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Abdelazim M. Negm *Editor*

Flash Floods in Egypt

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Flash Floods in Egypt

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Preface

Due to the scarcity of water in Egypt, the national water research plan of Egypt 2017–2037 focuses on using each drop of water including the rainfall water and flash floods water, in addition to the reuse of wastewater to close the gap between the demand and the supply. Springer published several books on the different aspects of water resources in Egypt without sufficient information on flash floods. Therefore, the idea of publishing a book on the flash floods comes to complete the picture of the water resources in Egypt. Why Egypt? Because it is a good example of arid countries located in MENA which are also almost arid regions. Consequently, the lessons learned from this book could be of great benefit for other countries in MENA regions particularly those in north Africa.

This book is divided into 17 chapters, written by more than 25 researchers, scientists, and hydrologist experts from several institutions and more than one country, and have a good experience in the domain of water resources and particularly the topic of flash floods and rainfall. One goal of the book is to assess the flash floods environment, its hazards, risk, harvesting, utilization, and management in Egypt as a typical example of an arid country with water scarcity. The book also highlights some important experiences and successful case studies that reflect the present challenges and their possible solutions.

The 17 chapters are presented in 5 parts in addition to the Introduction and Conclusions chapters. Part II is about Analysis and Design Aspects of the flash floods, while Part III is about the Recent Technologies for Investigating Flash Flood. The Environmental Approaches in Flash Flood are covered in Part IV. Part V discusses the Hazards, Risk, Harvesting, and Utilization of Flash Floods and Part VI is devoted to Prediction and Mitigation of Flash Flood in Egypt. The introduction chapter presents a summary of the technical elements of each chapter, while the conclusions chapter summarizes the most important conclusions and recommendations of the book in addition to presenting an update of the literature on flash floods.

The editor wants to introduce his great thanks to all who contributed in one way or another to make this unique, high-quality book a real source of knowledge and latest findings in the field of flash floods in Egypt. He appreciates too much the contributions of all authors. Without their patience and efforts in writing and revising the different versions of the manuscripts to satisfy the high-quality standards of Springer, it would not have been possible to produce this high-quality book. Many thanks are also owed to the editors of the series and his team for constructive comments, advice, and critical reviews. Acknowledgments must be extended to include all members of the Springer team who have worked long and hard to produce this book and make it a reality for the researchers, graduate students, and scientists in Egypt and worldwide, particularly the countries with similar aridity conditions.

The book editor would be pleased to receive any comments to improve future editions. Comments, feedback, suggestions for improvement, or new chapters for the next editions are welcomed and should be sent directly to the volume editor. The emails of the editor can be found inside the book in several chapters.

Zagazig, Egypt
November 2019

Abdelazim M. Negm

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Introduction

Introduction to "Flash Floods in Egypt"

Abdelazim M. Negm and El-Sayed E. Omran

Abstract

This chapter highlights the hydrogeological technical elements contained in the 17 chapters presented in the book according to its five themes. Therefore, this chapter contains information on analysis: extreme rainfall analysis and critical design aspects of flash floods, recent technologies for investigating flash flood, environmental approaches in flash flood, hazards, risk and utilization of flash floods, and prediction and mitigation of flash flood.

Keywords

Egypt • Sinai • Aswan • Extreme rainfall • Statistical analysis • Design aspects • Risk analysis • Hazard • Prediction • Harvesting • Early warning system • Monitoring • Environment • Assessment • Mitigation • Management

1 Background

Egypt which is located in the north of Africa is an arid country. Its water demand is now more than 100 billion cubic meters per year and about 50% of this demand is fulfilled form the Nile River waters. With the rapid growth of population, agricultural expansion, among other activities, the water demand increased. Egypt is planning to reuse the agriculture drainage water and the treated wastewater, and to harvest the flash floods from everywhere in Egypt as well. The book could thus greatly assist decision-makers in maximizing storing and using water from the harvest flash floods. From our results, climate change seems to affect patterns of rainfall. Therefore, Egypt received a different rainfall pattern for the last few years. One of these observations is recognized in the Aswan governorate in October 2019. It is documented in this book to help the concerned authorities to harvest, manage, and ultimately utilize the harvested heavy rains for the benefits of the communities in Aswan. The presented materials in the book are useful for different arid countries in the MENA regions as well. This book could be considered a follower to the previously published books by Springer on the water resources and agriculture in Egypt, Negm (2019a, b).

2 Themes of the Book

Therefore, the book intends to address the following main theme.

- Analysis and Design Aspects
- Recent Technologies For Investigating Flash Flood
- Environmental Approaches In Flash Flood
- Hazards, Risk, Harvesting, and Utilization of Flash Floods
- Prediction, Mitigation, and Management of Flash Flood.

3 Chapters' Summary

The next subsections present the main technical elements of each chapter under its relevant theme briefly.

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3.1 Analysis and Design Aspects

This theme is covered in three chapters. Chapter one deals with the analysis of extreme rainfall events and the critical design aspects of flash floods with examples from Egypt and Oman.

Chapter 2 is titled "Statistical Behavior of Rainfall in Egypt." In this chapter, the statistical characteristics of extreme rainfall in Egypt have been investigated based on historical daily rainfall records for 30 stations throughout the country. Six types of rainfall data from daily records have been collected: monthly rainfall, annual rainfall, the monthly number of rainy days, the annual number of rainy days, monthly maximum daily rainfall, and annual maximum daily rainfall. Generally, there is a great variation in all different aspects of the rainfall across the country. The rainfall indices have higher values in the north of the country than those in the middle and the south. The results indicate that Egypt's rainy season extends from October to March when a significant amount of precipitation is received by some stations. The dry season, on the other hand, extends from April to September. Furthermore, this research seeks to derive the design rainfalls through the GEV distribution along with the L-moments using annual maximum daily rainfalls in these stations. In the case study, the GEV distribution fits well with the annual maximum daily rainfall data. Although all stations not located on the north have low values of rainfall characteristics, some locations (e.g., Hurghada) have high values of design extreme rainfall. Therefore, further studies are required about the study of extreme rainfall at these sites.

Following this, Chap. 3 is concerned with the "Critical Analysis and Design Aspects of Flash Flood in Arid Regions: Cases from Egypt and Oman." It presents a brief review of flood definitions in general and in particular, flash floods. Also, two main case studies related to flash floods are presented in this chapter. The two main case studies from the Arab Republic of Egypt and Sultanate of Oman are investigated. Extreme events caused by cyclonic and convective storms are covered by the cases discussed. The presented cases caused damages to the properties and fatalities. For each case, detailed hydrological and hydraulic analyses carried out and the results are presented. Hydrological and hydraulic analyses are used to study the considered two cases to evaluate the effect of each case and compare it to the regular flood events (if any). Meanwhile, this chapter casts light on the difference between the effect of thunderstorms and cyclones on the corresponding peak flow and flood volume. It showed that cyclonic events were accompanied by a very high value of rain depth, which may be corresponding to thousands of years on the frequency distribution curves. These events of precipitation have created huge volumes of water which fill all dams and run the spillways to near maximum design flow values. The distribution of storms over 24 h, however, was almost uniform, suggesting moderate strength of rainfall.

3.2 Recent Technologies for Investigating Flash Flood

Chapters 4 and 5 cover this theme. Chapter 4 is titled "Developing an Early Warning System for Flash flood in Egypt: Case Study Sinai Peninsula." It explains how to develop an early warning system for flash floods in Sinai Peninsula. An early warning system is essential as flash floods can occur anywhere. When it comes to arid and mountain catchments where catastrophic events are more prevalent than wet and flat areas, it becomes more critical. Egypt can be considered one of the arid and semi-arid Arab countries in the coastal and Nile Wadi systems facing flash floods. In Egypt, particularly in the Eastern Desert, Red Sea Mountains, and Sinai, flash floods are occurring widely.

The Sinai Peninsula can be considered as the most important Egyptian areas common and subject to synoptic circumstances causing heavy rainfall due to its natural geography and context complex, causing severe damage due to flash flooding. This makes the study and analysis of the flash flood on the Sinai Peninsula a crucial and significant job. Because of the above-mentioned challenges, the latest numerical mesoscale meteorological model named the Weather Research and Forecasting (WRF-ARW) is selected to forecast rainfall and simulate the synoptic situation related to some flash flood events over Egypt. Mainly the US National Centre develops WRF for Atmospheric Research (NCAR) in collaboration with many other research centers and universities. WRF allows forecasting weather in complex terrains such as the one in Sinai and at the same time is considered for its orographic features' characteristics.

Also, flash floods occur along the Red Sea, where a series of mountains are there. Chapter 5 is presented to discuss "Flash Flood Investigations in Northern Red Sea Governorate Case El-Gouna." Understanding the flooding and its effects on human life and ecosystem requires fundamental analysis of the boundary conditions that geography, geology, atmosphere, and hydrology usually provide for the proper modeling of the flooding event for forecasting. In this chapter, all of these aspects were systematically analyzed and findings were introduced in a hydrological flow model. A morphological analysis of slopes in correspondence to the geological setting of the catchment of Wadi Bili is presented and the results of all analyses are discussed.

3.3 Environmental Approaches in Flash Flood

Chapters 6–9 address the environmental solution to flash floods. Chapter 6 is titled “Environmental Flash Flood Management in Egypt.” It is well know that flash floods have an adverse impact on human health and ecosystems. This may be extended to cause damage to infrastructure, livestock, and plants. Floodwater can cause a number of significant health effects, including deaths and/or injuries, contamination of drinking water, loss of electricity, disruption of the environment, and displacement among other effects. Therefore, this chapter will present the Egyptian national environmental action plan to face the natural environmental hazards (earthquakes–flash floods–dust and sand storm). Moreover, it will highlight the environmental and disaster risk reduction in Egypt and Arab Countries, and present the tools for implementing disaster risk reduction in environmentally hazardous zones.

The Egyptian experience with the floods has shown that much is remaining to be done to improve the use of water resources and protect our infrastructure that crosses dangerous areas. However, there are major challenges in the region, such as lack of continuous data for both flow and precipitation; lack of real-time data transmission; soil erosion problems in mountain areas; maximization of flood uses rather than flood risk management; the absence of a flash flood early warning system; the absence of a disaster risk management plan; little interest in the users of the flood; and the availability of a model to describe the hydrological conditions of the Arab region.

Due to the environmental problems of the flash flood, harvesting and management are essential. Chapter 7 with the title “Flash flood management and harvesting via groundwater recharging in wadi systems: An integrative approach of remote sensing and direct current resistivity techniques” aims to discuss how to (i) mitigate the flashflood hazards and assess the water resources in wadi systems using an integrative approach of remote sensing (RS), geomorphological, and geophysical data. The chapter addressed two case studies in two Egyptian wadis in which we use an innovative integrative approach to flash flood research and management. In workflow design, the chapter introduces a suggested strategy using the surface geological data and geophysical measurements. To reduce the uncertainty of geophysical data inversion, the conventional and non-conventional inversion algorithms are applied. Based on geophysical data inversion results, this chapter shows that it is possible to recognize sites for successful dam construction and groundwater bearing zones exploration. From the hydrogeological point of view, RS and GIS are used to estimate a hydrograph and runoff modeling for wadi systems. Accordingly, the calculated flashflood total discharges and the storage capacity can be recognized. Finally, the chapter provides some solution for scare water management, via locating potential areas suitable for surface water harvesting to promote the percolation of trapped water into the alluvium aquifers.

Harvesting and management of flash floods, and monitoring of needs: Chap. 8 deals with the “Environmental Monitoring and Evaluation of Flash Floods Risks Using Remote Sensing and GIS Techniques.” Therefore, this chapter attempts to synthesize the relevant database in a spatial framework to evolve a flood risk map for some study areas with the application of remote sensing and GIS techniques. The study has also focused on the identification of factors controlling flash floods risks in two study areas in Egypt. Satellite images of the study area have been collected and required field data have been gathered. Depending on the digital elevation model (DEM), this study extracts drainage networks and watersheds using ArcGIS Basins’ watersheds, drainage network, stream order, flow direction, and other basin characteristics. The watershed model was created in the GIS of the first study area, Firan catchment in Sinai. Hydrological characteristics of basins have been identified. Also, the runoff volume of flash floods has been calculated for the second study area Wadi Hashim 2 in the Egyptian Northern coast through the identification of land use from GIS, soil texture, and rainfall from field measurements. The location of the required Dam for flash floods has been proposed. Finally, GIS and remote sensing techniques have proved to be a successful tool for flash flood monitoring and assessment.

Following the above chapter, Chap. 9 discusses the “Sustainable Development of Mega Drainage Basins of the Eastern Desert of Egypt: Halaib-Shalatin as a Case Study Area.” The authors assess the South Eastern Desert of Egypt for the rainfall water harvesting (RWH) capabilities, with the determination of their optimum methods and techniques. Achieving this aim will assist in poverty alleviation, Bedouin and urban allocation, supporting animal husbandry, accelerating agricultural development, improved agricultural and food production for local inhabitants, combating desertification, resolving unemployment problems, and raising individual incomes. Bedouin and natives as the main end-users will be a major target of the project. Innovative ways to improve the capture, storage, and use of rainwater will have their own-bearing on the sustainable and profitable production of dry season vegetable crops in South Eastern Desert. According to the worldwide trends and techniques in RWH, which is applied aggressively in many neighboring countries, Egypt should enter the era of catching every water droplet for domestic and agricultural development. The findings of the current research work could set a good example to be applied both in other parts of the country and around the world. The chapter , therefore, focuses on using effective tools of monitoring and management of natural resources, based on the integration of modern techniques of remote sensing (RS), geographic information systems (GIS), and watershed modeling systems (WMS) to provide a plan for the RWH. Sustainable water supply is vital for the development of communities in arid regions, such as that of the South Eastern Desert of Egypt. The economic importance of the area is enormous, besides the fact that it has long been a target zone for mineral resources excavation and mining. One of the challenges facing this arid area is the limited water resources needed for agricultural, industrial, mining, or domestic uses. Bedouin depends mainly on rainwater, which constitutes the main source feeding their hand-dug wells and fracture springs. Rainwater harvesting (RWH), as a historical and worldwide trend, could fulfill the gap of water scarcity in arid or semi-arid regions. RWH is the accumulation and storage of rainwater for reuse before it reaches the aquifer system (Groundwater). The RWH could be used also for maximizing the recharge possibilities of groundwater. As a non-conventional water resource, RWH could provide water for gardens, livestock, irrigation, mining, cleaning of bathrooms as in the first flush, etc. The collected water is diverted to a deep pit with percolation in many places with similar climatic conditions to refill the groundwater for later use and protection, particularly in accumulations of structurally regulated groundwater. The harvested water could be used as drinking water if the storage is a tank that can be accessed and cleaned when needed. Additionally, the chapter's recommendations will be a good source for the up-to-date databases, which could be used effectively by the decision-makers, researchers, executive authorities, planners, and related governorates.

A second case study titled "Torrents Risk in Aswan Governorate, Egypt" is reported by Prof. El-Sayed Omran, the Dean of the Institute of African Research and Studies and Nile Basin Countries, Aswan University, Aswan, Egypt. In October 2019, Egypt was hit by a flood, which the country has not seen in terms of rising rates for 50 years. Floods started in mid-August on average and then increased in October, with rainfall on the Ethiopian plateau significantly higher than previous rates. Compared to previous years, the water level in Lake Nasser has reached a high level this year, 2019. Torrents and rain helped to raise Lake Nasser's level. This culminated, in the first time employees, were seen in the High Dam terminal (a river port on Lake Nasser, a gateway for passengers and commercial goods between Egypt and Sudan. The construction of the port began in 1964 after the transformation of the Nile River into the construction of the High Dam) the presence of high water in a pavement-side area that has long been totally dry.

Aswan's torrents arise as a result of precipitation on the government's eastern hills, where water flows into a group of valleys west to the Nile. The most prone areas are Wadi al-Sarraj area, Wadi Ajam area, Umm Habbal area, and Wadi Haymour Allaqi area. The streams that flow into Lake Nasser represent the minimum risk of torrents as there are no urban communities. Eastern Nile basins in the area between Edfu and Aswan cities are very risky, particularly in the area of Kom Ombo and east of Aswan city. In May 1979, the flood flow disrupted the railway lines and affected Edfu, Kom Ombo, and Aswan centers. About 300 families have been displaced and the falling of torrential rocks on some parts of the agricultural road and railway lines. Floods were repeated in 1980 and 1987, 2005, 2010, and 2014 (Saber et al. 2017). In 2010, some villages in Aswan city were severely hit by that torrent. About 500 families were evacuated from their houses that were at risk and lost their livestock and harvest, but they were indemnification by the Government through the donation account they have created for the Egyptian flash floods (Al-Momani and Shawaqfah 2013).

3.4 Hazards, Risk, Harvesting, and Utilization of Flash Floods in Sinai and Egypt

On the one hand, Sinai is one of the most vulnerable parts in Egypt, which is subjected to severe flash floods almost every year. On the other hand, Sinai is progressively suffering from an overwhelming water crisis. Flash flood and runoff water could be an answer to this issue. Therefore, this section which consisted of Chaps. 11–14 is devoted to discuss the flash flood issues in Sinai.

Chapter 11 is titled "Egypt's Sinai Desert Cries: Flash Flood Hazard, Vulnerability, and Mitigation." This chapter has three objectives. The first chapter objective is to determine the flood hazard occurrence in the vulnerable areas of Sinai. Remote sensing (RS) and geographic information system (GIS) are utilized to provide improved spatial considerate of basin response to storm rain events and flood monitoring. It is critically essential to precisely predict the occurrence of flash floods in terms of both timing and magnitude.

The second objective is to draw the vulnerability map for several wadis in southern Sinai. Flash floods in Sinai are an inadequately understood feature due to a lack of accurate environmental and hydrological data, which are challenging and expensive to develop and manage in such a region. It is important to understand that risk is determined not only by the climate and weather events, i.e., the hazards but also by the exposure and vulnerability to hazards, which have been induced by human activity. The produced risk map is useful to know the locations that have a high flood risk in order to avoid loss of life and reduce damages to property.

To mitigate flash flood damages and efficiently harvest the highly needed freshwater, the third chapter's objective is to manage and mitigate the flood hazard and minimize their effect. The main watersheds flowing through Sinai are classified into four categories where 4% of watersheds have very high risk, 10% have high risk, 38% have moderate risk, and 48% have moderate to low risk.

Flood risk assessment and flood mapping will help to show which places are most at risk and in what circumstances. After that, governments can take the correct strategy for flood risk reduction or mitigation. Because of the rapidity of flash flood occurrence and its power, flash flood experts recommend the use of early warning systems for reducing vulnerability. Flood risk assessment helps to create flood vulnerable map, and from the historical rainfall data, we can make an early warning system. The early warning system is very important to protect the city by reducing the losses and victims in the region.

However, the Chap. 12 titled "Egypt's Sinai Desert Cries: Utilization of Flash Flood for a Sustainable Water Management" is presented to discuss the utilization strategies of flash floods in Sinai. This is important for Sinai because its flash floods constitute a potential for non-conventional sources of freshwater. However, most floodwater discharges waste as runoff into the Suez Gulf, and if used effectively, this could satisfy some of the water requirements for a variety of uses. The wise use of floodwater to enable the sustainable management of water resources is a significant challenge in these fields. Therefore, the chapter objective is to put the best ways to mitigate and utilize the floods water as a new supply for water harvesting in Sinai.

Different low-cost storage mechanisms for floodwater harvesting were identified to suit the different technical and socio-economic conditions. Firstly, an underground concrete reservoir is one of the most appropriate water harvesting techniques and easily maintained by the Bedouins themselves. Secondly, a Haraba is a low-cost alternative to capture floodwater, often used by Bedouins. Thirdly, one of the potential technically and highly requested by the stakeholders is a low-cost gabions dam with an underground reservoir as the one constructed in Wadi Ghazala.

Low earthen or stone dykes in the Wadi beds (locally known as Oqum) are recognized. They are usually protected by vegetation remains. Masonry dams for the storage of water are also identified.

The total amount of rainfall and flash floods that could be used annually is estimated at around 1.3 billion cubic meters. This quantity can be increased to 1.5 billion cubic meters.

The establishment of the various dams leads to the presence of communities around the areas of these dams to work with agriculture and grazing, as well as to reduce wastage of water, and reduce the speed of the flooding and thereby protect the soil from water erosion. Disasters such as floods disaster in El-Arish (2010) may not return to the floods alone but as a result of the random nature of the establishment of the buildings in the corridors of the floods and without the work of the previous geological study of the area where the various facilities will be installed on them.

Chapter 13 is titled "Flash Flood Risk Assessment in Egypt." It presents an assessment of flash floods in Egypt. The assessment of the flash flood risk in Egypt is classified in this chapter based on three main perspectives.

1. How to deal with the current situation since all catchments are draining toward urban areas, agricultural land, and other assets?

After assessing the causes of some previous incidents, it was clear that the lack of drainage structures (whether due to poor design or flood plain encroachments), and lack of maintenance of existing ones are the main source of these catastrophic incidents. The 100 year return period was selected for the peak discharge calculations, that is subjected to stakeholder decision based on the allocated budget for flood mitigation measures. Due to the large variance of the catchments peak discharge and runoff volume, the box plot technique was employed to eliminate the ranking outlier values.

A map of peak discharge standardized risk classified into five categories (Very High Risk, High Risk, Moderate Risk, Low to Moderate Risk, and Low Risk) is proposed to highlight the reassessment priorities of the flood mitigation measures to control the catchment outlets affecting the exposed human lives, agricultural lands, and any other assets.

2. How to prioritize the rainfall harvesting projects to support in current water stress problem?

A map of runoff volume standardized risk classification is also provided for the same five categories used to assess the peak discharge. The classification based on the runoff volume can guide the designer accounting for rain harvesting projects that would increase the rate of investment return from both flood mitigation and the reduction of freshwater stress.

3. What to do in future planning for unavoidable urban and agricultural expansion?

A two-dimensional HEC-RAS rainfall-runoff model is conducted for Ras-Gharib City by using 30 × 30 DEM files. The DEM files could not capture the effect of the levels of Ras-Gharib El-Sheikh-Fadl road on the flow directions. The DEM file has been updated based on the available road topographical survey data. The flood plain, flow depths, and velocities were obtained, and accordingly, the flood intensity was calculated for all streams affecting Ras-Gharib City. The model was verified versus aerial photos for the 2016 incident. In order to assess the effectiveness of the newly constructed culvert (16 vents, 3 m × 3 m box culvert) with attached two dikes, another updated two-dimensional HEC-RAS rainfall-runoff model has been conducted and the results showed significant improvement in flood intensity values in Ras-Gharib City.

In order to harvest and use the water of flash floods, it is necessary to identify the potential location. Consequently, Chap. 14 comes with the Determination of Potential Sites and Methods for Water Harvesting in the Sinai Peninsula by Application of RS, GIS, and WMS Techniques to handle this issue with application to Wadi Dahab. Wadi Dahab has very high importance in a new development in southeastern Sinai, for its touristic position and promising water resources. RS, WMS, and GIS techniques are modern research tools that proved to be highly effective in mapping, investigation, and modeling the runoff processes and optimization of the RWH. In the present work, these tools were used to determine the potential sites suitable for the RWH in W. Dahab. The performed WSPM for determining the potentiality areas for RWH depended on the hydro-morphometric parameters of drainage density, infiltration number, maximum flow distance, overland flow distance, basin slope, basin area, the volume of the annual flood, and basin length. The WSPM model was accomplished through three scenarios: equal criteria weights (scenario I), authors' judgment (scenario II), and weights justified by the sensitivity analysis (scenario III). The obtained WSPM maps for defining the RWH potentiality areas classified W. Dahab basin into five RWH potentiality classes ranging from very low to very high. There are good matches between the three performed WSPMs' scenarios in results for the very high and high RWH potentiality classes, which are very suitable for RWH applications.

There are good matches between the three performed WSPMs' scenarios in results for the very high and high RWH potentiality classes, which are very suitable for RWH applications. These classes are frequently represented generally by El-Ghaaib, Dahab Trunk Channel, Zoghra, Nassab, Saal, and Ganah sub-watersheds, which represent about 62.94%, 56.95%, and 73.83% of the total area of the basin for scenarios I, II and, III, respectively. RWH utility system has been proposed to store runoff water and reduce flash flood risks in identified optimal locations.

3.5 Prediction, Mitigation, and Management of Flash Flood

This theme is covered in Chaps. 15 and 16. Chapter 15 is titled "Prediction and Mitigation of Flood in Egypt." The chapter presented an overview of flash flood including flood definition, flood causes, and comprises types of floods and damages caused by the flood. The chapter also presented the application of prediction and mitigation methods to a real case study in Egypt (Wadi Sudr, Sinai). Egypt has alluvial (wadi) systems, formed during fluvial time of the Tertiary and Quaternary Periods. These wadis suffer from flash flood, consequent to heavy precipitations. Wadi Sudr, Sinai has selected a case study to study the prediction and mitigation of flood in this area. The runoff flow paths are detected across the study area and their flow magnitudes under different rainfall events of 10, 25, 50, and 100-year return periods that have been used for designing the flood mitigation measures. Rational and SCS methods are used to facilitate the simulation process during this study and used as tools to convert rainfall to runoff discharges to determine flood quantity throughout the study area.

Once the flash flood or rainfall pattern is predicted, it could be harvested or collected in different ways. Chapter 16 utilizes Alexandria as a case study to switch in stormwater management from gray to green infrastructure. The chapter is titled "Gray-to-Green Infrastructure for Stormwater Management: an Applicable Approach in Alexandria City, Egypt." The green infrastructure systems have recently found successful applications for stormwater management and flood control. This chapter aims at reviewing the recent applications of the management of stormwater drainage projects. The discussed green infrastructures include bioswales, retention basins, ponds, wetlands, rain gardens, permeable pavements, and urban green spaces. These stormwater infrastructures tend to control runoff volume and timing and promote ecosystem services. In addition, this work would provide a better understanding of the barriers and facilitate factors affecting the management of reclaimed stormwater.

Alexandria is the second-largest city in Egypt that has been suffered from periodic flash floods due to rapid urbanization and various infrastructure-related problems. Stormwater management can be extended to an Alexandria Governorate case study to demonstrate the impact of climate change and urbanization on the performance of a city's drainage system, subject to repeated periods of heavy rain, flash flooding, and strong winds. The combination of traditional drainage systems with green infrastructure could be a viable solution to mitigate the stormwater runoff in Alexandria city, Egypt. The outputs of this work can assist water resource managers, government, professionals, and private and public sectors in maintaining flood risk management, especially in Egypt.

The book ends with the 17th chapter of conclusions and recommendations. Chapter 17 contains an update of recently published research works on flash floods including references from Bruins et al. (2019), Vema et al. (2019), Vemula et al. (2019), Sörensen and Emilsson (2019), Shariat et al. (2019), Alves et al. (2019), Piro et al. (2019), Osti (2018), Abdelkarim et al. (2019), Saber et al. (2017), and Al-Momani and Shawaqfah (2013) among others.

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Analysis and Design Aspects

Statistical Behavior of Rainfall in Egypt

Tamer A. Gado

Abstract

The extreme rainfall events have critical impacts on hydrologic systems and the society, especially in arid countries. Recently, Egypt has been subject to some flash floods, due to extreme rainfall events, in particular regions (e.g., Sinai, North Coast, and Upper Egypt) that caused severe damages in lives and vital infrastructure and buildings. This chapter investigates, therefore, the statistical characteristics of rainfall over Egypt based on historical daily rainfall records at 30 stations throughout the country. Six types of rainfall data were extracted from daily records: monthly rainfall, annual rainfall, the monthly number of rainy days, the annual number of rainy days, monthly maximum daily rainfall, and annual maximum daily rainfall. Rainfall frequency analysis, based on the generalized extreme value (GEV) distribution along with the L-moments parameter estimation method, was applied to analyze annual maximum rainfall series. Results of the numerical application indicate a great variation over the whole country in all different aspects of rainfall. The rainfall indices have higher values in the north of the country than those in the middle and the south. Also, the annual maximum daily rainfall data in the case study has been well described by the GEV distribution with negative values of the shape parameter for all stations except only one station (Ras Sedr).

Keywords

Precipitation • Rainfall frequency analysis • Rainfall extremes • Generalized extreme value • Egypt

1 Introduction

Extreme rainfall events have severe consequences on human society. Storms are natural hazards that cause a significant proportion of deaths and devastated infrastructure around the world. Consequently, an accurate estimation of extreme rainfall (magnitude, duration, and frequency) is vital. Furthermore, extreme rainfall estimation is crucial for the design, operation, and management of various hydraulic structures. Thus, improving the accuracy of extreme rainfall estimation has been the main objective of many studies. Rainfall frequency analysis (RFA) is usually used in this regard to estimate extreme rainfall at a specific location. In RFA, it is extremely important to find an accurate relationship between an extreme rainfall magnitude P and the corresponding recurrence interval T. The choice of a suitable method for estimating this relationship depends on the availability of the rainfall record at the site of interest. The commonly used extreme rainfall estimation models are based on annual maximum series (AMS). The AMS of rainfall data contains only the maximum peak rainfall in each year; therefore, for an n-year rainfall record, the AMS consists of n annual maximum rainfall values.

In Egypt, the severe damage caused by several flash floods, due to extreme rainfall events, points to the necessity to understand the characteristics of rainfall events to improve means of flood protection. Nevertheless, scanning the literature for statistical analysis of rainfall events in Egypt reveals that little has been done regarding estimation of extreme rainfall events. Thus, in this chapter, a thorough study of the statistical characteristics of rainfall in Egypt will be conducted to develop methods for extreme rainfall estimation in gaged and ungaged sites in Egypt.

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2 Literature Review

Characteristics of precipitation were widely investigated in the literature. For instance, storm precipitation in a mountainous watershed was studied in the southwestern British Columbia, Canada (Loukas and Quick 1996). They concluded that the time distribution of precipitation was not affected by the elevation, type of storm, storm duration, or storm precipitation depth. Spatial characteristics of precipitation over Jordan were depicted by calculating basic statistical parameters such as the amplitude of frequencies (Tarawneh and Kadioglu 2003). A database of daily rainfall, compiled from 75 gages in Catalonia covering the period 1950–2000, was used to obtain new statistical patterns of daily rain amounts (Burgueno et al. 2005). They evaluated the annual number of rainy days and its coefficient of variation. It was shown that the average annual number of rainy days has high values in the north of the country, whereas the relative dispersion is higher in the south. In north central Italy, the statistical properties of rainfall extremes were investigated, for storm duration ranging from 15 min to 1 day, and significant relationships between these properties and the mean annual precipitation (MAP) were detected (Baldassarre et al. 2006). Consequently, a regional model for estimating the rainfall depth for a given storm duration and recurrence interval was developed of the study region. In arid regions, short-duration rainfall data was analyzed in order to propose design storm distributions (Awadallah and Younan 2012). It was found that Bell ratios are adequate to represent rainfall patterns in arid regions for rainfall durations less than two hours.

To estimate rainfall intensity of different durations and return periods, Intensity-Duration-Frequency (IDF) relationships were developed by using different distribution models in different neighborhoods, see, e.g., (Nhat et al. 2006; Vivekanandan 2012; Jiang and Tung 2013). Many studies evaluated the performance of various probability models in order to identify the most suitable distribution that could provide accurate extreme rainfall estimates in different regions in the world, see, e.g., (Nguyen and Mayabi 1990; Nguyen et al. 2002; Vivekanandan 2015; Wdowikowski et al. 2016). For example, the design extreme rainfalls were estimated by using annual maximum daily rainfall in 38 stations in Korea (Lee and Maeng 2003). They used the L-moments method to estimate the parameters of three different probability distributions: GEV, GLO, and GPA. In Catalonia, the maximum daily rainfall depths, for several established return periods, were determined with a high spatial resolution by using the Gumbel distribution along with the L-moments (Casas et al. 2007). The maximum daily rainfalls in 12 stations located in Upper and Middle Odra River Basin (Poland) were estimated based on nine probability distributions (Wdowikowski et al. 2017).

An extensive empirical investigation on the extreme value distribution was performed by using a collection of 169 of the longest available rainfall records worldwide (Koutsoyiannis 2004). The results showed that the shape parameter of the GEV distribution was constant for all examined geographical zones with value $\kappa = 0.15$. Furthermore, it was concluded that the shape parameter κ was very hard to estimate on the basis of an individual series, even in series with length 100 years or more. The GEV distribution was fitted to the annual maximum daily rainfall of 15,137 records from all over the world, with lengths varying from 40 to 163 years (Papalexiou and Koutsoyiannis 2013). This analysis revealed that the record length strongly affected the estimate of the GEV shape parameter, and the geographical location might also affect its value. In recent times, a general procedure was presented for assessing the performance of ten commonly used probability distributions in rainfall frequency analyses based on their descriptive and predictive abilities in Ontario, Canada (Nguyen et al. 2017). Their proposed assessment approach was shown to be more efficient and more robust than the traditional selection method. Also, they concluded that the GEV model was the best model for describing the distribution of annual maximum rainfalls in this region. Additionally, an improved procedure was proposed to describe the distribution of extreme rainfalls in consideration of the scale-invariance properties of extreme rainfall processes for different durations by using the GEV distribution (Punlum et al. 2017). The proposed procedure was applied on a network of nine rain gage stations located in the north and northeast region of Thailand during the period 1950–2010.

Recently, few studies have analyzed extreme rainfall events in Egypt. For Wadi Watir in Sinai, an early warning system (EWS) for flash floods was developed (Cools et al. 2012). The study stated that only 20 significant rain events were measured over a period of 30 years (1979–2010); nine of them resulted in flash floods. In Wadi El Arish in Sinai, the flash flood that occurred on January 18, 2010 was analyzed based on the integration of remote sensing and GIS (Moawad 2013). The wadi was subjected to severe thunderstorms on January 17 and 18, 2010 followed by an extreme violent flood that claimed six victims, tens of injured, and devastated vital infrastructure and hundreds of houses (Moawad 2013). This flash flood was also analyzed by using the Weather Research and Forecasting (WRF) model over different parts of Sinai Peninsula (El-Afandi et al. 2013). The results show that the WRF model was able to capture heavy rainfall events in the case study. Furthermore, the performance of WRF model was evaluated in heavy rainfall prediction in Egypt (Ibrahim and El-Afandi 2014).

To estimate rainfall intensity of different durations and return periods, Intensity-Duration-Frequency (IDF) relationships were developed by using different distribution models. IDF curves were constructed for Sinai Peninsula by using rainfall frequency analysis (El-Sayed 2011; Fathy et al. 2014). Regional IDF formula was proposed to estimate rainfall intensity for various return periods and rainfall durations at ungaged sites in Sinai (El-Sayed 2011). A recent study (Salama et al. 2018) assessed the performance of some of the most popular probability distributions to identify the most suitable model that could accurately estimate extreme rainfall events in different regions in Egypt. The results indicated that the Log-Normal and Log-Pearson Type III distributions were the best models for most studied stations in Egypt.

Apart from Sinai, very few studies investigated extreme rainfall events in other parts of Egypt. In Alexandria, two rainfall prediction models were developed (El-Shafie et al. 2011): Artificial Neural Network (ANN) and Multi Linear Regression (MLR). The study concluded that the performance of the ANN model is better than that of the MLR and recommended more detailed studies to quantify the uncertainties inherent in the ANN models. Changes in extreme precipitation over Alexandria region during the period 1979–2011 were discussed (Said et al. 2012). The impact of extreme precipitation events on both water resources quality and water supplies was investigated in Alexandria region and Upper Egypt (Yehia et al. 2017). In Qena, the flash flood that occurred on January 28, 2013 was studied, and the surface runoff was estimated (Moawad et al. 2016). To the best of the author's knowledge, this chapter introduces the first study for the analysis of extreme rainfall events in the whole of Egypt.

3 Statistical Analysis

3.1 Study Area

Egypt is located between latitudes 22° and 32 °N, and longitudes 25° and 35 °E with an area of 1,001,450 km^2 (Fig. 1). The majority of Egypt's landscape is desert except

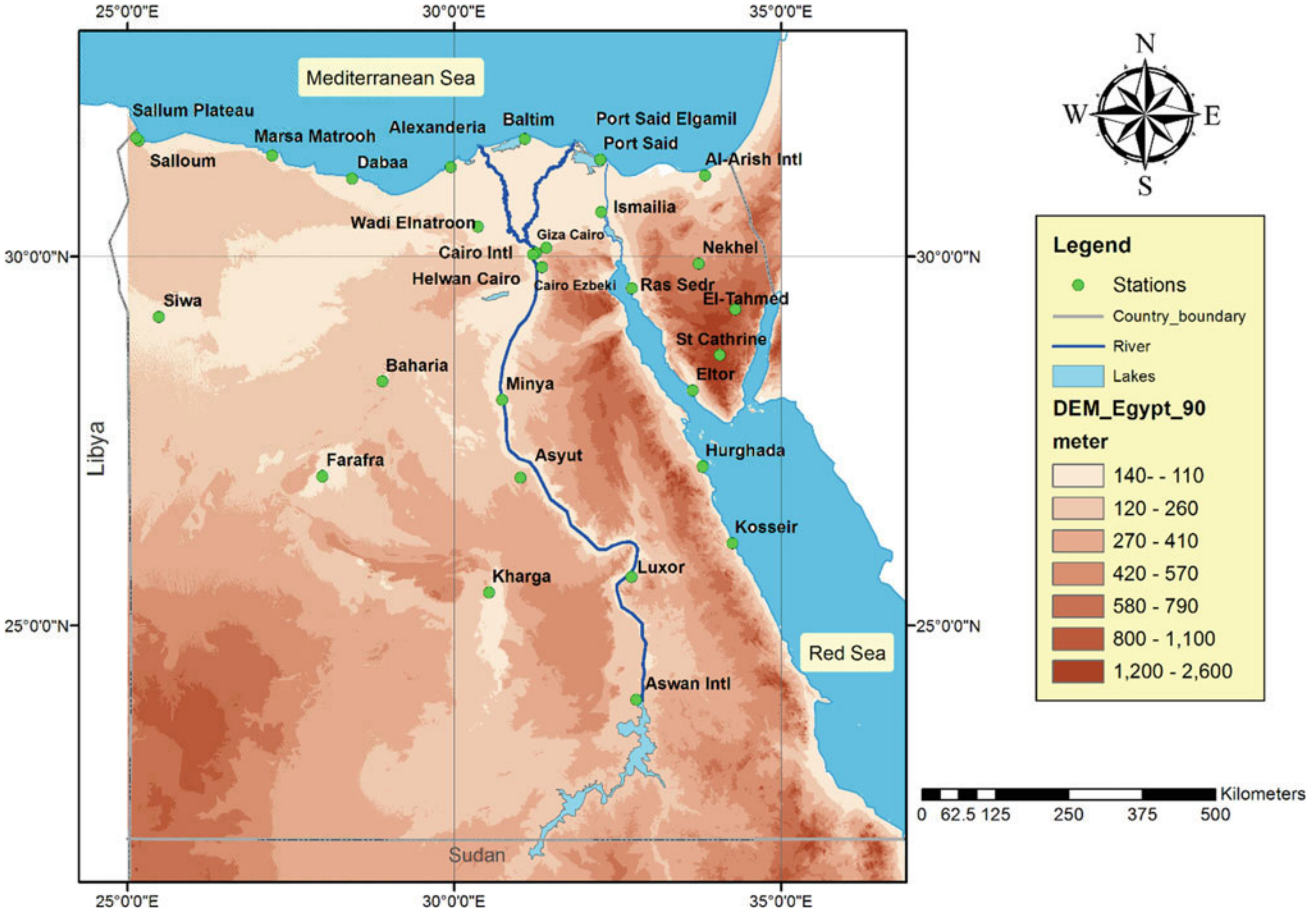

Fig. 1 Map of the studied rainfall stations in Egypt

the Nile Valley and few scattered oases. The climate of Egypt is characterized by four seasons: winter, spring, summer, and autumn. Most of the rainfall occurred in winter when it is cold and moist. The summer, on the other hand, is hot, dry, and rainless. Whereas spring and autumn are transitional seasons. Special characteristics of rainfall over Egypt are generally affected by the closeness to the Mediterranean coast, where rainfall is concentrated in the Egyptian north coast and decreases rapidly inland becoming rare in the south. However, in autumn and winter, extreme rainfall events in some cases cause flash floods over the Red Sea Mountains and the Sinai Peninsula (Ibrahim and El-Afandi 2014). The common characteristics of rainfall events in Egypt are locality, convective, high spatial variability, and short duration.

3.2 Data

In this chapter, the database consists of 30 stations throughout Egypt (Fig. 1). The database was taken from a previous study (Gado 2017). The characteristics of the selected stations used in this chapter are shown in Table 1. The period of record and the record length for each station are also listed in Table 1. The rainfall record length varies from a minimum of 14 years at Nekhel station to a maximum of 81 years at Marsa Matrooh station, with an average of 30 years. Six types of rainfall data were established as follows:

1. The monthly rainfall: the sum of daily rainfall over each month;
2. The annual rainfall: the sum of daily rainfall over each year;
3. The monthly number of rainy days: the sum of rainy days over each month;
4. The annual number of rainy days: the sum of rainy days over each year;
5. The monthly maximum daily rainfall: the maximum daily rainfall each month; and
6. The annual maximum daily rainfall: the maximum daily rainfall each year.

3.3 GEV Distribution

In this chapter, rainfall frequency analysis, based on annual maximum series (AMS), was used to estimate the amount of rain falling at a given point in a specified duration and for a particular return period. In general, several probability distributions are used for the frequency analysis of extreme rainfalls. Here, the Generalized Extreme Value (GEV) distribution along with the L-moments parameter estimation method were used to analyze the AMS as they were found to be an efficient approach for extreme event estimation according to the literature, see, e.g., (Hosking et al. 1985; Gado and Nguyen 2015). The cumulative distribution function (CDF) or the probability of non-exceedance [F(q)] for the GEV distribution is given as (Gado and Nguyen 2016):

$$\begin{aligned} F(q) &= \exp\left[-\left(1-\frac{\kappa(q-\xi)}{\alpha}\right)^{1/\kappa}\right]\kappa \neq 0 \\ &= \exp\left[-\exp\left(-\frac{q-\xi}{\alpha}\right)\right]\kappa = 0 \end{aligned} \tag{1}$$

where q is the extreme observation rainfall; and ξ, α, and κ are, respectively, the location, scale, and shape parameters of the distribution. The quantiles (P_T) can be computed using the following relation:

$$\begin{aligned} P_T &= \xi + \frac{\alpha}{\kappa}\{1-[-ln(p)]^{\kappa}\}\kappa \neq 0 \\ &= \xi - \alpha ln[-ln(p)]\kappa = 0 \end{aligned} \tag{2}$$

in which $p = 1/T$ is the probability of interest.

4 Results

First of all, available rainfall data have been tested for independence, homogeneity, and outlier. The data were verified to be independent and homogeneous, and very few outliers were detected and then removed from the database. Six types of rainfall data were investigated as mentioned before: monthly rainfall, annual rainfall, the monthly number of rainy days, the annual number of rainy days, monthly maximum daily rainfall, and annual maximum daily rainfall.

4.1 Analysis of Monthly Rainfall Data

The mean monthly precipitation data of the available rainfall stations in Egypt is shown in Table 2. Overall, the mean ranged from zero at some stations in different months to 41 mm at Alexandria in January. Great variations of the monthly precipitation could be noticed not only among the studied rainfall stations but also over different months. The rainy season in Egypt extends from October to March when some stations receive a significant amount of rainfall (Table 2), while the dry season extends from April to September as the monthly rainfall did not exceed 5 mm at most stations (Table 2).

Figure 2 shows the mean monthly precipitation for January at all stations in descending order. For January, the

Table 1 Summary of the characteristics of the studied rainfall stations in Egypt (Gado 2017)

Station ID	Station name	Latitude	Longitude	Elevation (m)	Period of record	Missing years	Record length (years)
62337	Al-Arish Intl	31.07	33.84	36.9	1985–2015	–	31
62318	Alexandria Intl	31.18	29.95	−1.8	1957–2015	1967–1972	53
62414	Aswan Intl	23.97	32.78	200	1957–2015	1967–1972	21
62393	Asyut	27.04	31.01	226	1957–2014	1967–1972	19
62420	Baharia	28.33	28.90	130	1957–2015	1967–1982, 1992	24
62325	Baltim	31.55	31.08	2	1994–2015	–	22
62366	Cairo Intl	30.12	31.41	75	1944–2015	1947–1956, 1967–1972	51
147728	Cairo Ezbekiya	30.05	31.25	20	1909–1957	1941–1943	46
62309	Dabaa	31.03	28.44	18	1963–2015	1967–1998	21
	El-Tahmed	29.30	34.30	625	1922–1955	–	31
62459	Eltor	28.21	33.65	35	1960–2015	1967–1993	22
62423	Farafra	27.05	27.98	92	1957–2014	1967–1975, 1977–1992	16
62375	Giza Cairo	30.03	31.21	28	1924–1957	1941–1943	31
147730	Helwan Cairo	29.86	31.34	116	1904–1957	–	54
62463	Hurghada	27.18	33.80	14	1991–2015	2000, 2006, 2008, 2009, 2011, 2012	16
62440	Ismailia	30.59	32.25	13	1987–2013	–	26
62435	Kharga	25.46	30.53	73	1957–2014	1958–1959, 1967–1972, 1975–1981	15
62465	Kosseir	26.14	34.26	11	1960–2014	1967–1972	25
62405	Luxor	25.67	32.71	99	1944–2015	1946–1956, 1967–1972	32
62306	Marsa Matrooh	31.33	27.22	30	1920–2015	1923, 1941–1944, 1967–1973, 1975, 1976	81
62387	Minya	28.08	30.73	37	1957–2015	1967–1972, 1978	30
62452	Nekhel	29.91	33.74	403	2001–2014	–	14
62333	Port Said	31.28	32.24	2	1957–2015	1967–1972, 1974–1978, 1990	22
62332	Port Said Elgamil	31.28	32.24	6	1987–2014	–	27
62455	Ras Sedr	29.58	32.72	16	2000–2015	–	15
62300	Salloum	31.53	25.18	6	1957–1995	1967–1979	26
62305	Sallum Plateau	31.57	25.13	6	1996–2015	2013	19
62417	Siwa	29.20	25.48	–12	1920–2015	1923, 1941–1944, 1967–1978, 1984, 1986, 2014	59
623664	St Catherine Intl	28.69	34.06	1331	1934–2006	1938–1979	31
62357	Wadi Elnatroon	30.40	30.36	1	1996–2015	1999, 2013. 2014	17

mean exceeded 30 mm at four stations located on the North Coast (Fig. 1): Alexandria Intl (41 mm), Baltim (36 mm), Dabaa (36 mm), and Marsa Matrooh (35 mm). On the other hand, the mean was zero at four stations (Baharia, Aswan Intl, Asyut, and Minya) located in the middle and the south of the country (Fig. 1). Figure 3 displays the average monthly rainfall data for Alexandria station estimated from the period 1957–2015. It can be noticed that the highest month in total rainfall in Alexandria was January then December.

Table 2 Average of the monthly rainfall (mm) of the studied stations in Egypt

Month station	1	2	3	4	5	6	7	8	9	10	11	12
Al-Arish Intl	23	15	16	5	4	0	0	1	0	6	5	16
Alexandria Intl	41	27	12	2	1	0	0	0	1	8	25	37
Aswan Intl	0	0	0	1	0	1	0	0	0	0	0	0
Asyut	0	1	1	2	0	1	2	0	0	1	0	2
Baharia	0	0	1	0	0	0	0	0	0	0	0	0
Baltim	36	34	12	4	1	0	0	0	5	9	12	34
Cairo Intl	5	6	6	1	1	0	0	1	1	1	5	5
Cairo Ezbekiya	5	4	4	2	2	0	0	0	0	2	2	5
Dabaa	36	15	10	2	4	0	0	0	1	16	14	19
Eltor	1	0	1	1	0	0	0	0	3	0	2	3
Farafra	1	0	0	3	0	0	1	0	0	1	1	0
Giza Cairo	3	3	4	1	1	0	0	0	0	3	4	4
Helwan Cairo	6	5	4	2	3	0	0	0	0	1	3	6
Hurghada	4	0	10	0	10	0	0	3	5	5	5	7
Ismailia	12	7	7	6	0	0	1	0	4	4	1	4
Kharga	1	0	0	1	1	1	0	0	0	0	0	1
Kosseir	1	0	0	1	1	0	1	1	1	1	0	0
Luxor	1	0	1	1	3	1	1	0	0	0	1	2
Marsa Matrooh	35	21	16	8	7	3	0	0	1	12	20	34
Minya	0	2	0	2	0	0	0	1	2	1	1	0
Nekhel	7	4	3	2	0	0	0	0	2	4	0	2
Port Said	3	3	2	2	0	0	0	0	0	3	3	4
Port Said Elgamil	22	16	7	8	6	0	0	2	4	6	13	8
Ras Sedr	3	2	2	0	1	0	0	0	0	0	1	2
Salloum	16	9	5	1	2	3	4	0	1	5	6	10
Sallum Plateau	12	11	3	2	2	1	0	0	6	5	2	8
Siwa	1	1	1	1	1	0	0	0	0	1	0	2
Wadi Elnatroon	6	11	2	1	1	0	2	0	0	3	2	8

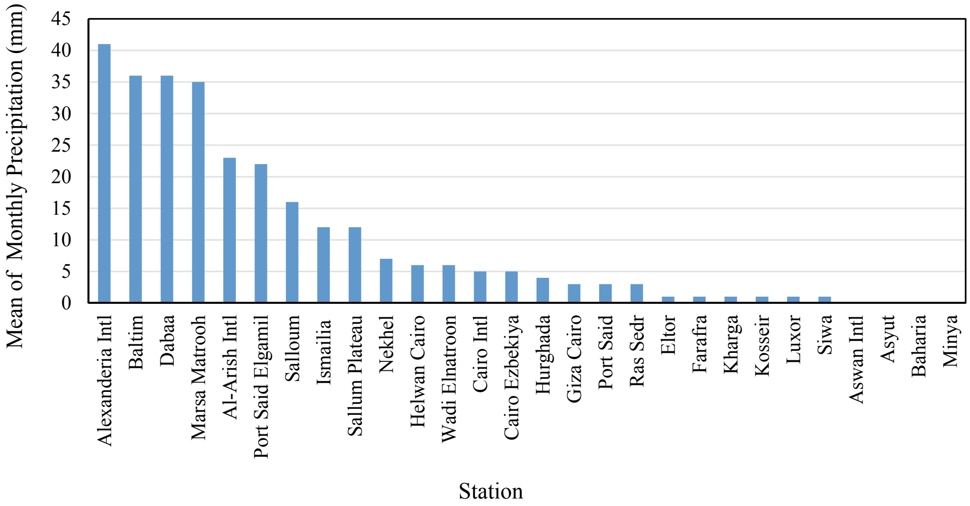

Fig. 2 Mean of monthly precipitation of the studied stations for January

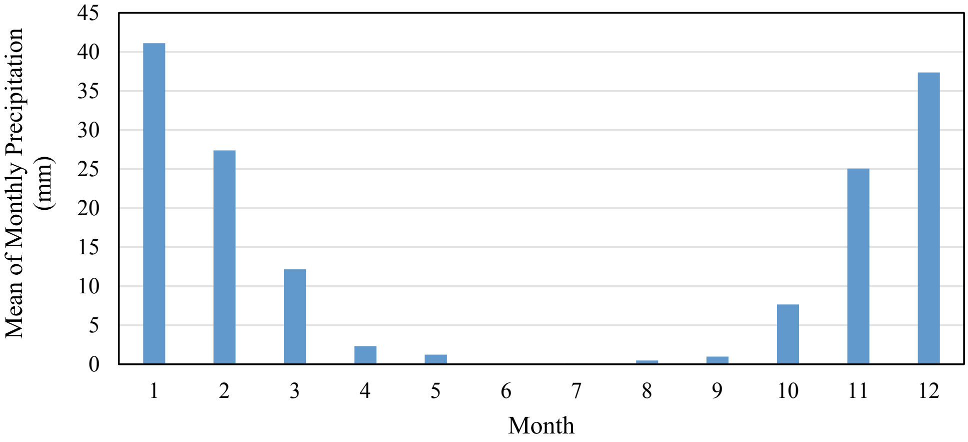

Fig. 3 Average monthly rainfall data for Alexandria station (1957–2015)

4.2 Analysis of Annual Rainfall Data

Basic statistical characteristics such as the mean, the standard deviation, the coefficient of variation, the maximum, and the minimum were derived from the annual precipitation data of the available rainfall stations in Egypt (Table 3). Great variations of the statistical characteristics of the annual precipitation among the studied rainfall stations could be noticed. Overall, the mean ranged from 5 to 153 mm; the standard deviation (6–85 mm); the coefficient of variation (0.46–2.81); the maximum (27–401 mm); and the minimum (0–9 mm). The maximum of the annual precipitation in the case study was 401 mm, and it occurred at Marsa Matrooh in 1994 (Table 3).

The mean annual precipitation of all stations is shown in Fig. 4 in descending order. The mean exceeded 100 mm at four stations located on the North Coast (Fig. 1): Alexandria Intl (153 mm), Baltim (139 mm), Marsa Matrooh (122 mm), and Dabaa (108 mm). On the other hand, the mean annual precipitation did not exceed 10 mm at four stations located on the middle and the south of the country (Fig. 1): Baharia (5 mm), Aswan Intl (9 mm), Siwa (9 mm), and Ras Sedr (10 mm). Figure 5 displays the annual rainfall of Alexandria station for the period 1957–2015. The annual rainfall varied between a minimum amount of 7.4 mm in 1975 and a maximum of 352 mm in 2004 (Table 3).

4.3 Analysis of the Monthly Number of Rainy Days Data

The mean monthly number of rainy days of the studied stations in Egypt is presented in Table 4. Overall, the mean ranged from zero days at some stations in different months to nine days at Baltim in January. Table 4 confirms that the dry season in Egypt includes six months from April to September when the mean of the monthly number of rainy days was equal or less than two days at almost all stations.

Figure 6 shows the mean monthly number of rainy days for January at all stations in descending order. For January, the mean exceeded seven days at four stations located on the North Coast (Fig. 1): Baltim (9 days), Alexandria Intl (8 days), Dabaa (8 days), and Marsa Matrooh (7 days). On the other hand, the mean was one day at nine stations (Baharia, Aswan Intl, Asyut, Farafra, Hurghada, Kharga, Kosseir, Luxor, and Minya) located in the middle and the south of the country (Fig. 1). Figure 7 displays the average monthly number of rainy days at Alexandria station estimated for the period 1957–2015. It can be concluded that Alexandria witnessed at least one rainy day each month on average during the recorded period.

4.4 Analysis of the Annual Number of Rainy Days Data

Basic statistical characteristics of the annual number of rainy days at the studied stations are presented in Table 5. The characteristics include the mean (1–31 days), the standard deviation (0.63–13.31 days), the coefficient of variation (0.36–1.03), the maximum (3–64 days), and the minimum (1–6 days). The maximum of the annual number of rainy days in the case study was 64 days which occurred at Dabaa in 2000.

The mean annual number of rainy days for all stations was shown in Fig. 8 in descending order. The mean exceeded 20 days at six stations located on the North Coast: Baltim (31 days), Alexandria Intl (30 days), Dabaa (30 days), Marsa Matrooh (28 days), Port Said Elgamil (23 days), and Al-Arish Intl (20 days). In contrast, the mean did not exceed 5 days at 12 stations located on the middle and the south of the country (Fig. 1): Farafra, Aswan Intl,

Table 3 Summary of the statistical characteristics of the annual precipitation of the studied stations

Station	Mean (mm)	Standard deviation (mm)	Coefficient of variation	Maximum (mm)	Minimum (mm)
Al-Arish Intl	89	53	0.59	205	9
Alexandria Intl	153	85	0.56	352	7
Aswan Intl	9	25	2.81	117	1
Asyut	30	76	2.56	316	1
Baharia	5	6	1.25	27	0
Baltim	139	64	0.46	236	4
Cairo Intl	38	32	0.84	129	1
Cairo Ezbekiya	24	19	0.76	92	1
Dabaa	108	63	0.58	257	5
Eltor	16	23	1.39	83	1
Farafra	13	18	1.39	70	1
Giza Cairo	22	16	0.74	61	3
Helwan Cairo	30	20	0.68	92	1
Hurghada	42	45	1.05	147	1
Ismailia	45	67	1.49	310	3
Kharga	14	25	1.80	73	1
Kosseir	14	15	1.10	53	1
Luxor	20	31	1.53	124	1
Marsa Matrooh	122	80	0.65	401	1
Minya	15	24	1.54	80	1
Nekhel	22	17	0.76	60	4
Port Said	45	45	0.99	168	1
Port Said Elgamil	89	76	0.86	397	7
Ras Sedr	10	7	0.69	32	1
Salloum	63	52	0.84	189	1
Sallum Plateau	51	41	0.80	173	3
Siwa	9	10	1.09	42	1
Wadi Elnatroon	34	33	0.98	111	2

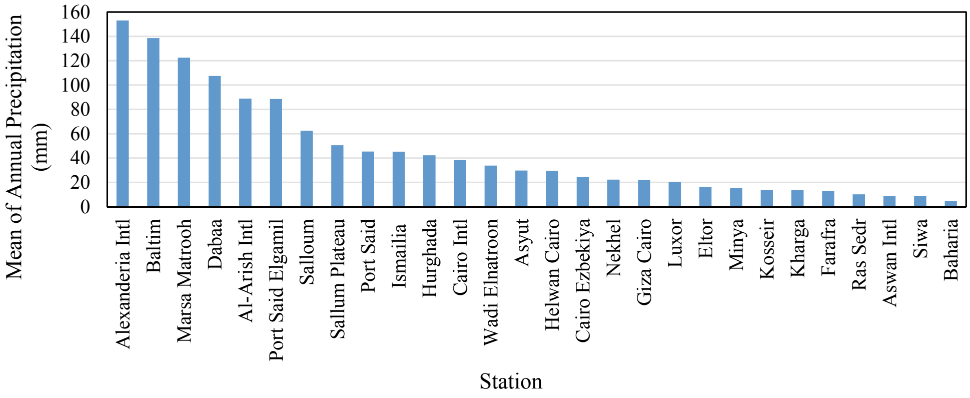

Fig. 4 Mean of annual precipitation of the studied stations in Egypt

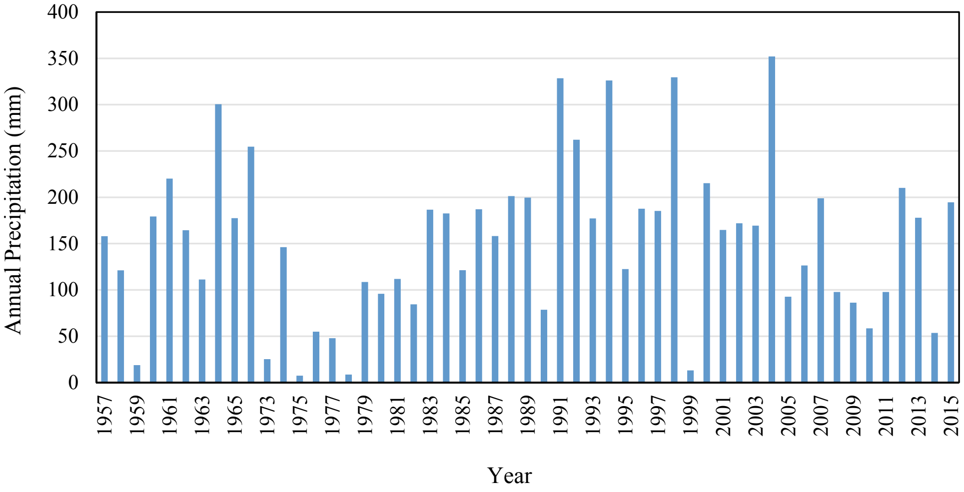

Fig. 5 Annual rainfall of Alexandria station (1957–2015)

Table 4 Average of the monthly rainy days (day) of the studied stations in Egypt

Month station	1	2	3	4	5	6	7	8	9	10	11	12
Al-Arish Intl	6	5	4	2	1	1	2	1	0	2	2	4
Alexandria Intl	8	6	4	2	1	1	2	1	1	3	4	6
Aswan Intl	1	1	1	1	1	1	2	1	2	2	1	1
Asyut	1	1	1	2	1	1	2	1	0	1	1	2
Baharia	1	2	1	1	1	0	2	1	1	2	1	1
Baltim	9	8	4	2	2	0	2	0	1	3	3	7
Cairo Intl	3	2	2	2	1	1	2	1	2	1	2	3
Cairo Ezbekiya	2	2	2	1	1	1	0	0	0	2	1	3
Dabaa	8	6	4	2	2	0	2	0	2	3	4	6
Eltor	2	1	2	1	2	0	2	0	1	1	1	2
Farafra	1	1	1	1	1	0	2	0	0	1	2	2
Giza Cairo	3	2	2	1	2	0	0	1	1	2	2	3
Helwan Cairo	3	3	2	2	2	1	0	0	0	1	2	3
Hurghada	1	0	1	0	1	1	2	1	1	1	2	2
Ismailia	4	3	2	2	2	0	2	0	1	2	2	3
Kharga	1	1	2	1	1	1	2	0	1	0	1	1
Kosseir	1	1	1	1	1	1	1	1	1	1	1	2
Luxor	1	1	2	2	1	1	2	1	1	2	1	1
Marsa Matrooh	7	6	4	2	2	1	2	2	1	3	4	5
Minya	1	1	1	2	1	0	1	1	1	2	1	1
Nekhel	2	2	2	2	2	0	0	0	1	2	1	2
Port Said	4	4	3	2	1	0	0	0	1	3	3	4
Port Said Elgamil	6	5	4	2	2	1	1	1	1	3	3	4
Ras Sedr	2	2	1	1	2	0	1	0	0	1	1	2
Salloum	5	4	3	2	2	1	3	0	1	3	2	4
Sallum Plateau	4	4	2	1	2	1	2	0	2	3	2	3
Siwa	2	1	2	1	2	1	2	0	1	2	1	2
Wadi Elnatroon	3	2	2	1	2	0	1	0	0	1	1	2

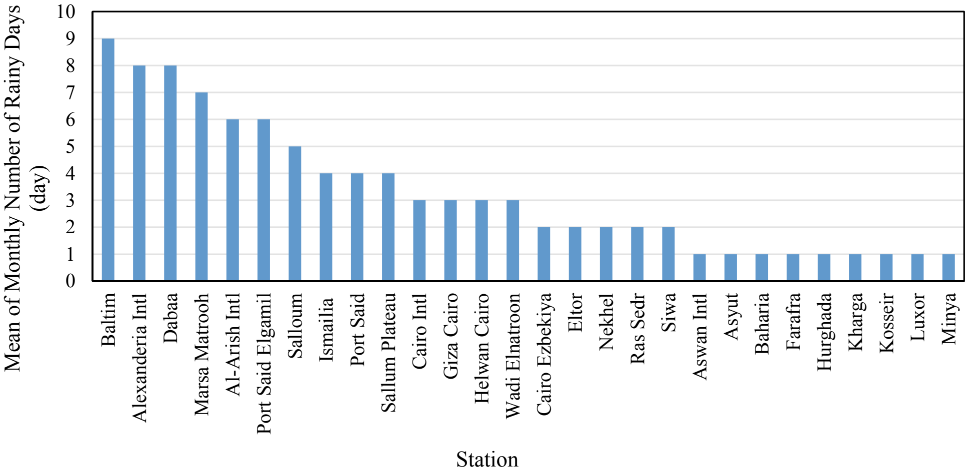

Fig. 6 Mean of monthly number of rainy days of the studied stations for January

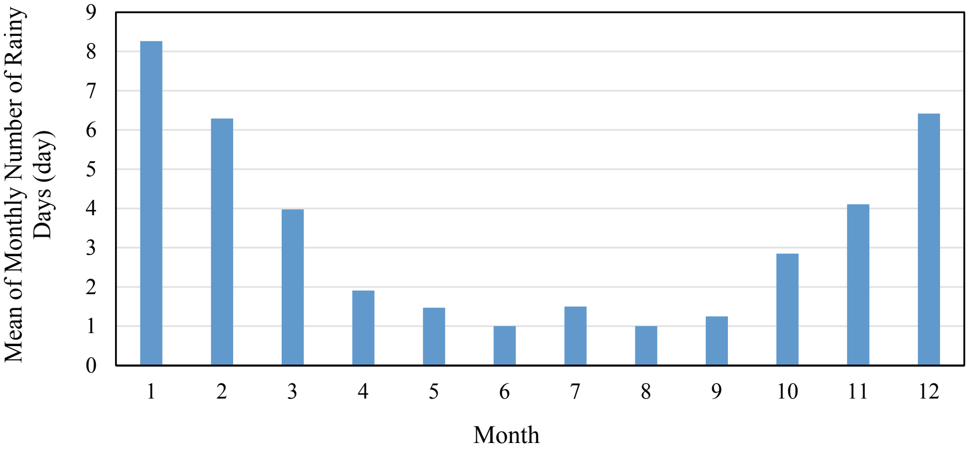

Fig. 7 Average monthly number of rainy days of Alexandria station (1957–2015)

Asyut, Baharia, Hurghada, Kharga, Kosseir, Luxor, Eltor, Minya, Siwa, and Ras Sedr. Figure 9 displays the annual number of rainy days at Alexandria station for the period 1957–2015. The annual number of rainy days varied between a minimum of two days in 1975 and a maximum of 56 days in 1991 (Table 5).

4.5 Analysis of Monthly Maximum Daily Rainfall Data

The mean of the monthly maximum daily rainfall of the studied stations in Egypt is shown in Table 6. Overall, the mean ranged from zero at some stations in different months to 19 mm at Port Said Elgamil in January. Table 6 confirms the great variations among the stations over the different months. Figure 10 shows the mean of the monthly maximum daily precipitation for January at all stations in descending order. For January, the mean exceeded 12 mm at four stations located on the North Coast (Fig. 1): Port Said Elgamil (19 mm), Alexandria Intl (14 mm), Marsa Matrooh (14 mm), and Dabaa (12 mm). Whereas the mean was zero at five stations (Aswan Intl, Asyut, Baharia, Farafra, and Minya) located in the middle and the south of the country (Fig. 1). Figure 11 displays the average monthly maximum daily rainfall at Alexandria station estimated for the period 1957–2015.

4.6 Analysis of Annual Maximum Daily Rainfall Data

Here, the annual maximum daily rainfall series from 30 stations in Egypt have been analyzed to determine the annual maximum daily precipitation for several established return periods in different regions of Egypt.

Basic statistical characteristics such as the mean, the standard deviation, the coefficient of variation, the maximum, and the minimum were derived from the annual maximum daily rainfall data of the 30 available rainfall

Table 5 Summary of the statistical characteristics of the annual number of rainy days of the studied stations

Station	Mean (day)	Standard deviation (day)	Coefficient of variation	Maximum (day)	Minimum (day)
Al-Arish Intl	20	9.12	0.45	37	3
Alexandria Intl	30	13.24	0.45	56	2
Aswan Intl	2	1.03	0.65	4	1
Asyut	2	1.79	0.87	8	1
Baharia	2	1.46	0.71	6	1
Baltim	31	11.56	0.37	48	4
Cairo Intl	10	5.58	0.55	30	1
Cairo Ezbekiya	7	3.74	0.51	15	1
Dabaa	30	13.31	0.45	64	6
Eltor	3	1.93	0.66	8	1
Farafra	1	0.63	0.44	3	1
Giza Cairo	7	4.51	0.67	23	1
Helwan Cairo	9	4.47	0.50	22	1
Hurghada	2	0.80	0.41	3	1
Ismailia	12	5.19	0.44	20	3
Kharga	2	0.74	0.48	3	1
Kosseir	2	1.54	0.67	7	1
Luxor	2	1.91	0.86	10	1
Marsa Matrooh	28	13.31	0.47	54	1
Minya	3	1.46	0.58	6	1
Nekhel	6	2.58	0.45	10	2
Port Said	16	9.92	0.61	35	1
Port Said Elgamil	23	8.52	0.36	47	4
Ras Sedr	5	2.90	0.54	13	1
Salloum	17	10.71	0.61	37	1
Sallum Plateau	14	8.31	0.58	32	3
Siwa	3	3.37	1.03	19	1
Wadi Elnatroon	8	4.27	0.51	15	2

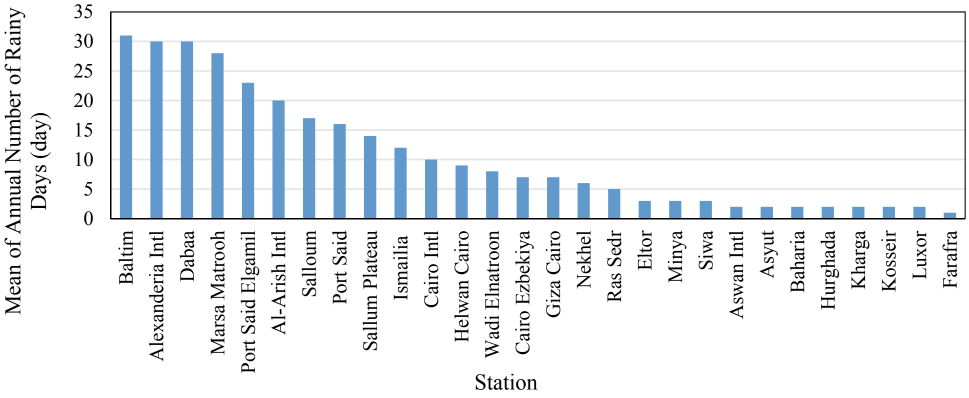

Fig. 8 Mean of annual number of rainy days of the studied stations in Egypt

Fig. 9 Annual number of rainy days of Alexandria station (1957–2015)

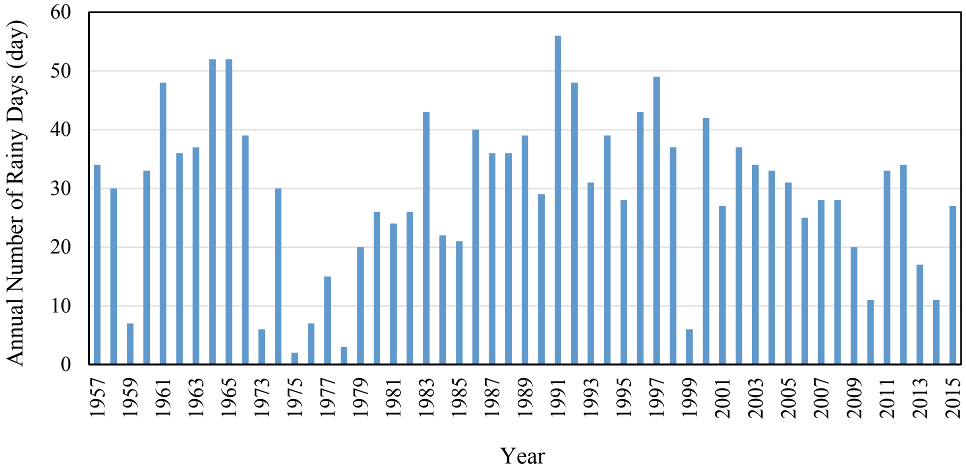

Table 6 Average of the monthly maximum daily rainfall (mm) of the studied stations in Egypt

Month station	1	2	3	4	5	6	7	8	9	10	11	12
Al-Arish Intl	11	9	11	3	4	0	0	1	0	5	3	10
Alexandria Intl	14	12	7	2	1	0	0	0	1	5	13	16
Aswan Intl	0	0	0	1	0	1	0	0	0	0	0	0
Asyut	0	1	1	1	0	1	1	0	0	1	0	1
Baharia	0	0	1	0	0	0	0	0	4	0	0	0
Baltim	11	13	7	2	1	0	0	0	5	6	6	14
Cairo Intl	3	5	7	3	4	3	3	5	5	5	9	9
Cairo Ezbekiya	4	3	3	1	2	0	0	0	0	1	2	3
Dabaa	12	6	6	1	4	0	0	0	0	12	8	9
Eltor	1	0	1	1	0	0	0	0	3	0	2	2
Farafra	0	0	0	3	0	0	1	0	0	1	0	0
Giza Cairo	2	2	3	1	1	0	0	0	0	3	3	2
Helwan Cairo	4	3	3	2	2	0	0	0	0	1	2	4
Hurghada	4	0	12	0	12	0	0	3	6	6	4	8
Ismailia	10	6	5	4	0	0	1	0	4	3	1	2
Kharga	1	0	0	1	1	1	0	0	0	0	0	1
Kosseir	1	0	0	1	1	0	1	4	1	1	0	0
Luxor	1	0	0	1	3	1	1	0	0	0	1	2
Marsa Matrooh	14	10	9	7	7	2	0	0	1	8	11	15
Minya	0	2	0	2	0	0	0	1	2	1	1	3
Nekhel	5	3	2	2	0	0	0	0	2	3	0	1
Port Said	1	2	1	1	0	0	0	0	0	2	2	3
Port Said Elgamil	19	10	4	7	5	0	0	2	3	4	7	4
Ras Sedr	3	2	1	6	0	0	0	0	0	0	1	2
Salloum	8	5	4	1	1	3	2	0	1	3	4	6
Sallum Plateau	6	7	2	2	1	1	0	0	6	4	2	5
Siwa	1	2	1	1	1	0	0	0	0	1	0	2
Wadi Elnatroon	5	9	2	0	1	0	2	0	0	3	2	8

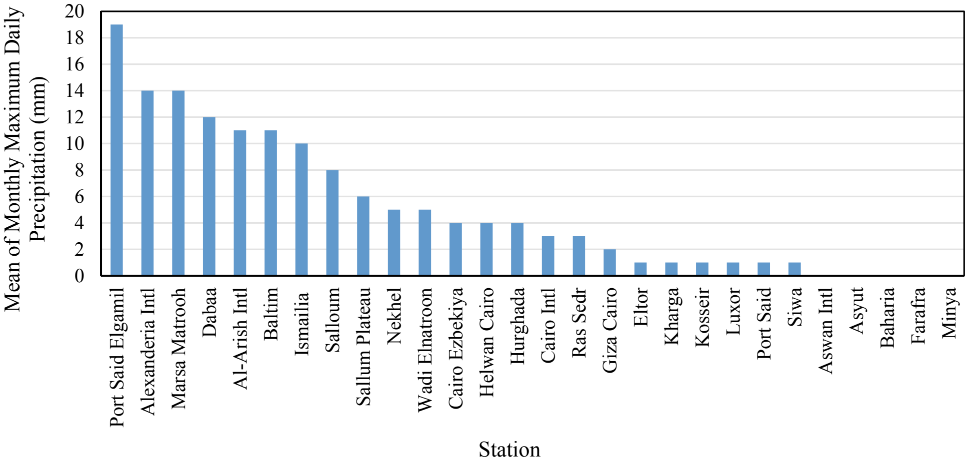

Fig. 10 Average monthly maximum daily precipitation of the studied stations for January

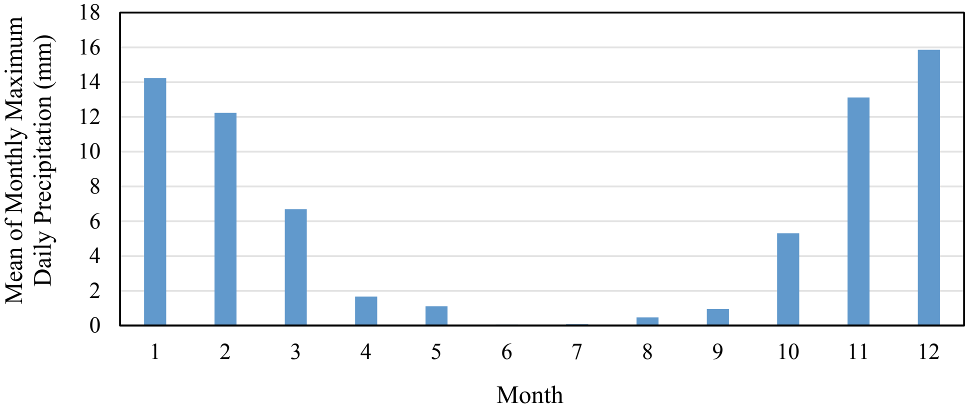

Fig. 11 Average monthly maximum daily rainfall of Alexandria station (1957–2015)

stations (Table 7). Overall, the mean ranged from 3 to 35 mm; the standard deviation (2–38 mm); the coefficient of variation (0.5–2.5); the maximum (8–142 mm); and the minimum (0–6 mm). The maximum of the annual maximum daily rainfall in the case study was 142 mm that occurred at El-Tahmed station in 1925 (Table 7). Figure 12 shows the mean annual maximum daily precipitation of all stations in descending order. It can be observed that the mean exceeded 25 mm at only four stations (Fig. 12): Hurghada (35 mm), Al-Arish Intl (29 mm), Alexandria Intl (29 mm), and Marsa Matrooh (26 mm). On the other hand, the mean did not exceed 5 mm at two stations (Fig. 12): Baharia (3 mm) and Ras Sedr (4 mm). Figure 13 displays the annual maximum daily rainfall data at Alexandria station for the period 1957–2015. The annual maximum daily rainfall varied between a minimum of 6 mm in 1978 and a maximum of 102 mm in 2004 (Table 7).

GEV distributions were fitted to each of the 30 annual maximum series of daily precipitation depths using the L-moments method. The values of the parameters in the GEV functions fitted to each series are shown in Table 8. The averages over all stations and the dispersion characteristics (minimum and maximum values and standard deviations) of the three parameters of the GEV distribution are shown in Table 9. The most important parameter is the shape parameter (κ) because it determines the shape of the distribution and consequently the behavior of its tail. However, the estimation of the shape parameter involves a great deal of uncertainty because it depends on the skewness whose value cannot be specified accurately (Koutsoyiannis 2004). The estimated values of the shape parameter range from -0.75 to 0.11 as shown in Table 8. It can be noticed that the estimated κ is negative for all stations except only one station (Ras Sedr) whose $\kappa = 0.11$ (Table 8) which implies an upper bound. In this case, it may be better to use the GEV with shape parameter equal to zero, i.e., the Gumbel distribution (Papalexiou and Koutsoyiannis 2013).

The maximum daily precipitation for each station corresponding to return periods between 5 and 1000 years have been estimated by using the GEV distribution with L-moments (Table 8). For the return period of 100 years as an example, the daily extreme rainfall estimation ranges from 11 mm at Ras Sedr to 203 mm at Hurghada (Fig. 14). The 100-years daily extreme rainfall (P_{100}) exceeded