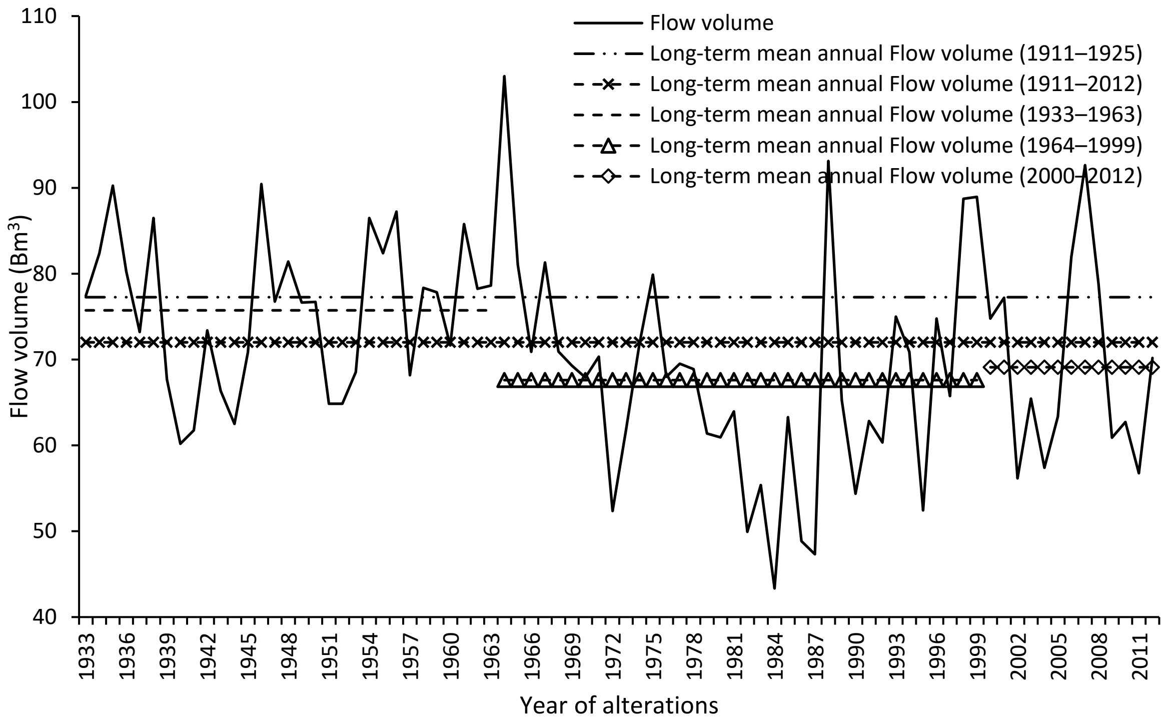


Figure 4-10 Annual deviation of altered discharge to long-term unaltered discharge at Tamaniat station.

The long-term mean annual discharge for the different time-windows and the annual discharge for the natural condition between 1911 and 1925 for the Tamaniat station are presented in (Figure 4-10). The long-term mean annual discharge for the natural condition was the highest with 77.3 Bm^3 between all the periods.

The second place was taken by the annual discharge for the period between 1933 and 1963 with a record of 75.7 Bm^3. The situation for the 3rd and 4th position was different than the situation in Dongola station. The 3rd position was for the period 2000–2012 with a mean annual discharge 75.7 Bm^3, then the lowest value was for the period 1964–1999.

It was also observed from Figures 4-9 and 4-10 that the sharpest drop in the annual flows were in the period 1964–1999, and especially in the 1980s. The reason that this period suffered a spell of severe drought especially year 1984. Year 1984 had a low percentage anomaly through the all years of study and at both study stations is due the drought occurred in this year and the cumulative drought effect in the period 1964—1999, the SPI values were (-2.2) for Blue basin, (-2.6) for Atbarah basin, and (-1.1) for Sobat basin.

4.4.2 Annual, monthly median discharge and percentiles anomaly

The long-term annual median discharge for the pre-damming period was 1574 m^3/s for Dongola and 1595 m^3/sec for Tamaniat. Figure 4-11 show the anomalies in the median of the annual discharge and Table 4-9 and Figure 4-12 shows the anomaly of the monthly median discharge of the post-damming period to the median discharge of the pre-damming flow regime at Dongola.

The first alteration period (1933–1963) had only 5 records with a median greater than that of the median of the normal condition period, the discharge median varied between (-26%) as a minimum value in year 1953 and a maximum value of 11.3% increase in the year 1934.

The second time-window (1964–1999) had only 4 records with a median greater than the normal condition period. The percentage of decrease in the median was greater than that occurred in the previous period 1933–1963, and even the increase in the median was less than the one between 1933–1963. The minimum value represented a decrease in the median by -39.7% in year 1995, and the highest increase in the median by almost 31% in 1965.

The last time window 2000–2012 there was a dramatic change, all the values were below the median flow. The percentage of decrease ranged from -15.7% in 2000 to the highest decrease in the alteration period -45.6% in year 2004.

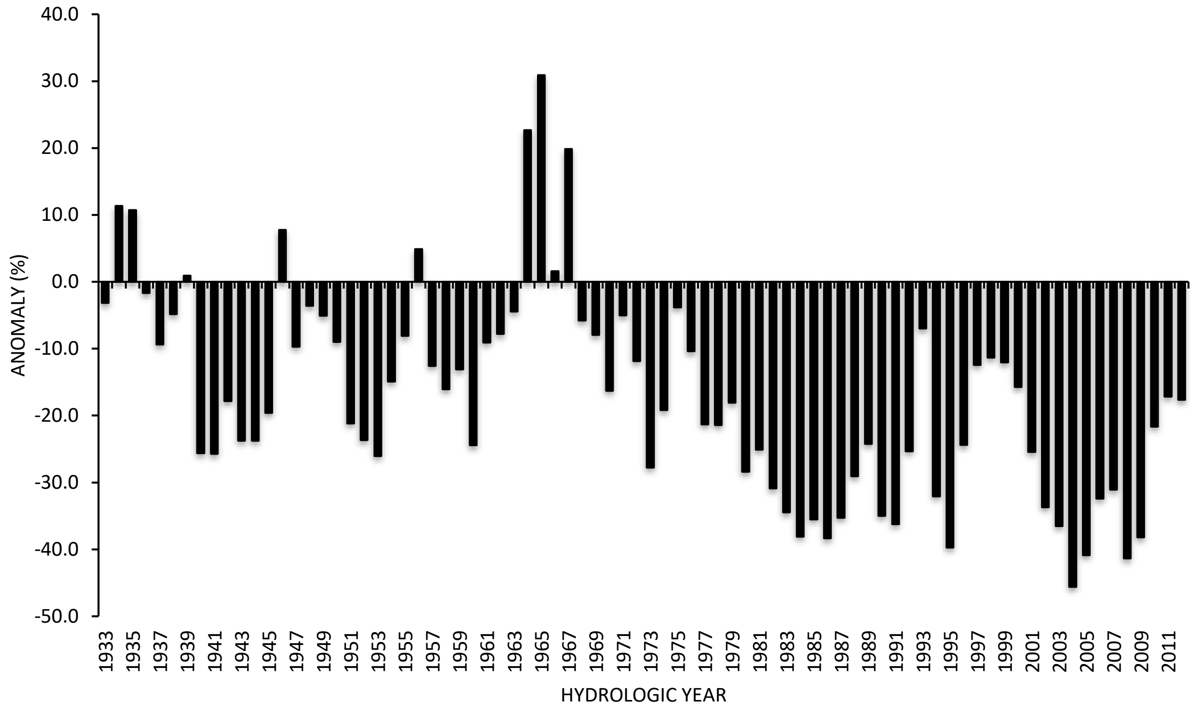


Figure 4-11 Annual median anomaly between 1933 and 2012 for Dongola station.

Regarding the monthly median discharge for Dongola station showed in Table 4-9 and Figure 4-12, the pre-alteration period long-term monthly median varied between 515 m^3/s in May and 8623 m^3/s in September as illustrated in Table 4-9 and Figure 4-12. For the first time period (1933–1963), the median ranged between 686 m^3/s as the minimum measurement in May with an increase in anomaly by 33%.

Table 4-9 Long-term monthly median flows for the pre- and post-alteration periods and anomaly rates for Dongola

Month	Discharge (m^3/s)				Anomaly (%)		
	1900–1925	1933–1963	1964–1999	2000–2012	1933–1963	1964–1999	2000–2012
July	1627.84	1866.41	2023.6	2228.94	15	24	37
August	7187.13	6944.07	6511.35	7462.66	-3	-9	4
September	8622.69	8707.56	6460.26	6365.74	1	-25	-26
October	5600.36	5412.19	3255.68	2736.71	-3	-42	-51
November	2739.2	2685.19	1724.54	1242.28	-2	-37	-55
December	1848.12	1624.85	1234.51	1030.47	-12	-33	-44
January	1387.02	1220.88	1014.78	877.39	-12	-27	-37
February	975.53	954.86	896.58	876.32	-2	-8	-10
March	690.71	923.31	717.22	780.32	34	4	13
April	545.91	932.87	1041.09	923.23	71	91	69
May	515.23	685.86	1128.47	1061.08	33	119	106
June	657.79	716.44	940.39	1037.42	9	43	58

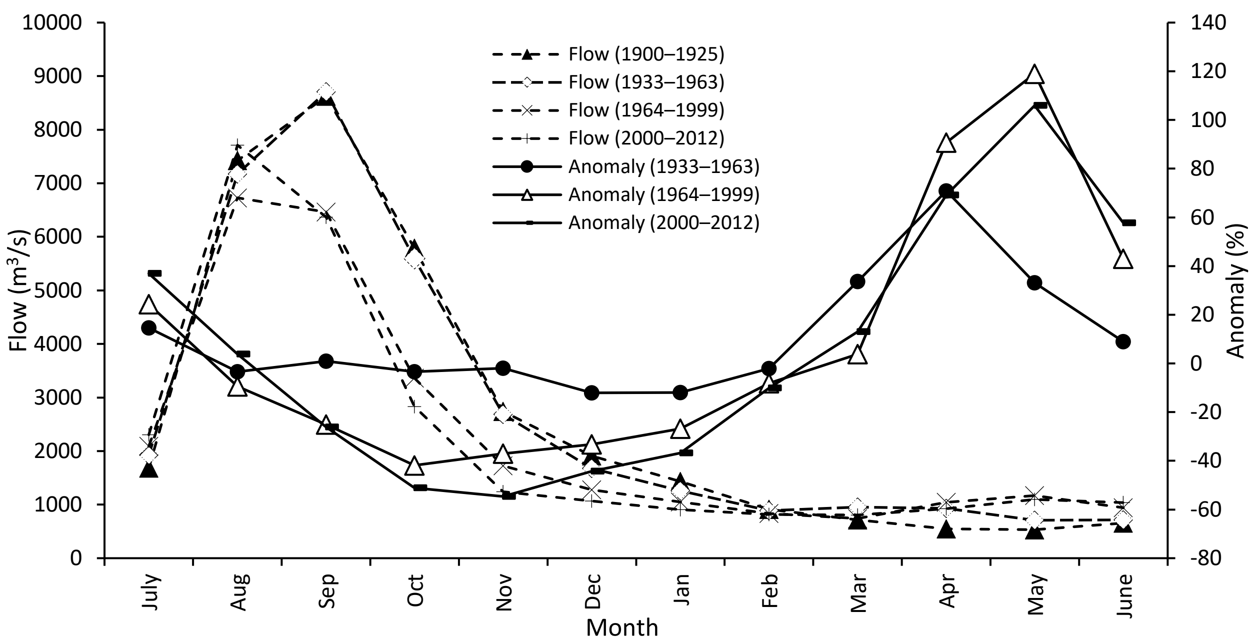


Figure 4-12 Long-term monthly median discharge and anomaly in the median for the altered discharge period at Dongola station.

The maximum value was 8708 m^3/s, which represents an increase of 1% compared to the pre-damming flow condition. For the second period of alteration (1964–1999), the monthly median minimum value was 717 m^3/s in March, and the maximum value was 6511 m^3/s in August.

The peak and minimum values of the medians in period 1964–1999 changed from September and May to be in August and March. Finally, for the high alteration period (2000–2012), the minimum monthly discharge was 780 m^3/s in March and the highest value was 7463 m^3/s in August. The changes in the discharge regime continued in the last time window with maximum value in August instead of September and minimum value in March instead of May.

The anomaly for the time windows 1933–1963, 1964–1999 and 2000–2012 ranged between -12% and 71%, -42% and 119%, and -55% and 106%, respectively.

The first period the alterations (1933–1963) was an increase in the medians for 6 months, most of them were in the dry period. The second 6 months suffered decrease in medians 4 months with decrease less than 10% and 2 months with -12%.

The situation became more critical in period 1964–1999, the number of months with a decrease in the median increased to be 7, in addition, the percentage of decrease increased for more than 25% in 5 months. On the other hand, the increase in May was the highest in all the periods by 119%, even though, May was the minimum value in the normal and 1st alteration period.

The final period had the sharpest decrease in the median for 6 months, all with decrease exceeding 10% reaching -55%. The highest increase also was on the month of May.

The analysis of the median discharge for the Tamaniat station (Fig. 4-13) was sort of like what occurred for the median discharge at Dongola station, but with a slight difference in values and number of occurrences.

The period between 1933–1963 witnessed only one year with positive anomaly of 7% in year 1933, less than the situation in Dongola station in the number of positive anomaly and value. The highest value for the negative anomaly occurred in year 1940 with a -38.4% anomaly.

The period 1964–1999 had 4 positive anomaly and were at the same years of the Dongola station, even the year with the highest record was the same year 1965, but with different value of 25.9%. the worst anomaly occurred in year 1986 with anomaly of -40.7%, and this was the worst record for all the study period.

For the period between 2000–2012, there was a single positive value of 1.2% in year 2007. It was also noticed that the (-ve) anomalies in the high altered period were less than that of Dongola. The worst year anomaly was -31.7% in year 2011, while for Dongola station the situation was sharper with -45.6% in year 2004.

The small difference between the medians and the Dongola and Tamaniat stations could be due to the extra human activities in area between the two stations which led to higher water regulation and abstraction, that eventually affected the discharge.

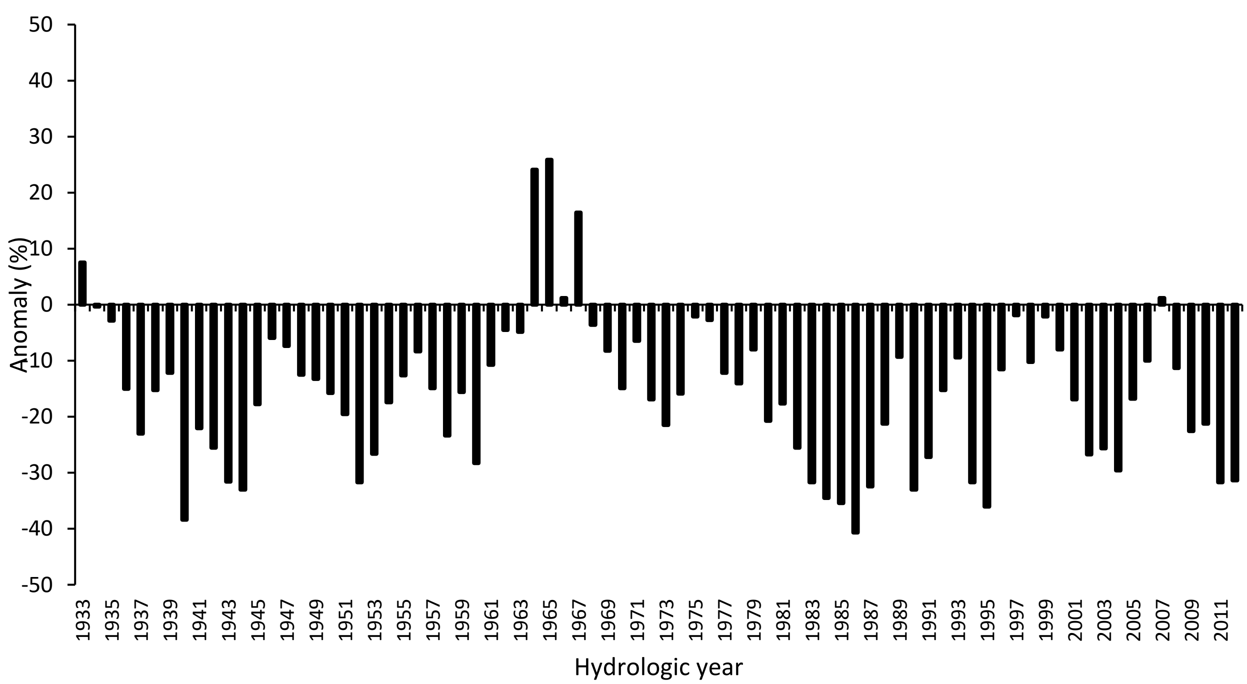


Figure 4-13 Annual median anomaly between 1933 and 2012 for Tamaniat station.

The monthly median for the Tamaniat station was also analyzed (Table 4-10 and Figure 4-14). There were also changes in the monthly median discharge at the Tamaniat station, the minimum value for the pre-damming flow condition was 567 m^3/s in April and the maximum was in September with 6752 m^3/s. The anomaly for the time windows 1933–1963, 1964–1999 and 2000–2012 ranged between -13% and 65%, -34% and 130%, and -40% and 97%, respectively.

The period 1933–1963 had its minimum value on May with 721 m^3/s and its maximum value in August with 6384.41 m^3/s, and there was decrease in the medians of 4 months. There was an increase in the median of August and decrease in the median of September which led to the change in the peak value to be in August instead of September.

This shift in discharge continued to the period 1964–1999, even there was decrease in the August median value by 8.4% but, the decrease was greater for September by 26.3%. the minimum value was found on March by 887 m^3/s.

The month of August kept its position in the 4th time-window and was the highest value between the 12 months with 6422 m^3/s. The month with the minimum value (March) was the same as that of period 1964–1999 with a value of 874 m^3/s.

The study of the median discharge at both stations showed continuous increase in some months, continuous decrease in other months and other were not steady. For Dongola station, there was a decrease in the median for months from October to February, for Tamaniat station September and months from November to January had continuous decrease.

For Dongola station, months from March to July showed increase in median for the altered periods than the normal condition, Tamaniat station had increase in months from February to June.

Table 4-10 Long-term monthly median flows for the pre- and post-alteration periods and anomaly rates for Tamaniat

Month	Discharge (m^3/sec)				Anomaly (%)		
	1900–1925	1933–1963	1964–1999	2000–2012	1933 – 1963	1964 – 1999	2000 – 2012
July	2426.82	2576.16	2191.61	2579.9	6.15	-9.69	6.31
August	6197.73	6384.41	5675.03	6421.74	3.01	-8.43	3.61
September	6751.54	6288.58	4976.85	5015.43	-6.86	-26.29	-25.71
October	4106.93	4144.27	2714.31	2542.56	0.91	-33.91	-38.09
November	2307.1	2021.6	1593.36	1385.03	-12.37	-30.94	-39.97
December	1646.51	1456.09	1237.68	1176.08	-11.57	-24.83	-28.57
January	1254.48	1179.81	1121.94	1019.27	-5.95	-10.57	-18.75
February	830.85	967.26	896.99	954.86	16.42	7.96	14.93
March	642.17	989.4	886.72	873.66	54.07	38.08	36.05
April	567.13	933.64	1302.08	1118.83	64.63	129.59	97.28
May	634.71	720.58	1207.81	1213.41	13.53	90.29	91.18
June	1022.38	1030.09	1086.03	1338.73	0.75	6.23	30.94

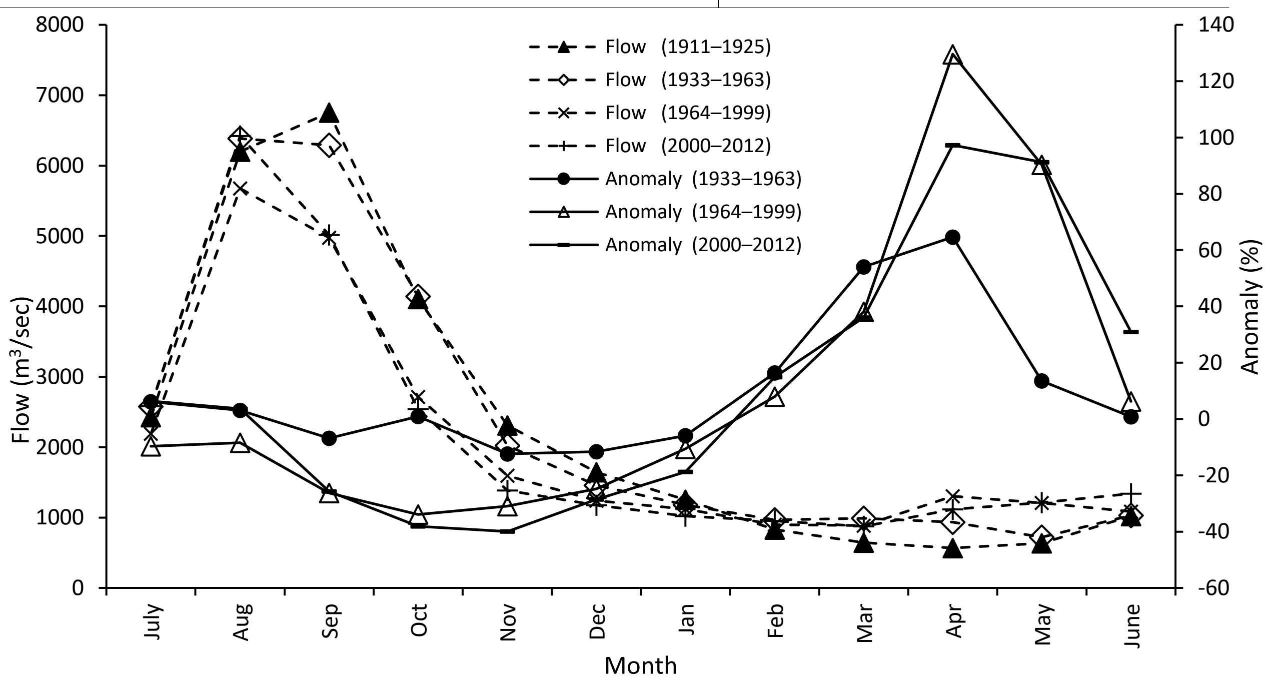


Figure 4-14 Long-term monthly median discharge and anomaly at Tamaniat station.

The median discharge represents the 50th percentile and the other remaining percentiles (10th, 25th, 75th and 90th percentiles) are considered important statistical tools to identify the changes of hydrologic characteristics within a basin. The percentiles were calculated for all time span pre- and post-alteration periods. The percentiles for the discharge at Dongola station are presented in Tables 4-11, and 4-12.

Table 4-11 Long-term monthly percentiles discharge for the pre- alteration at Dongola station

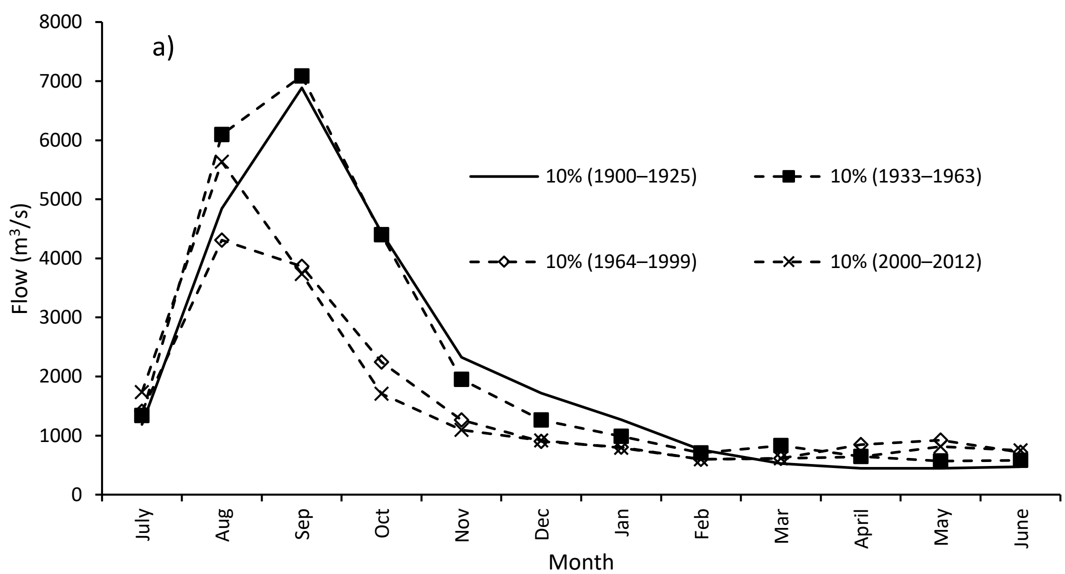
Month	Pre-Impact: 1900-1925 discharge (m^3/sec)				
	10%	25%	50%	75%	90%
July	1186	1481	1682	2200	2378
August	4842	6134	7427	8054	8758
September	6887	7282	8623	9770	10571
October	4437	4909	5787	6819	7581
November	2323	2474	2739	3360	4051
December	1719	1800	1910	2231	2537
January	1267	1355	1433	1595	1995
February	758	837	910	1109	1497
March	529	639	714	797	1231
April	446	503	546	678	833
May	446	490	532	660	706

Table 4-12 Long-term monthly Percentiles of discharge for the post-alteration at Dongola station

Month	Post-Impact period: 1933–1963 discharge (m^3/sec)				Post-Impact period: 1964–1999 discharge (m^3/sec)				Post-Impact period: 2000–2012 discharge (m^3/sec)			
	10%	25%	75%	90%	10%	25%	75%	90%	10%	25%	75%	90%
July	1341	1579	2277	2652	1411	1820	2291	2843	1732	2031	2469	2702
August	6093	6461	8639	9164	4308	5216	7696	8743	5633	5941	8372	9344
September	7087	7676	9348	10424	3862	5272	7592	9460	3731	4900	6983	8508
October	4400	4845	6077	6731	2242	2579	4060	5423	1709	2245	3310	3771
November	1952	2176	2930	3353	1264	1503	2408	2710	1095	1150	1485	1888
December	1264	1463	1824	2028	899	1081	1495	1777	919	965	1200	1248
January	985	1160	1437	1591	803	913	1281	1546	791	829	1015	1109
February	703	728	1051	1165	598	667	927	1223	598	640	910	1024
March	829	862	979	1053	613	656	879	1000	613	667	968	1013
April	644	765	975	1004	848	928	1153	1360	640	679	1154	1229
May	568	629	971	1082	920	1038	1249	1384	813	864	1111	1299
June	581	622	857	1125	717	816	1121	1246	751	910	1354	1507

By comparing the results in Tables 4-11 and 4-12 and Figure 4-15 representing the percentiles at Dongola station, the discharge that was equal to or exceeded the threshold at 90% for the wet period, a decrease was found between the natural condition and the altered period. For the pre-damming flow condition in September, the 90th percentile value decreased only slightly from 10571 m^3/s to 10424 m^3/s between 1933 and 1963. For the 3rd and 4th time-windows, there was a considerable decrease in the 90th percentile for September between 1964–1999 to be 9460 m^3/s as well as between 2000–2012 to be 8508 m^3/s.

Flows that were equal or exceeded the threshold at 90% of the time increased for the months after the falling limb of the hydrograph and before the start of the rising limb (from April to June). For example, the 90th percentile was 891 m^3/s in June of the normal condition period, and increased to 1125, 1246 and 1507 m^3/s between 1933–1963, 1964–1999 and 2000–2012, respectively.



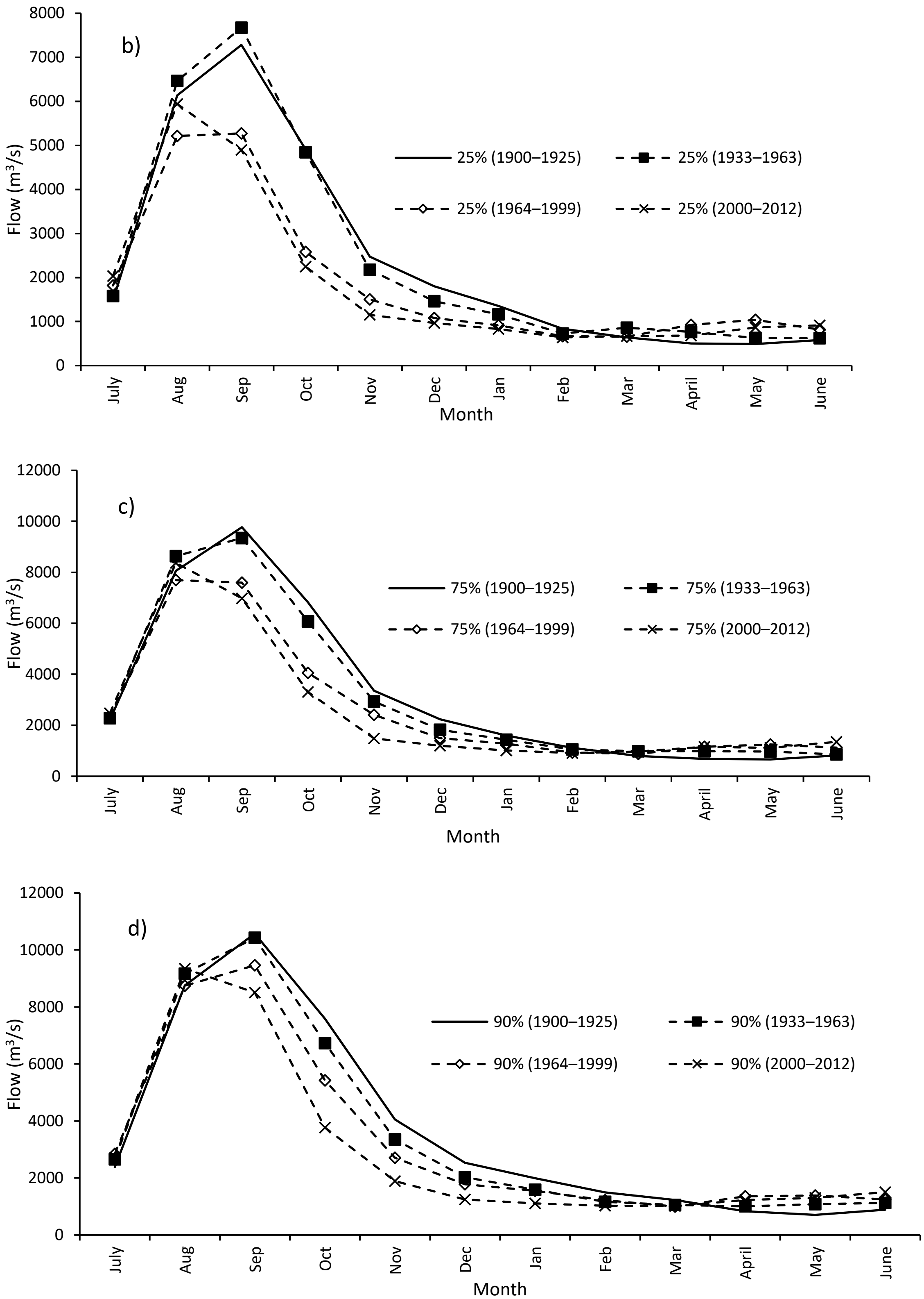


Figure 4-15 Percentiles at Dongola for (a) pre-damming flow condition; (b) altered flow from 1933–1963; (c) altered flow from 1964–1999; and (d) altered flow from 2000–2012

Figure 4-15 shows the 10th, 25th, 75th, and the 90th percentiles for each time-window for the discharge at Dongola station. The 10th and the 25th percentile presented in Figure 4-15 (a) and (b) for both natural condition and years from 1933 to 1963 had almost the same regime in terms of rising limb, falling limb, and peak value which was in September. Years from 1964 to 1999 and from 2000 to 2012 showed a shifting in the shape of the hydrograph, the peak was in August instead of September, beside a dramatic decrease in the amount of discharge in September.

For the 75th percentile shown in Figure 4-15 (c), the discharge regime for the natural condition period and the period between 1933 and 1963 had the peak value in September. Then the intermediate alteration period had a shared peak between August and September, Finally, the for the highest alteration period between 2000 and 2012 the peak changed to be in August instead of September.

The 90th percentile of the discharge had its peak for the natural condition period, low alteration period, and the intermediate alteration period in September. The period with the highest intervention was 2000—2012 where the peak was in August instead of September.

What was observed is that there was a direct relation between degree of alteration and the increase of the discharge percentile for the dry period, and the decrease in the peak of discharge in September. The highest the alteration is the higher the shift was found. This is an indication how the human intervention affected the discharge regime.

Figure 4-16 is a comparison between the percentiles of each time-window. Figure 4-16 (a) illustrates the pre-damming flow condition percentiles, the difference between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles were 6441, 6792, 9111 and 9865 m3/s, respectively.

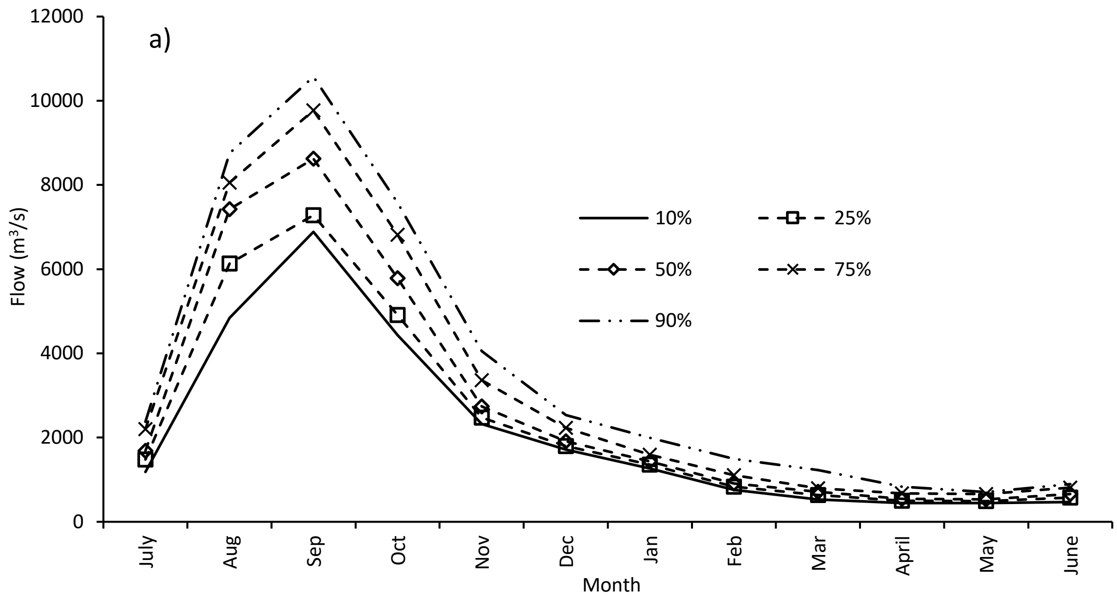


Figure 4-16 (a) percentile of years between 1900 and 1925 at Dongola.

For the years between 1933 and 1963 (Figure 4-16 (b)), the 10th and the 25th percentiles showed a slight increase in the difference between the minimum and maximum values compared to the pre-damming flow conditions. The 10th percentile increased by 1.2% and the 25th percentile increased by 3.9%.

Regarding the 75th and 90th percentiles, decreases of 6.8% and 4.5%, respectively, were 8491 for the 75th percentile and 9420 for the 90th percentile.

The period from 1964 to 1999, the difference between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles decreased by 42%, 32%, 25% and 14%, correspondingly. Finally, for the period from 2000–2012, decreases between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles of 22%, 22%, 18% and 16%, respectively, were noted.

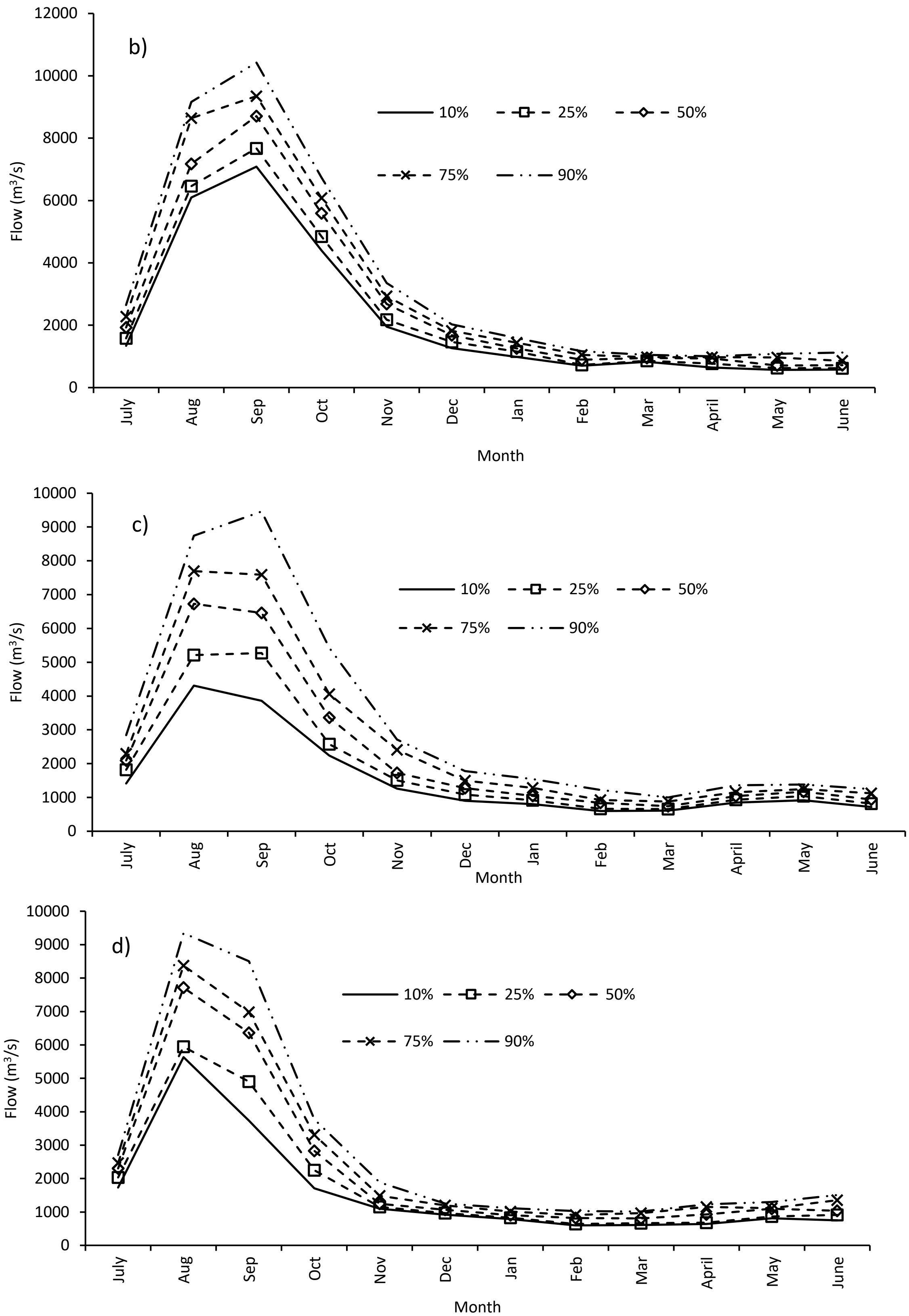


Figure 4-16 (a) years 1900–1925 (b) years 1933–1963; (c) years 1964–1999; and (d) years 2000–2012 percentile for altered and unaltered flow conditions at Dongola.

For the pre-damming flow condition period and the second time-window between 1933 and 1963, the shape of the hydrograph was almost the same with the peak value in September for all percentiles. The period between 1964 and 1999 which is characterized by the intermediate intervention had the peak value in September in the 90th percentile only. As the human induced factors increased the hydrograph in the last time-window changed for all percentiles.

Tables 4-13 and 4-14 present the 5-percentile addressing the discharge for both natural condition flow and the altered flow with all its time-windows at Tamaniat station.

All the percentiles at the pre-damming flow condition had their peak at the month of September. The minimum value was in April for all the percentiles.

The comparison between the data in Table 4-13 and 4-14 yielded the following, the period 1933–1963 had its peak discharge at the month of August for the 10th, and 25th percentiles instead of September compared to the case of normal condition period, the 75th and 90th percentile kept its peak on the month of September. The change in the position occurred due to the increase in the percentile of August and the decrease in September.

The increase in August was 24% for the 10th percentile, 2% for the 25th percentile, 3% for the 75th percentile, and 3% for the 90th percentile. The decrease in September was found in the 25th percentile by 2%, 6% for the 75th percentile, and 11% for the 90th percentile.

The minimum value was found on the month of May for all percentiles except for the 90th it was shifted to be in March. Although, the minimum percentiles were found in

May, there was also increase in the values of the minimum percentiles. The increase was 14%, 15%, 35%, and 49%, for the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile, respectively.

Table 4-13 Long-term monthly percentiles of discharge for the pre- alteration at Tamaniat station

Month	Pre-Impact: 1911-1925 discharge (m^3/sec)				
	10%	25%	50%	75%	90%
July	1873	2192	2427	2875	3033
August	4406	5712	6198	6758	7236
September	5015	5787	6752	7446	8627
October	3142	3635	4107	4947	6818
November	1901	2029	2307	2562	3508
December	1406	1501	1647	1781	2213
January	1040	1154	1254	1428	1786
February	704	765	831	1056	1473
March	512	584	642	784	1086
April	482	529	567	629	765
May	521	549	635	689	783
June	782	853	1022	1144	1282

The period 1964–1999 had another shift in the position of its peak value compared to period 1933–1963 and the normal condition period, all the percentiles had their peak value in August except for the 90^{th} percentile had its peak on the month of September. There were drops in the percentiles of the rainy season between period 1933–1963 and 1964–1999, the decrease was 31%, 21%, 13%, and 5% for the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentiles, respectively, for the month of August. The drop in the percentiles in the month of September were, 84%, 41%, 17%, and 5% for the 10%, 25^{th}, 75^{th}, and 90^{th} percentiles, respectively.

The minimum value was found on the month of February for the 10^{th} and 25^{th} percentiles except for the 75^{th} and 90^{th} were found on March.

Table 4-14 Long-term monthly Percentiles of discharge for the post-alteration at Tamaniat station

Month	Post-Impact period: 1933–1963 discharge (m^3/sec)				Post-Impact period: 1964–1999 discharge (m^3/sec)				Post-Impact period: 2000–2012 discharge (m^3/sec)			
	10%	25%	75%	90%	10%	25%	75%	90%	10%	25%	75%	90%
July	1848	2020	2918	3054	1454	1842	2599	3039	1687	2143	2875	3280
August	5451	5824	6926	7467	4163	4811	6123	7094	5249	5414	7654	7990
September	5285	5671	7041	7793	2867	4029	6038	7388	3574	4861	6173	7701
October	3207	3487	4611	5152	1953	2265	3170	4686	1932	2035	2905	3328
November	1520	1699	2280	2458	1157	1338	2049	2569	1157	1227	1539	1900
December	1139	1284	1594	1714	932	1051	1408	1747	952	1135	1266	1359
January	799	920	1281	1393	808	936	1374	1469	813	896	1191	1282
February	827	872	1081	1124	690	802	1012	1269	732	752	1004	1158
March	773	874	1058	1098	754	840	1004	1135	681	765	1045	1119
April	625	760	1088	1138	1055	1176	1424	1487	907	1038	1277	1366
May	594	629	928	1165	896	1015	1312	1469	852	915	1273	1413
June	829	928	1169	1412	845	941	1330	1647	895	1019	1427	1787

The period 2000–2012 had also witnessed changes in the values of the percentiles and the position of the peak and minimum values than the previous periods. The minimum value was similar to the period between 1964–1999, the minimum rank was shared by the months of March and February. March had the lowest value in the 10^{th} percentile, while February had the lowest 25^{th}, 75^{th}, and 90^{th} percentile.

The maximum percentile values were for the month of August. By comparing the rainy period between the period of 2000–2012 and 1964–1999, an increase was found for the months of July, August, and September. The increase in July was 16% for the 10^{th} and 25^{th} percentile, 11% and 8% for the 75^{th} and 90^{th} percentile, respectively. August was accompanied with increase to be the month with the greatest discharge value in all the months of the 2000–2012 period, the increase was 26%, 13%, 25% and 13% for the 10^{th}, 25^{th}, 75^{th} and 90^{th} percentiles. The percentile for August in this period increased to be the greatest value in all the periods.

There was an increase in September percentile between 1964–1999 and 2000–2012. The increase was not enough to make the percentile of September the highest as the case in the first two periods. The increase was 25%, 21%, 2%, and 4% for the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile, respectively.

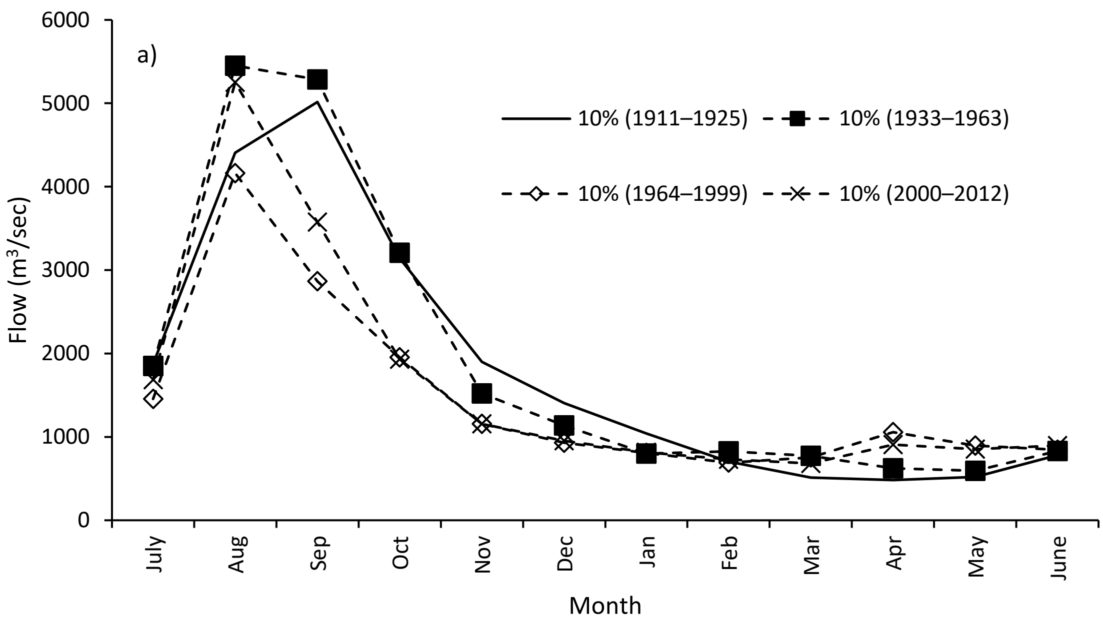
Changes in the 90th percentile for the Tamaniat station were not the same for all the months on different time-windows. Months September, October, November, December, January, and February witnessed a decrease in all the time windows compared to the pre-damming flow condition. There was an increase in the 90th percentile for the rest of the months, except for August there was decrease in the time window 1964–1999 as seen in Tables 4-13 and 4-14.

Figure 4-17 shows the comparison between each percentile for the different time-windows. The changes in the discharge between the pre-damming flow condition period and the successive periods can be observed in the 10^{th} percentile. Only the natural condition period had its peak on September, then a shift was noticed in the peak value in the successive periods, the value of August increased relatively to the values in September and the difference between August and September increased with time. The months from October to February suffered decrease, then from March to July there was an increase.

Figure 4-17 (b) shows the 25^{th} percentile and how it changed between the different time-windows. The shape of the hydrographs between the two periods (1911–1925 and 1933–1963) were alike each other, by overlaying both hydrograph a difference can be found, the values of the maximum value between August and September were very close to each other, but in period 1911–1925 the peak was in September while in period 1933–1963 the peak was in August.

The months from October to February showed a decrease between period 1911–1925 and 1933–1963 then the rest of months showed increase in the flow.

The moderate and high altered periods 1964–1999 and 2000–2012, respectively, had different hydrographs than the previous periods. There was a noticed decrease in the values of August and September, in addition, a difference was found between August and September values to leave August the peak value. The rest of the months the 25th percentile was almost consistent between the two periods 1964–1999 and 2000–2012 in the shape of hydrograph and even the values with a slight difference.



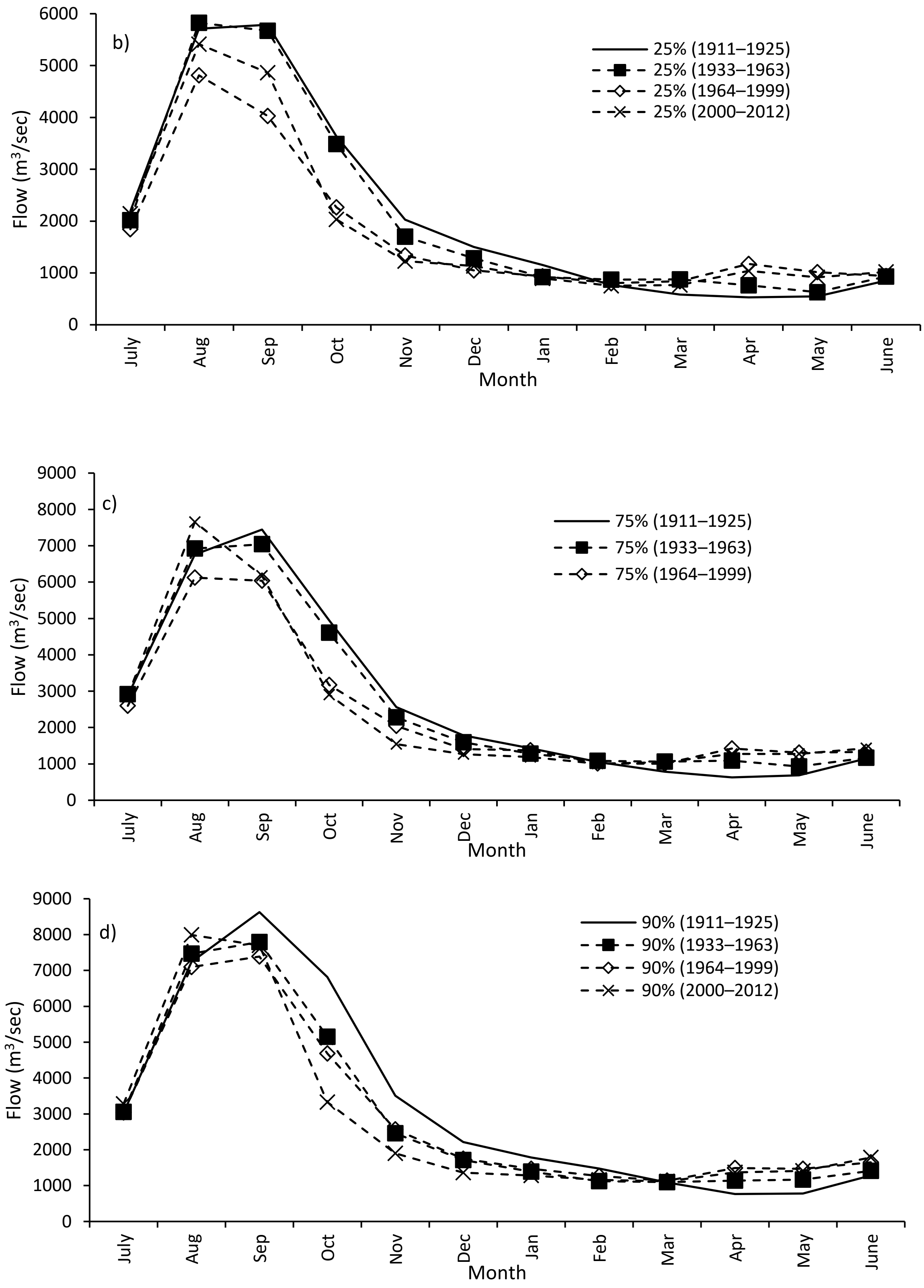


Figure 4-17 Percentiles at Tamaniat for (a) pre-damming flow condition; (b) altered flow from 1933–1963; (c) altered flow from 1964–1999; and (d) altered flow from 2000–2012

The 75th percentile of the pre-damming flow condition (Figure 4-17 (c)) had its peak in September with a considerable difference of 10% greater than the value of August. The period 1933–1963 had its peak also in September, but the difference between the values of the month of August and September was very small of 2%. The values of the 75th percentile for the month of August and September for the period 1964–1999 decreased from the previous two time-windows, but in this period the peak was found at August instead of September, but with a slight difference of 1%.

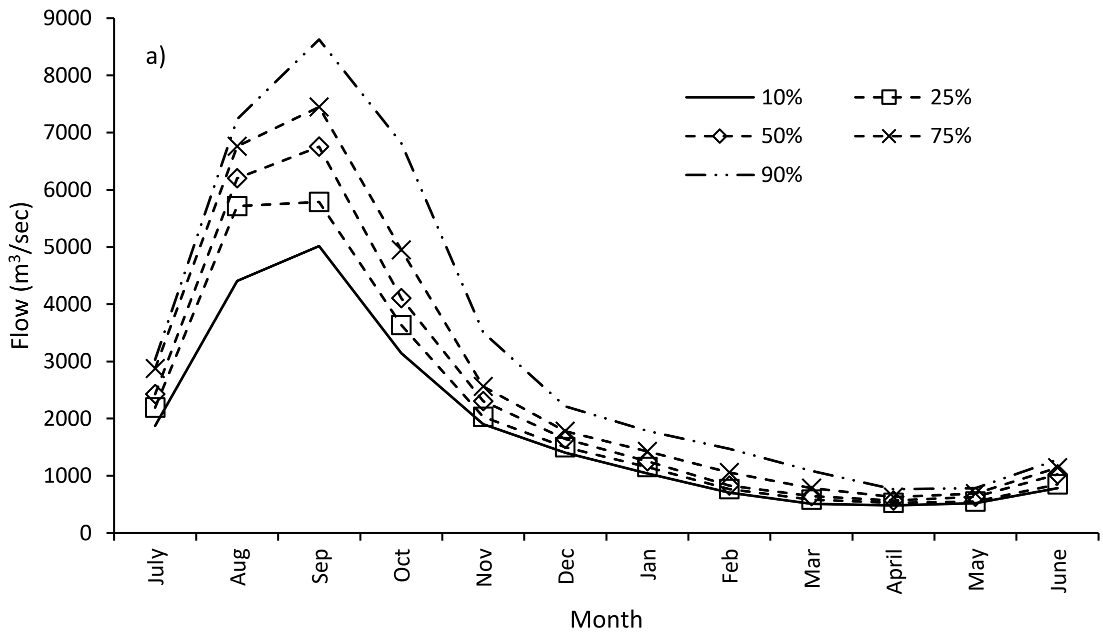
The 75th percentile for period 2000–2012 had a clear peak value in August with a wide difference than September by 24%. Gradual decrease was found between each period and the successive period(s) in the months from October to February, from March to June the situation was changed to be increase instead of decrease between the different time-windows.

The 90th percentile for the first three periods had its peak value in September, only the last period had its peak value in August (Figure 4-17 (d)). Months from October to March were consistent for periods 1933–1963 and 1964–1999, the last period 2000–2012 had the least values in these months. Months from April to June were at minimum values in the pre-damming flow conditions, while the value of the 90th percentile increased with the increase of alteration.

The pre-damming flow period for the Tamaniat station was much alike the Dongola station all the percentiles had the peak value in September. For the period between 1933 and 1963, only the 90th percentile had its peak in September and as the percentile decreased the difference between the values in August and September decreased until the peak value was in August. For the last two periods the peak, the period between

1964 and 1999 only the 90th percentile peak was in September while the rest of the percentiles were in August, the period between 2000 and 2012 the peak value of all the percentiles were in August.

Figure 4-18 is a comparison between the percentiles of each time-window. Figure 4-18 (a) illustrates the pre-damming flow condition percentiles, the difference between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles were 4533, 5258, 6817, and 7862 m^3/s, respectively. It was also observed that all the percentiles had their peak values in September.



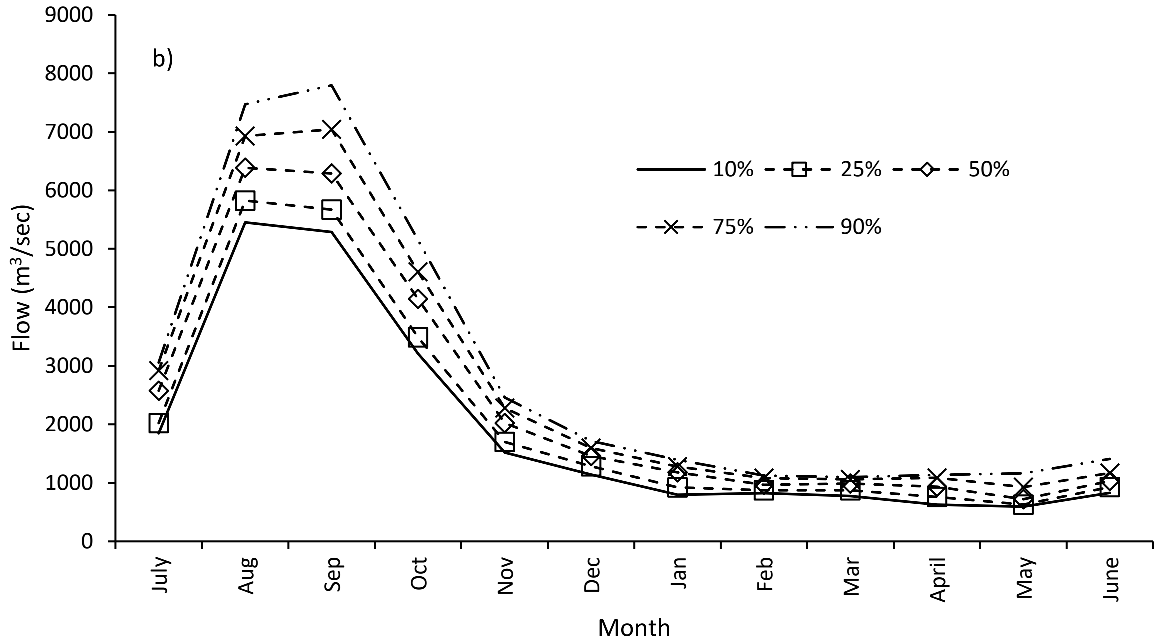


Figure 4-18 percentile for altered and unaltered flow conditions at Tamaniat for (a) years 1911–1925; and (b) years 1933–1963.

For the years between 1933 and 1963 (Figure 4-18 (b)), the change in the position of the peak value can be seen, and how it changed from September in the 90th percentile to move gradually to be in August as the percentile decrease.

The differences between the maximum and minimum values for the different percentiles of period 1933–1963 were, 4857, 5195, 6113, and 6695 m^3/s, for the 10th, 25th, 75th, and 90th percentiles, respectively.

the 10th percentile showed a slight increase in the difference between the minimum and maximum values compared to the pre-damming flow conditions. The 10th percentile increased by 7%. Regarding the 25th, 75th and 90th percentiles, decreased by 1%, 12% and 17%, respectively.

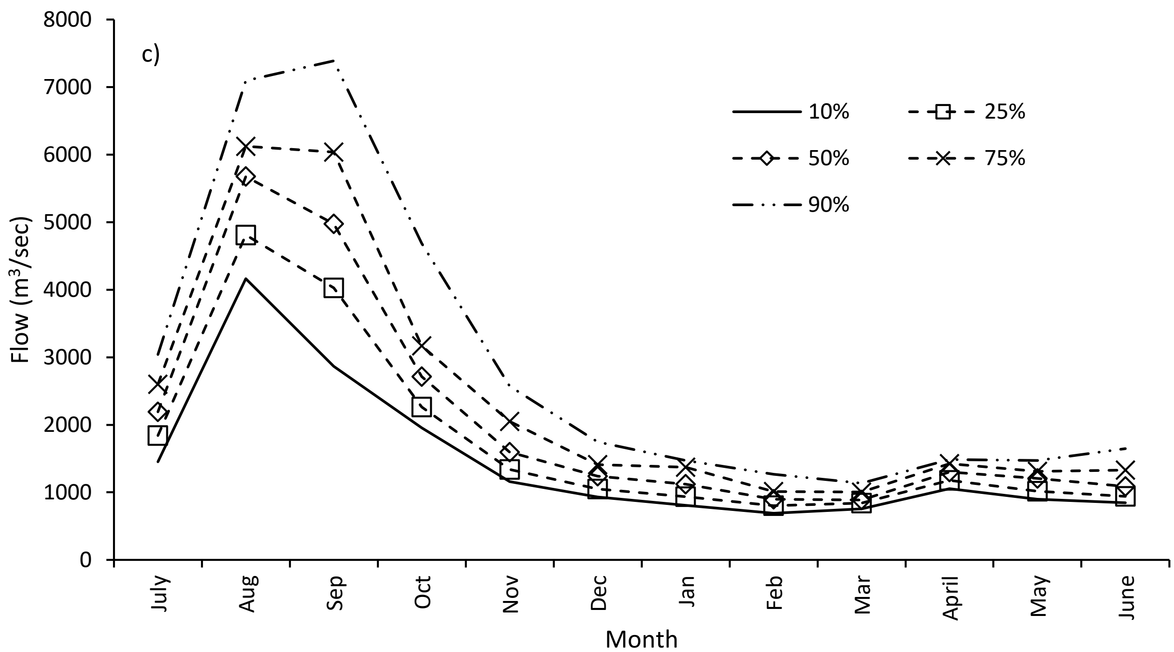


Figure 4-19 percentile for altered and unaltered flow conditions at Tamaniat (c) years 1964–1999.

For the period from 1964 to 1999, only the 90th percentile had its peak at the month of September, as the percentile decreased the position of the peak moved gradually to be in August instead of September. the differences between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles were, 3473, 4009, 5111, and 6253 m^3/s, and decreased than the period 1933–1963 by 40%, 30%, 20% and 7%, respectively.

Finally, for the period from 2000–2012, differences between the minimum and maximum values for the 10th, 25th, 75th and 90th percentiles were 4568, 4662, 6650, and 6871 m^3/s, respectively. From the comparison of these values with the previous period 1964–1999, an increase in difference was found to be 32%, 16%, 28% and 10%, respectively.

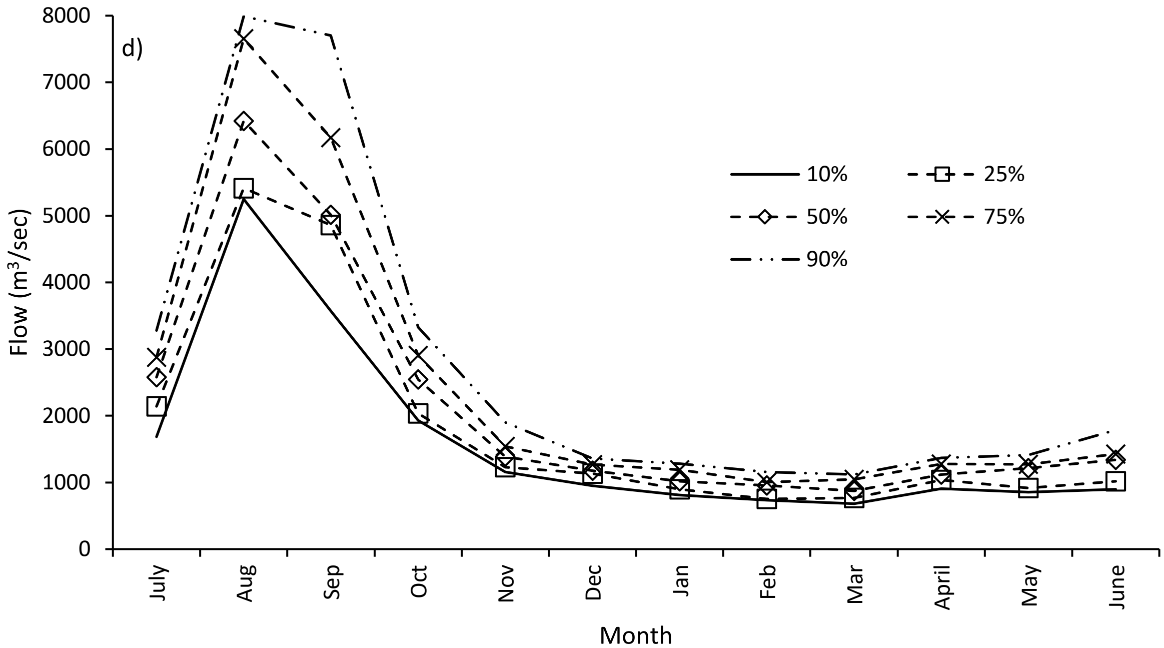


Figure 4-20 percentile for altered and unaltered flow conditions at Tamaniat (d) years 2000–2012.

The decreases highlighted above indicate that the nature of the discharge was changed. The hydrograph deformed in the altered conditions, especially from 2000–2012, compared to the hydrograph for the pre-damming flow period. One of the concerns linked to the changes in the hydrograph is that the area subjected to flooding by the Nile river will decrease. This will result in more area being cultivated, which results in more consumption of river water for irrigation and subsequently to more pollutants from drainage water leaching into the river. A decrease in water quantity and quality will follow such a development.

4.4.3 Changes in FDC

Figure 4-21 and 4-22 show the FDC for both stations Dongola and Tamaniat. Figure 4-21 represents the discharge at Dongola station, it was observed that at low percentiles the pre-damming flow conditions and the discharge between 1933 and 1963 were alike, also the discharge for the periods (1964–1999) and (2000–2012) had the same slope with a slight difference in values. By reaching the 65% and greater there was difference in the discharge in the three altered periods and the pre-damming flow conditions. The three periods had the same slope and the values were almost equal. The Tamaniat station FDC had the same profile as that of Dongola.

The familiarity of the FDCs for both stations and the steady slope with percentage in the three altered periods indicates the effect of the structures and how they affected the discharge.

The effect of the climate variability coupled with the human intervention had a significant effect of the river discharge which agreed with the hypotheses. The hypotheses states that a shifting and alteration in the river discharge will happen with the decreased precipitation patterns, increased drought events and the degree of human intervention.

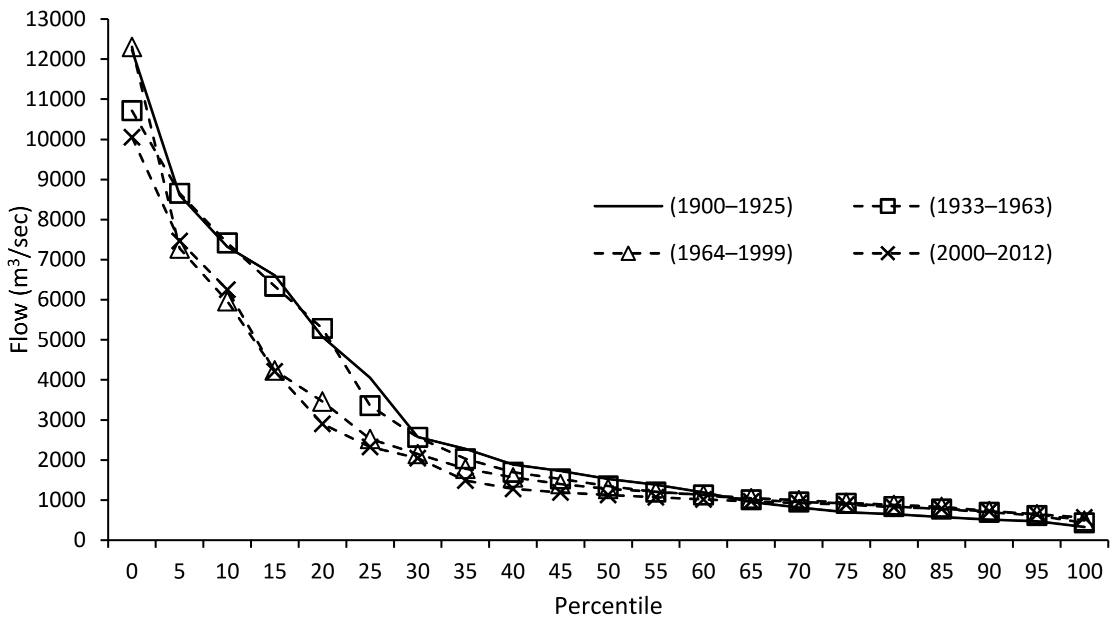


Figure 4-21 Flow duration curve at Dongola station.

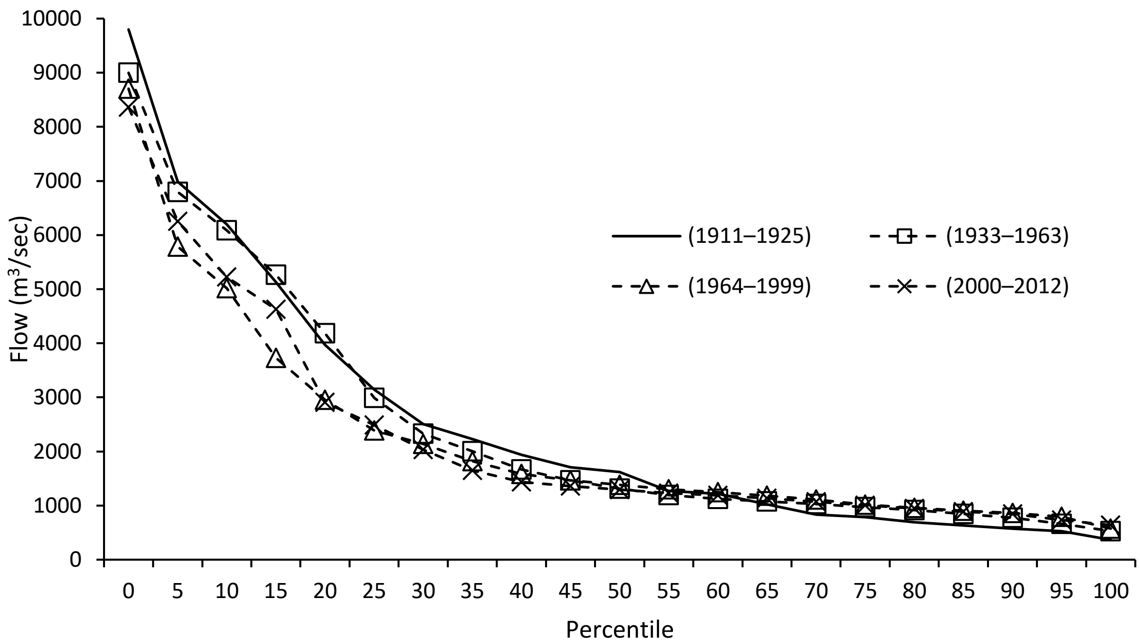


Figure 4-22 Flow duration curve at Tamaniat station.

Chapter Five: Discussion

The results from the methodology used to achieve the research objectives and aim will be analyzed and discussed in this chapter starting with objective 1: finding reliable meteorological data-sets in scarce areas, then objective 2: evaluation of the climate variability and drought on unaltered and altered discharge, and finally, objective 3: assessing the alteration in discharge based on the degree of alteration and climate variability.

5.1. Consistency between land-station and processed datasets

Finding a reliable data set is important to build strong analyses related to climate variability and drought. It is problematic to find meteorological data sets in some parts of the globe and another problem is to share meteorological data between countries. In order to overcome this problem some processed data sets are used.

In this research the problem of finding reliable data set from ground stations was a problem. In order to mitigate this challenge other sources of processed data have been used, but before using the processed data set some correlation tests with the data from the available ground stations have been applied to the data set.

More than one data set have been chosen to apply the correlation tests with the available scarce ground stations data. The data sets were the GPCC and CFSR. By observing Table 3-1 it can be found that there was not a big difference in mean, standard deviation, maximum, and minimum annual precipitation values when compared between the ground stations and the GPCC data sets, with difference in reading less than 10% for the mean annual precipitation for Abu-Hamed and the average reading of neighboring GPCC stations, and less than 3% for Khartoum and the average reading of neighboring GPCC stations. For the standard deviation the difference between Abu-Hamed and the average reading of neighboring GPCC stations was 1%, and 7% between Khartoum and the average reading of GPCC neighboring stations. The maximum annual precipitation difference between the Ahu-Hamed and the average reading of neighboring GPCC stations was 7%, and 12% for Khartoum and the average reading of neighboring GPCC stations. There was a high correlation between the values of the ground stations (Khartoum and Abu-Hamed) and the neighboring GPCC stations exceeding 97% for Abu-Hamed and neighboring GPCC stations and more that 89% for Khartoum and neighboring GPCC stations. The results found to be more reliable than the results when the ground stations were compared with the CFSR processed stations.

Using the GPCC data-set in the Nile basin for precipitation data is recommended compared to different data sets due to the high correlation with the land-station observations and the lowest mean square error compared to land-stations observation, in addition to sufficient precipitation simulation performance (Abdelwares et al., 2020). The GPCC also showed the best performance in terms consistency and lowest mean square error when compared to other gridded data-sets in arid zones and be used in different hydrological and climatic applications (Ahmed et al., 2019).

A study in 2014 discussed using the CFSR data in scarce data areas, the study was applied on 4 small basins in the Blue Nile basin. The data was promising in two of the four basins and the general conclusion of this research is that CFSR can be used for scarce data areas (Dile & Srinivasan, 2014).

Since the data of CFSR was acceptable to be used by researchers and the GPCC showed better results when compared with ground stations from periodicals and the GPCC had a longer record, The GPCC was used in this study and recommended to be used in familiar locations.

The uncertainty in the GPCC is highly dependent on the quality control of the land-stations observation and the number of land-stations used in modelling the grid. The number of the land-stations differs from a year to another (Dinku, 2019). The main problem will happen when there is a continuous decline in the of land-stations contribution in the GPCC dataset. This problem can be prevented by increasing the number of stations in the developing countries and the smoothness of meteorological data sharing between the governments and other interested parties.

5.2. Trend Analysis of climatic and river discharge data

The trend analyses of the climate variability and discharge were part of the fulfilment of the second objective “the evaluation of the impact of climate variability and droughts in unaltered and altered flow conditions”.

The trend analysis has been applied for each station of the 9 sub-basins of the Nile basin and for the whole basin. The results in Table 4-1 showed that 7 of the 9 basins had no trend in the annual precipitation for the non-parametric test, while for the linear trend 7 basins showed a decreasing trend even though it was a very mild slope that can cause strong effect on the total amount of discharge. This indicates that there is neither or a decreasing or increasing trend in the amount of precipitation and if it is considered from the linear trend it will be with very low influence.

Figure 4-2 and Table 4-2 showed how the location and the contribution in the total precipitation matters. The location of the stations in the downstream of the Blue Nile and near the borders with Sudan and far from the location Ethiopian highlands is the location with the highest rate of precipitation in the basin.

The precipitation trend in the basin is affected not only by the number of stations with increasing or decreasing trend as the case in Sobat basin, but also by the location of the station in the basin and amount of contribution of the location of the station to the total basin precipitation as the situation in the Atbara and Blue Nile basins.

The results indicated that there is a small decline in the precipitation by considering the linear regression method and no trend if considered non-parametric test on the annual time scale. Steady or small decline in annual rate of precipitation means steady annual rate of discharge unless any human intervention occurred.

The trend analysis was also applied at monthly scale for the 3 main basins contributing to the river discharge. The results showed that there was not a strong decline in the precipitation values along the study period that can cause dramatic changes in the river discharge.

Different published research agrees with the results of the trend analysis in this study. In 2016 the rainfall trends in the Nile basin was discussed. The research studied 39 stations in the whole basin and the years of data were not consistent, ranged from 43 years to 95 years of data. The trend detection method used was the Mann-Kendall. The results of this study showed that not all the stations had the same trend, some stations had increasing trends while others had decreasing trends on both annually and monthly scale (Onyutha et al., 2016).

Different studies discussed the trend in rainfall at the Nile basin and sub-basins, most of the studies mentioned that no significant change was detected and other researchers concluded that there was slight decrease and slight increase in different areas of the Nile basin (Girma, 2013).

The trend analysis was also applied for the two river discharge stations, the Dongola and the Tamaniat stations. The changes occurred in the monthly river discharge and the annual river discharge were not consistent with the changes occurred in the precipitation. The inconsistency of the change in trend between the precipitation and the river discharge led to further investigation of the reason of the decline of the river discharge trend. This result is agreeing with (Tesemma, 2009), It was found that there was a decreasing trend in the flows at the stations of Dongola and Tamaniat and recommending it was because of human intervention.

Further investigation considered the drought events severity and duration that might have a huge impact on certain period or more than one period in this study, and the human intervention and how they might have affected the freshwater discharge.

5.3. Drought events

The investigation of the drought events severity was also part of the fulfilment of the second objective "the evaluation of the impact of climate variability and droughts in unaltered and altered flow conditions" beside the trend analysis. In addition, it contributes to the fulfilment of objective 3: assessing the alteration in discharge based on the degree of alteration and climate variability.

The drought investigation in this research was accomplished using the SPI, which is based on the precipitation in the calculation of the severity of the drought event. The

SPI was applied for the 3 sub-basins which are the larger contributors in the river flow reaching Egypt.

The drought events were assessed for the whole record of data (1901—2012) but were classified by the degree of alteration in the river discharge based on the number of structures.

5.3.1 Drought events in the Blue Nile basin

For the Blue Nile basin, the drought events were not steady or following a certain or constant pattern. The 25 years of the pre-damming period (1901—1925) were classified as 6 wet and normal years, 17 near normal, 1 moderate dry and 1 severe dry (Table 4-8). By considering the months, we can classify the months by flooding months and dry months. The flooding or rainy months are July, August and September and the rest months of the year have low precipitation. Month of January had 4 years wet or normal rainy conditions and 14 year near normal rainy conditions and 5 years moderate dry and 2 years severe dry. Month of January had the worst drought events, 28% of the months of January in this period was between moderate and severe dry. This is considered a problem because when drought hit low precipitation month it can lead to water scarcity. The month of February had the best raining condition with only 1 moderate dry event and zero severe dry event.

The rainy season had good raining condition, the drought events did not exceed 16% of the raining season months for this period and the rest are normal or wet.

By assessing this period and the condition of the precipitation and human induced factor, the time-window 1900—1925 could be considered the best condition of river discharge and a benchmark for assessing the discharge for the other time-windows.

The second time-window between 1933—1963 had the best annual raining conditions with only 1 year considered severe drought and no moderate drought events. It is expected to have the highest mean precipitation between all the other time-windows.

The drought events for the months of January, October and November in period 1933—1963 were almost identical to that of period 1901—1925, but the events became tougher in the months of February, and April, and better for the rest of the months.

Based on this observation it is expected that there will be constant mean precipitation and mean runoff for the months January, October, and November unless there is water abstraction in the upstream. Then, there will be decrease in mean precipitation for the months of February and April, which might lead to more storage in the upstream and more use of water for irrigation for the rain fed crops, that eventually, will lead to decrease in the mean runoff due to decrease in precipitation and water abstraction. It is expected the mean precipitation will increase in the months of March, May, June, July, August, September and December, and if there is no influence for the human induced factors in the upstream, an increase in the mean runoff is expected.

The Precipitation condition became more critical in the period between 1964—1999. The moderate drought events on the annual scale jumped to be 8 years instead of 1 year in the pre-damming period and zero events in the period between 1933—1963 which resembles 22% of the years in this period. The severe drought events also witnessed an increase from 1 event for the first 2 time-windows to 5 events which is 14% in the period between 1964—1999.

This change in the precipitation condition and 36% of the years were between moderate and severe drought had negative effect on the mean precipitation in this period and caused a decrease in the mean precipitation, which might encourage upstream countries to store and consume much water from stored water. The decrease in the mean precipitation and the human induced factors will have huge impact on the mean runoff in this period (1964—1999).

The months that had better precipitation condition for period 1964—1999 compared to the pre-damming condition period (1901—1925) were January and March only while the rest of the months had more drought events either moderate or severe. The effect of the increased drought events will affect the mean precipitation and especially in the dry months. The dry months are characterized by low values of precipitation and the effect of the drought events is exacerbated compared to wet months, and the mean runoff will witness a decrease for the whole period.

The last time-window (2000—2012) had the worst drought events compared to the rest 3 time-windows. The annual scale did not witness any wet year, and 46% of the years had drought events 38% moderate drought and 8% severe drought events. This period is expected to have the worst mean annual precipitation and since this period is the highest in term of interventions it is expected to have the lowest mean annual runoff.

Months of January, April, August, September, and November in time-window 2000—2012 had better precipitation conditions than the pre-damming period. This should be reflected in the mean precipitation for these months and also on the runoff especially of August and September.

5.3.2. Drought events in the Atbara basin

The precipitation conditions for the Atbara basin on the annual scale was not different than the precipitation condition in the Blue Nile basin (Table 4-9). The time-window 1933—1963 had the best precipitation condition with no severe drought and only 3% with moderate drought. The pre-damming time-window (1901—1925) came second with no severe drought events and 8% moderate dry events. Then came the time window 1964—1999 and the worst precipitation condition on the annual scale was 2000—2012.

The month of January had the best precipitation condition in the pre-damming condition with no drought events, then the time-window 1933—1963 16% moderate dry and no severe drought events, the last two time-windows were almost the same.

The arrangement of the time-windows in terms of the precipitation situation for the months of February, March, and May were familiar to that of January.

The months of April and June had slight shifting in the arrangement of the time-windows. The best time-widow with precipitation condition was 1933—1963, then the pre-damming period, then 1964—1999 and finally 2000—2012.

For the months of July, September and December the time-window between 1933—1963 and the pre-damming time-window had the best raining conditions respectively, then came the 4th time-window (2000—2012), the worst raining conditions for the months of July, September and December were in the 3rd time window (1964—1999). Month of August was familiar to most of the months, the best raining conditions were for the pre-damming time window and 1933—1963 time-window respectively, then came 2000—2012 and the worst raining condition were for the 1963—1999 time-window. There was a shift in the raining conditions for the months of October and November. The time-window 2000-2012 had the second-best raining conditions and came directly after the pre-damming period (1901—1925).

According to the drought events observation for Atbara basin the highest value of mean annual precipitation will be in the period 1933—1963 with a slight difference compared to the pre-damming period, then the period 1964—1999 and the worst mean annual precipitation in the time-window 2000—2012.

The raining conditions should have direct reflection on the discharge situation for the 4 time-windows and should follow the same time-window arrangement of the mean annual precipitation. Any disarrangement will be due to the effect of the human induced factor.

The time-windows 1964—1999 and 2000—2012 were under higher drought stress than the pre-damming condition time-window and the 1933-1964 time-window on the monthly scale.

According to the observation from Table 4-6 there will be high stress especially for the months with low rainfall and river discharge. The situation will be more complicated when there is water abstraction and water use in the upstream and water consumption for irrigation for rainfed crops.

5.3.3 Drought events in the Sobat basin

The annual precipitation for the Sobat basin had its best condition in the time-window 1933—1963 with 3% of the annual precipitation record as moderate drought events no severe drought events (Table 4-10). The situation became slightly worse in the pre-damming and the 1964—1999 time-windows with 12% of the annual precipitation record as moderate drought and 4% as severe drought for the pre-damming time-window, and 8% of the annual precipitation record as moderate drought and 6% as severe drought for the 1964—1999 time-window. Then, there was a dramatic effect of drought in the 2000—2012 time-window with 31% of annual precipitation as moderate drought and 38% as severe drought events.

The monthly precipitation at Sobat basin was generally in its best situation in the pre-damming period (1901—1925) and the period between 1933—1963, except for the months June, July, September, and November. The months of June, July and September were in their best raining conditions in the period between 1963—1999, and November was in its best raining conditions in the period between 2000—2012.

The results indicate that the for most of the months and especially the dry months there were stress on the fresh water source (the precipitation) that will have dramatic effect on the river discharge and might encourage the upstream countries to store water and consume more water that will affect the downstream countries.

The results and drought analysis suggests that the mean annual precipitation for the Blue Nile, and Atbara basins will be in its highest value in the period between 1933—1964, then between 1901—1925, then 1964—1999, and finally the highest dammed period between 2000—2012. The Sobat basin should has different arrangement than the other 2 basins, the highest value for mean annual precipitation will be between 1933—1963, second highest mean annual precipitation is expected to be in the period 1964—1999, then in pre-damming period (1901—1925).

The drought and its severity agreed with the results of (Bayissa et al., 2018), the study used six different drought covering years from 1970 and 2010. The study detected years with severe drought events, and these were the same as the results of the present study.

The results also agreed with (Elkollaly et al., 2017), the study used the same drought index but different tool to calculate with. The study covered years from 1965—2000, and the study indicated several drought events in this period.

Another study in 2013 assessed the drought events in Ethiopia (the Blue Nile) using 174 stations and a period from 1971 to 2011. The study divided Ethiopia or the basin to zones. What was found that each decade from the 40 years had drought events but the intensity of drought events was higher in the 80s and from 2000 until 2011 (Viste et al., 2013). The results indicate how the drought events increased in severity and intensity over time which is agreeing with the results of the present research.

This research used study period of 112 years, which is more than the previous studies and make it more accurate since the SPI gives more accurate results when the timespan is 30 years and more.

5.4 Changes in climate and river discharge pattern

The investigation of the effects of drought events severity on the precipitation pattern and the investigation of the drought events and human intervention on the river discharge pattern was also part of the fulfilment of the second objective “the evaluation of the impact of climate variability and droughts in unaltered and altered flow conditions” beside the trend analysis. In addition, it contributes in the fulfilment of objective 3: assessing the alteration in discharge based on the degree of alteration and climate variability.

5.4.1 Precipitation pattern in the Blue Nile, Atbara and Sobat basins

The drought events occurred in the Blue Nile, Atbara and Sobat basins had direct effect on the precipitation pattern (Figures 4-27, 4-28, and 4-29, respectively). The precipitation pattern agreed with what was expected from the effect of drought events on each time-window. The drought events and their influence on the precipitation pattern for each time-window might encourage upstream countries for more water consumption and storage especially in drought periods, this will appear in the river discharge pattern.

5.4.2 River discharge pattern at Dongola and Tamaniat stations

The river discharge is affected by both climate variability and drought events, and human induced factors. The river discharge at the Dongola and Tamaniat stations are presented in Figures 4-31 and 4-32. The river discharge volume should take the same pattern of the precipitation if there were not any effect to human induced factor. The results confirmed the presence of influence of the human induced factor on the river discharge. The highest value of the volume of discharge at both stations was in the pre-damming period which is contradicting with the mean annual precipitation. The second highest value of volume of discharge was in the time-window between 1933—1963, this indicates the influence of the human induced factors and how they manged to affect the runoff of the precipitation.

The time-window 1964—1999 was the third highest volume of discharge and the time-window 2000—2012 was the last and with least value at the Dongola station. The third and last rank of the volume of discharge of time-windows was switched at the Tamaniat station, the third highest volume of discharge was the time window 2000—2012 and the last was the time-window 1964—1999.

The reason of the difference in ranking of the time-windows between the two stations is the location of the stations. The flow of the Blue Nile and Sobat basins passes through the Tamaniat station, while the flow of the Blue Nile, Sobat, Atbara and Main Nile basins passes through the Dongola station (Figure 3-2). The time-window 2000—2012 had 2 more dams at the Atbara and Main Nile basins (Tekeze and Merowe dams) than the previous time-windows that affected the river discharge at Dongola station more than Tamaniat station.

5.4.3 Annual and monthly median discharge and percentiles anomaly

The results of the annual median rivers discharges at Dongola and Tamaniat stations showed the effects of the drought events and the impact of the human interventions on the river discharge.

89% of the years at Dongola station suffered a decreased annual median river discharge than the annual median in the pre-dammed period (Figure 4-33). 93% of the years at Tamaniat station suffered a decreased annual median river discharge than the annual median in the pre-dammed period (Figure 4-35).

The situation becomes more critical when the human intervention is coupled with the drought events and the degree of severity of the drought event.

The monthly medians were also affected by the drought events and human induced factors. The results showed a modification in the monthly median river discharge from period to another (Tables 4-13 and 4-14). Some successive months suffered a continuous decrease in the median values, while other months witnesses increase in the value of medians.

The results indicated a significant increase in the median of dry months. The minimum observed median in the pre-dammed was 515 m^3/sec, for the period 1933—1963 the minimum median increased to be 686 m^3/sec, the period 1964—1999 had a minimum value of 717 m^3/sec, the last time-window had a minimum median with 780 m^3/sec.

The previous results showed how induced factors decreased the effects of drought in the downstream countries. The previous results showed how the human induced factors and dam construction can be beneficial for downstream sectors or countries by producing a steady discharge or decreasing the effects of floods and drought.

The results of the analysis of the river discharge percentiles (10^{th}, 25^{th}, 75^{th}, 50^{th} and 90^{th}) at the stations of the Dongola and Tamaniat showed the power of the human induced factors in controlling the river discharge. The anomaly occurred in the peak of the river discharge and how it was moved from September to August, and the increase of river discharge in low flow or dry months.

The human induced factor and the dam construction in the upstream had significant effect on the river discharge and the effect is directly proportional with the intensity of the human induced factor.

The increased intensity of water abstraction in the upstream will facilitate the controlling of the river discharge to the upstream countries and might be dramatic effect to the downstream countries.

Different studies in different river basins discussed the changes occurred in the riverine system due to the climate variability and the human intervention (Al-Faraj et al., 2014; Lu et al., 2014; Mwakalila, 2008; Zahar et al., 2008).

5.4.4 Validation of Hydrologic Alteration

Relationships between the dams constructed and the alteration in the corresponding discharge will be explored in this section. The Sennar Dam (0.93 Bm^3) was the first structure to be constructed upstream (Sudan) of the transboundary basin in 1925. Through the first alteration period from 1933–1963, four dams were constructed: two in Sudan, one in Ethiopia and the Owen Falls dam in Uganda, which added considerable storage capacity to the lake (Table 3-1). The Sennar dam has a storage capacity accounting for 1.06% of the long-term mean annual unaltered discharge volume. The next major construction project resulted in the construction of the Jebel Aulia dam in 1937. By 1953 and 1954, Tis Abay and the Owen Falls dam, respectively, were constructed.

Through the period of first alteration, 12 out of 31 years had annual mean flows equal or greater than the long-term annual mean discharge prior alteration. Three out of the twelve high discharge readings were taken between the construction of the first and second dam, while six out of twelve high discharge readings were taken after the construction of all dams in this period, which gives an indication that these years were wet ones.

For the second period of alteration, another four dams were constructed between 1964 and 1995. The construction of these four dams increased the storage of water by 6.77 Bm^3/year compared to the storage of the first alteration period. In this period, only 7 out of 36 years had mean annual flows greater than the long-term annual discharge for the unaltered period. This period has also suffered a drought represented by the years with the lowest mean annual flows.

The third altered period from 2000–2012 had the construction of eight dams. Through this time window, only one year had an annual mean discharge greater than the long-term annual mean discharge for the unaltered period.

Irrigation in agriculture demands is usually the highest consumer of available water resources. The irrigation schemes linked to the study relate to the hydraulic structures constructed. In Sudan, the major irrigation schemes are as follows (UNEP, 2007): Gezira and Managil (870,750 ha), New Halfa (152,280 ha), Rahad (121,500 ha), Gash Delta (101,250 ha), Suki (35,235 ha), Tokar Delta (30,780 ha), Guneid Sugar (15,795 ha), Assalaya Sugar (14,175 ha), Sennar Sugar (12,960 ha); Khashm El-Girba (18,225 ha), Kenana Sugar (45,000 ha), White Nile Pump Schemes (192,375 ha), Blue Nile pump Schemes (112,590 ha), Northern Pump Schemes (41,715 ha) and other areas (132,300).

The irrigated crops were Sorghum (678,700 ha), Wheat (254,600 ha), Millet (8,200 ha), other cereals (61,700 ha), Cotton (157,300 ha), Groundnuts (45,000) ha), Vegetable (95,000 ha), Sugarcane (70,700 ha), Sunflower (20,900 ha), Potatoes (15,900 ha), other roots and tubers (15,900 ha) and Fodder (139,030 ha). The different crops had different water requirements to be irrigated but the total water withdrawal for irrigation was 25.910 BCM/year and this represents 96% of the water withdrawal for Sudan (FAO, 2015). While according to the late statistics in 2016 Ethiopia water withdrawal for irrigation is 9 BCM/year (FAO, 2016).

The Gezira scheme irrigation area reached gradually 0.87 Mha. The area dedicated to irrigation comprised initially 126,000 ha due to the construction of the Sennar dam in 1925, reaching 420,000 ha by 1950.

After the construction of the Roseiris dam in 1966, the irrigation area for the Gezira and Managil extensions increased the total to 756,000 ha (World Bank, 2010). Thereafter, this area increased again to approximately 870,750 ha in 2010.

The New Halfa on the Atbarah River benefits from the water storage of the Khasm el Gibra dam. The Rahad irrigation scheme uses water from the Blue Nile serving the Roseires dam, which began its operation in 1978. Furthermore, Assalya and Kenana are located on the White Nile (Awulachew et al., 2007).

5.5 Limitation of the Study

The presented study has some limitations in the data. The data that should be used to produce an adequate study and analysis to achieve the objectives and aims according to previous studies discussed in literature are the river discharge data, meteorological data, and hydraulic structure data.

The data should be:

1) for the river discharge should be daily discharge time-series, inflows to the dams and releases from the reservoirs, and as many hydrometric stations as possible.
2) the meteorological data should be daily precipitation, temperature, evaporation, potential evapotranspiration, wind speed and humidity data and various meteorological ground stations.
3) for the assessment of the human intervention and water abstraction the data should be existing dams with the purpose of use, the storage capacity of the reservoirs and the operation of the reservoir. Irrigation schemes and the efficiency of the irrigation system.

It was intended to collect all the previous data to produce more reliable analysis. The only data available was the monthly data especially the hydrometric stations are out of Egypt borders and there is no access to these stations. It was also difficult to find more than two hydrometric station for assessing the river discharge of the eastern Nile basin and was operating for all the 112 years of the study period.

The meteorological data in the study area were scarce in number as mentioned in data collection section and were not operating continuously for the study period. The modelled data used and covering the study period focused only on the precipitation. Considering the human intervention and water abstraction data, the only data that was collected from different resources is existing dams, storage capacities and purpose of use.

The smoothness of sharing of the river discharge data, meteorological data in addition to water abstraction structures and projects operation data simultaneously between the riparian countries could help in overcoming the limitation problem and produce more robust studies.

Chapter Six: Conclusions

6.1 Introduction

This thesis develops a methodology and approach to study the effect of the climate variability coupled with upstream human intervention on river discharge reaching downstream countries in large transboundary basins.

This chapter explains how the objectives of this study were achieved and combined to deliver the main aim of the research: a framework that can help in better understanding and expecting the effect of climate variability and human intervention in large transboundary basins, in order to manage the resources of the basin sustainably.

6.2 Achievement of Research Aim and Objectives

To reach the aim, three objectives were achieved. The results of the objectives achievement are covered through the thesis and concluded below:

Objective 1: To introduce a methodology for finding metrological data sets in scarce data areas and use it in measuring climate variability studies and drought events. Some areas have scarce meteorological data and if it is available it is hard to acquire, the studied area is one of these areas. This objective was achieved in the Methodology chapter and discussed in the discussions chapter. It was found that the GPCC dataset was highly consistent with the land-based data and reliable to be used in research of the study area.

The conclusion reached from this objective can help researchers and engineers in overcoming the problem of scarce data in critical locations to produce a reliable statistical studies.

Objective 2: to evaluate the impact of climate variability and droughts on river discharge in pre-dammed conditions and in intervened conditions. After using the appropriate data set to be used in the research, trend analysis was applied to the chosen meteorological data.

The trend analysis discussed in this research was the linear regression as an example of parametric tests and Mann-Kendall test as an example of non-parametric tests.

The assessment of the climate variability was not limited to assessment of the trend analysis. One of the good indications how the precipitation is affected is the drought. The drought analysis was accomplished using the precipitation data and the SPI. The drought analysis was applied for the 3 critical sub-basins: Blue Nile basin, Sobat basin, and Atbarah basin, it was found that more the severity the drought event is, more the river flow reduction was. The second objective was achieved in the results and discussion chapters.

This objective was important in order to understand the climatic nature of the study area and how the climate changed in the past years and what was its effect on the river flow.

Objective 3: to analyze the river discharge, and to assess the changes in the river discharge according to the degree of human intervention.

The study area suffered both from climate variability and human construction activities affecting the river discharge. This led to partly severe drought events. For example, dams with different purposes in the upstream countries like Sudan and Ethiopia had a considerable impact on the downstream river discharge especially when coupled with climate change within the Nile river basin part located in Egypt.

The third objective was achieved in the results and discussion chapters.

Hydraulic alterations of the Nile basin are likely to increase in the future. The construction of mega dams such as the Renaissance dam in Ethiopia and the increase of the irrigation schemes will impact significantly on future river discharge. Moreover, droughts represent a great threat and their effects are exacerbated by the increased upstream use of water.

The conclusion achieved from the proposed methodology can help the downstream countries to plan the demand requirements based on the changes occurred in the river discharge. The findings can also help to build a sloid ground for negotiations for a basin wide sustainable management.

The conclusion of the research can be summarized to the following points:

1. The GPCC dataset showed satisfactory levels when compared to ground station data and can be used in the Nile basin area.
2. Mild declining trend or no trend was noticed in the precipitation of the gridded stations distributed in the Nile basin.
3. Decreasing trend was found in the river discharge at Dongola and Tamaniat stations.
4. The drought events number and severity increased with time.
5. The precipitation is strongly affected by the drought events which eventually affected the river discharge.
6. The river discharge was strongly affected by the human intervention occurred on the Nile river.

6.3 Contribution to Knowledge

The thesis delivered a strong methodology that can help in the water resources sustainable management of large transboundary river basins of limited water resources.

The Nile river basin can be good representative for other transboundary basins witnessing the same conditions.

Findings will support and guide water managers to better management of the basin, to a more proper and wider scale of management referring to the transboundary level. Moreover, it will help in taking more optimum decisions, that helps in sustaining the water resources, for the downstream riparian country, to handle and cope with the potential combined effect of climate change and upstream intervention.

6.4 Recommendation of Future Improvements

The author recommends further research to identify the climate varaibility impacts on river and tributary flows and separate them from different human-induced intervention categories.

The impact of change in land use and urban planning should be assessed for different sub-basins in future studies. Also, further research and investigation of the mitigation measures to decrease the influence of human interventions in the upstream and climate change and variability in the transboundary basins.

The prediction of future drought events, with putting in consideration the climate change scenarios and how they can affect the future river discharge especially when combined with human intervention.

Study different adaptation techniques to mitigate the changes occurred in the river discharge and choose the most appropriate measure to help in better management of the water resources in transboundary river basins.

This study faced some limitations due to the lack of cooperation between riparian countries. Applying this study with less limitations could produce better and more accurate results and better understanding of the relation between the river discharge and climate variability and human induced factors.

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Appendices

Appendix 1 published paper and online sources

Appendix 2 Figures and Tables

Table 8-1 Contribution of the Blue Nile basin stations with trend.

Blue Nile basin Stations	Long (º)	Lat (º)	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)
110	32.75	14.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
113	33.25	13.75	0.01	0.00	0.00	0.02	0.05	0.10	0.18	0.22	0.14	0.07	0.01	0.00
115	33.25	14.25	0.01	0.00	0.01	0.02	0.06	0.11	0.24	0.28	0.18	0.07	0.02	0.00
118	33.25	14.75	0.01	0.00	0.01	0.02	0.06	0.10	0.26	0.30	0.19	0.10	0.02	0.00
128	33.25	15.25	0.00	0.00	0.01	0.02	0.06	0.08	0.27	0.30	0.18	0.08	0.02	0.00
0	33.75	14.25	0.02	0.00	0.01	0.03	0.12	0.21	0.39	0.43	0.32	0.17	0.06	0.00
16	33.75	12.75	0.09	0.07	0.03	0.09	0.23	0.44	0.47	0.53	0.48	0.34	0.09	0.00
104	33.75	12.25	0.13	0.11	0.04	0.13	0.25	0.42	0.42	0.46	0.45	0.35	0.10	0.01
117	33.75	14.75	0.03	0.00	0.01	0.03	0.10	0.15	0.35	0.39	0.27	0.17	0.04	0.00
127	33.75	15.25	0.01	0.00	0.01	0.02	0.07	0.09	0.25	0.29	0.19	0.10	0.02	0.00
56	34.25	11.75	0.02	0.07	0.06	0.33	0.55	0.80	0.70	0.77	0.84	0.59	0.15	0.02
103	34.25	12.25	0.11	0.11	0.06	0.22	0.42	0.66	0.62	0.69	0.70	0.49	0.13	0.01
105	34.25	12.75	0.09	0.06	0.04	0.12	0.34	0.59	0.62	0.66	0.61	0.41	0.11	0.00
116	34.25	14.75	0.02	0.00	0.01	0.04	0.14	0.23	0.40	0.47	0.32	0.20	0.05	0.00
126	34.25	15.25	0.01	0.00	0.00	0.03	0.07	0.10	0.22	0.28	0.18	0.10	0.02	0.00
129	34.25	15.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
53	34.75	10.25	0.19	0.40	0.65	1.16	1.22	0.97	0.72	0.75	0.97	1.67	1.29	0.29
60	34.75	10.75	0.04	0.17	0.36	0.90	1.14	0.95	0.68	0.80	0.92	1.64	1.27	0.11
62	34.75	11.25	0.01	0.07	0.13	0.50	0.77	0.88	0.71	0.79	0.90	0.99	0.51	0.04
65	34.75	11.75	0.01	0.06	0.06	0.33	0.55	0.81	0.70	0.77	0.84	0.59	0.14	0.03
97	34.75	12.25	0.04	0.06	0.05	0.26	0.47	0.73	0.66	0.73	0.75	0.51	0.13	0.01
99	34.75	12.75	0.05	0.04	0.04	0.12	0.32	0.62	0.64	0.72	0.59	0.38	0.09	0.00
125	34.75	15.25	0.00	0.00	0.00	0.03	0.06	0.08	0.16	0.19	0.12	0.06	0.02	0.00
3	35.25	11.25	0.07	0.19	0.29	0.69	1.21	1.47	1.12	1.25	1.35	1.73	0.82	0.16
59	35.25	10.75	0.13	0.25	0.46	0.95	1.38	1.44	1.06	1.19	1.34	1.98	1.15	0.22
64	35.25	11.75	0.04	0.12	0.16	0.50	0.86	1.14	0.91	1.02	1.09	1.12	0.46	0.08
61	35.75	11.25	0.26	0.29	0.41	0.85	1.38	1.79	1.38	1.49	1.59	2.08	0.99	0.28
63	35.75	11.75	0.19	0.26	0.39	0.89	1.38	1.77	1.37	1.49	1.57	2.02	1.01	0.26
95	35.75	12.25	0.08	0.15	0.19	0.51	0.89	1.19	0.96	1.05	1.12	1.05	0.44	0.16
91	36.25	12.25	0.32	0.30	0.34	0.78	0.87	1.19	1.08	1.04	1.05	1.09	0.59	0.44
%age of basin precipitation			2	2.78	3.83	9.57	15.0	19.11	17.55	19.39	19.27	20.16	9.76	2.12
min			0	0	0	0	0	0	0	0	0	0	0	0
max			0.32	0.40	0.65	1.16	1.38	1.79	1.38	1.49	1.60	2.08	1.29	0.44

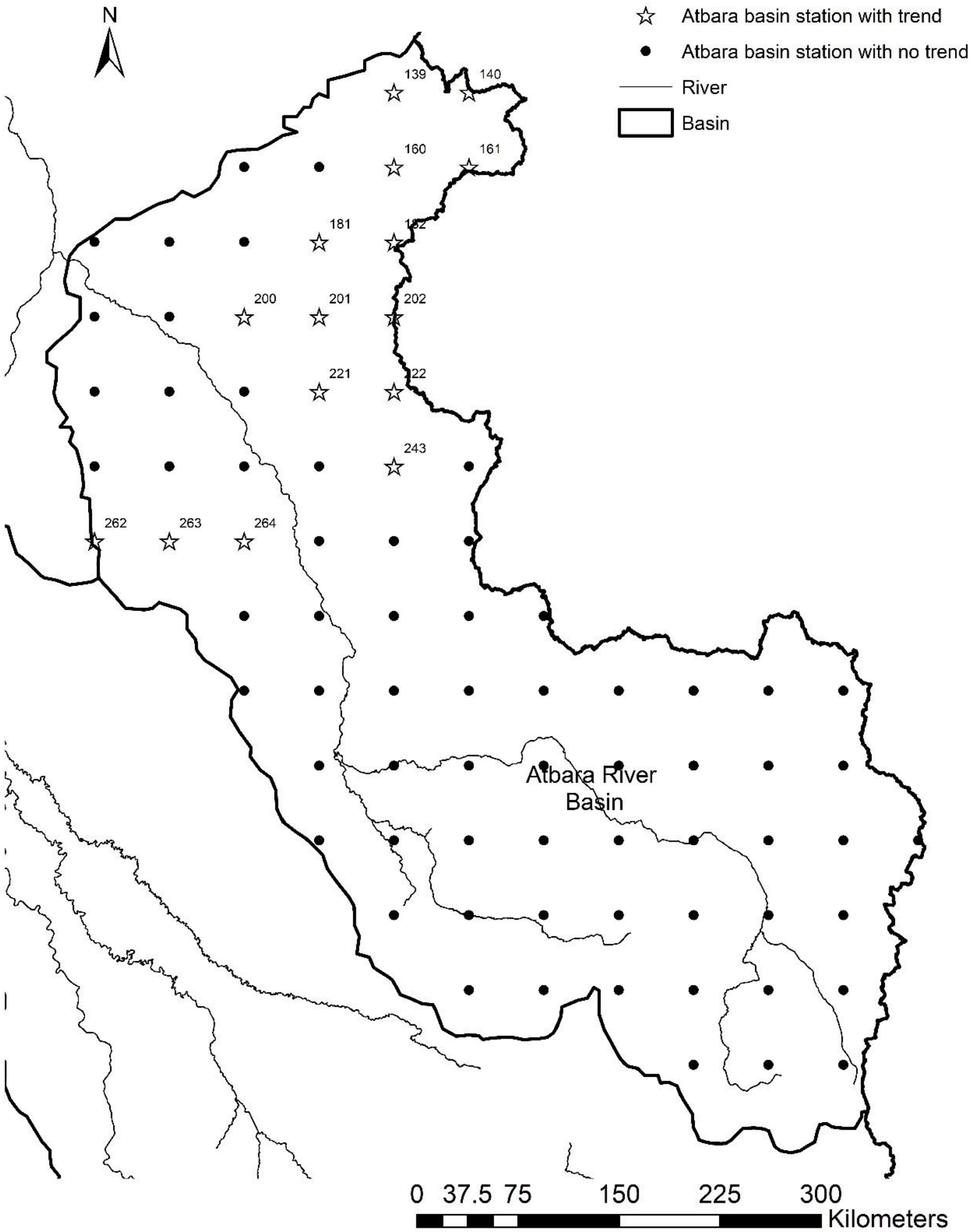

Figure 8-1 Atbara basin stations with and without trend

Table 8-2 Contribution of the Atbarah basin stations with trend.

Atbarah basin Station	Long (º)	Lat (º)	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)
262	34.25	15.75	0.00	0.00	0.00	0.05	0.12	0.12	0.24	0.31	0.30	0.20	0.02	0.00
263	34.75	15.75	0.00	0.01	0.02	0.11	0.28	0.22	0.51	0.67	0.61	0.36	0.09	0.00
264	35.25	15.75	0.00	0.02	0.03	0.09	0.26	0.24	0.51	0.68	0.61	0.34	0.11	0.00
243	36.25	16.25	0.04	0.03	0.04	0.09	0.27	0.29	0.46	0.58	0.54	0.34	0.12	0.02
221	35.75	16.75	0.01	0.03	0.02	0.05	0.24	0.15	0.29	0.47	0.36	0.29	0.10	0.03
222	36.25	16.75	0.08	0.06	0.03	0.04	0.23	0.15	0.25	0.39	0.29	0.25	0.10	0.07
200	35.25	17.25	0.04	0.07	0.01	0.05	0.22	0.11	0.24	0.39	0.26	0.37	0.31	0.09
201	35.75	17.25	0.08	0.10	0.02	0.05	0.25	0.13	0.24	0.41	0.27	0.32	0.20	0.20
202	36.25	17.25	0.28	0.13	0.04	0.04	0.14	0.07	0.12	0.21	0.14	0.17	0.15	0.28
181	35.75	17.75	0.31	0.21	0.06	0.10	0.22	0.13	0.19	0.31	0.20	0.37	0.31	0.55
182	36.25	17.75	0.79	0.31	0.09	0.11	0.16	0.09	0.14	0.22	0.14	0.30	0.44	1.03
160	36.25	18.25	0.89	0.38	0.15	0.15	0.20	0.12	0.16	0.24	0.15	0.45	0.70	1.76
161	36.75	18.25	1.43	0.56	0.10	0.12	0.14	0.07	0.12	0.17	0.10	0.34	0.75	2.10
139	36.25	18.75	0.99	0.40	0.18	0.16	0.24	0.10	0.18	0.25	0.16	0.53	0.92	2.36
140	36.75	18.75	1.02	0.37	0.12	0.12	0.16	0.06	0.13	0.18	0.11	0.40	0.78	1.78
%age of basin Precipitation			5.98	2.69	0.92	1.35	3.14	2.05	3.79	5.48	4.25	5.04	5.11	10.28
min			0.00	0.00	0.00	0.04	0.12	0.06	0.12	0.17	0.10	0.17	0.02	0.00
max			1.43	0.56	0.18	0.16	0.28	0.29	0.51	0.68	0.61	0.53	0.92	2.36

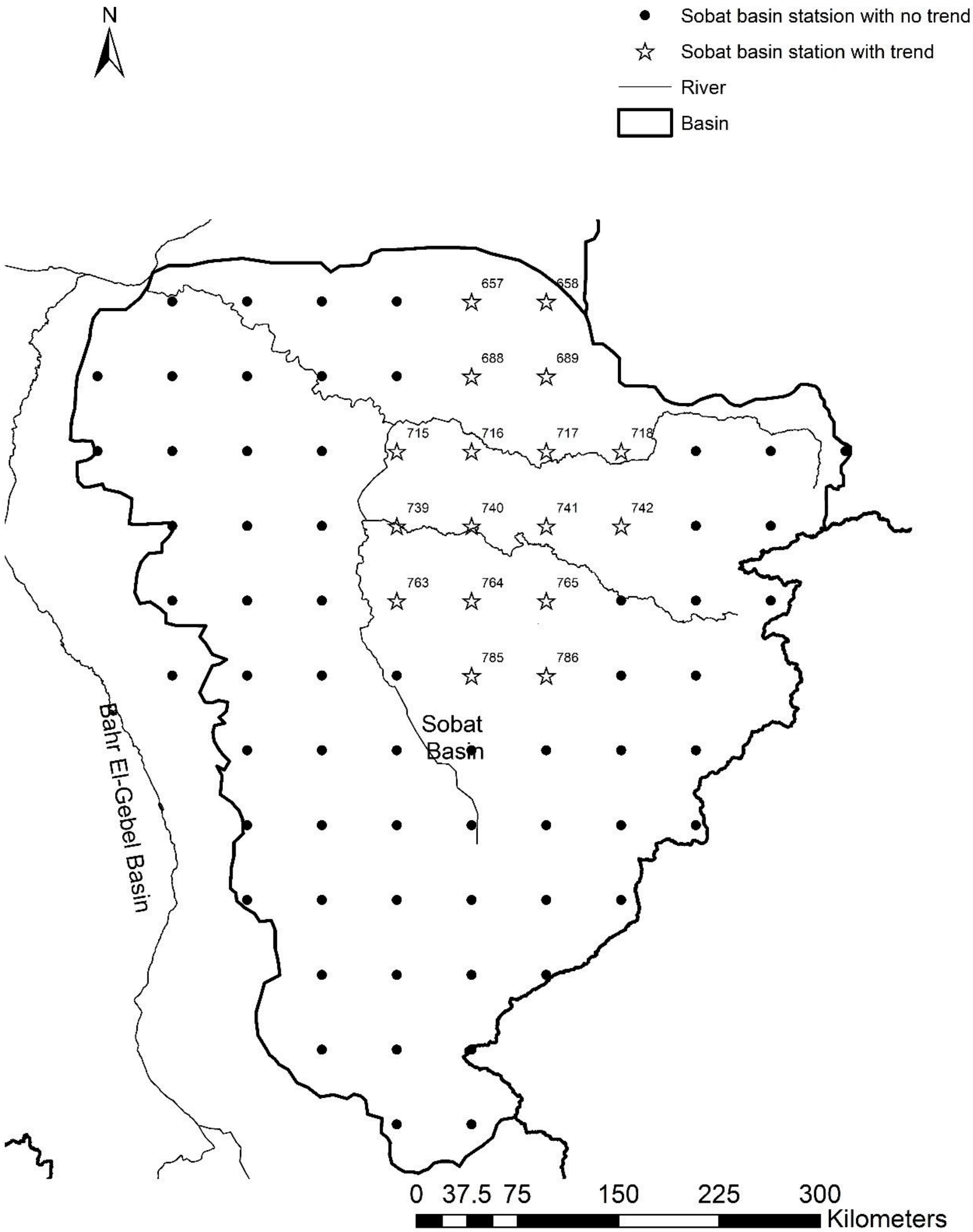

Figure 8-2 Sobat basin stations with and without trend

Table 8-3 Contribution of the Sobat basin stations with trend.

Sobat basin stations	Long (º)	Lat (º)	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)
785	33.75	6.75	1.22	1.05	1.18	1.24	1.18	1.20	1.34	1.18	1.28	1.25	1.36	1.17
786	34.25	6.75	3.36	2.27	2.39	2.08	1.90	1.76	1.54	1.66	1.75	1.75	2.27	3.07
763	33.25	7.25	0.69	0.72	0.89	1.06	1.01	1.06	1.28	1.05	1.16	1.14	1.15	0.79
764	33.75	7.25	1.21	1.09	1.16	1.20	1.22	1.27	1.42	1.26	1.35	1.28	1.40	1.16
765	34.25	7.25	4.98	3.64	2.94	2.20	2.35	2.32	1.97	2.14	2.24	2.16	2.95	4.06
739	33.25	7.75	0.70	0.69	0.87	1.02	1.08	1.13	1.35	1.17	1.21	1.17	1.18	0.75
740	33.75	7.75	0.68	0.72	0.87	1.06	1.33	1.39	1.62	1.58	1.39	1.32	1.30	0.79
741	34.25	7.75	2.23	1.78	1.59	1.46	1.87	1.92	1.93	2.03	1.85	1.74	1.99	1.95
742	34.75	7.75	5.06	3.88	2.93	2.13	2.54	2.52	2.14	2.32	2.45	2.31	2.92	3.93
715	33.25	8.25	0.58	0.65	0.84	1.03	1.30	1.37	1.59	1.53	1.37	1.32	1.23	0.67
716	33.75	8.25	0.55	0.64	0.84	1.06	1.50	1.52	1.74	1.78	1.49	1.38	1.30	0.68
717	34.25	8.25	0.68	0.73	0.93	1.11	1.56	1.57	1.76	1.78	1.53	1.40	1.31	0.75
718	34.75	8.25	1.20	1.27	1.41	1.41	1.93	1.77	1.65	1.69	1.75	1.61	1.22	1.02
688	33.75	8.75	0.75	0.84	1.07	1.22	1.67	1.58	1.64	1.64	1.50	1.41	1.20	0.75
689	34.25	8.75	0.96	1.10	1.33	1.42	1.92	1.69	1.56	1.54	1.57	1.41	1.13	0.89
657	33.75	9.25	0.23	0.33	0.51	0.74	1.16	1.33	1.31	1.35	1.24	1.44	0.66	0.24
658	34.25	9.25	0.40	0.58	0.74	0.90	1.29	1.35	1.21	1.22	1.30	1.21	0.65	0.37
%age of basin Precipitation			25.5	21.9	22.5	22.3	26.8	26.8	27.0	26.9	26.4	25.3	25.2	23.0
minimum			0.2	0.3	0.5	0.7	1.0	1.1	1.2	1.1	1.2	1.1	0.6	0.2
maximum			5.1	3.9	2.9	2.2	2.5	2.5	2.1	2.3	2.4	2.3	3.0	4.1

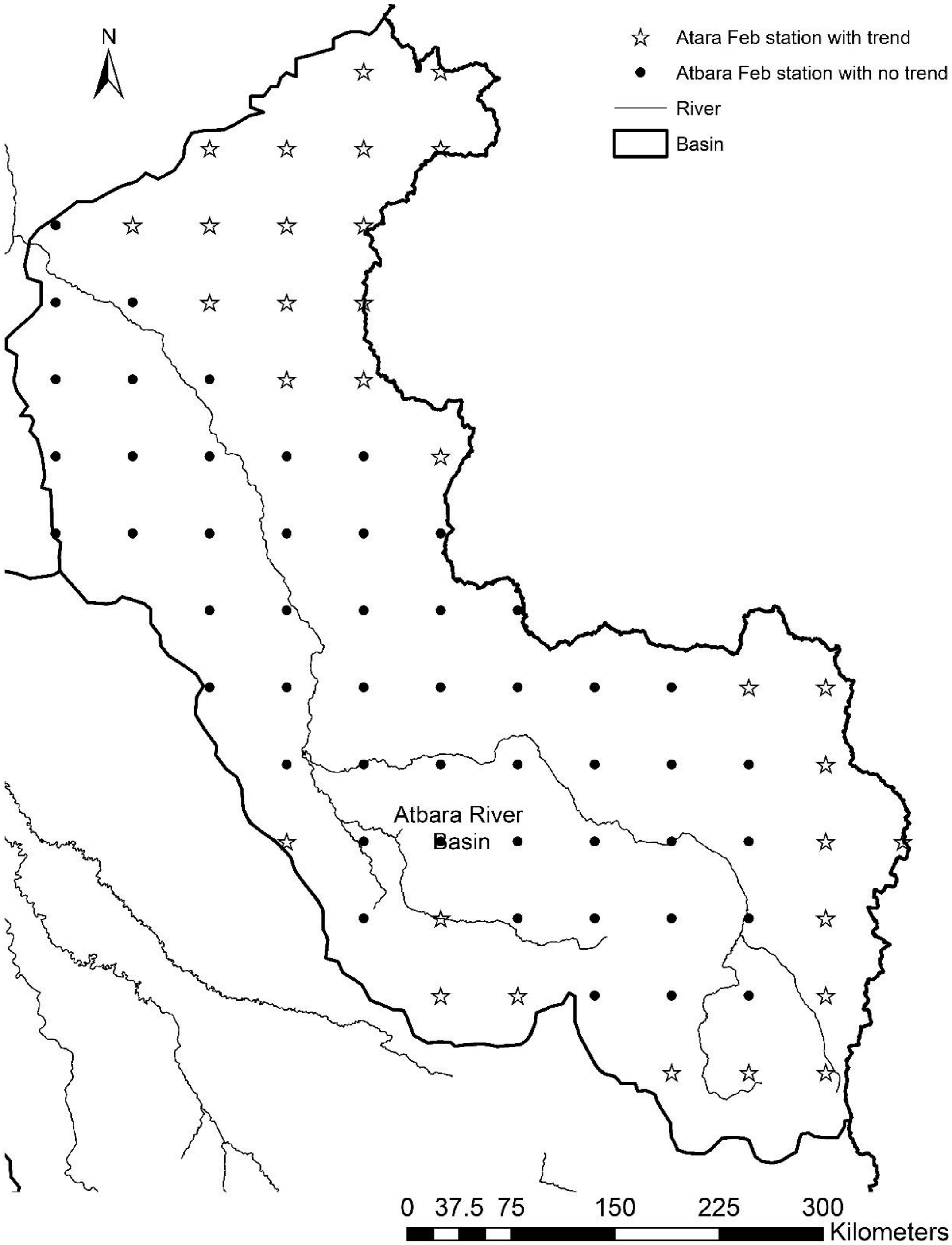

Figure 8-3 Atbara basin stations with and without trend on February.

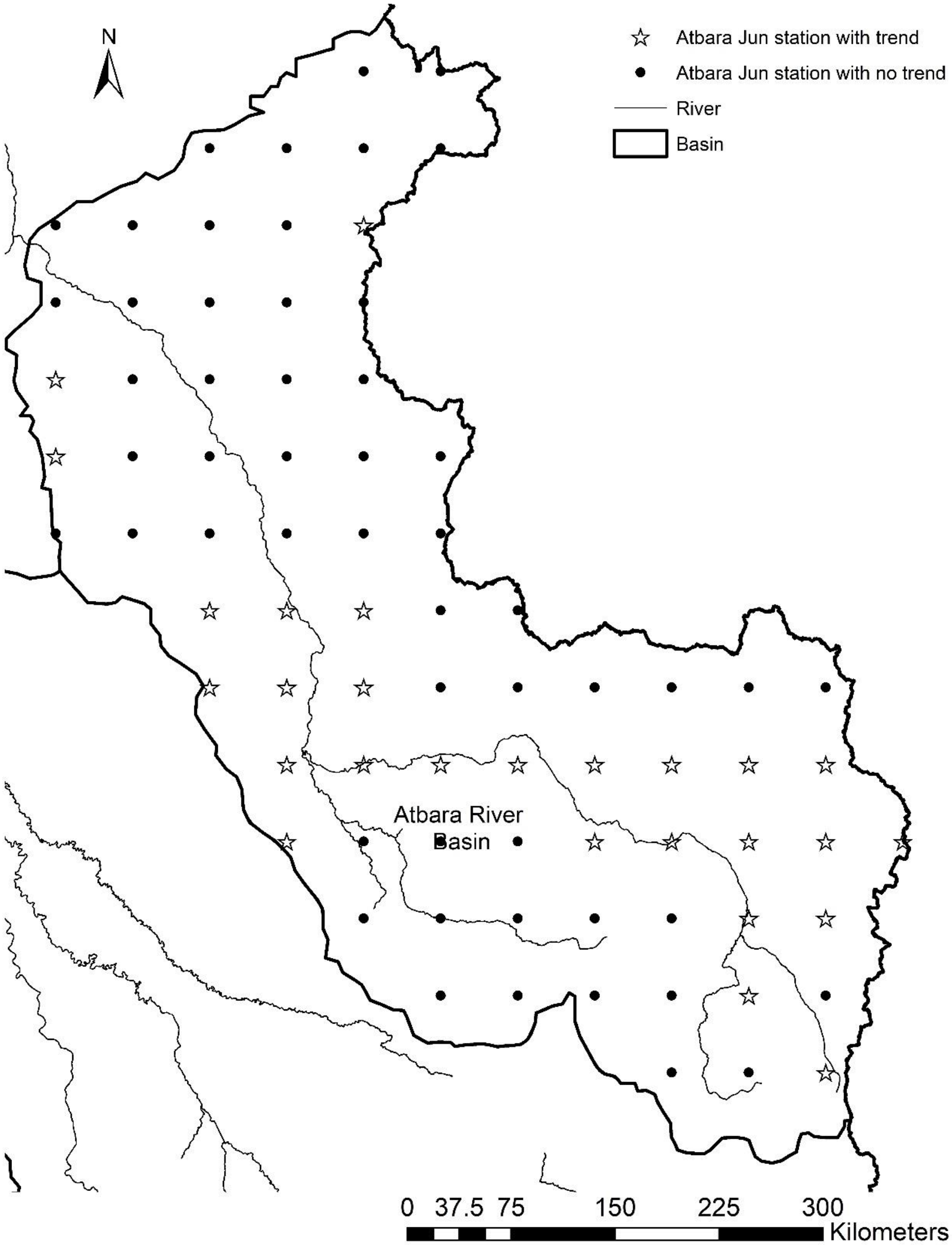

Figure 8-4 Atbara basin stations with and without trend on June.

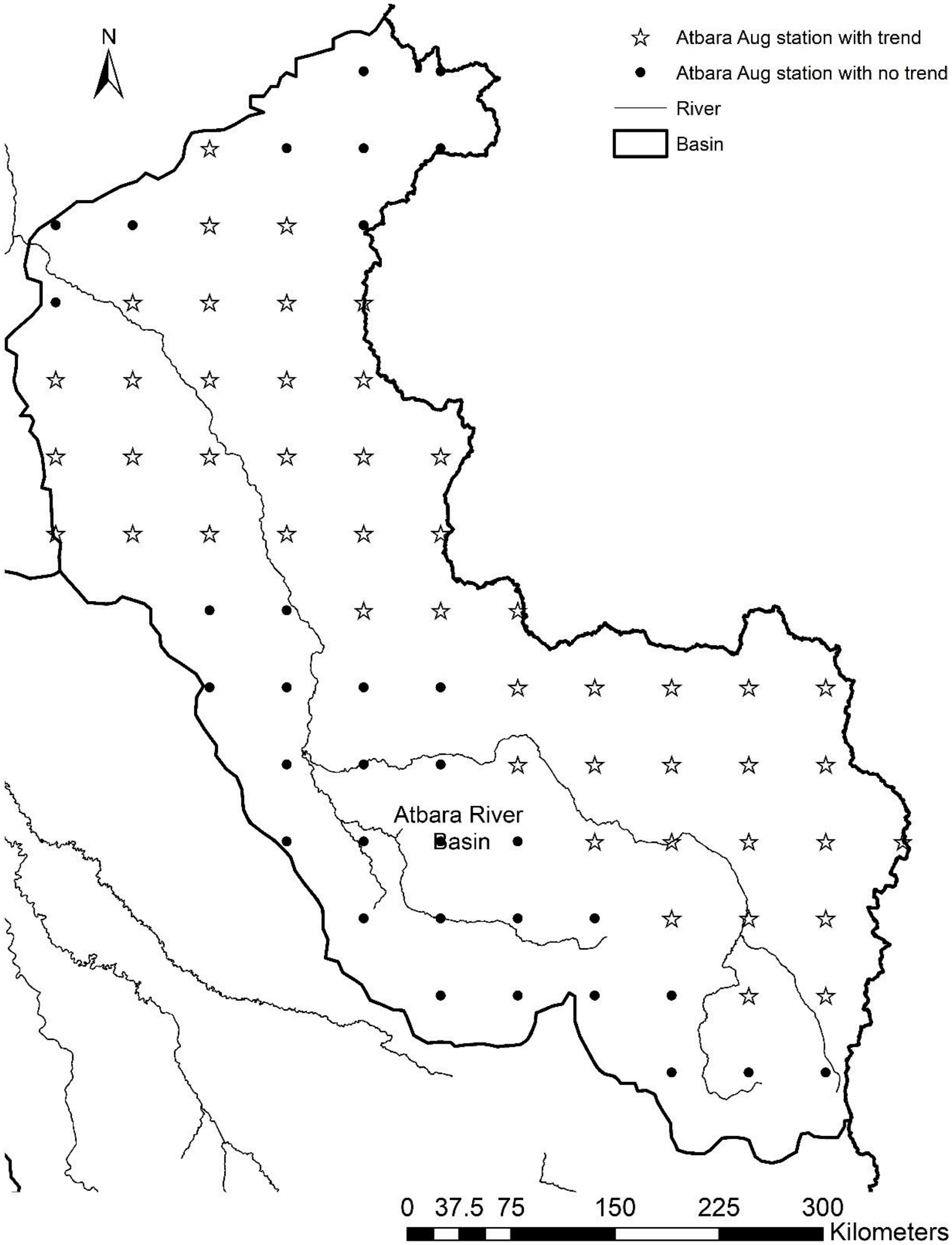

Figure 8-5 Atbara basin stations with and without trend on August.

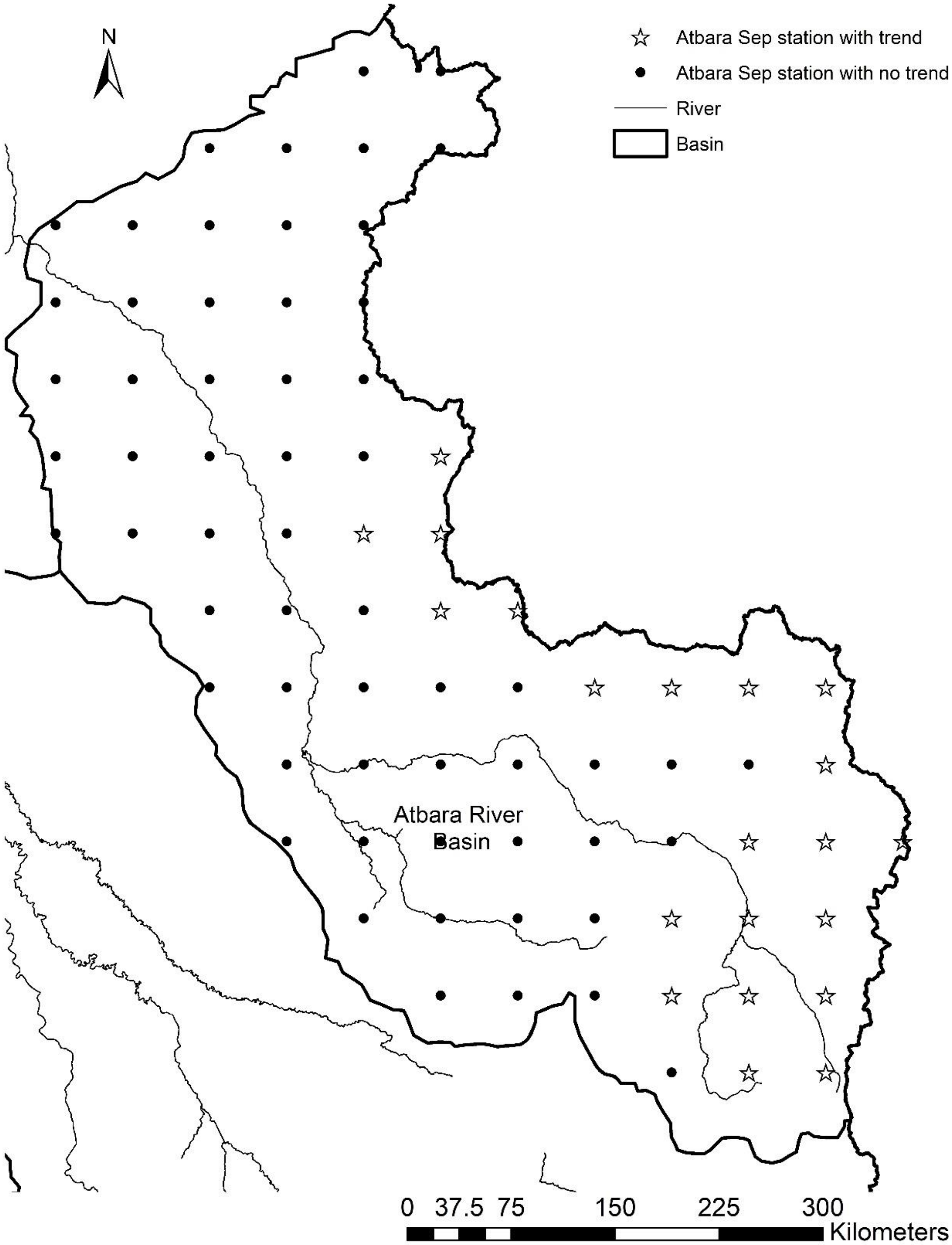

Figure 8-6 Atbara basin stations with and without trend on September.

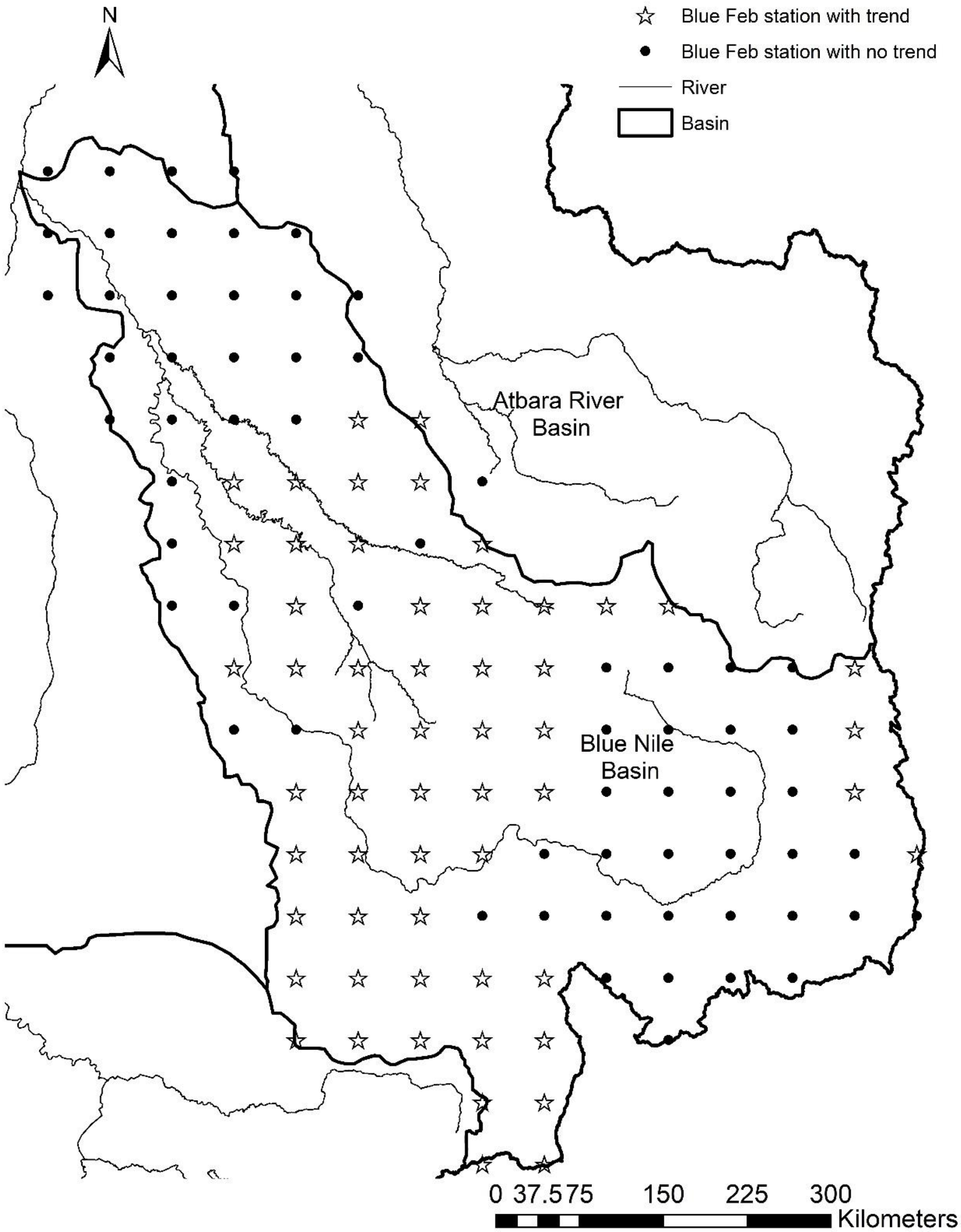

Figure 8-7 Blue Nile basin stations with and without trend on February.

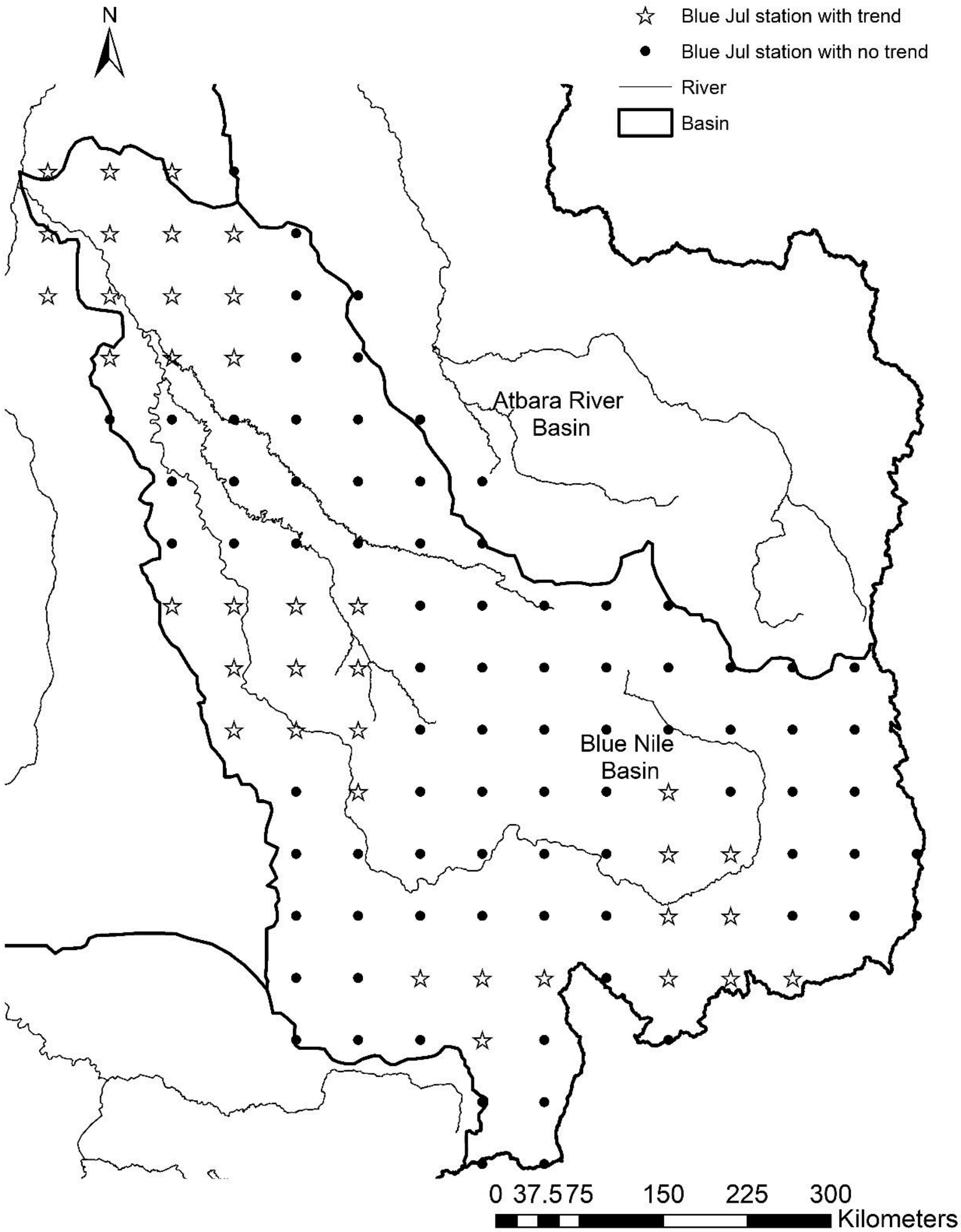

Figure 8-8 Blue Nile basin stations with and without trend on July.

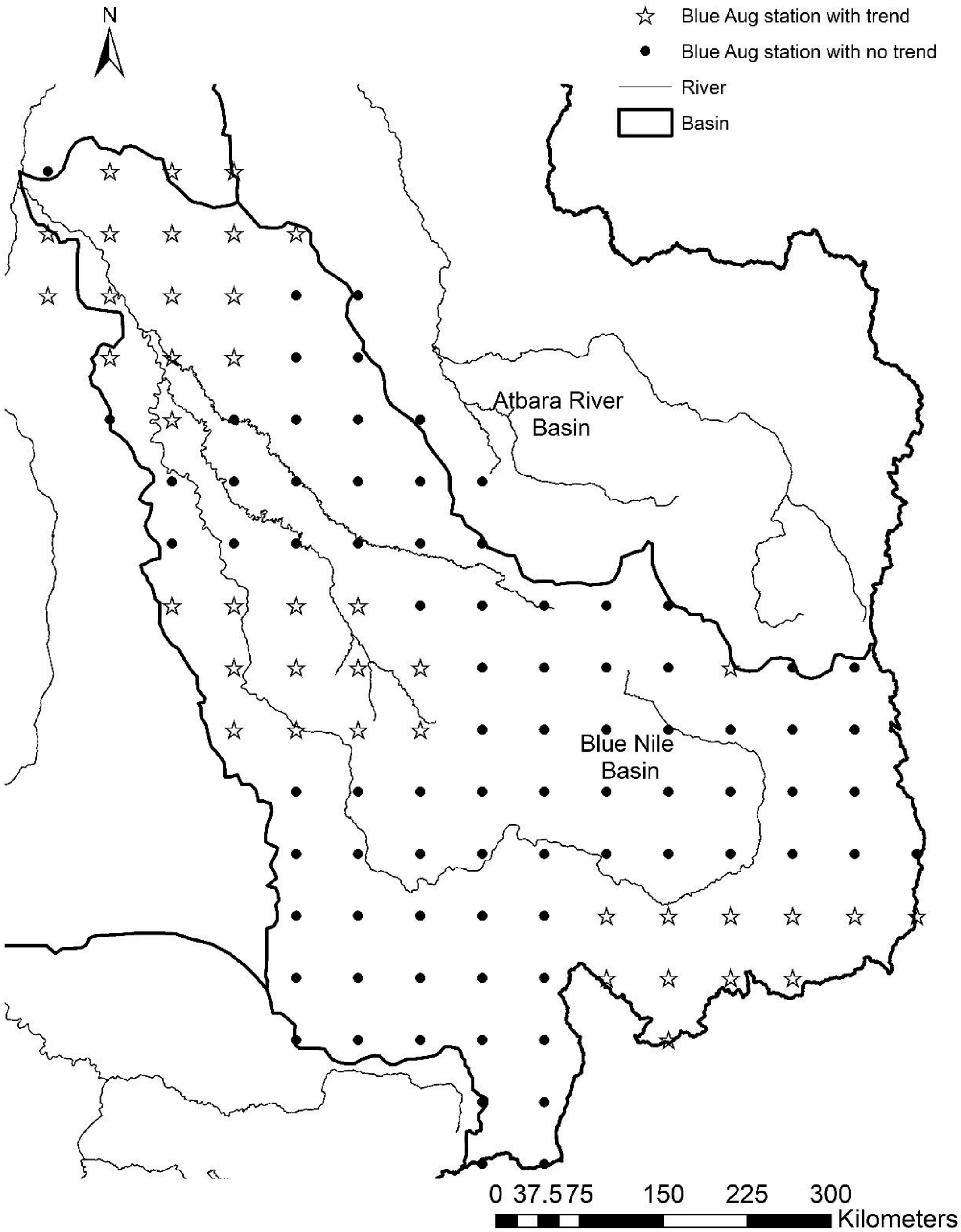

Figure 8-9 Blue Nile basin stations with and without trend on August.

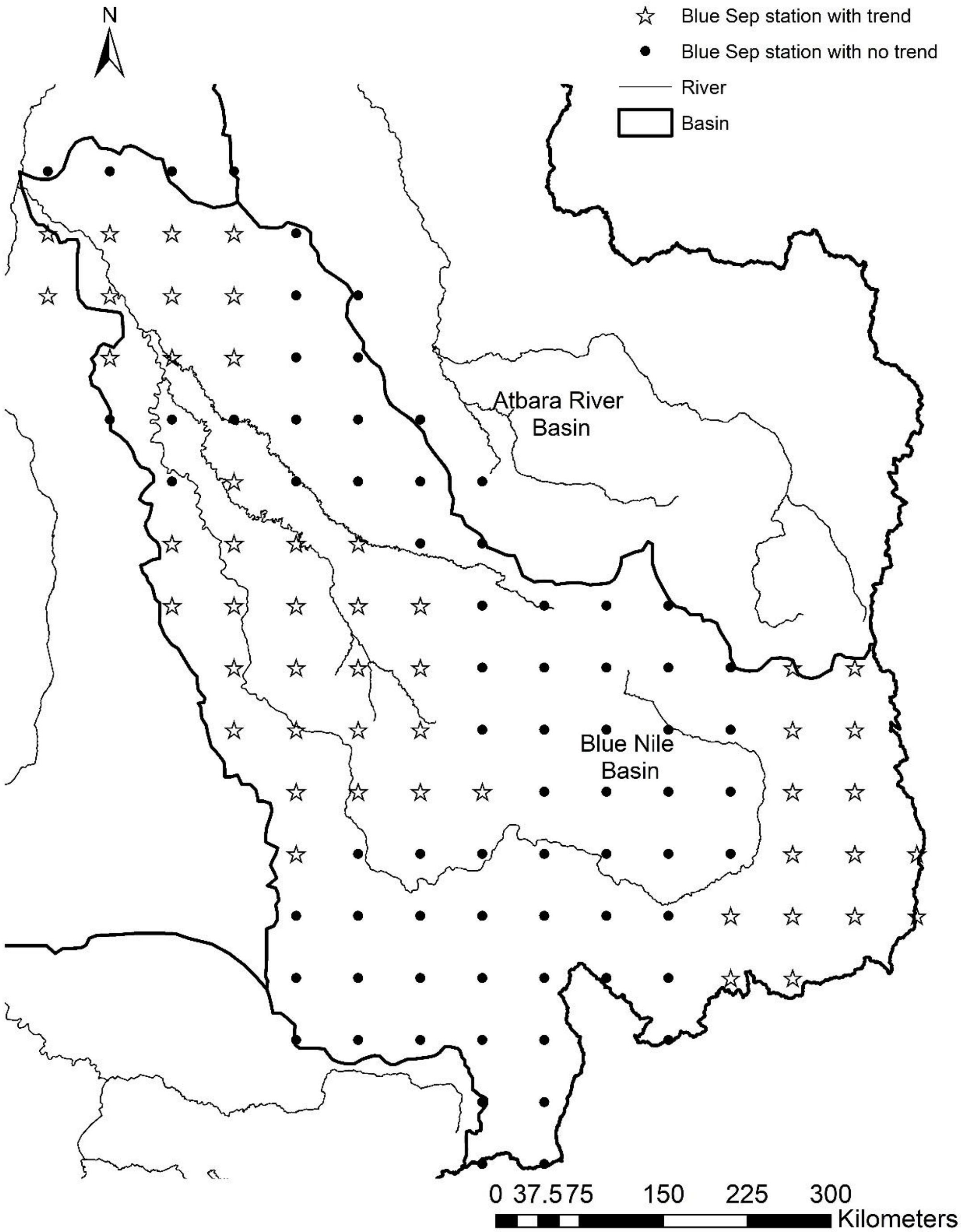

Figure 8-10 Blue Nile basin stations with and without trend on September.

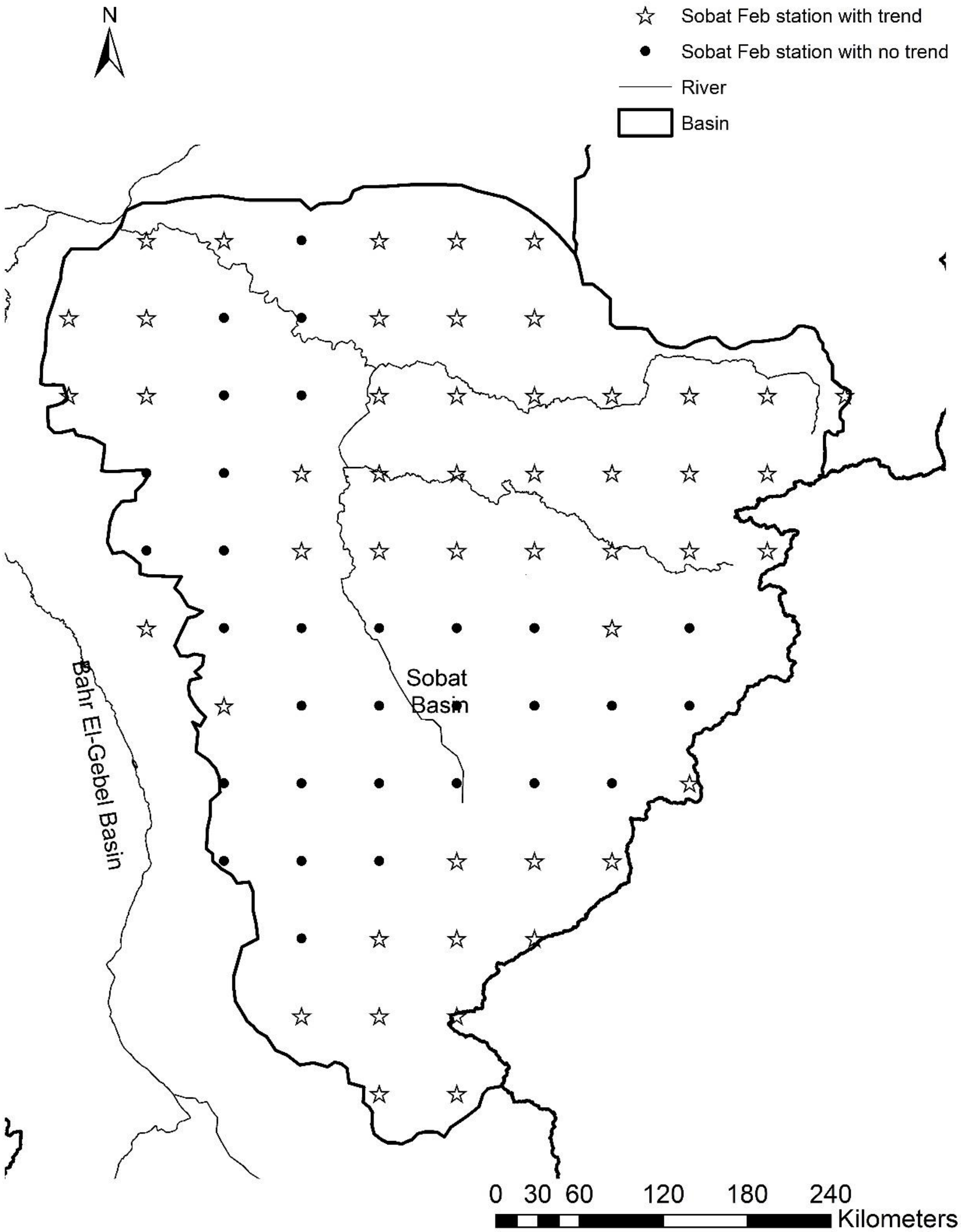

Figure 8-11 Sobat basin stations with and without trend on February.

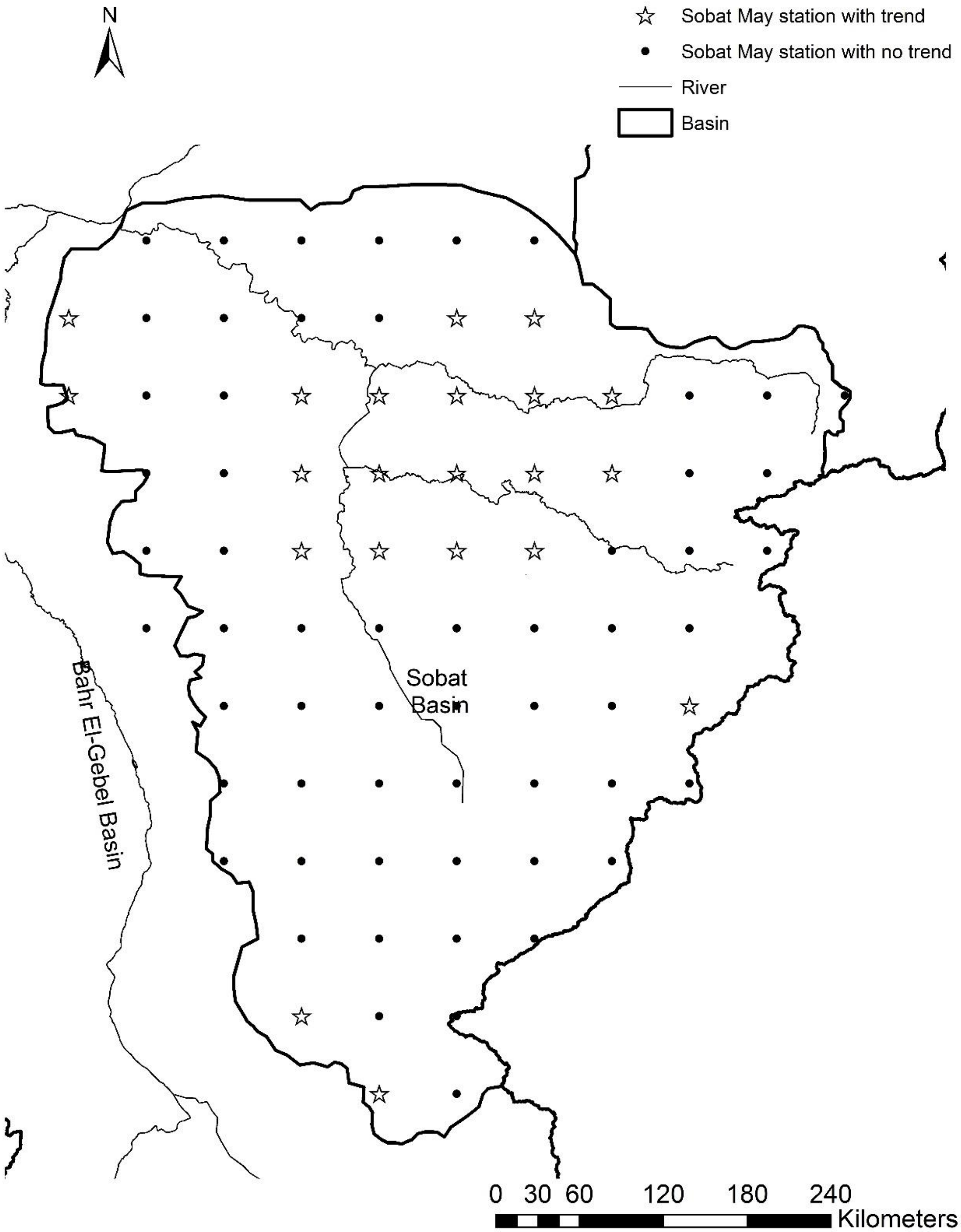

Figure 8-12 Sobat basin stations with and without trend on May.

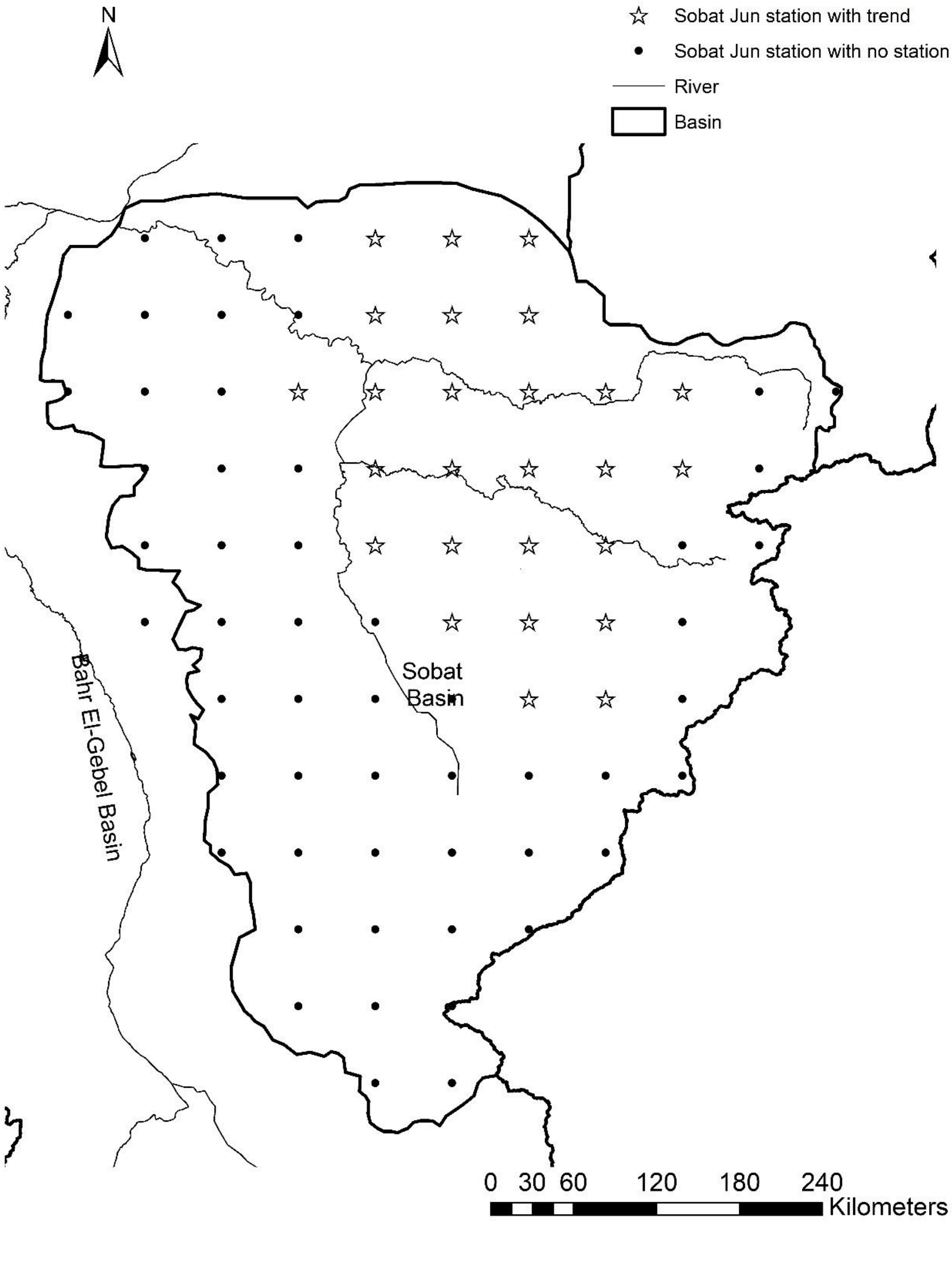

Figure 8-13 Sobat basin stations with and without trend on June.

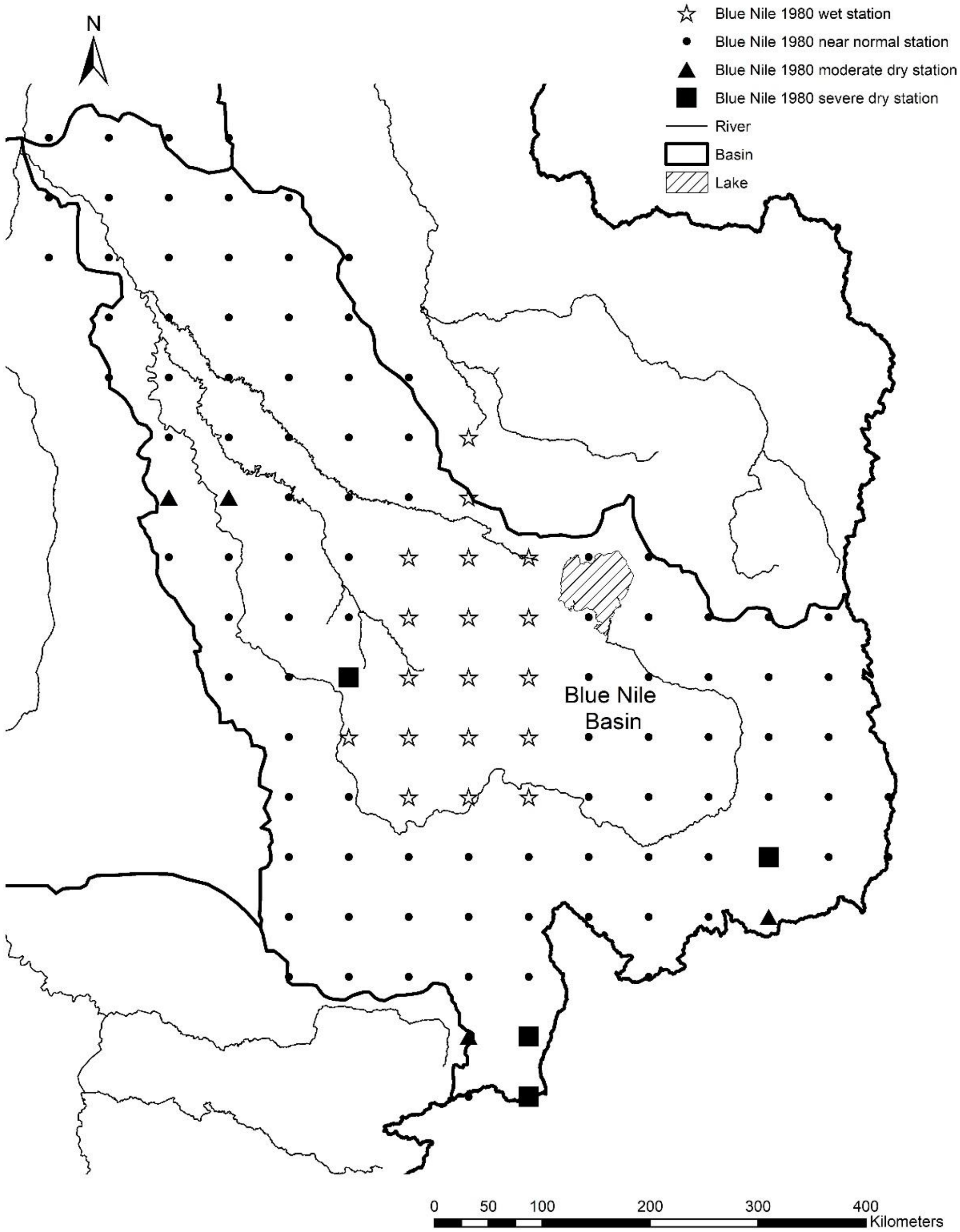

Figure 8-14 Blue Nile basin near normal year stations distribution.

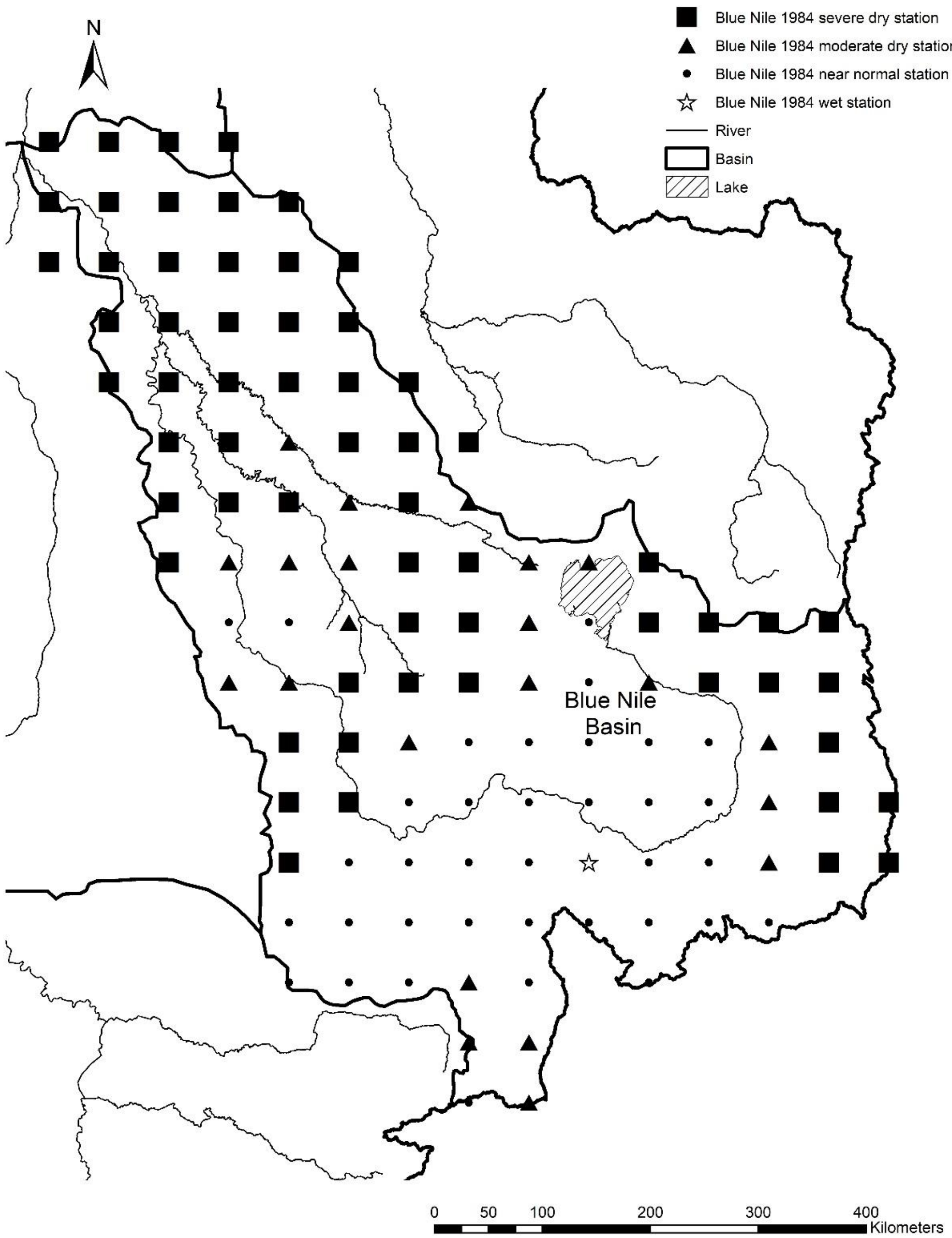

Figure 8-15 Blue Nile basin severe dry year stations distribution.

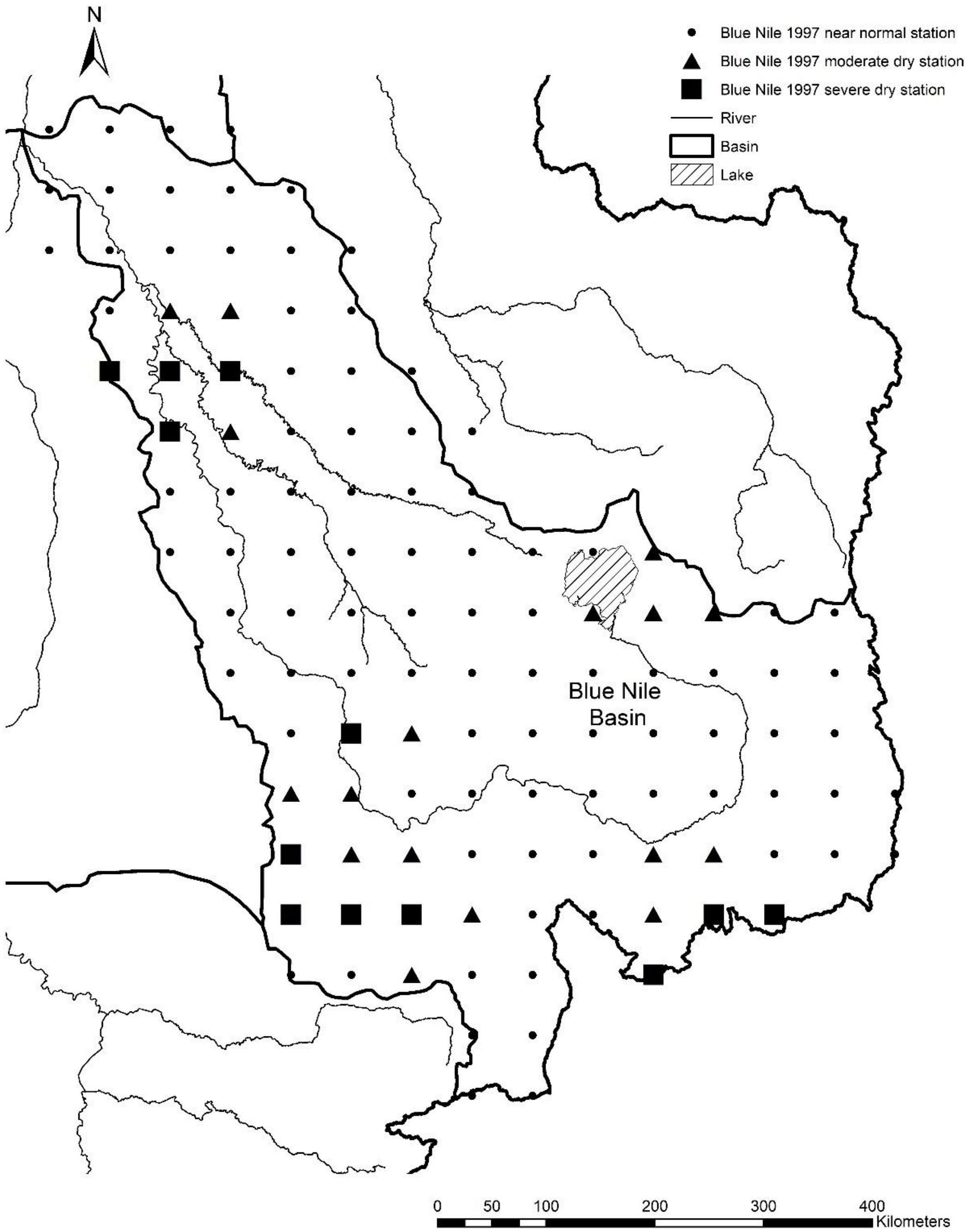

Figure 8-16 Blue Nile basin moderate dry year stations distribution.

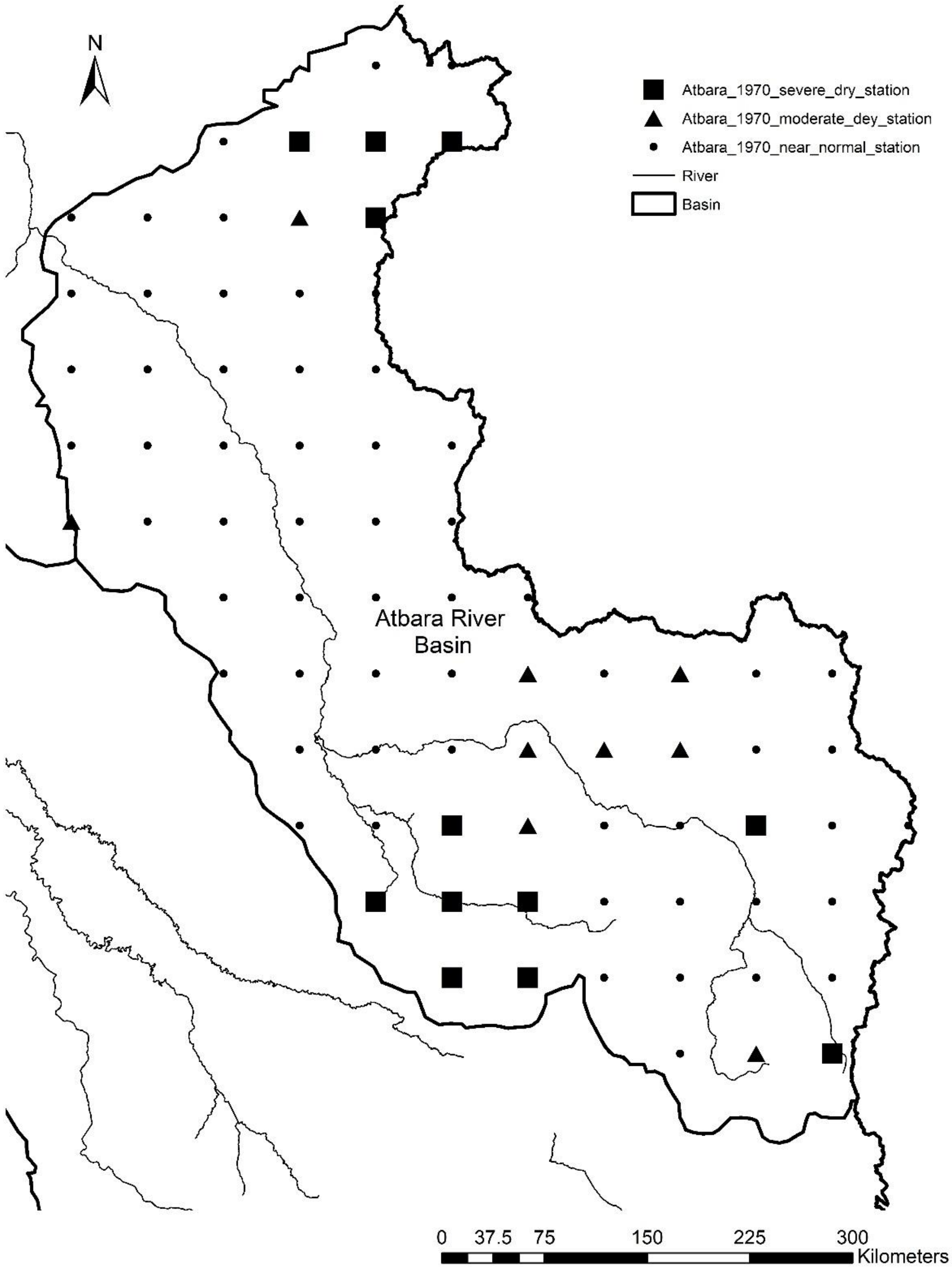

Figure 8-17 Atbarah basin moderate dry year stations distribution.

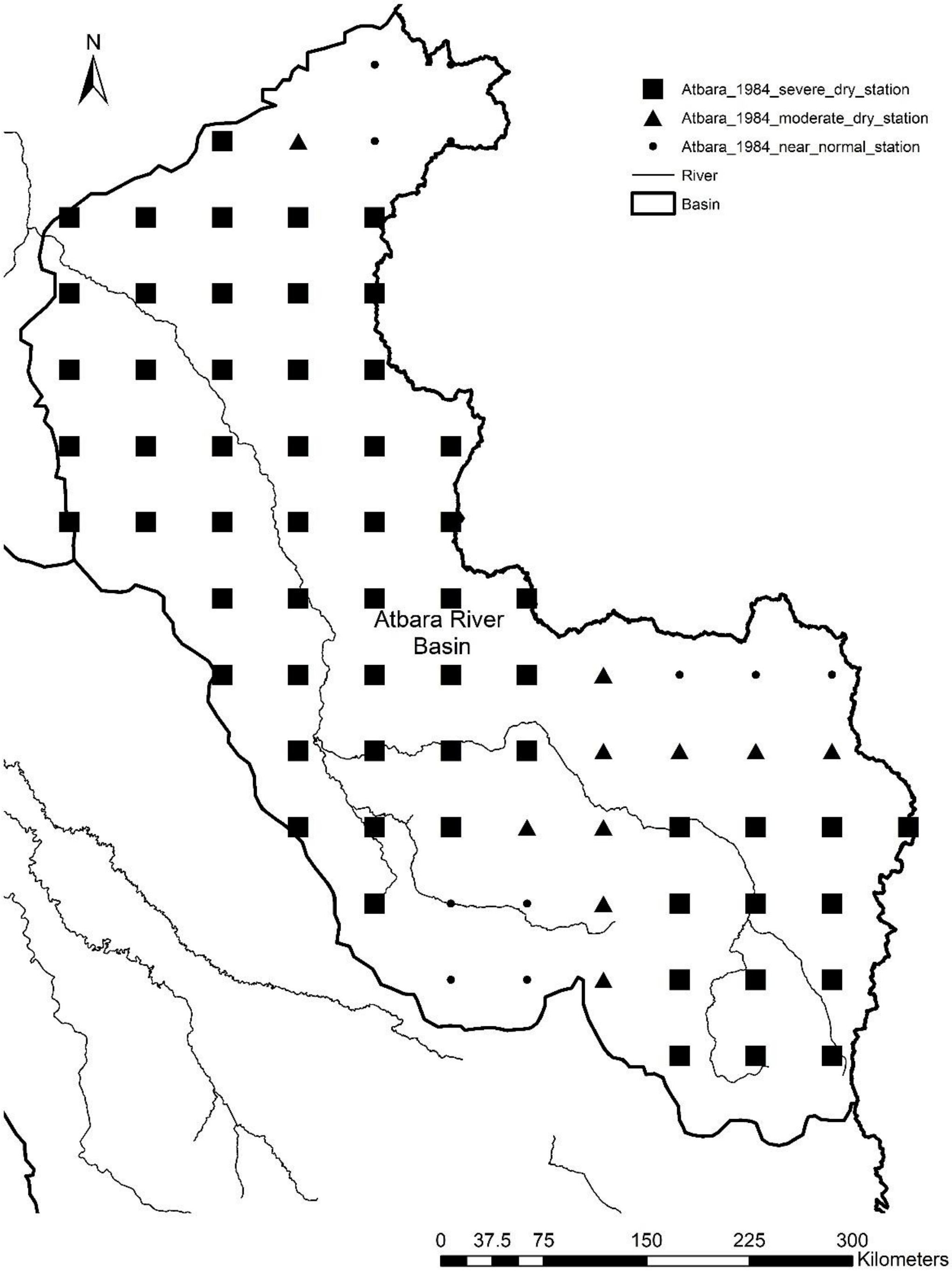

Figure 8-18 Atbarah basin severe dry year stations distribution.

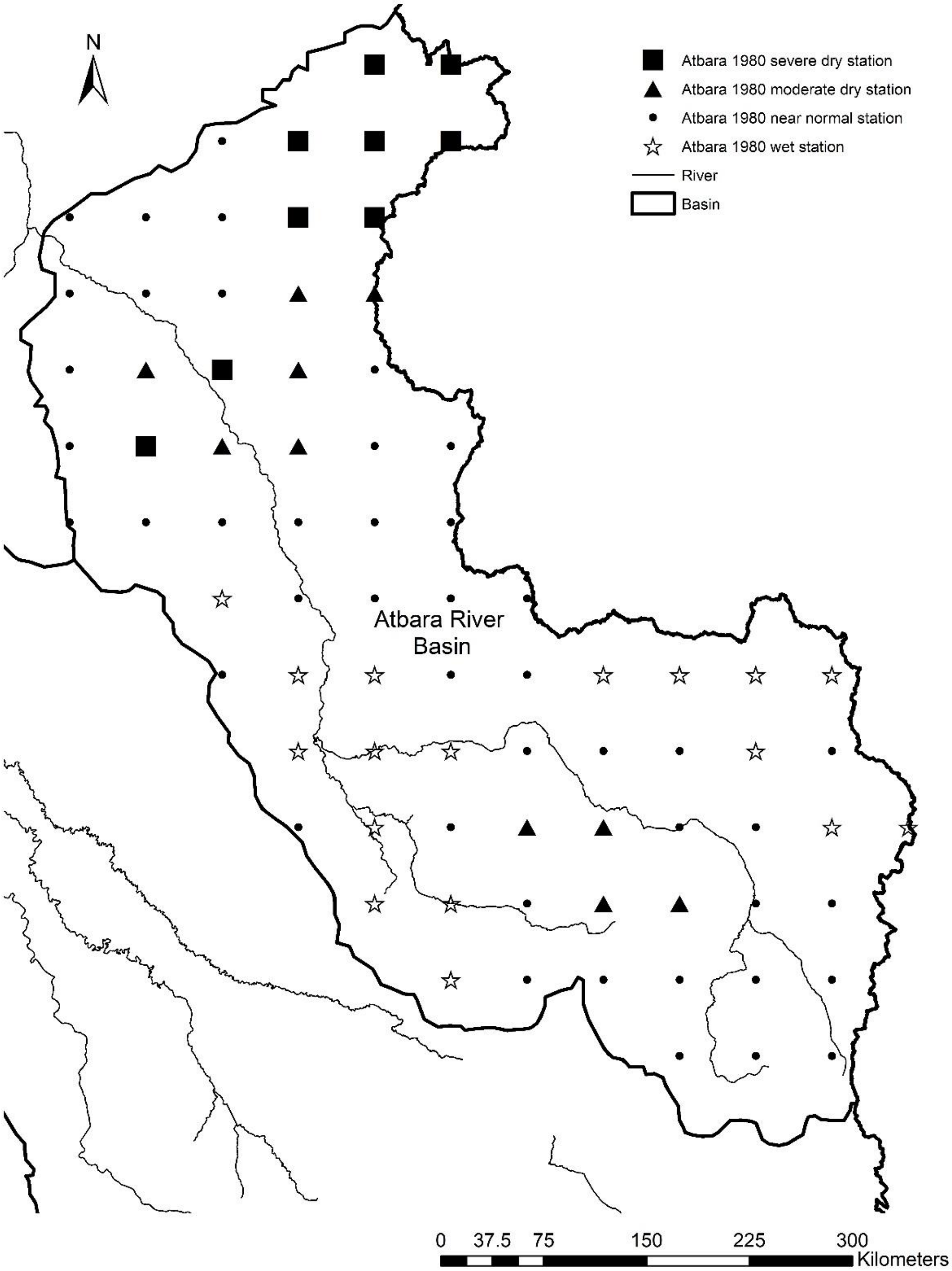

Figure 8-19 Atbarah basin near normal year stations distribution.

Figure 8-20 Sobat basin near normal year stations distribution.

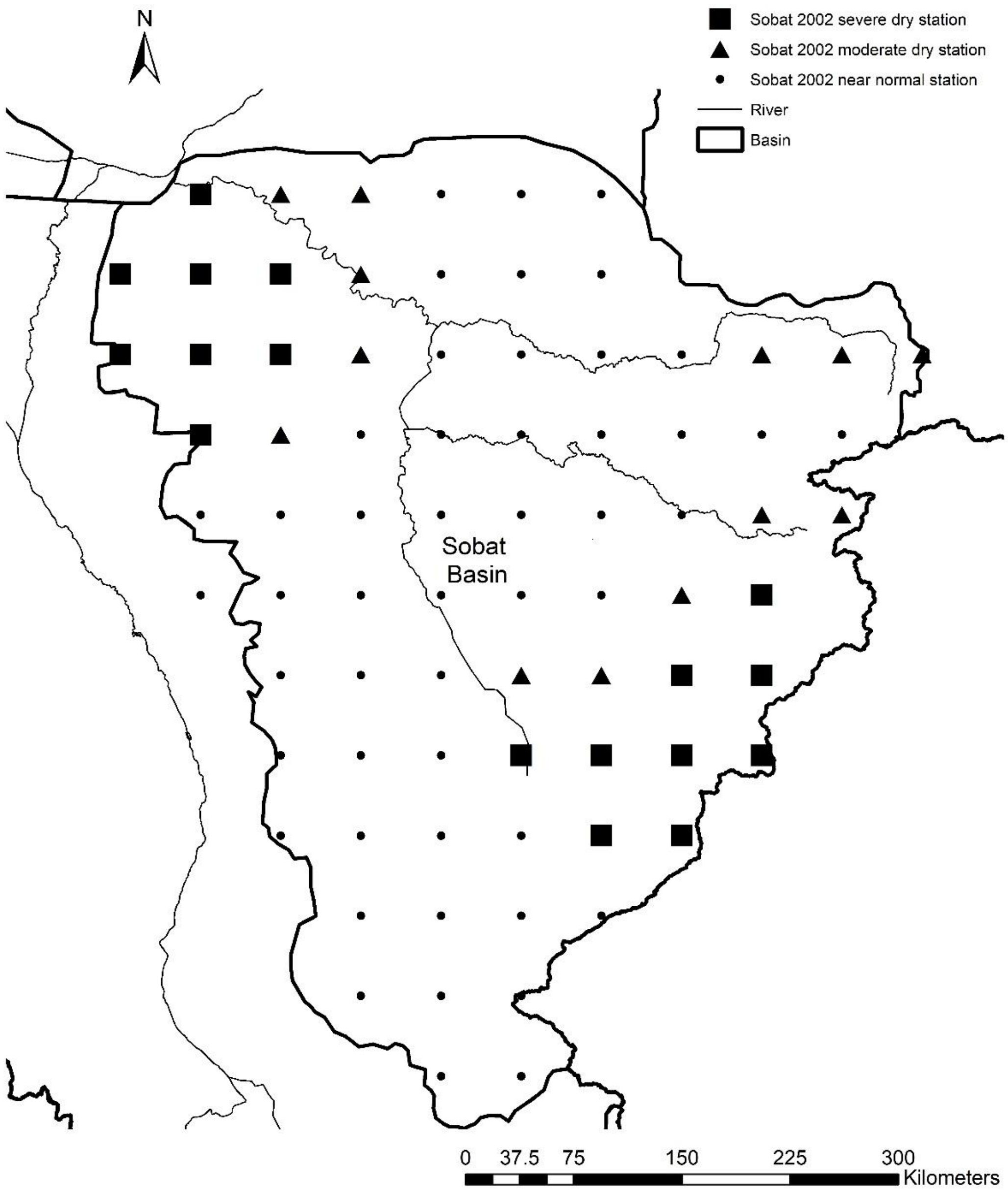

Figure 8-21 Sobat basin moderate dry year stations distribution.

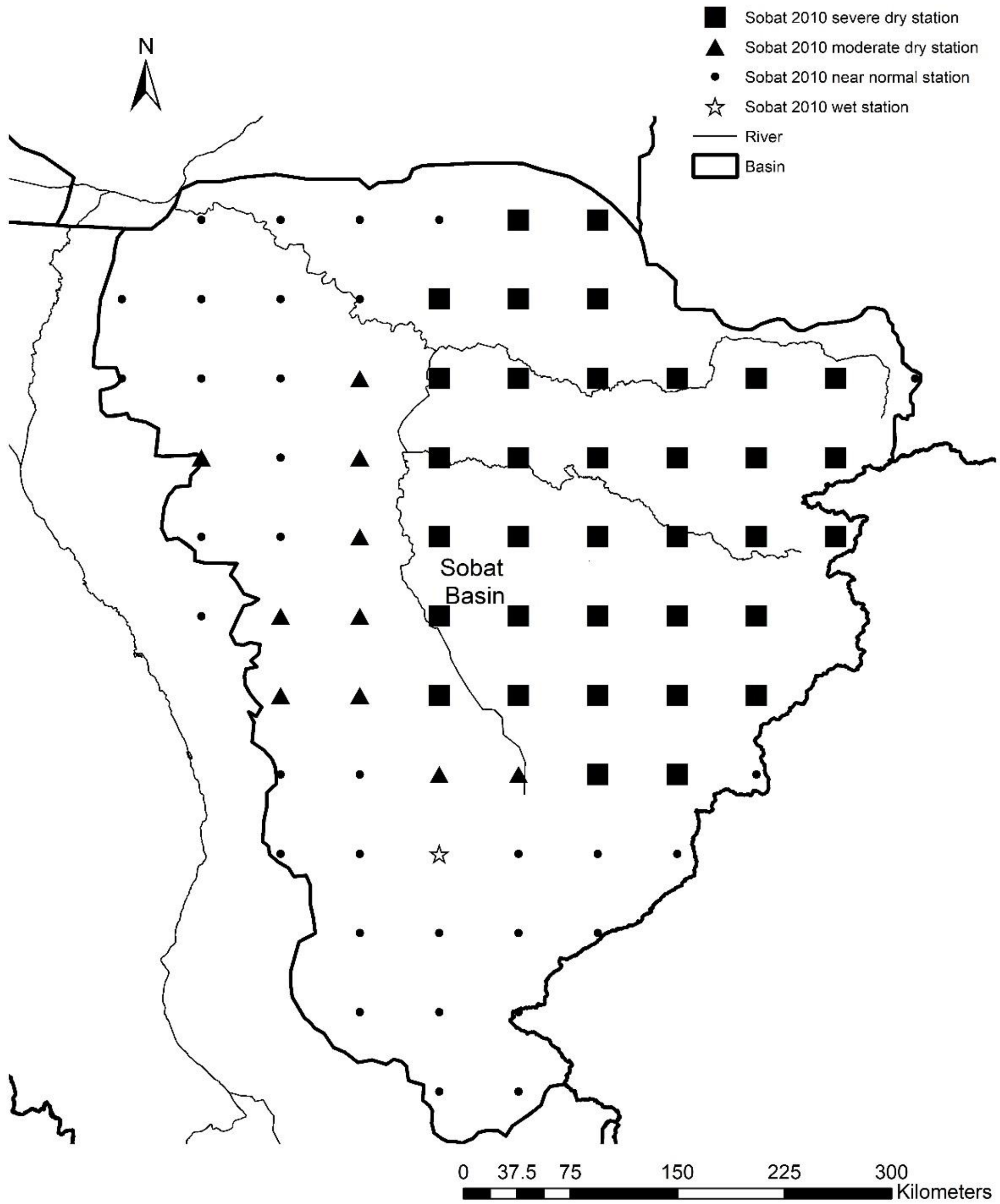

Figure 8-22 Sobat basin severe dry year stations distribution.

Table 8-4 Anomaly of the annual mean discharge for the altered period to the long-term annual discharge for the unaltered discharge at Tamaniat

Water Year	Discharge (m^3/sec)	Discharge volume (Bm^3)	% of long-term mean annual discharge volume (1911-1925)	Water Year	Discharge (m^3/sec)	Discharge volume (Bm^3)	% of long-term mean annual discharge volume (1911-1925)
1933	2455.68	77.4	100.18	1973	1960.74	61.8	79.99
1934	2613.3	82.37	106.61	1974	2278.27	71.81	92.95
1935	2863.44	90.25	116.81	1975	2534.11	79.87	103.38
1936	2546.3	80.26	103.88	1976	2156.43	67.97	87.98
1937	2322.81	73.21	94.76	1977	2205.17	69.5	89.96
1938	2744.27	86.49	111.95	1978	2184.61	68.86	89.13
1939	2147.68	67.69	87.61	1979	1947.79	61.39	79.46
1940	1909.34	60.18	77.89	1980	1933.33	60.94	78.88
1941	1959.6	61.76	79.94	1981	2028.51	63.94	82.76
1942	2328.14	73.38	94.98	1982	1583.82	49.92	64.61
1943	2105.03	66.35	85.88	1983	1756.67	55.37	71.67
1944	1982.82	62.49	80.88	1984	1375.18	43.34	56.1
1945	2247.81	70.85	91.7	1985	2007.95	63.29	81.92
1946	2869.91	90.45	117.07	1986	1549.56	48.84	63.22
1947	2434.74	76.74	99.33	1987	1501.2	47.32	61.25
1948	2582.47	81.4	105.36	1988	2954.82	93.13	120.54
1949	2431.7	76.64	99.2	1989	2070.77	65.27	84.48
1950	2433.98	76.72	99.3	1990	1724.31	54.35	70.35
1951	2057.06	64.83	83.91	1991	1993.1	62.82	81.31
1952	2057.44	64.85	83.94	1992	1914.29	60.33	78.09
1953	2174.33	68.53	88.7	1993	2378.78	74.98	97.05
1954	2744.27	86.49	111.95	1994	2248.95	70.88	91.74
1955	2613.3	82.37	106.61	1995	1663.77	52.44	67.87
1956	2767.5	87.23	112.9	1996	2372.69	74.78	96.79
1957	2162.52	68.16	88.22	1997	2086	65.75	85.1
1958	2485.38	78.336	101.39	1998	2814.71	88.71	114.82
1959	2469.39	77.83	100.74	1999	2822.32	88.95	115.13
1960	2273.32	71.65	92.74	2000	2372.3	74.77	96.78
1961	2721.05	85.76	111	2001	2449.21	77.2	99.92
1962	2482.33	78.24	101.27	2002	1781.8	56.16	72.69
1963	2494.52	78.62	101.76	2003	2076.48	65.45	84.71
1964	3267.77	103	133.32	2004	1820.63	57.38	74.27
1965	2570.66	81.02	104.87	2005	2010.61	63.37	82.02
1966	2249.33	70.9	91.77	2006	2599.22	81.92	106.03
1967	2579.04	81.29	105.22	2007	2938.82	92.63	119.89
1968	2250.85	70.94	91.82	2008	2499.85	78.79	101.98
1969	2197.93	69.28	89.67	2009	1932.57	60.91	78.84
1970	2154.15	67.9	87.89	2010	1990.44	62.73	81.19
1971	2231.44	70.33	91.03	2011	1800.83	56.76	73.47
1972	1661.49	52.37	67.78	2012	2226.87	70.19	90.85