Integrated Hydro-geomorphological Approach to Flash Flood Risk Assessment and Mitigation Strategies in Wadi Systems

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by

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Dedicated to my loving parents, my wife & my uncle Mohammed Sayed...........

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Abstract

The generation and processes of wadi flash floods are very complex and are not well understood. Therefore, the flash floods modeling, risk assessment, mitigation and management in the arid region are hindered by the unique characteristics of wadi system, lack of powerful hydrological models and data deficiency. In this thesis, we developed an integrated approach was developed based on geomorphometric analysis, hydrological modeling, risk assessment, mitigation and management. The Qena, Abadi, (The Eastern Desert of Egypt), Samail and Aday wadis (north coast of Oman) were selected to apply and validate the developed approaches and methods. The challenges related with the arid wadi flash floods were highlighted and the previous wadi flash floods studies were critically reviewed.

To investigate the relationship between variations in geomorphometric and rainfall characteristics and the responses of wadi flash floods Qena Wadi was employed and was divided into 14 sub-basins with areas ranging from 315 to 1,488 km^2. The distributed Hydrological River Basin Environment Assessment Model (Hydro-BEAM) was used to obtain a good representation of the spatial variability of the rainfall and geomorphology in the basin. Thirty-eight geomorphometric parameters representing the topographic, scale, shape and drainage characteristics of the basins were considered and extracted using geographic information system (GIS) techniques. A series of flash flood events from 1994, 2010, 2013, and 2014, in addition to synthetic virtual storms with different durations and intensities, were selected for the application of this study. The results exhibit strong correlations between scale and topographic parameters and the hydrological indices of the wadi flash floods, while the shape and drainage network metrics have smaller impacts. The total rainfall amount and duration significantly affect the relationship between the hydrologic response of the wadi and its geomorphometry. For most of the parameters, we found that the impact of the wadi geomorphometry on the hydrologic response increases with increasing rainfall intensity.

Flash flood simulation and risk assessment is essential to construct efficient warning, mitigation and management of the increasing threat of flash floods in wadi systems. The Rainfall Runoff Inundation (RRI) distributed model and sensitivity analysis for its parameters were applied and implemented in Wadi Samail as a case study for the extremist flash floods events in Oman (1,000 years return period). The most severe tropical cyclone in the recent history in Oman, Gonu-2007 and Phet-2010 were used to calibrate and validate the hydrological model. The results and the statistical analysis indicating that RRI model could efficiently simulate the extreme flash flood events in the arid wadi system. Where for model calibration, Nash-Sutcliffe efficiency (NSE) and Percent bias (PBIAS) indices equal to 0.93 and -14.3 respectively and for model validation NSE and PBIAS equal to 0.86 and -12.0 respectively. Further improvements for RRI model is recommended to include the transmission losses and groundwater processes for better representation of the wadi system. Flash flood susceptibility has been assessed using the significant geomorphometric parameters and flash flood index.

After the wadi flash floods were simulated and its risk was assessed, additional objectives to evaluate different mitigation scenarios in the arid wadi systems using the case study of Wadi Abadi at the Eastern Desert of Egypt were investigated. The proposed approach based on remote sensing data integrated in GIS tools and the Hydro-BEAM model, which was upgraded by adding a dam and reservoir routing module. High-resolution Digital Elevation Model (DEM) data and additional satellite imagery were utilized to propose the locations and design characteristics of flood management dams based. Sensitivity analysis of the hydrological model parameters was implemented indicating the most significant parameters controlling the wadi flood peak are soil thickness and porosity, runoff coefficient, sub-surface layer horizontal outlet coefficient and channel roughness. The results indicated that 2014 flood event is more severe compared to that of 2010 flood event. Flood Mitigation scenarios of using a single concentrated dam or group of distributed dams have been assessed. The distributed dams scenario outperform the concentrated dam in the flood mitigation and water resources management water aspects, whereas the concentrated dams scenario has relative merits in the cost and operation point of view. Finally, an integrated wadi flash flood management was proposed.

Key Words: arid catchment, wadi, flash floods, hydrological modeling, Hydro-BEAM, RRI, hydrologic response, quantitative geomorphology, flood risk assessment, flood mitigation, structural measures

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Chapter 1 Introduction

1.1 Motivation

The arid regions are vulnerable for opposite two disasters, the flash floods and drought. The main feature, at the same time problematic of flash floods are their sudden nature and fast-moving water, along with no enough time for preparing, warning, relief and evacuation. In addition, flash flood in arid environment is infrequent, therefore the community and even the officials are not ready to handle such disaster. Many people tend to underestimate the dangers of flash floods that increase the human losses. Due to short time factor, the most important challenge is how to predict the flash floods. For flash flood prediction, hydrological models are indispensable which are challenging at arid regions mainly for model calibration due to the limitation of observational data for both rainfall and discharge.

Wadi Flash Floods (WFFs) threat frequency has been increased in the recent decade. Meanwhile, these floods are vital source of water for such arid regions. For instance, Egypt and Oman are arid countries, that facing raising challenges to manage the devastating WFFs risk. The extremist flash flood event occurred in Oman are due to Gonu-2007 tropical cyclones, which was subjected to the strongest tropical cyclone ever been recorded on its recent history since 1890, causing 50 fatalities. The estimated damages cost of this exceptional event is 3.9 billion USD which equals to 13% of the GDP of Oman (Al Khatry and Helmi, 2008). While Egypt faced large-scale flood in Jan. 2010 causing 10 fatalities and hundreds of destroyed homes. Until today, no proper integrated basin scale management for most of the Arabian wadis. Extreme floods affected Saudi Arabia and Yemen from 2008 to 2009 with an estimated total economic damage of approximately 1.3 billion USD. In January 2013, the winter storm that hit Palestine caused more than $50 million in economic damages and severally affected the agricultural sector. Tropical cyclones pose a hazard in the Arab region (UNISDR-ROAS, 2013).

Usually desert communities suffering from absence of disaster management strategy, random housing activities and poverty, which decrease the resilience of the community to face flash flood. For instance, in some areas, construction of houses and land reclamation are made across the wadi channel without proper mitigation measures. Flash floods are destructive natural disasters and an essential source of water, especially in arid areas, where flash floods could provide these regions with a renewable fresh water particularly for groundwater recharge. Therefore, using an appropriate decision support system based on effective methodologies could manage this infrequent valuable water resource.

Flash flood have severe impacts on people, environments, infrastructure and economy. At the same time, many benefits of flash flood could be gained. In general flood hazards are most prevail in humid regions, but they are could be existed in more dangerous form at arid and semiarid regions, in the form of flash floods, which occur suddenly and wash away anything that comes in its front. Flash flood disaster at arid environment is associated with several challenges originated from many reasons that related to the features of the flash flood itself, arid environments characteristics, data limitation and methodology limitation. In the following sections, we will try to highlight and discuss the different dimensions of flash flood phenomena, reasons and resulted impacts. The different flash flood problems could be summarized at Fig. 1-1.

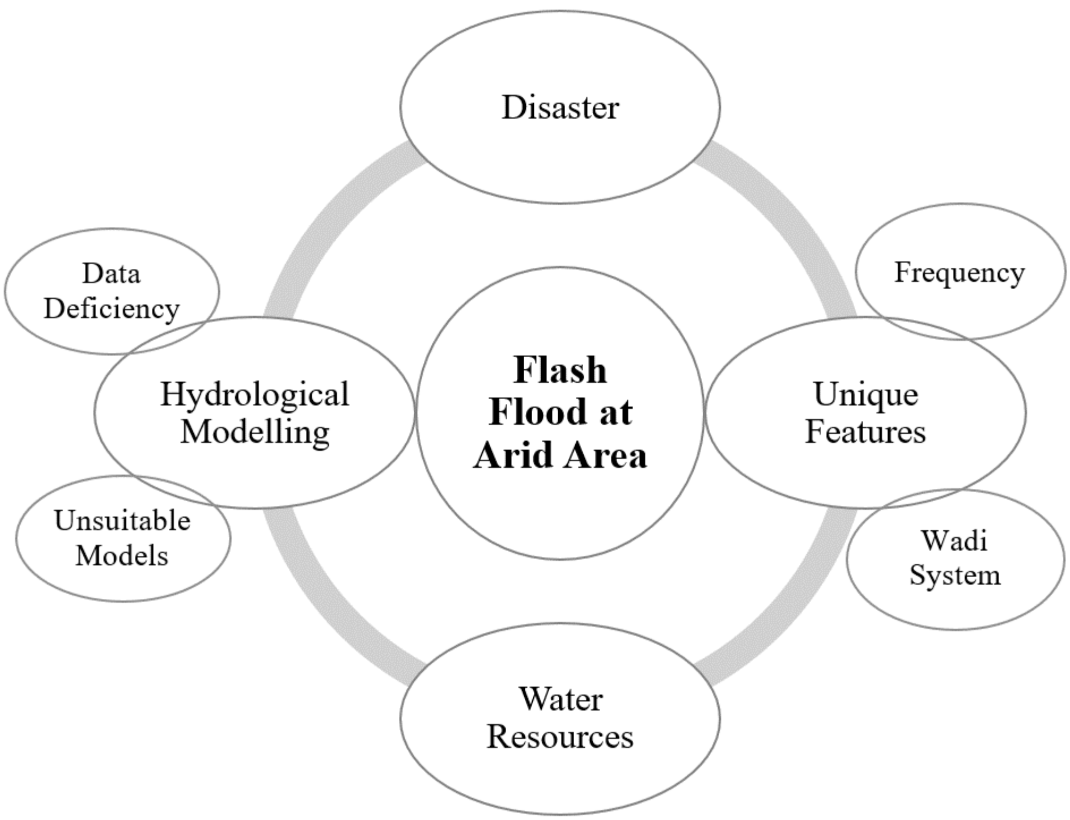

Fig. 1-1 Flash flood problems in arid environments after Saber (2010).

1.1.1 Flash flood disaster in wadi system

Floods as a natural disasters occur worldwide, however, their impact is greater ibn the developing countries (Alcantara-Ayala, 2002). The United Nations Office for Disaster Risk Reduction (UNISDR) reported that recently the Arab region was affected by more than 270 disasters during 30 years, causing in more than 150,000 deaths and affecting approximately 10 million people (EM-DAT, 2015). In recent years, flash floods hit Egypt several times causing life losses and significant damages. Destructive flash floods frequently occurred in Egypt between 1972 and 2016 as shown in Table 1-1. The information included in this table were collected from the available reports, newspaper, dissertations and published articles as Eliwa et al. (2015). These floods destroyed main infrastructures such as roads, buildings, power towers, villages, agricultural lands, pipelines, injured and killed human and animals. For instance, Oct. 2016 flash floods have left 26 dead people and dozens of millions of USD as damages in Ras Gharib City only. Oman has more severe causes for flash floods, which is tropical cyclones. As presented in Table 1-2 severe rainfall events caused several times in the last decades in Oman that triggered several destructive flash floods.

Fig. 1-2 Egyptians cross a flooded area in the Egyptian town of Rafah on the border with the Gaza Strip on January 20, 2010 (© Photo courtesy AF), b) Taba and Nweba flash flood May, 2010 (© El-Masry Elyoum).

Table 1-1 Main events and impacts of flash flood in Egypt.

Date	Affected area	Recorded damages
Oct. 2016	Ras Gharib, Red Sea region	29 death, roads, cars and agriculture damages
Feb. 2015	Sinai, Red Sea region	Road damages
Mar.& May 2014	Taba, Sohag, Aswan, Kom Ombo	Dam failure at Sohag, road damages
2013	South Sanai	2 death, road damage
2012	W. Dahab , Catherine area	Dam failure, destroyed houses
Jan. 2010	Along the Red Sea coast, Aswan, Sinai	12 death, damaged houses& roads
Oct. 2004	W. Watier	Road damage
Mar. 2002	Southern Egypt-Shalatein	4 death, 800 displaced persons
May 1997	Safaga, El-Qusier	
Nov. 1996	Hurghada, Marsa Alam	200 death, destroy roods, demolished houses damaged vehicles
Sep. Nov. 1994	Assiut (Dronka), Sohage, Qena, Safaga, El-Qusier, Dhab	
Mar. Aug. 1991	Marsa Alam, W. Aawag	Destroyed houses
Oct. 1990	W. El-Gemal, Marsa Alam	
Jan. 1988	W. Sudr	5 death
Oct. 1987	South Sanai	1 death, roads damage
May., Oct. 1979	Aswan, Kom Ombo, Idfu, Assiut, Marsa Alam, El-Qusier	23 death. demolished houses
Feb. 1975	W. El-Arish	20 death, road problems
1972	Giza	Destroying houses, roads and farms

Table 1-2 Cyclones history in Oman since 1970 (Al Barwani, 2015).

Date	Name& Type	Rainfall (mm)
Dec 1971	Cyclonic storm	99
Jun 1977	TC	430
Mar 1999	Low pressure-Sur	122
Oct 1999	Deep Low Pressure	69
May 2002	Cyclonic storm	58
Sep 2004	Low Pressure	116
Jun, 2007	Gonu, TC	626
June, 2010	Phet, TC	603
June, 2015	Ashoba, TC	204

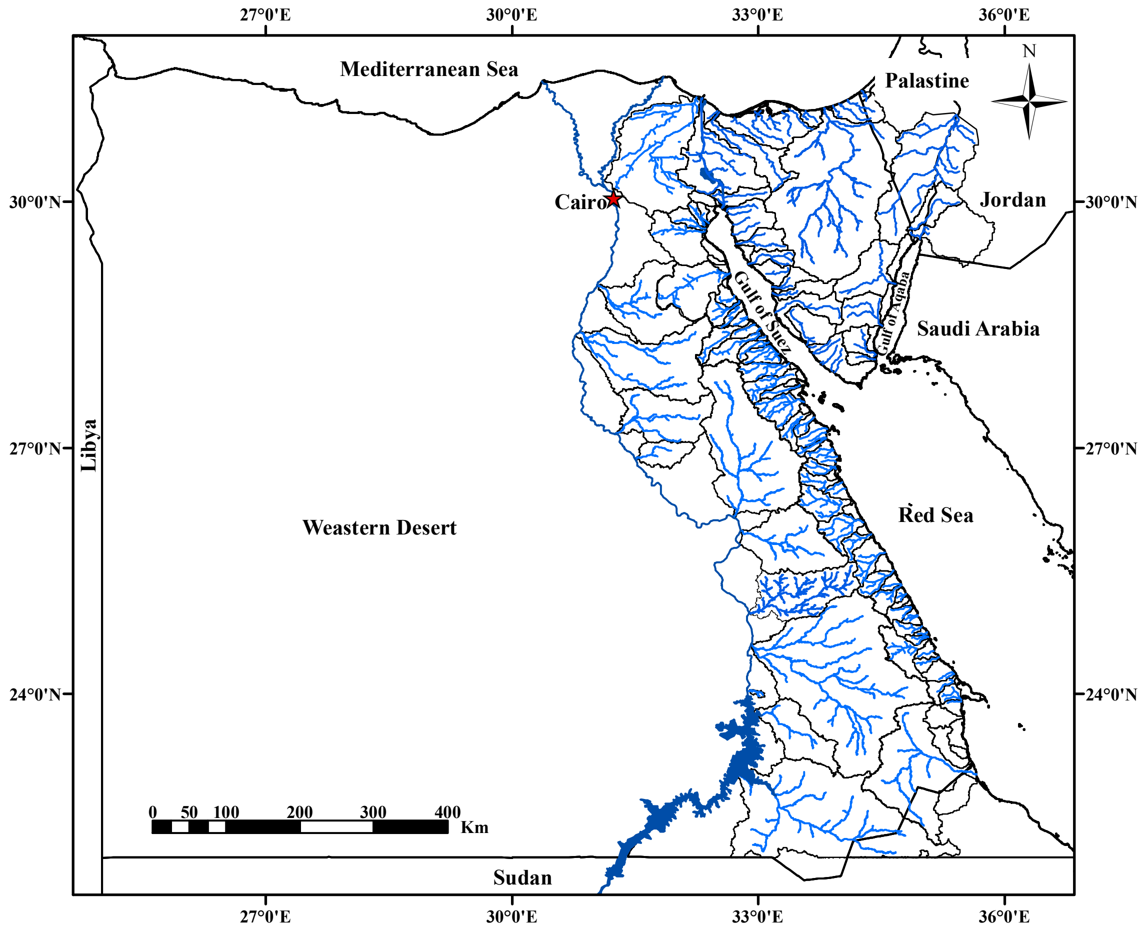

Fig. 1-3 Main wadis of the Eastern Deseret& Sinai Peninsula of Egypt.

1.1.2 Water resources shortage

Arid and semiarid environments cover 40% of the global land surface and are populated by approximately 1 billion humans (Veron et al., 2006). In addition, 40% of Africa's population lives in arid, semi-arid, and dry sub-humid areas (IPCC, 2001). According to the World Bank, 2009 the Middle East region is the world's most water-scarce region. The World Bank states that the average global water availability per person is close to 7,000 cubic meters per person per year (m^3/person/year); the Middle East region, however, has only about 1,200 m^3/person/year, and the population is expected to grow from about 300 million in 2012 to about 500 million in 2025. Water per capita availability is expected to halve by 2050 (Bank, 2009). Water scarcity in the Middle East could disturb human welfare, the economic growth and stability in the region. Several efforts are needed to prevent the expected crisis in the Middle East region and to avoid potential conflicts in the area that might arise because of water shortages. Perhaps the most important of these activities is exploring alternative renewable water sources as flash flood. To achieve that we must also understand the hydrological processes of the wadi system.

In particular, the Arabian countries lack permanent and renewable surface water resources such as streams and lakes because they lie within the arid belt of the earth. The people of these countries are dependent on groundwater (from both shallow and deep aquifers), and a small number of springs. The two latter resources are seriously depleted at present because of misuse, excessive pumping and poor maintenance, where large volume needed for domestic, agriculture and other purposes. Groundwater is depleted which means that these countries are facing a real water shortage problem. Currently, they are also using desalinated water regardless of the high cost of its production.

Groundwater recharge is one of the main positive impacts of flash flood. Generally the majority of countries in arid and semi-arid regions depend either on groundwater (from both shallow and deep aquifers) or on desalinization for their water supply, both of which enable them to use water in amounts far exceeding the estimated renewable fresh water in the country (Saber, 2010). However, there are some important water-related problems in these countries. These include the depletion of aquifers in several areas, saline-water intrusion problems, and water quality problems such as those associated with industrial, agricultural, domestic activities and human effect (Saber, 2010).

Egypt lies in arid and hyper-arid regions, where its rainfall is very low, irregular and unpredictable and the desert covers most of the land. Annual rainfall ranges between a maximum of about 200 mm in the northern coastal region to a minimum of nearly zero in the south, with an annual average of 51 mm (FAO-AQUASTAT, 2014). Nile water is insufficient to meet all the Egyptian demand especially in the future due to increasing of the population. According to the general census of Egypt for population monitor, the population has reached 95 million inhabitants (86.8 million inside Egypt inhabitants (Egypt, 2014) of whom about 99% are concentrated in the Nile Valley and Delta. In addition to its fixed Nile quota, a deep groundwater reservoir, which is not renewable, may be utilized with a rate of 2.7 BCM/year over a period of 100 years. The higher the exploitation rate, the shorter the period of use will be (Allam and Allam, 2007). Water demand in Egypt is increasing due to population growth, higher standard water of living, reclaiming new land, and advancing industrialization. Available water per capita per year for all purpose in 1999 was about 900m^3; nonetheless, it is expected to fall to 670m^3 and 536m^3 by the years 2017 and 2025, respectively (OECC, 2005).

Egypt share of the Nile River could be effected by anthropogenic effect as dams construction in the Nile river upstream countries. To make matters worse, rainfall fluctuation and climate change are expected to increase water scarcity in Egypt. These combined factors will drive Egypt to severe water stress. Therefore, it is a major challenge facing Egypt today is to manage escalating demand for water and flash flood management is so critical.

Oman is located in the southeastern part of the Arabian Peninsula and exist location on the arid and semi-arid region where water resources are very scarce. Groundwater is the main source of water supply representing 92% of the total renewable water resources where the rest is surface water (Ghaily Aflaj, wadi base flow) (Al Sulaimani and Tariq, 2010). After the next fifteen years, the water demand for water (i.e., domestic, industrial, commercial and municipal purposes) is expected to increase by more than 50% as a result of population growth, increased demand for food and domestic water, improvement and extension of water services and increased industrial water demand within the economic development (MPWS, 2003). Oman continues to increase the supply of desalinated water to respond to growing demand for residential water (Kotagama et al., 2016). The scarcity of water and threats of flash floods in Egypt Oman require further understanding the natural processes of water resources in order to manage and sustain current water resources and search for alternatives.

1.1.3 Data and tools limitation

Unfortunately, modeling the response of arid wadis to a rainfall event is challenging, due to lack of data, special characteristics of wadi, and consequently, developing powerful hydrological models is difficult. Different rainfall modeling tools and methodologies have been widely used, but almost all of them have been originally developed for humid area applications. However, arid and semi-arid regions facing severe scarcity of water resources and flash flood threat conversely this issue has received a little attention. It has been commonly stated that the major limitation of the development in arid-zone hydrology is the lack of high quality observations (Pilgrim et al., 1988). Precipitation events are irregular and highly variable in space and time and often highly localized. Flow measurements are lacking or uncertain. Moreover, many of the hydrological models however are built for more humid conditions that are not representing the arid conditions well (Cools et al., 2012).

Arid and semi-arid regions have a main feature of scarcity and high variability of water. Amount of water gain a single rainfall event can exceed the total runoff from yearly hydrographs. Another fundamental difference between arid and humid environment is that significant amounts of water are lost in the downstream locations in arid and semi-arid regions. These are mainly due to evaporation and infiltration losses. In some locations, such transmission losses can be up to 100% of the original discharge, which means there is no surface flow in the wadi. In general, in humid regions, discharge increases in the downstream direction, whereas and regions Just the opposite is valid. In humid regions, groundwater contributes to rivers during dry periods, but in arid regions the surface flow is very much reduced or absent because the groundwater table is usually already depressed (Sen, 2008b).

Due to aforementioned reasons, the hydrological processes of arid lands are different from that of humid areas, and raise particular challenges. Developing the hydrological models and methodologies are highly required in arid and semi-arid regions.

Flow measurement is particularly difficult in arid zones for several reasons according to many studies (e.g., Abushandi, 2011; Kilpatrick and Cobb E., 1985; Lange et al., 1999; Lin, 1999; Pilgrim et al., 1988; Rodier and Roche, 1978) and could be summarized as following: 1) The quick rise and fall of the water level during flash floods; 2) Difficulty of securely installing measurement devices within the study area; 3) Lack of suitable natural control sections in streams with movable beds, and high cost of artificial control; 4) Harsh climatological and physical conditions; 5) Sediment transport, moving rocks and debris may damage instruments placed in the wadi; 6) Access difficulty due to few drivable roads, especially during the rainy and flooding seasons; 7) Usually low population density at the arid environments; 8) Lack of awareness of floods studying and monitoring importance and 9) Cost of flood monitoring devices especially for developing countries such as Egypt.

1.2 General description of the study area

The study area is located in the arid belt of North Africa and the Arabian Peninsula that contain many wadi systems vulnerable any time for risky flash floods. Tow countries representing different climatic, hydrological, land use and observations characteristics, which are Egypt and Oman contain the study areas as indicated in Fig. 1-4 Table 1-3. Egypt has very dry and arid climate with low average annual rainfall, whereas has semiarid to arid climatic condition and higher average annual rainfall. The storm types causing wadi flash floods are different in the both countries, where Oman could has tropical cyclones. For water resources, Egypt is totally depend on Nile River and Oman depend on the harvested rainfall water, groundwater and desalination. Oman has much better observations for rainfall and wadi flow than Egypt where most of wadis are completely ungauged. Therefore, selecting wadis from both countries expected to cover wide range of wadi system unique characteristics and challenges. Four typical wadi systems in Egypt (Qena and Abadi wadis) and Oman (Samail and Aday wadis) have been selected (Fig. 1-4) to study WFFs issues with area ranging from 300 km^2 to 16,000 km^2 and average annual rainfall from 20mm to 90mm.

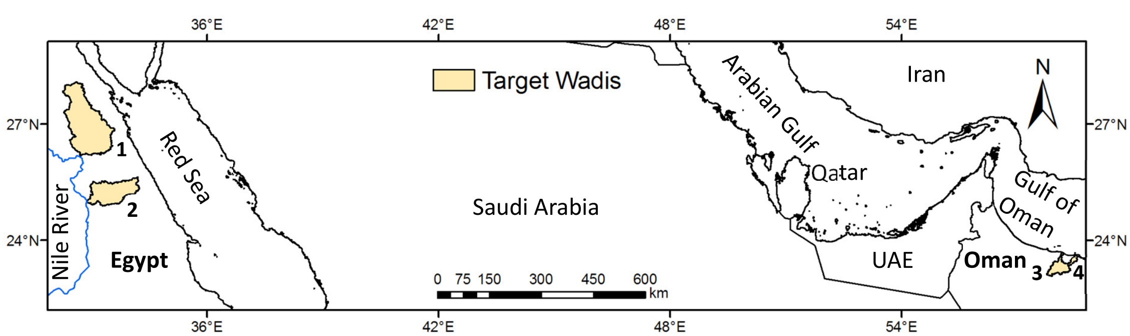

Fig. 1-4 This study target wadis location map: 1) Wadi Qena, 2) Wadi Abadi, 3) Wadi Samail and 4) Wadi Aday.

Table 1-3 General comparison between wadi's characteristics for the selected case studies in Oman and Egypt.

Aspect\Case study	**Egypt**	**Oman**
Climate	Hyper arid to arid	Arid to semi-arid
Storm types	Convective storm	+Tropical Cyclones, Cold Frontal Troughs (Al Barwani, 2015)
Rainfall frequency & intensity	Lower	Higher
Wadi flow	Base flow is totally absent	Intermittent base flow could be existed in some wadis
Topography	Medium relief	High relief
Developing	Downstream only	More distributed
Data	Rare& Poor	Better

1.3 Overall objectives

Objectives of this study are: 1) to review the key terms and studies related to hydrological process, assessment, mitigation and management of the wadi flash floods in Egypt and the Arabian peninsula; 2) to understand the main process impacting the wadi flash flood generation; 3) to propose an approach of wadi flash flood assessment under the data scarcity situation in the wadi system; 4) to evaluate and compare between different hydrological models to find the best option suitable for wadi unique characteristics; 5) to propose and evaluate variant mitigation measures for wadi flash floods and 6) to

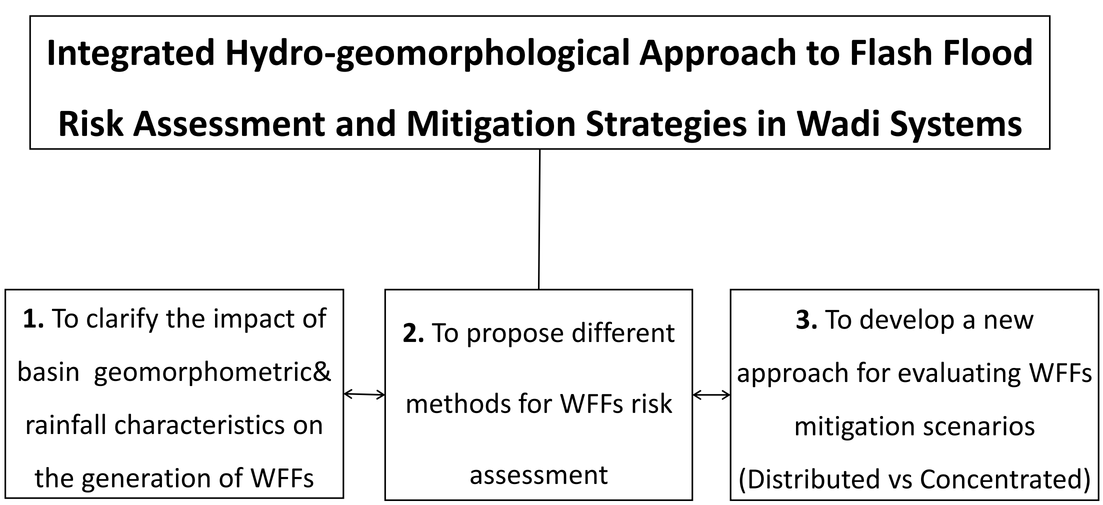

Fig. 1-5 The overall objectives of this thesis.

propose an integrated management strategy for wadi flash floods. The overall objectives are summarized in Fig. 5-1

1.4 Layout of the thesis

The general structure of the thesis is indicated in Fig. 1-6 as following:

Chapter 1 Introduction: we introduce the motivation of this study including general introduction of the flash floods in the wadi system, the target study areas and summarizing of the chapters involved in this thesis.

Chapter 2 Theoretical bases and state-of-art: defines the key terms included in this thesis the detailed literature review of the previous studies and challenges related to the thesis objectives.

Chapter 3 A Geomorphometric and hydrological approach to understanding the generation of wadi flash floods: explains the main geomorphometric and hydrological factors contribution to wadi flash floods using Wadi Qena, Egypt as a case study.

Chapter 4 Wadi flash flood risk assessment: analysis the main toots used for the flash flood evaluation and compare between two hydrological models application and performance in the wadi system. Furthermore the flash flood susceptibility has been assessed.

Chapter 5 Evaluation of the structural wadi flash flood mitigation measures: includes a framework for assessment of wadi flash floods mitigation measures using variant dams setting and quantification the benefits and disadvantage of each mitigation strategies based a number of management issues.

Chapter 6 Integrated management of the wadi flash floods: presents general framework for flash floods management in the wadi system, which involving several aspects that should be involved for sustainable and integrated management.

Chapter 7 Conclusions and recommendations: summarizes the conclusions and outcomes of this thesis and provides recommendations for future studies.

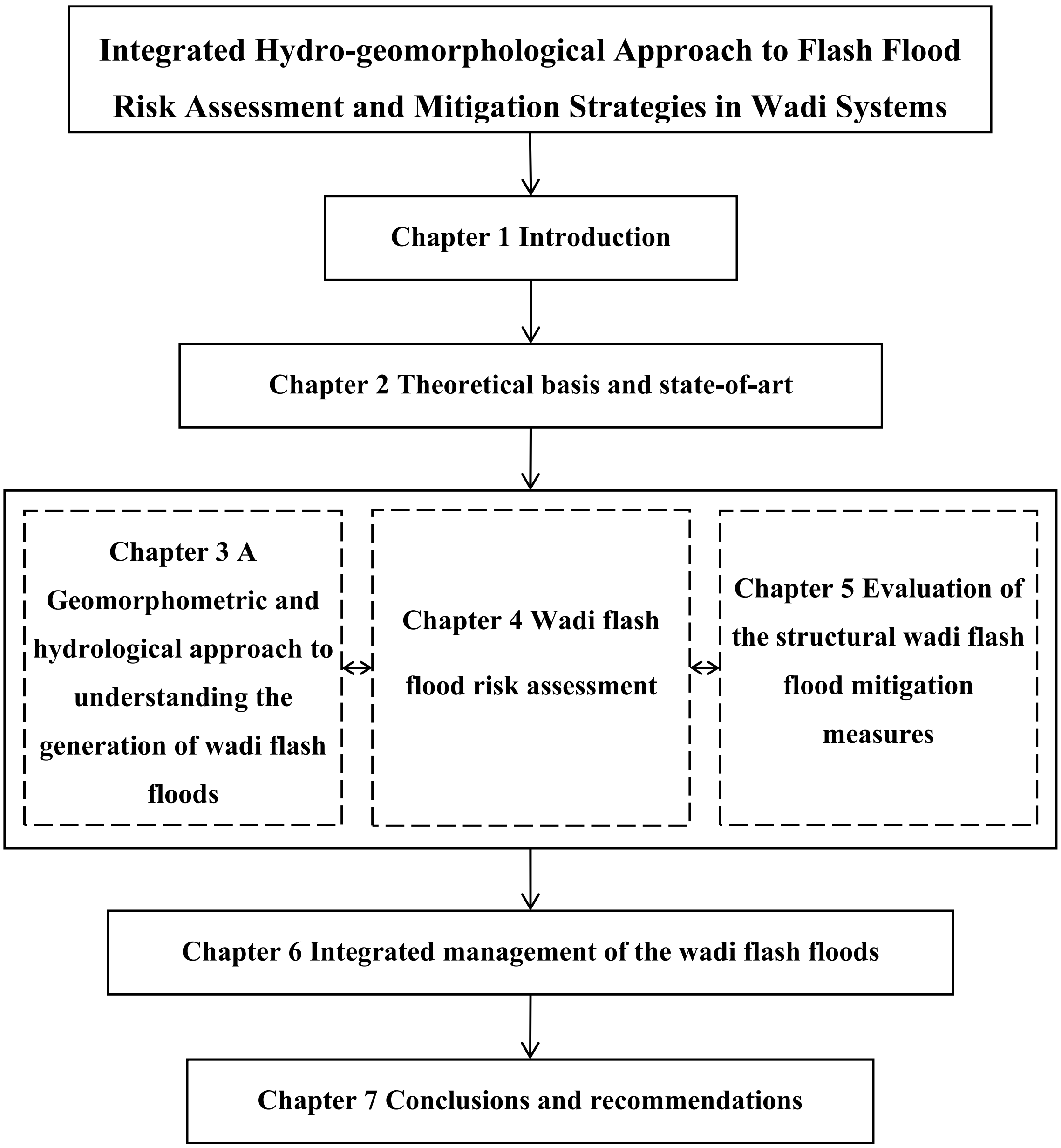

Fig. 1-6 Structure of the thesis.

Chapter 2 Theoretical bases and state-of-art

2.1 Key terms in the thesis

2.1.1 Wadi

Wadi is an Arabic term, which refers to a valley and usually its channel is dry except during heavy rain events (Sen, 2008b). It can be used to describe the ephemeral streams in arid regions, and usually wadi represents an important source of water in deserts and most of arid countries. Wadi Hydrology has emerged as a distinct scientific area within the last decade, within and without the Arab region due mainly to the increasing interest about wadi and its water resources. This has been due to the recognition that the hydrology of arid and semi-arid areas is very different from that of humid areas and raises important scientific, technical and logistical challenges, and that an improved science base is essential to meet current and future needs of water management (Wheater, 2002).

Generally, wadi basins are suffering from drought conditions all year as shown in Fig. 2-1 except during infrequent rainfall events, which could transformed to a disaster in a short time, in the form of flash floods as indicated in Fig. 2-2. The flash flood in the wadi basin is occurring within a short duration and rapidly rising water flow level due to the causative event of intense rainfall or dam failure resulting in a greater danger to human life and severe infrastructural damages (Fig. 2-2). It is almost accompanied by landslides, mudflow and debris flow (Saber et al., 2010).However wadi is rich in resources, there are lack of development. Therefore, the scarcity of data and the lack of high quality observations are important characteristics of the ephemeral streams in arid regions. Consequently, the assessment of hydrological processes is very difficult in wadi system.

The following general arid region characteristics could describe the wadi system:

1. Stream flow characterized by absence of base flow and flash-floods during infrequent high-intensity rain events,
2. High flow variability, extended periods of zero surface flow and the general absence of low flow except during the recession periods immediately after moderate to large high flow events (Knighton and Nanson, 1997),
3. The rainfall regime characterized by short duration events that are of highly localized spatial extent (Wheater et al., 1991), so surface runoff is characterized by discontinuous flow,
4. High evaporation rates,
5. Sparse plant cover and organic matter (McIntyre and Al-Qurashi, 2009).

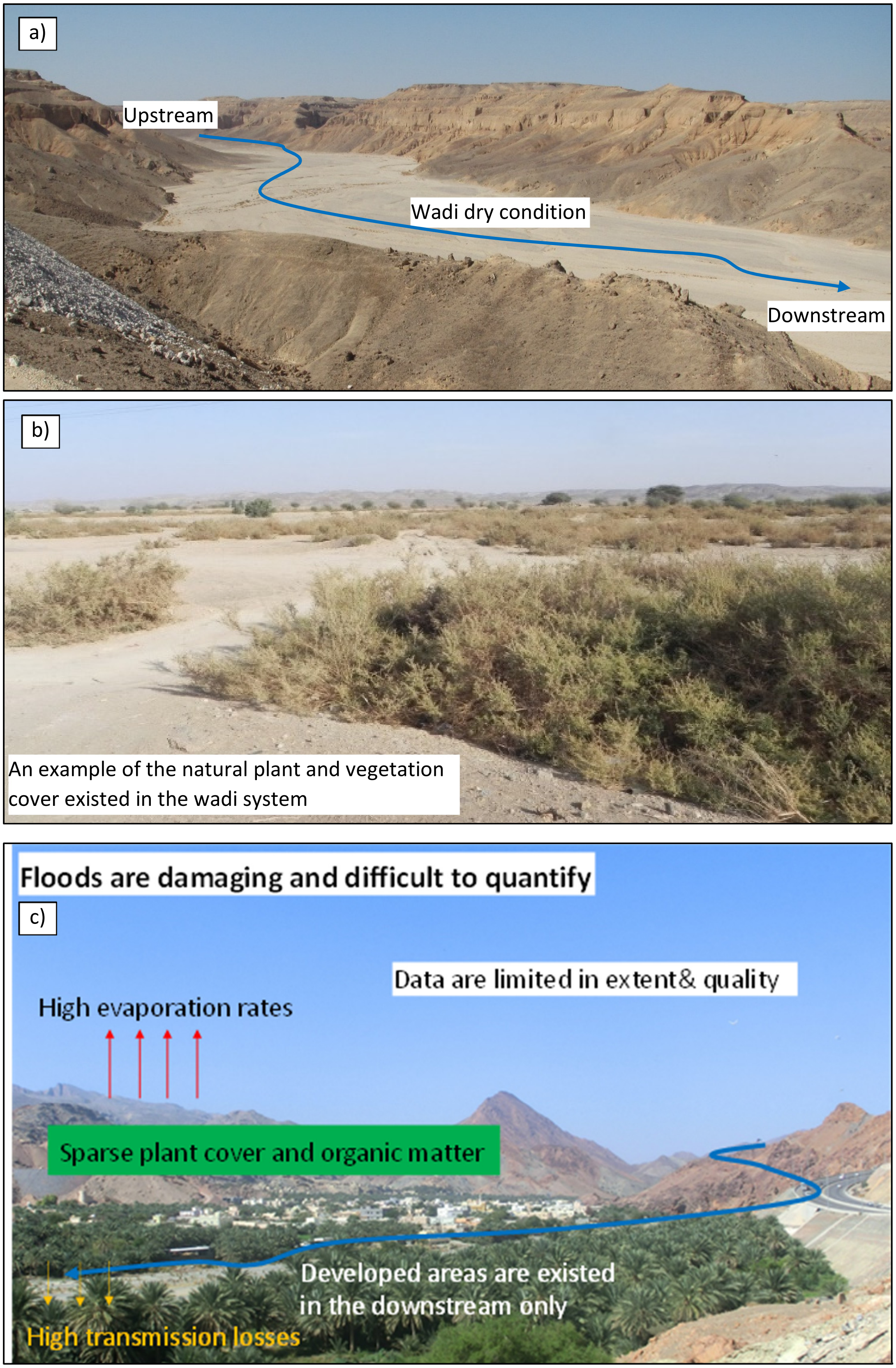

Fig. 2-1 Arid wadi system in: a) Wadi Qena, b) Wadi Abadi and c) Wadi Samail and summary of wadi characteristics.

2.1.2 Flash floods

Floods, as in of the most common natural hazards are caused by rive r overflow, heavy rainfall, tidal surges, snowmelt and groundwater seepage (Shah et al., 2015). Flash flood is a flood produce in a very short time and can be caused by extreme storm, particularly when it takes place in steep slopes with shallow, impermeable soils, bare rocks and rare sparse vegetation (Lin, 1999) or a saturated area where rain has previously fallen or the ground impermeable. In those conditions the excess rain runs off over the surface and the subsurface flow accumulates in streams and rivers at a much accelerated pace. A flash flood can also result from a failure of dams, embankments, other hydraulic structure or even natural dams created by landslides or debris. Heavy rains, most frequently connected with convection clouds, cover small regions and are short-lived (from a few minutes to a few hours), but very intense such as 100 mm (or 100 Liters per square meter) in the duration of an hour or more (APFM, 2007). Flash floods in deserts could be danger, where these rains often fall on poorly absorbent and often clay-like soil, which greatly increase the amount of runoff higher than rivers and other water channels capacity (Saber, 2010)

Topographical factors are key for the genesis and evolution of the quasi-stationary convective systems (or in simplified terms “slow moving rainfall cells that release large amounts of water over a relatively small area”) that are often the cause of flash floods. From the hydrological point of view, on the other hand, factors that have a decisive influence on the occurrence of flash floods - apart from the intensity and duration of the rainfall - are the topography, soil conditions, and coverage of the terrain. Topographical conditions such as high-exposure (steeply sloping) highland terrains, narrow valleys or ravines hasten the runoff and increase the likelihood of flash flood occurrence. Saturated soil or shallow watertight geological layers increase surface runoff. Terrain coverage can have a similar effect. Urbanization processes and affiliated construction with watertight materials are thought to make runoff 2 to 6 times greater in comparison to terrains with natural coverage (fields, meadows, forests).

Fig. 2-2 Flash floods in Wadi Aday (MRMWR, 2012).

In summary there are various factors contributing to flash flood risk, some being influenced by human intervention and others entirely rather independent from human action. The phenomenon of the flash flood is one of the most difficult natural hazards to predict in terms of time and place of occurrence. As a result, it is challenging for the concerned authorities and communities to respond appropriately and response plans are indispensable too (APFM, 2007).

During a flash flood, there is a sudden rise in the water level in rivers and streams, and flow velocity can be very high. The force of the water can be so great as to tear away boulders, uproot trees, and destroy bridges and buildings that stand in its path. Rushing water often changes the riverbed, and it can therefore appear in places where it usually does not. Water at a depth of 1 m and a speed of 1 m/s can pose a deadly danger for an adult person, while flash floods often flow at significantly higher speeds, making a water level of just a dozen cm very dangerous (APFM, 2007). Early warning system could be the key element in reducing the risk to lives and property. Conventional forecasting methods cannot provide adequate warning and people have insufficient time to move away from the floods.

Another source of flash flood hazard is the transported sediments and debris during flood (Fig. 2-3). Hungr et al.(1987) described the debris flow hazards as follows: (1) hazards related to the direct impact of high-energy coarse-grained debris that can destroy structures, (2) hazards due to the indirect impact lower-energy of coarse and fine grained debris that can bury structures, and (3) hazards from flood

Fig. 2-3 A drifted and buried vehicle in the downstream part of Wadi Urana at Makkah, KSA during the 30th of December, 2010 flash flood (El Bastawesy et al., 2013).

waters that are forced from the normal channel by debris deposits and have the potential to erode unprotected surfaces and cause flood damage.

2.1.3 Aridity

Aridity in English meaning being without water or extremely dry. In climatology, aridity is a climatic phenomenon reflecting shortage of moisture, that is based on average climatic conditions over a region (Agnew and Anderson, 1992). A fundamental distinction exists between aridity, which is a long-term climatic phenomenon and droughts, which are a temporary phenomenon (water deficit). Both the arid climate and topographic variations contribute to the variation in rainfall. Arid regions includes Northern Africa, the Arabian Gulf, Southwestern part of United States, the western coast of South America, Australia, and Northern China (Fig. 2-4). Egypt and Oman are classified as hyper-arid to arid country (Fig. 2-4). The term aridity describes a dry hot climate, with a precipitation threshold less than 250 mm per year.

2.2 Previous work

The geology, geomorphology, and hydrogeology of wadi system have been studied by many studies as (e.g., Abdel Moneim, 2005; Abdelkareem and El-Baz, 2015; Elewa and Qaddah, 2011). However, other wadi aspects, which more related to flash flood like hydrological modelling, risk assessment and integrated management not sufficiently covered. We will tray in the following section to summarize the literature that related to flash floods at the arid wadis.

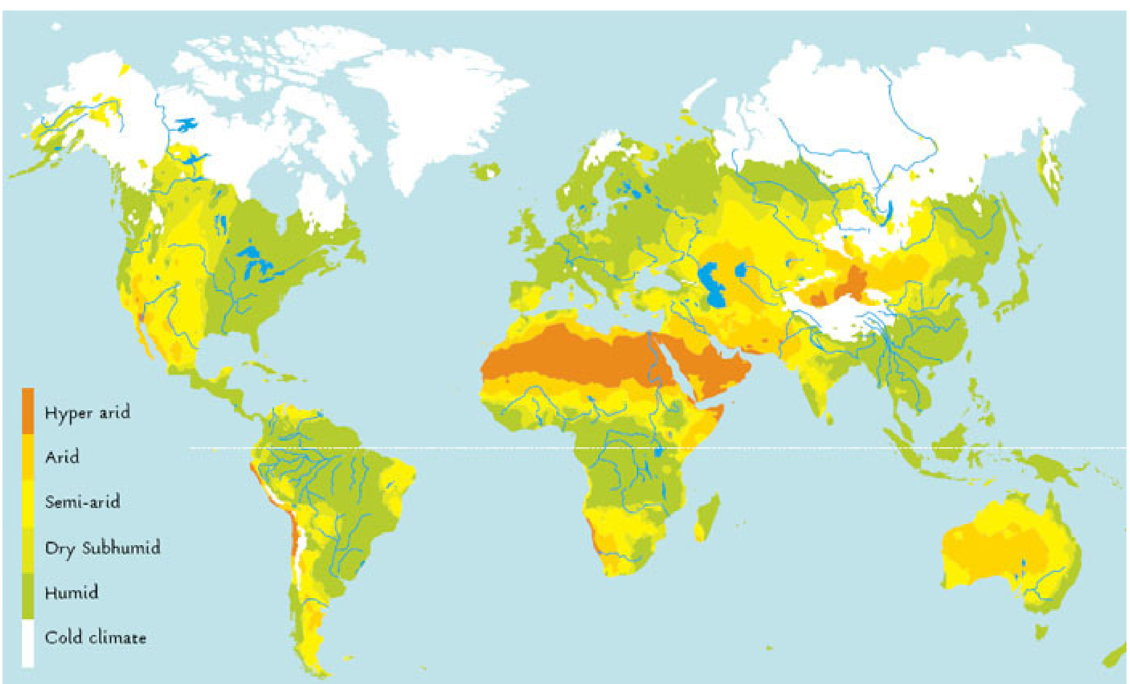

Fig. 2-4 Arid zone all over the world © CRU / UEA, UNEP / DEWA.

Table 2-1 Wadi flash floods literature review summary.

Reference	Study area	Main tools	Field
(Nouh, 1990)	Southern KSA		
(Al-Weshah and El-Khoury, 1999)	Petra, Jordan	HEC-1, SCS, CN	RRM , FF manag. and mitig.n
(McLane and Wüst, 2000)	Valley of Kings, WD, Egypt	Field Inv., Planning	FF management and mitigation
(Foody et al., 2004)	Idfu-Marsa Alam road (Red Sea), Egypt	RS, HMS, field inv.	RRM
(Nouh, 2006)	Arabian Gulf	Measured data, SA	SA, Regression analysis
(Sen, 2008a)	W., Baysh, KSA	EE, UH, measured data	SA, RRM using EE and UH
(El Bastawesy et al., 2009)	W. Hudain, ED, Egypt	RS, GIS,	RS, RRM
(Milewski et al., 2009)	Main wadis in ED& SP, Egypt	RS, RESDEM, GIS, SWAT	RS& RRM, GW recharge
(Youssef et al., 2009)	Red Sea Safaga (W. El-Baroud) to Quseir (W. Ambagi), ED, Egypt	GIS, RS, Field inv., Elshamy model	Morphometry, FF HA (Elshamy), Mass movement HA
(Abou El-Magd et al., 2010)	Abu-Dabbab, Marsa-Alam, ED, Egypt	GIS, RS	FF estimates
(Al-Rawas and Valeo, 2010)	North Oman wadis	Measured data, SA	SA, morpho, regression analysis
(Al Saud, 2010)	Jeddah, KSA	GIS, RS	HA
(Arnous et al., 2011)	Suez Gulf, ED, Egypt	GIS, RS	FF HA (Elshamy)
(Dawod et al., 2011)	Makkah, KSA	GIS, SCS	RRM, Morphometry
(Youssef et al., 2011)	Feiran-Katherine road, ED	GIS, RS, Field inv., Elshamy model	Morphometry, FF HA (equal weight classes & Elshamy)
(Omran et al., 2011)	W. Dahab, Suez gulf, SP	GIS	Morphometry, RA
(Ibrahim et al., 2011)	W. Abadi, ED, Egypt	RS, GIS, Field inv., SMADA6	Morphometry, HA, RRM, Hydrogeology, GW qual.
(Abdel-Lattif and Sherief, 2012)	W. Sudr, W. Wardan, SP, Egypt	RS, GIS, El-Shamy	Morpho, HA (Elshamy), RRM using EE
(Soussa et al., 2012)	W. Hodin, ED, Egypt	WMS, HEC-1, SCS for losses and UH	RRM
(Subyani et al., 2012)	Yanbu, Makkah, Jeddah KSA	GIS, SA	Morpho, SA
(Ghoneim and Foody, 2013)	Idfu-Marsa Alam road (Red Sea), Egypt	RS, HMS, field inv.	RRM
(Hadadin et al., 2013)	Jeddah, KSA	UH, SA	RRM
(Taha et al., 2013)	Nabq Protectorate, Sainai, Egypt	GIS, RS. El-Shamy	HA (Elshamy)
(Sen et al., 2013)	W. Hali and W. Yiba, southwestern KSA	Field inv.	HA
(Youssef and Maerz, 2013)	KSA	RS, Field inv.	HA, General overview
(Bajabaa et al., 2014)	W. Al Lith, KSA	GIS	HA
(Shi, 2014)	6 wadis in west of KSA	GIS, morphometry, UH, EE	HA, RRM
(Elkhrachy, 2015)	Najran, KSA	AHP, RS, GIS, HEC-HMS, SCS	HA, RRM
(Eliwa et al., 2015)	Egypt	Literature review	Literature review, FF causes, management
(Youssef et al., 2015)	W. Al-Aska basin, Jeddah, Egypt	GIS, AHP	HA
(Abuzied et al., 2016)	Nuweiba, SP, Egypt	GIS, RRM, SCS, EE, RS	Morpho, HA, RRM using SCS
(Abdelkareem, 2017)	W. Asyuti	GIS, RS	HA
(Abdel-Fattah et al., 2017)	W. Qena, ED, Egypt	GIS, RS, SA	RRM , HA

AHP Analytical Hierarchical Process, ED Eastern Desert, EE Empirical Equation, FF Flash Flood, GIS Geographic Information System, Gw Groundwater, HA Hazard Assessment, RRM Rainfall-Runoff Modelling, PCDs Physical Catchment Descriptors, RA Risk Assessment, RESDEM Remote Sensing Data Extraction Model, RS Remote Sensing, SA Statistical Analysis, SP Sinai Peninsula, SWAT Soil Water Assessment Tool, UH Unit Hydrograph, W. Wadi, WD Western Desert

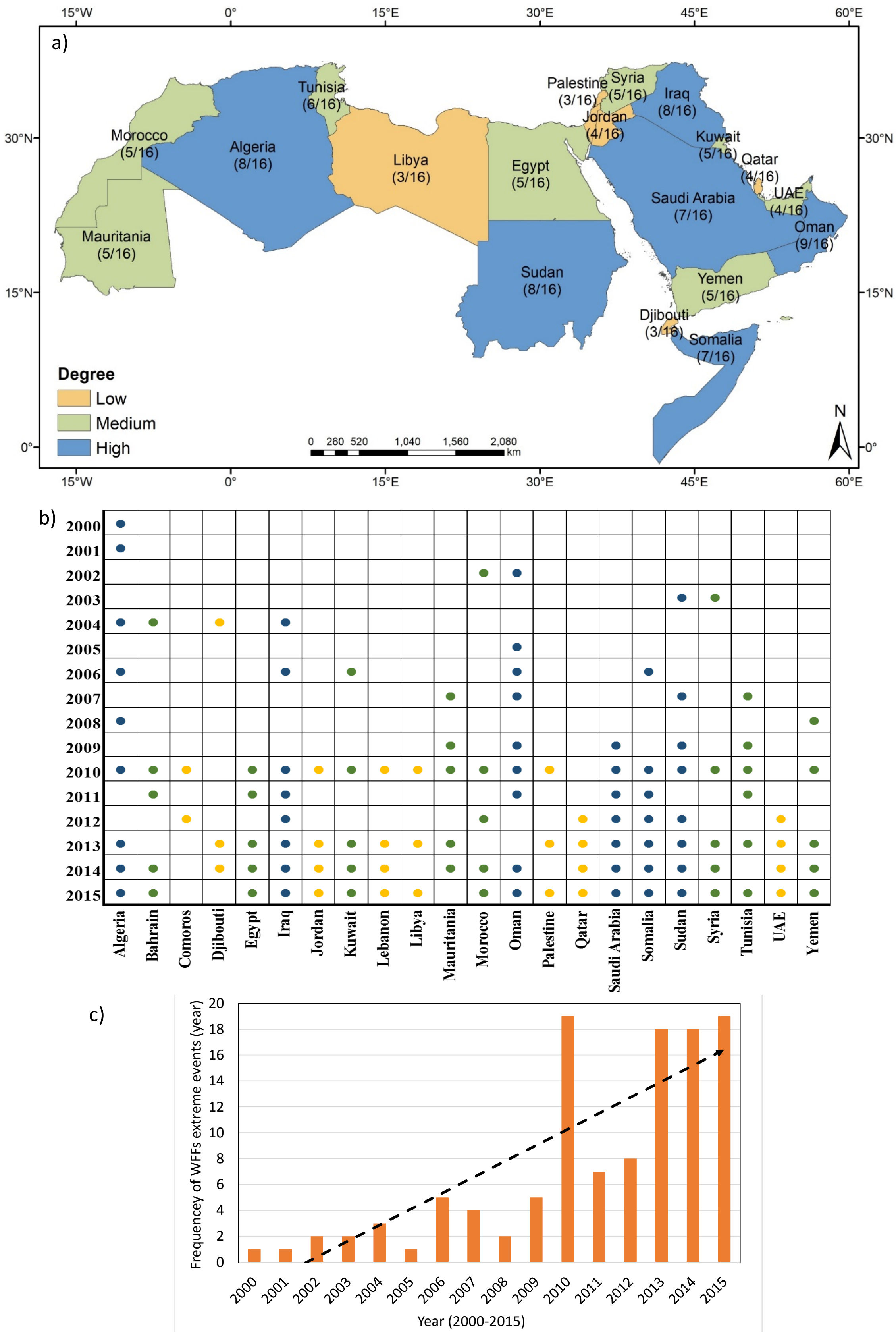

Fig. 2-5 Flash floods extreme events in the Arabian Region (2000-2015): a) flash flood events frequency map, b) flash flood records per country, c) flash flood frequency per year all over the Arabian Region.

2.2.1 Hydrological modelling

The complex real hydrological system could be simplified using the hydrological models. These models mathematically represent the different hydrological processes as surface flow and groundwater processes and comprise essential tools for controlling and managing water resources. Hydrological models are indispensable due to the limitations of hydrological measurement techniques and complexity of the natural hydrological systems (Beven, 2011).

a) Hydrological modelling in arid region

Flash floods in arid regions result from irregular and extreme rainfall storm. These events occur when conditions, such as soil moisture, infiltration conditions, steep slope (Rodier and Roche, 1978), and high rainfall intensity, are fulfilled. Stream flow in arid and semi-arid regions is usually has a rapid responses to intense rainfall events. Such events frequently have a high degree of spatial variability, coupled with poorly gauged rainfall data. These conditions limit the ability of the rainfall-runoff model to regenerate the observed flow (Wheater et al., 2008).

Only a limited number of rainfall-runoff models have been applied, modified and developed for wadi environments as: the IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evapotranspiration and Streamflow) model in Oman (McIntyre and Al-Qurashi, 2009), The KINEROS2 (Kinematic Runoff and Erosion) model in Oman (Al-Qurashi et al., 2008), the HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System) model in Oman, West Bank-Palestine and UAE (Al-Rawas and Valeo, 2008; Shadeed and Almasri, 2010; Sherif et al., 2010), and the SWAT (Soil Water Assessment Tool) model in UAE (Abushandi, 2011; Al Mulla, 2005).

In addition to the aforementioned researches, there are several trials as Al-Weshah (1999) who has applied and calibrated HEC-1 model utilizing SCS and curve number CN methods in Petra region in Jordan and further used this hydrological modeling tools to check the impact of several mitigation scenarios. Abdulla et al.(2002), developed a simple single event watershed model to simulate the surface runoff in the western part of Iraq. In Saudi Arabia, Al-Turbak (1996) applied a geomorpho-climatic model, where rainfall intensity and duration are calculated from physically-based infiltration components, in three arid catchments. In Palestine, Lange et al. (2000) studied the importance of single events in arid zone rainfall-runoff modeling. This study concluded that separate analysis of single events is crucial for understanding of high magnitudes floods in arid regions. Finally, the Spatial Water Budget Model (SWBM) and HEC-HMS model were applied to manage water resources in the Zarqa River basin (Abushandi, 2011; Al-Abed et al., 2005). Dawod et al. (2011; 2012) have been incorporated SCS or curve number method in GIS for assessing the flash flood, the impact of some basin geomorphometric parameters on the estimated flood characteristics in Makkah metropolitan and to classify the flood hazard degree in the city roads.

Foody et al. (2004) predicted sites at risk from large peak flows associated with flash flooding in wadis intersecting the Idfu-Marsa Alam road (near to Red Sea), using HEC-HMS model and field observation of the soil texture and infiltration capacity. This study was further updated using the same model setting by Ghoneim and Foody (2013) to investigate the impact of rainfall depth, areal coverage and location on flash flood generation.

El Bastawesy et al. (2009) presented an approach for modelling flash floods by integrating remote sensing and DEM data in GIS. In this research the parts of a catchment that have been affected by a recent flood event discriminated from unaffected parts, using a time series of Landsat images due to the increasing spectral reflectance of channels affected by flash floods, as result of deposition of fine sediments in these channels. This synthetic GIS-based system only, cannot be relied on to model the hydrographs reliably, but physical parameters, such as rainfall intensity, distribution, and transmission loss, must be considered.

In the study of Ismail et al. (2010) the Flood Routing Processing (FRP) as a rainfall-runoff model and GIS used to calculate direct runoff volume, peak discharge and morphometric parameters at W. Abu Ghusun south of the Eastern Desert. Flash flood for some rainfall events for Nile River wadis simulated by Saber et al. (2010) linking the Hydrological River Basin Environment Assessment Model (Hydro-BEAM) with different satellite data.

Kehew et al., (2010) reconstruct high magnitude flash flood in W. Isla, South Sinai, using palaeohydrological parameters, where flood velocity and discharge is related to the size of boulders transported within the wadi though various theoretical and empirical methods. Further, the amount of rainfall necessary to generate a flood of the calculated magnitude range estimated using the calibrated SWAT model. W. Abadi was studied by Ibrahim et al. (2011) targeting to assess, evaluate hydrology and flood hazard degree and including potentials of both surface and groundwater resources in the wadi. Paleo flood height measured at the field utilized with rating curve to expect peak flow at Jan. 2010 flash flood event. Then this peak flow used in hydrological modelling parameters calibration.

Hydrological modeling conducting in Wadi Hodin using HEC-1 model by Soussa (2012) using SCS method to calculate the losses. (Hadadin et al., 2013) used routing and Snyder synthetic unit hydrograph methods to estimate the peak flow in 12 main basins at Jeddah City in KSA. Fathy et al. (2014) develop a lumped model to solve the hydrologic problems in arid watershed and compared with results from Watershed Modeling System (WMS). His model is applied to W. Sudr in Sinai Peninsula. The peak runoff discharge of six basins in western Saudi Arabia were estimated using the Snyder Unit Hydrograph and three empirical models (Nouh's model, Farquharson's model and Al-Subai's model) by Shi (2014). Abuzied (2016) conducted a hydrological modeling at Wadi Watier using SCS method.

Surface runoff interaction with the groundwater

There are some authors interested in groundwater recharge by surface runoff and rainfall events as Gheith and Sultan (, 2002#326) who investigate recharge of the alluvial aquifers flooring wadi El-Arish in Sinai and Eastern Desert (W. Tarfa, W. Asyuti, W. Qena, W. Hammamt). At these studies, a hydrological model that combined the spatial and temporal distribution of rainfall, suitable infiltration parameters, and appropriate sub-basin unit hydrographs used to estimate initial upstream loss, transmission losses along stream networks, and downstream runoff. The model incorporate remote sensing, meteorological, and geological data in a geographic information system (GIS) environment.

Milewski et al. (2009) made rainfall–runoff and groundwater recharge computations for main wadis at Sinai Peninsula and Eastern Desert due to heavy rainfall events between 1998 to 2007. That study basically rely on wide-range of global remote sensing data sets. For the investigated watersheds the average annual precipitation, average annual initial losses, average annual runoff, and average annual recharge through transmission losses were estimated. Also this methodology utilized to estimate average annual recharge for the Nubian Sandstone aquifer at South Sinai wadis (Sultan et al., 2011).

Good example for practical and cost-effective integrated (geochemistry, geophysics, and modeling) solutions that utilize web-based GIS technologies and global remote sensing data sets is presented by Becker et al. (2012) at Eastern Desert and Sinai Peninsula wadis. This study adopted methodologies to develop a conceptual model for hydrogeological settings conducive to groundwater accumulations of meteoric origin at different aquifers types, and construct a hydrologic model to estimate average annual runoff and recharge over the major watersheds.

2.2.2 Risk assessment

Regarding flash flood assessment El-Shamy, (1992) develop a method to evaluate the recharge and flash flood possibility at the different sub-basins, utilizing some of the geomorphometric parameters as bifurcation ratio, drainage density and drainage frequency. This model has been adopted later by many studies (Geriesh et al., 2001, Youssef and Hegab, 2005, El-Behiry et al., 2006, Youssef et al., 2009, Arnous et al., 2011, Youssef et al., 2011, Abdel-Lattif and Sherief, 2012, Taha et al., 2013, Abdalla et al., 2014).

Al Saud (2010) has been used high resolution satellite images to identify the 2009 flood damage in Jeddah City, KSA. Omran et al. (2011) used the standardization of morphometric parameters with same weight for basin based flash flood hazard assessment in Wadi Dahab, Saini Peninsula, Egypt. Same method applied in Wadi Al Lith (Bajabaa et al., 2014) and at Wadi Yanbu, Wadi Rabigh, Wadi Khulais, Wadi El-Qunfza, Wadi Baish and Wadi Jizanhe in KSA (Shi, 2014).

By integration of geological, geomorphological, field data and remote sensing data, a GIS-based geomorphological hazard assessment and mapping have been made at many areas in Egypt like Red

Sea area between Safaga and Quseir using El Shamy model (Youssef et al., 2009) and along the Feiran–Katherine road, South Sinai (Youssef et al., 2011). Presenting the effect of flash flood hazard on different urban infrastructures proposing dam sites to minimize the flood hazard. Hazard probability estimation of the different basins based on the morphometric parameters (El-Shamy, 1992a). Moreover, the morphometric analyses have been used to estimate the flash flood risk levels of sub-basins within the watersheds.

Flash flood hazards assessment also has been made in Abu Dabbab drainage basin. Remote sensing data were used to delineate the alluvial active channels, which were integrated with morphometric parameters extracted from DEM into GIS environment to construct a hydrological model that provides estimates about the amount of surface runoff and the magnitude of flash floods (Abou El-Magd et al., 2010).

Sen et al. (2013) has been proposed a procedure for establishment of flood inundation maps in the southwestern Kingdom of Saudi Arabia using surveyed cross sections of the flood plain. The main geological hazards and flash flood causes and main rainfall events in KSA have been summarized by Youssef et al. (2013).

Analytical Hierarchical Process (AHP) has been used by Elkhrachy (2015) to determine the flood hazard index in Najran, Saudi Arabia employing main controlling parameters of flash flood such as channel discharge, soil type, surface slope, surface roughness, drainage density, distance to main channel and land use. AHP further used by (Youssef et al., 2015) to utilizing variant geological, geomorphological, and geographical features in an approach of urban development in Wadi Al-Aska, Jeddah, KSA.

Abuzied et al. (2016) study has used multisource geospatial data with remote sensing techniques, GIS analyses, and field investigation to evaluate flash flood hazard in Nuweiba area based on the basin morphometric analysis and hydrological modeling indices using SCS method.

Abdelkareem (2017) has used three approaches basedon GIS and remote sensing tools to delineate the potential subabsins and areas that relatively more prone to flash floods in Wadi Asyuti utilizing the flood controling parameters such as the morphometric parameters and rainfall characterstics. The first method used smple classification of the morphometric parameters assumig that eadh paramter has the same weight on the resulted flood hazard whease the second method was assinging the parameter weight by standardization of the morphpmetric pramters values. Abdelkareem (2017) has stated that the previous basin based flood hazard assessmnt information are not effective in supporting the leaders and decision makers to take action in reducing flash flood hazards, because the hazard assessement is giving the same hazard degree for the entire sub-basin. Therefore he has used the rainfall anomalyies, drainage density and slope for more detailed flood hazard assessement in wadi system.

2.2.3 Flash flood mitigation and management

In wadi system, very few researchers study the different alternatives of flash flood mitigation, such as Al-Weshah (1999) who compare between various combinations of mitigation measures such as afforestation, terracing, construction of check and storage dams, and various combinations of these measures suing hydrological modeling tools in Jordan. McLane and Wüst (2000) make a master plan to mitigate the impact of flooding on the historic tombs in the Valley of Kings watershed. Integrated management approach proposed by Masoud (2004), which focuses on the integration of remote sensing and GIS techniques for flash flood potentiality, mitigation, and floodwater resource management in Safaga area at the Red Sea coast. Flood risk prone areas were mapped, suitable sites for building dams were detected, and highly probable sites for recharging water were located. Further, several rainfall-runoff analysis and discharge forecasting as well as flash flood inundation mapping techniques were performed to fully assess the flood potential. Eliwa et al. (2015) summarize the status of flash flood at Egypt, showing the development of management strategy.

a) Water resources and harvesting

To determine potential sites of surface runoff recharge at Sinai, remote sensing, GIS and watershed modeling were integrated to produce a multi-criteria-decision support system of different layers like volume of the annual flood, lineaments frequency density, basin morphometric parameters, average overland flow distance and soil infiltration. These criteria were used for conducting a Weighted Spatial Probability Modeling to determine the potential areas for the rainwater harvesting. The potential runoff available for harvesting was estimated by applying Finkel-SCS rainfall runoff methods (Elewa et al., 2012). Further, the same methodology used to propose the best dams location for the surface runoff control at W. El-Arish, design criteria and technical considerations were given for the proposed control structures (Elewa et al., 2013).

For groundwater recharge estimation and surface runoff, the relation between rainfall and runoff was calculated depending on the paleo-flood hydrology information. Two models were used to calculate the rainfall–runoff relationships for El-Hawashyia basin and Ghazala sub-basin (Gulf of Suez). To evaluate the flood hazard of the studied basins, some morphometric parameters with a direct effect on flooding have been studied, and their relationship with the flash flood was analyzed (Masoud et al., 2013).

Al Zayed et al. (2013) evaluated the water harvesting potential at W. Watier, South Sinai. The analysis is based on the Integrated Water Resources Management (IWRM) guidelines. Therefore, physical, social, environmental and institutional analyses were carried out. The potential runoff was estimated by applying the Soil Conservation Services (SCS) method using the Hydrologic Engineering Center (HEC-1) model, and then GIS was used to examine the potential sites by combining different geology, slope and land use layers.

2.3 Conclusion and recommendation

From the previous detailed review for flash floods in wadi system, the flash floods processed not well understood. The methods used in hydrological modelling mainly are simple empirical equations. The distributed models are rare to be used in wadi system. The flash flood mitigation studies are still missing and no integrated management concept or approach was presented in most of the arid wadis. The wadi flash floods research gabs and challenges are summarized in Fig. 2-6. We will try to fill some of the highlighted research gabs in the following chapters.

Fig. 2-6 Research gabs and challenges that related to wadi flash floods.

Chapter 3 A Geomorphometric and hydrological approach to understanding the generation of wadi flash floods

3.1 Introduction

Flash flood disasters occurring in the arid environment of a wadi, which means valley in Arabic, are associated with several challenges related to the unique characteristics of wadi systems, current data limitations and the use of inconsistent methods (Abdel-Fattah et al., 2016; Cools et al., 2012; McIntyre and Al-Qurashi, 2009). Arid wadis are characterized by the prevalence of a dry climate throughout the entire year, except during infrequent rainfall events that can produce flash floods. Costa (1987) indicated that arid or semiarid environments may experience more severe floods than humid areas with greater rainfall intensity. The infrequent nature of wadi flash floods (WFFs) and the absence of efficient disaster management strategy, combined with recent unplanned development activities and increased poverty, have reduced the ability of the wadi community to face such devastating disasters. In wadis, land reclamation and housing construction usually occur across the wadi channel and floodplain without undertaking the proper mitigation measures. However, floods in arid wadis are also an essential source of water, particularly for groundwater recharge.

Egypt is one of the arid countries that suffers from the effects of WFFs in the coastal and Nile River dry wadis (Fig. 3-1). For instance, during the January 2010 floods, ten people died and hundreds of houses were destroyed in Sinai and Southern Egypt, and the May 2014 flood resulted in approximately 150 million USD of damages in Taba City. Although water demand in Egypt is increasing due to population growth and several recent development activities, Egypt's share from the Nile River could be reduced by the completion of the planned dams in upstream countries (e.g., the Renaissance dam in Ethiopia). To mitigate flood disasters and solve the problem of limited water supply, an appropriate decision support system should be established based on effective methodologies. The first step towards achieving this goal is to understand the natural processes that occur during WFFs.

Because the flood peak originates from the optimal combination of storm intensity and variant basin characteristics (e.g., geomorphology, land use, vegetation cover and soil type), the use of only one component cannot adequately express flood size or occurrence (Costa, 1987). In arid regions, vegetation cover has only a minor effect, therefore, the impacts of wadi geomorphology and rainfall on flood generation are more significant than those of vegetation cover. Basin hydrology and geomorphology interact each other. The hydrology is a response of basin scale, slope and shape, on the other hand, erosion (responding to hydrology) forms the catchment and determines the flow routes over the geologic ages (Willgoose and Perera, 2001). The hydrologist has long dreamed of being able to predict the unit hydrograph of a catchment on the basis of the information available from a contoured map (Chutha and

Dooge, 1990). To move forward towards this dream the geomorphology-hydrology relationship should well understood.

Therefore, the following questions arise:

1. What kind of relationship exists between wadi geomorphology and its hydrologic responses?

2. What changes in this relationship will occur when different storm duration intensities are applied?

The hydrologic response varies from one basin to another according to its climatic characteristics, geomorphology, soil type, land use, vegetation cover, etc. Basin hydrology and geomorphology interact each other. The hydrology is a response of basin scale, slope and shape, on the other hand, erosion (responding to hydrology) forms the catchment and determines the flow routes over the geologic ages (Willgoose and Perera, 2001). Many researcher investigate the relationship basin geomorphology and hydrologic response using many strategies. For instance using the observation based hydrologic data, as discharge, peak flood discharge for the different return period or rainfall for the natural or experimental watersheds and correlate them to their estimated morphometric characteristics (e.g., Baker, 1977; Benson, 1964; Biswal and Marani, 2010; Costa, 1987; Harlin, 1984; Newson, 1978; Patnaik et al., 2015; Patton and Baker, 1976; Potter, 1953; Price et al., 2011), utilizing the physical watershed models to prove or establish this relationship (e.g., Black, 1972; Roberts and Klingeman, 1970), or using the mathematical models to simulate and predict the hydrological indices and link to basin morphometry (Bertoldi et al., 2006; Beven et al., 1988; Garbrecht and Shen, 1988; Howard, 1990; Marani et al., 2001; Schmidt et al., 2000). There are also trials to derive the basin unit hydrograph based on the geomorphological features termed the Geomorphological Instantaneous Unit Hydrograph (GIUH) employing probabilistic concepts. Rodríguez-Iturbe and Valdes (1979) make the first step to develop the GIUH, since that the GUIH theory have been discussed, improved and applied by many studies (e.g., Biswal and Singh, 2017; Chutha and Dooge, 1990; Gupta et al., 1980; Kumar et al., 2007; Rinaldo and Rodríguez‐Iturbe, 1996; Rodríguez‐Iturbe et al., 1982).

Benson (1964) reported that basin characteristics effect is decreasing as recurrence interval increase especially for extreme rare events (as 1000 yr floods) and the flood magnitude may totally related to rainfall amount and intensity. While Patton and Baker (1976) found that the same morphometric parameters give better correlation with the maximum flood records in high flood potential areas. Costa (1987) conclude that the morphometric characteristic's alone cannot find interpretation of the size or occurrence of the floods size or occurrence and the rain intensities must interact with existing basin characteristics to optimize the flash flood peaks. Therefore, we investigated this confusing and complex impact of rainfall intensity on the geomorphology-flood link.

The previous reviewed analysis of the relationship between geomorphologic parameters and hydrologic response is very rare for wadi systems compared to humid environments. Few studies have discussed this relationship for wadi systems (e.g., Al-Rawas and Valeo, 2010; Nouh, 1990; Sen, 2008a; Subyani et al., 2012). Some authors used measured wadi flow data (Al-Rawas and Valeo, 2010; Nouh, 1990) that were barely related to spatially homogenous storms, which could have had a deceptive effect on this analysis. Other researchers used empirical equations to estimate hydrological indices, such as peak discharge, using the wadi area, which may not represent the real characteristics of the basin and thus may not yield a reliable relationship with morphometric parameters (e.g., Subyani et al., 2012). Although geomorphologic parameters have been used for WFF hazard assessment (e.g., Abuzied et al., 2016; Arnous et al., 2011; Basahi et al., 2016; Youssef et al., 2011), this assessment was mainly based on morphometric analysis, whereas the hydrologic component was not sufficiently covered.

The hydrological models are indispensable due to the limitations of hydrological measurement techniques and complexity of the natural hydrological systems (Beven, 2011), however, most of the arid wadis are ungauged catchments (Sen, 2008a), which represent major challenge for selecting the best method of rainfall-runoff modeling. Many researchers have discussed the methods that could be applied to wadi systems, however there is still inadequate guidance on the choice of model type (e.g., lumped or distributed and conceptual or physical-based) (McIntyre and Al-Qurashi, 2009). The simple hydrological modeling methods such as rational method are usually used in practical hydrology due its simplicity and the effective compromise between theory and data availability (Grimaldi and Petroselli, 2015), however, the recent progress in computational resources and data measurement techniques such as remote sensing encourage the hydrologists to use more advanced tools. Nouh (1990) stated that none of the indirect regional methods provide accurate predictions of flood peaks in arid catchments, whereas Kumar (Kumar et al., 2007) argued that the Rodríguez-Iturbe GIUH is only applicable to the direct surface runoff component of the stream flow. Sen (2008a) reported that synthetic hydrograph methods are incompatible with the morphological and meteorological characteristics of wadi systems, which limits the use of the unit hydrograph model (Liu et al., 2003).

Physically-based, distributed models make predictions that are distributed in space by discretizing the catchment into a large number of elements, with state variables constrained within specific ranges that represent the average local physical condition of each element, whereas the lumped models treat the catchment as a single unit with state variables that represent averages over the catchment area (Beven, 2011). There are some drawbacks to the application of distributed models due to the relatively more requirements of data, model complexity and computational burden compared to the lumped models (Sharif et al., 2010). However, some previous studies highlighted the necessity to consider the spatial features of the rainfall and the variability of losses and surface characteristics through using the distributed models after matching the model complexity to the available data (Foody et al., 2004; McIntyre and Al-Qurashi, 2009; Reed et al., 2007). Moreover, the distributed hydrologic models can possibly have the same performance or outperform the calibrated lumped models (McIntyre and Al-Qurashi, 2009; Reed et al., 2007; Sharif et al., 2016; Sharif et al., 2010) and can be consisted with the regional analysis methods (Moretti and Montanari, 2008) in the arid or ungauged basins. Therefore, the use of a physical-based distributed model in addition to high-resolution topographic data may be more representative of wadi geomorphology and the key hydrological processes related to WFFs.

The Hydrological River Basin Environment Assessment Model (Hydro-BEAM), which is a physically-based distributed model (Kojiri et al., 1998), was adopted based on the former discussion to answer the raised questions by this paper and due to the successful recent applications of this model in humid (Kojiri et al., 2008; Sato et al., 2013), semiarid (Saber and Yilmaz, 2016) and arid environments (Abdel-Fattah et al., 2015; Saber et al., 2015), where, it is able to simulate saturation-excess surface runoff, subsurface flow through the soil, groundwater flow and additionally can reflect some unique features of the wadi system such as transmission losses.

The main objectives of this chapter are twofold: to propose a consistent methodology in order to obtain the reliable simulation and assessment of WFFs in cases of limited field data and to better understand and assess the contributions of wadi geomorphology and rainfall variations to the generation of WFFs. Following the descriptions of the study area and methods, the results of WFF hydrological modeling and geomorphometric analysis are presented, analyzed and discussed.

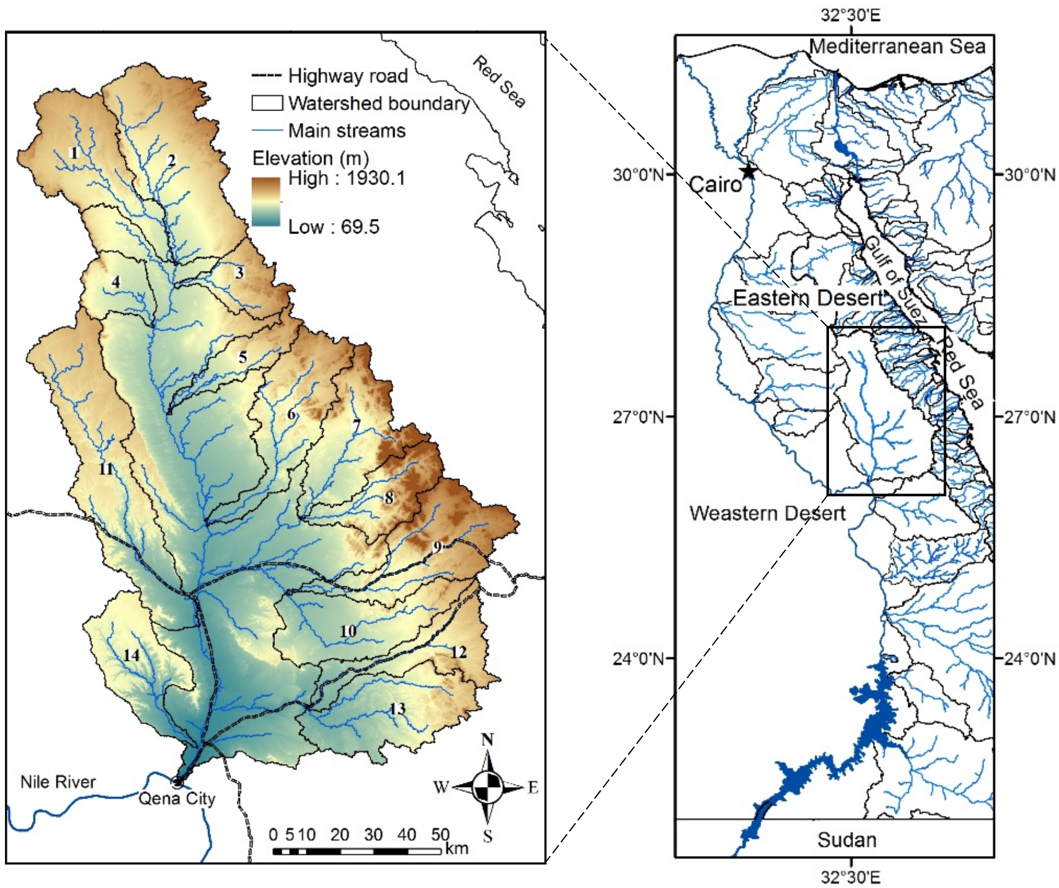

Fig. 3-1 Location map of Wadi Qena showing the existing highway roads, target sub-basins, main streams and its topography with the main drainage systems of Egypt in the Eastern Desert and Sinai Peninsula

3.2 Study area

Wadi Qena, which is located in the Eastern Desert, is one of the largest wadi basins in Egypt and is bounded by the Red Sea to the east and the Nile River to the west (Fig. 3-1). Wadi Qena covers a total area of 16,000 km^2, extending 215 km southward from its most remote point in the north to its main outlet at the Nile River, with an average width of 75 km. The wadi flows from the northeast to the southwest, unlike the other major Egyptian Nile drainage systems, which are generally oriented from east to west. Hence, it has been described as a critical area in a stable shelf (Said, 1962) due to its unique geomorphic and geologic features. Wadi Qena records varying geological formations on both sides of its main channel. The Red Sea Mountains, which are located in the eastern part of Wadi Qena, comprise igneous and metamorphic rocks. The majority of the remaining outcrops in Wadi Qena consist of sedimentary rocks, which are mainly Eocene limestone. The surface Quaternary deposits, which are mainly alluvial hills and terraces, are composed of gravels and sands (Abdel Moneim, 2014).

The Wadi Qena catchment is a typical arid basin (Fig.3-2), with an extremely high evaporation rate (yielding an average monthly evapotranspiration rate of 6.2 mm/day (Moawad et al., 2016)) and low precipitation (with an average annual precipitation of 7.0 mm for the period 2000 to 2013 (TRMM, 2013)). However, intense precipitation (usually occurring between October and March) occasionally results in flash floods, such as those that occurred in 1987, 1994, 1997, 2010, 2014 (Moawad et al., 2016) and 2016. However, Wadi Qena was chosen as a study site not only due to its flood hazards but also because it is one of the most promising areas for national development. The highways (Fig. 3-1) connecting the Nile River and Red Sea governorates run through Wadi Qena, representing a vital tourism pathway from highly populated cities to Red Sea resorts or rich touristic sites in the south, such as Luxor. These important roads have been severely damaged by flash floods several times. Surrounding the aforementioned roads are vast, flat land areas (Fig.3-2-a) that are suitable for reclamation (Abdel Moneim, 2014). Wadi Qena contains numerous natural resources, such as vast quarries of sand, gravel, limestone, marl and shale. Some cement factories have also been constructed in this area. The Egyptian government has invested approximately 200 million USD (NUCA, 2015) in the New Qena City project, which is located 8 km from old Qena City and lies completely within the region downstream of Wadi

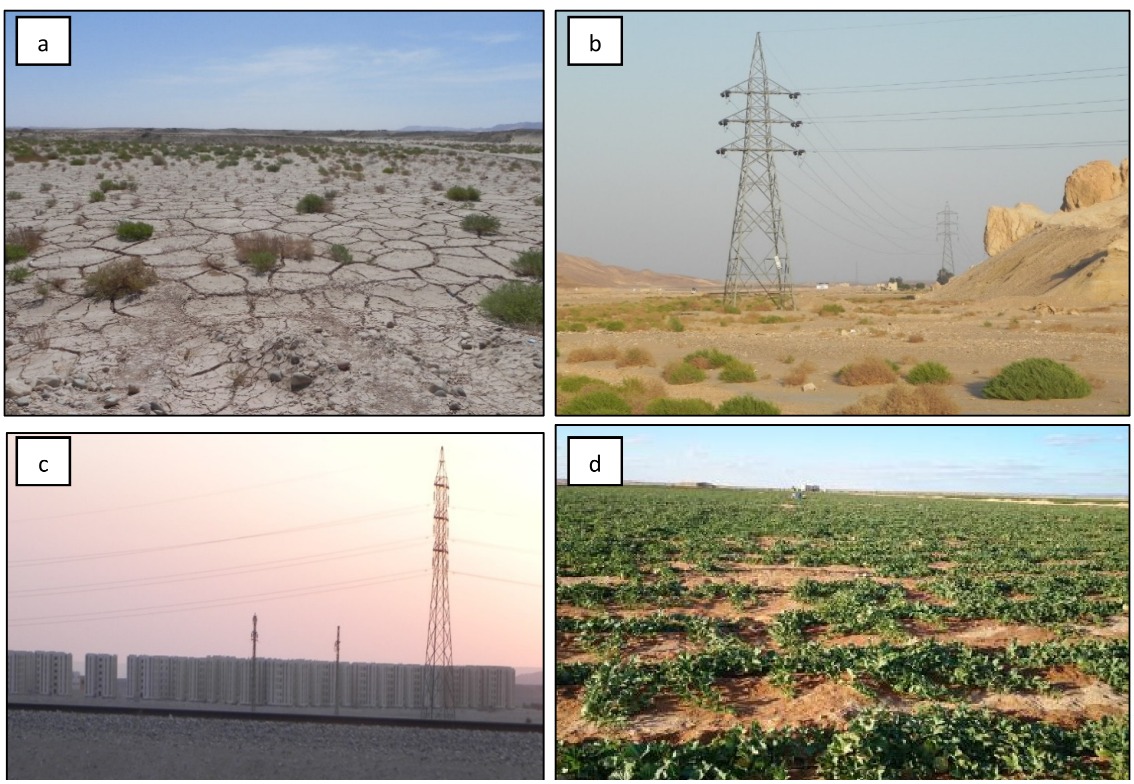

Fig.3-2 Wadi Qena. a) Main channel showing the dry conditions and limited vegetation of the wadi, b) electricity towers located in the main channel of the wadi c) New Wad Qena city and d) desert reclamation project (observed during a field trips in 2013and 2015).

Qena. However, it is challenging to implement these development activities due to the threat of floods, which should be managed to achieve sustainable development in this promising wadi.

The geomorphology, paleodrainage setting, geology and hydrogeology of Wadi Qena have been extensively studied (e.g., Abdel Moneim, 2014; Abdelkareem and El-Baz, 2015; Hussien et al., 2017; Philobbos et al., 2015). However, other aspects that are more related to WFFs (e.g., hydrological modeling, risk assessment and integrated management) have attracted less attention. In some Wadi Qena hydrological modeling studies, authors focused on only the hydrologic characteristics of the wadi and did not make any connections to its geomorphometry (e.g., Gheith and Sultan, 2002; Milewski et al., 2009; Moawad et al., 2016; Saber et al., 2015). Hence, the present study addresses a crucial issue of rainfall-runoff analysis and contributes to the nexus of geomorphology-hydrology studies in this vital area and in other general wadi systems.

3.3 Data and methods

Despite facing increasing challenges due to WFF hazards and the stress on water resources in arid regions, the application of rainfall-runoff models can be used to evaluate and manage flash flood disasters as well as to sustain precious water resources. The most valuable merit of the adopted approach is its applicability to arid basins, where data are usually limited. This methodology consists of two main parts. The first part is the use of hydrological modeling tools (i.e., the Hydrological River Basin Environment Assessment Model (Hydro-BEAM model)) along with remote sensing data (e.g., Global Satellite Mapping of Precipitation (GSMaP) and Digital Elevation Model (DEM)) to simulate real WFFs or virtual storms. The second part is based on quantitative geomorphological analysis and is linked to hydrological indicators. A summary of the methodology and data used is illustrated in Fig.3-3. Field investigations were conducted in the Wadi Qena in order to 1) identify land use types (Fig.3-2-a), 2) explore wadi channel geometry, and 3) investigate the current applied flood mitigation structures.

Geographic information system (GIS) tools were used for data acquisition, the preprocessing and analysis of input data, the estimation of different spatial and geomorphometric parameters, and the visualization and export of maps. The delineated watershed and other topographic information (i.e., flow direction, channel and hillslope gradient) were also used as inputs for the hydrological model. A total of 14 sub-basins were delineated, with areas ranging from 315 km^2 to 1488 km^2. Each sub-basin does not have any other upstream basin so that the hydrologic response of each individual sub-basin can be assessed without any effects from adjacent sub-basins. Inaccurate watershed delineation could be generated due to errors in the DEM data such as flat or sink areas (Wang et al., 2009), that can be found in the low relief or flat areas (Kenny et al., 2008; Lindsay and Creed, 2005).

The generated streams were confirmed and validated by comparing available satellite images from Google Earth and geological maps. This manual verification is an efficient method in such arid wadi, where bare land or mountains with no vegetation represent more than 95 of the total area. The final product of stream network has good matching with the used satellite images because of the following reasons 1) most of the flat and low relief areas of the basin were excluded from this study as indicated in Figure 1 and the used 14 sub-basins could be considered as high relief basins with less expected errors from DEM processing than the flat or low relief regions; 2) The adopted methodology of watershed delineation was not fully automated, however, after the generation of the stream network it was manually check and modified using the overlaid satellite images throughout the entire basin and 3) employing of a relatively high resolution DEM data (SRTM 1s) comparing to the other available products.

Thirty-eight geomorphometric parameters, as indicated in Table 3-1 and Fig.3-4, were analyzed for the target sub-basins in the study area and classified into four categories: scale, topographic, shape and drainage network parameters. The highlighted parameters were identified using high-resolution remote sensing data, GIS tools and other in-house developed codes (i.e., FORTRAN codes and Python GIS scripts). Four flash flood events (Nov. 1994, Jan. 2010, Jan. 2013 and Mar. 2014) with different characteristics were simulated. When the rainfall pattern over the drainage basin is uniform, the hydrograph shape may reflect only the effects of certain catchment characteristics (Black, 1972). Therefore, an additional nine synthetic storms with total rainfall amounts of 40 mm, 60 mm and 80 mm and durations of 1 h, 3 h and 5 h were homogeneously applied over all the sub-basins of Wadi Qena. These parameters were chosen because 40 mm is the amount of effective rainfall that can begin to generate hillslope surface runoff, whereas 60 mm and 80 mm are the estimated rainfall amounts for the return periods of 50 years and 100 years, respectively (MWRI, 2014). The storm durations were chosen based on the work of Gheith and Sultan (2002), which states that storm durations in Egyptian wadis are approximately 1 h to 3 h; the storm duration of 5 h was recorded in the used rainfall satellite data.

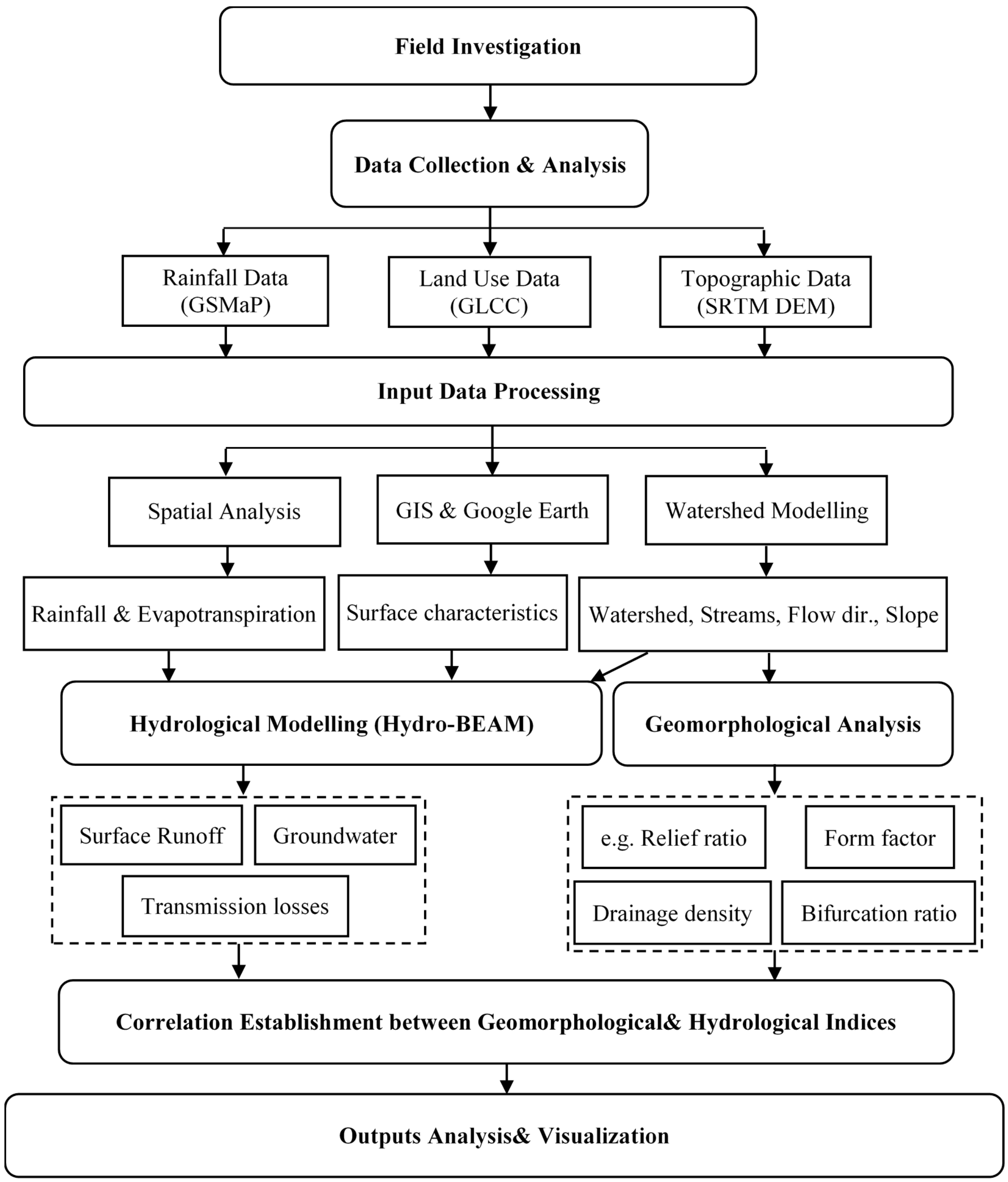

Fig.3-3 Simplified outline of the proposed Hydro-geomorphometric approach in this chapter to understand the key parameters controlling the generation of wadi flash floods.

Table 3-1 List of the used morphometric parameters, ranges, standard deviations and methods of calculation.

Parameter (Abbreviation)	Unit	Range	SD	Formula	Reference
Scale metrics					
Area (A)	km^2	314.9-1487.9	328.7	Basin area	
Perimeter (P)	km	134.5-427.3	72.6	Basin perimeter	
Basin length (L_b)	km	27.2-112.3	19.6	Basin maximum dimension	
Time of concentration (T_c)	h	3.3-11.7	2.26	$T_c = 0.542(L_{ms} / S_{ms})^2$	(Johnstone and Cross, 1949)
Topographic metrics					
Mean elevation (H_{mean})	m	426.9-727.4	95.9	Mean basin elevation	
Relief (R)	m	472.5-1601.3	391.7	$R = (H_{max} - H_{min})$	(Schumm, 1956)
Relief ratio (R_r)	-	0.005-0.036	0.0084	$R_r = R / L$	(Schumm, 1956)
Melton relative relief (R_M)	km^{-1}	0.0152-0.07	0.0169	$R_M = R / \sqrt{A}$	(Melton, 1965)
Hypsometric Integral (HI)	-	0.185-0.675	0.137	$HI = (H_{mean} - H_{min}) / R$	(Pike and Wilson, 1971)
Ruggedness number (R_n)	-	1.202-4.228		$R_n = R * D_d$	(Melton, 1957)
Dissection index (D_i)		0.54-0.85	1.00	$D_i = R / H_{max}$	(Singh and Dubey, 1994)
Mean basin slope (S_b)	%	4.3-15.3	2.98	Average basin slope	
Mainstream slope (S_{ms})	%	0.34-1.61	0.39	Main stream average slope	
Slope ratio (R_s)	-	0.049-0.197	0.0414	$R_s = S_{ms} / S_b$	(Al-Rawas and Valeo, 2010)
Longest stream slope (S_{ls})		0.35-1.68	0.42	Longest stream average slope	
Shape metrics					
Form factor (F)	-	0.11-0.43	0.083	$F = A / L_b^2$	(Horton, 1932)
Compactness (C)	-	2.13-3.65	0.36	$C = P / 2\sqrt{\pi A}$	(Horton, 1932)
Circularity ratio (R_c)	-	0.075-0.22	0.034	$R_C = 4\pi A / P^2$	(Miller, 1953)
Elongation ratio (R_e)	-	0.374-0.737	0.098	$R_e = 2 A / \pi / L_b$	(Schumm, 1956)
Eccentricity (τ)	-	0.48-4.94	1.17	$\tau = \sqrt{\left\|L_C^2 - W_L^2\right\|} / W_L$	(Black, 1972)
Drainage network aspects					
Total stream number (TN_s)	-	970-4812	1030.3	Total stream number	
Total streams length (TL_s)	km	873.2-3835.6	879.1	Total stream length	
Mainstream length (L_{ms})	km	43.8-159.6	26.8	Main stream length	
Longest stream length (L_{ls})	km	45.1-160.0	26.3	Longest stream length	
Main stream sinuosity (Si_{ms})	-	1.432-1.926	0.155	$Si_{ms} = L_{ms} / Straight\ length$	(Mueller, 1968)
Longest stream sinuosity (Si_{ls})	-	1.509-1.959	0.146	$Si_{ls} = L_{ls} / Straight\ length$	(Mueller, 1968)
Drainage frequency (D_f)	km^{-2}	3.56-4.11	0.117	$D_f = TN_S / A$	(Horton, 1945)
1st order streams frequency (F_1)	km^{-2}	2.218-2.623	0.097	$D_f = Total\ 1^{st}\ order\ streams / A$	
Drainage density (D_d)	km^{-1}	2.42-2.85	0.117	$D_d = TL_S / A$	(Horton, 1932)
Channel maintenance (C_m)	km	0.351-0.413	0.016	$C_m = 1 / D_d$	(Schumm, 1956)
Overland flow length (L_o)	km	0.175-0.207	0.008	$L_o = 1 / 2D_d$	(Horton, 1945)

Table 3-1 (continued)

Parameter (Abbreviation)	**Unit**	**Range**	**SD**	**Formula**	**Reference**
Drainage texture (*T*)	km^{-1}	7.72-9.02	0.34	$T = D_d * D_f$	(Smith, 1950)
Texture ratio (R_t)	km^{-1}	4.9-11.3	1.87	$R_t = TN_S / P$	(Smith, 1950)
Fineness ratio (R_f)	-	4.4-11.1	1.68	$R_f = TL_S / P$	(Melton, 1957)
Stream order (S_u)	-	1-9		Hierarchical rank	(Strahler, 1957)
Main trunk length (L_{umax})	km	17.7-122.7	25.9	Highest stream order length	
Bifurcation ratio (R_b)	-	3.596-5.43	0.421	$R_b = N_u / N_{u+1}$	(Horton, 1932)
Length ratio (R_l)	-	2.02-3.61	0.386	$R_l = Ls_u / Ls_{u-1}$	(Horton, 1932)
Area ratio (R_a)	-	3.93-6.74	0.68	$R_a = As_u / As_{u-1}$	(Horton, 1932)

SD: Standard deviation, H_{min}: Minimum elevation, H_{max}: Maximum elevation, L_c: Distance from basin centroid to its outlet, W_c: Basin width at the centroid

To determine the relationship between the characteristics of the basin and its hydrologic response, simple correlations were established between the estimated flood hydrograph indices, such as the outlet peak discharge (Q_p), the time to peak discharge (T_p), and the assessed geomorphologic metrics under different rainfall characteristics. The coefficient of determination R^2 (i.e., the Pearson product-moment correlation) was divided into the following classifications: very strong (0.9-1), strong (0.65-0.9), good (0.35-0.65), weak (0.1-0.35) and very weak (0-0.1). To compare values of Q_p throughout target sub-basins with different scales, the Q_p values were standardized by the basin area *A*, and Q_p/A ($m^3s^{-1}km^{-2}$) was used to represent the unit area contribution to the peak discharge at the outlet. To highlight the dependent and independent geomorphometric parameters, a linear intercorrelation matrix was established between them, which is indicated in Fig.3-5.

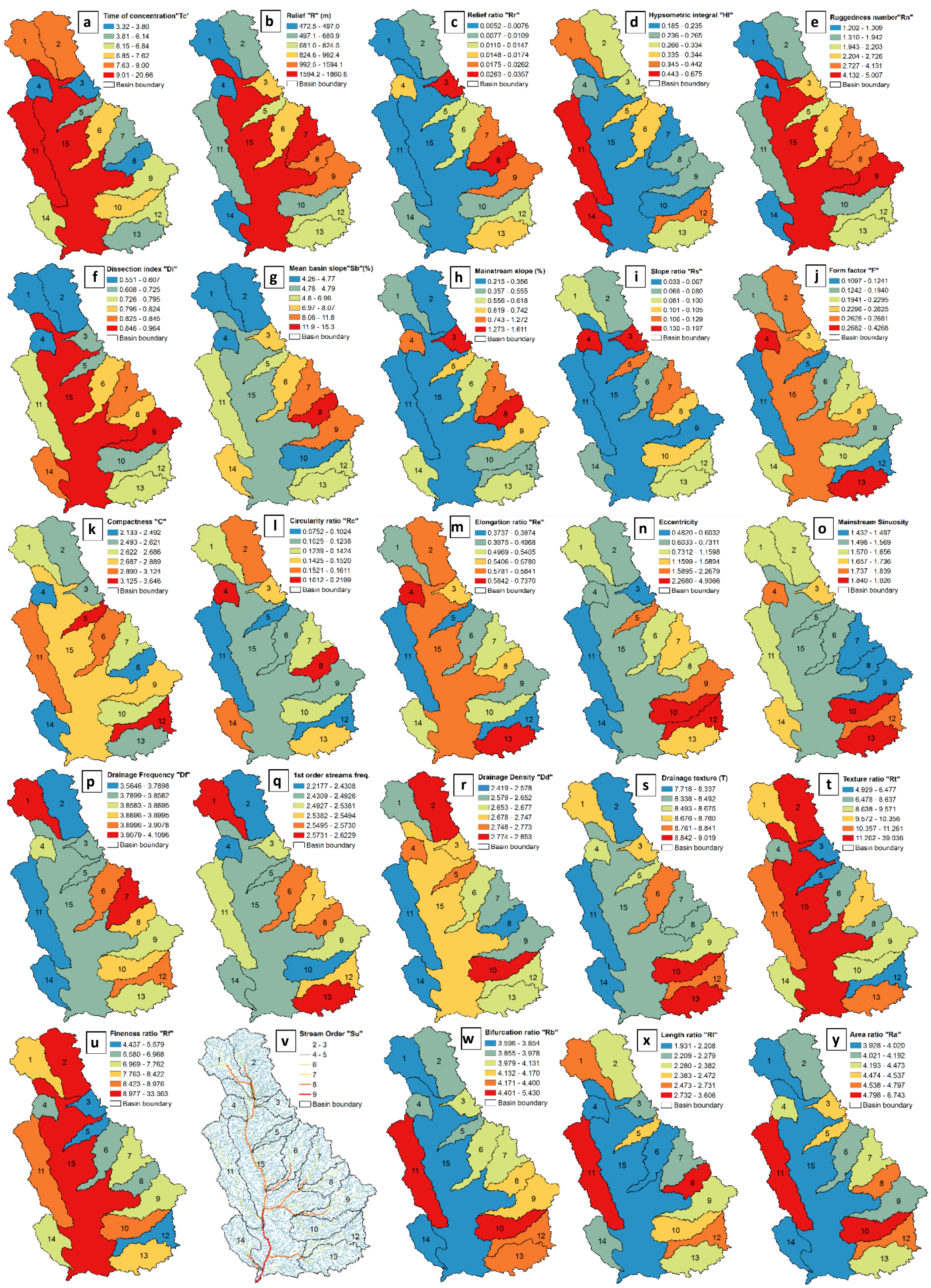

Fig.3-4 Wadi Qena geomorphometric analysis. The inner basin (15) records the average parameter values of the entire Wadi Qena basin.

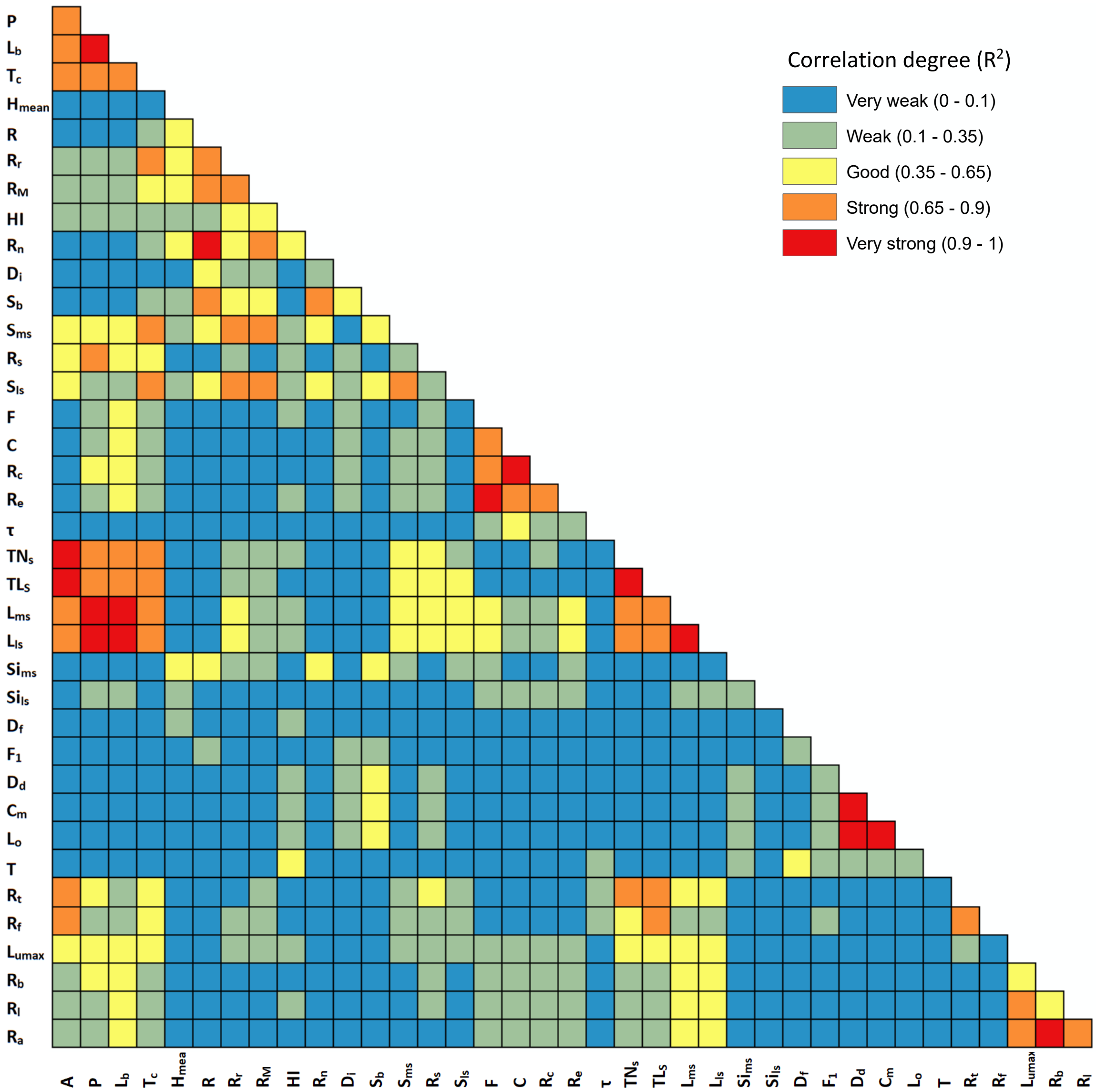

Fig.3-5 Correlation matrix between the assessed geomorphologic parameters based on R^2 values. This figure indicates that each geomorphologic parameter is best correlated with the other metrics of its same group.

3.3.1 Data processing

a) Topographic data

The main input data used for the geomorphometric and hydrological analysis are DEM data. The effect of the topographic data scale has been documented by many researchers (e.g., Moussa, 2003); this effect indicates that the estimated channel length decreases when low-resolution topographic data are used. We tested different DEM spatial resolutions to select the most suitable DEM resolution that can facilitate the best identification of streams. Fig.3-6 shows the tested SRTM DEM products (USGS, 2015), which include SRTM 1 arc-second (~30 m) and two other SRTM products with lower resolutions of 3 arc-seconds (~90 m) and 30 arc-seconds (~900 m). The small stream channels are only discernable in the 1 arc-second DEM, in which larger stream channels are much more clearly characterized. Furthermore, the elevation range is different at each resolution; the 1 arc-second DEM has an elevation range of 69.5-1930 m, while the 30-second DEM has an elevation range of 74-1644 m. The rough DEM resolution underestimates the maximum elevation and overestimates the minimum elevation because the elevation is averaged over a large mesh area. Therefore, the 1 arc-second void-filled SRTM DEM was used to accurately regenerate the topographical conditions of the target wadi basin.

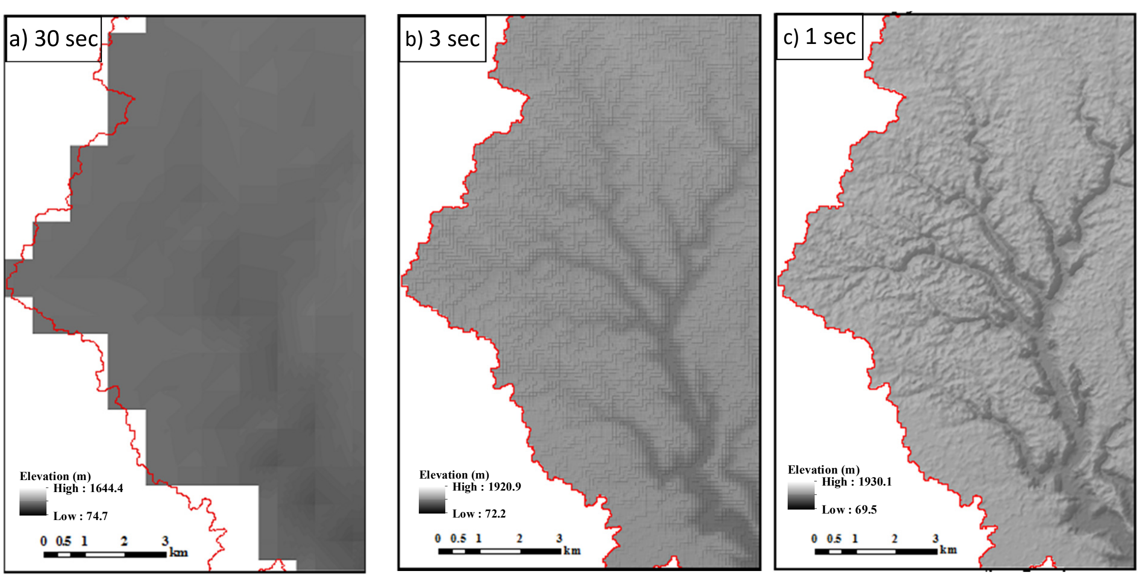

Fig.3-6 Comparisons between different SRTM Digital Elevation Model (DEM) data: a) 30 arc-sec resolution, b) 3 arc-sec resolution and c) 1 arc-resolution; the last dataset captures the drainage system better than the lower resolution DEM data, and is thus the preferred choice with which to study the flash floods at Wadi Qena.

b) Rainfall data

The most important meteorological input for the hydrological modelling is precipitation, which its intensity, duration and spatial distribution have paramount impacts on flood generation. For the 1994 event, which was used for model verification, interpolated measured rainfall data from Gheith and Sultan (2002) were used. For other flood events, the rainfall data used were the GSMaP data (TRMM, 2013). These global data have a temporal resolution of 1 hour and a spatial resolution of 0.1 degrees (10 km). Due to the well-known uncertainty in rainfall satellite data, bias correction was applied using measured Global Precipitation Climatology Centre data (GPCC) (Schneider et al., 2011). We refer the reader to Saber et al. (2015) for more information about the GSMaP bias correction methodology. Because there are only two stations located within the vast Wadi Qena area (MWRI, 2014) and because these stations produced very inconsistent and poor data, the corrected satellite rainfall data were used.

c) Land use data

Global Land Cover Characterization (GLCC) data were used to identify different land use types (GLCC, 2008a) and to specify the surface (e.g., roughness, runoff coefficient, infiltration rate) and subsurface (e.g., porosity, thickness of the model layers, storage tank coefficients) characteristics for each mesh in the hydrological model grid. The original GLCC land use data consist of 24 types of land that were grouped and reclassified as forest, field, desert, urban and water. Desert land represents more than 95% of the total area of the Wadi Qena. The other types of land use occupy less than 5% of the total area and mainly lie in the developed downstream region. Therefore, the applied land use is nearly homogenous. It is advantageous to have this homogenous parameter setting throughout the wadi to focus solely on the impacts of geomorphometric and rainfall characteristics on the hydrologic response.

3.3.2 Hydro-BEAM model

The Hydro-BEAM model was originally developed by Kojiri et al. (1998) and has been used in many studies as a river basin environment model for assessing water quantity, water quality, sediment, reservoir operations, and the impacts of climate change and anthropogenic activity (e.g., Kojiri et al., 2008; Sato et al., 2013). However, all of these applications were limited to environments with humid conditions until the model was later modified for flash flood simulations in the arid wadis (Abdel-Fattah et al., 2015; Saber et al., 2015) and semi-arid basins (Saber and Yilmaz, 2016).

The most beneficial merit of distributed hydrological models such as Hydro-BEAM is their representation of the spatial variations in watershed characteristics and hydrological processes. The watershed under investigation is divided into number of unit mesh cells (in this study, approximately 16,000 mesh cells with a resolution of 1 km). The unit grid mesh is divided into two pairs of rectangular hill slopes and one river channel. The river channel geometry (depth and width) is related to the upstream area and is tested using Google Earth and DEM data. Vertically, each mesh is represented by a combination of one surface layer and three subsurface layers (Fig. 3-7). The integrated kinematic wave model is used to describe the flow over the surface layer A and throughout the channel by considering the diverse surface characteristics of the different land use types, as expressed in Fig. 3-7-b. The subsurface layers (layers B, C and D) are modeled using the linear storage model (Fig. 3-7-c). The Natural Resources Conservation Service (NRCS) method is used to calculate the initial losses in the target catchments (SCS, 1997), and a regression formula developed for the arid regions and wadis by Walters (1990) is adopted to estimate the instantaneous transmission losses with runoff.

The integrated kinematic wave model used to describe layer A considering the diverse surface characteristics of different land use types, as expressed in Fig. 3-7-b and the following equations:

$$\frac{\partial h_{Al}}{\partial t} + \frac{\partial q_{Al}}{\partial x} = rf_{Al} \qquad \text{(Eq. 3-1)}$$

$$q_{Al} = \begin{cases} \alpha\left(h_{Al} - d_A\right)^{m_b} + ah_{Al} & (h_{Al} \geq d_A) \\ ah_{Al} & (h_{Al} < d_A) \end{cases} \text{, where, } d_A = \lambda_A D_A,\ m_b = 5/3 \qquad \text{(Eq. 3-2)}$$

$$a = \frac{k \sin\theta}{\lambda_A},\ \alpha = \frac{\sqrt{\sin\theta}}{n} \qquad \text{(Eq. 3-3)}$$

where, h is the water depth (m), q is the discharge per unit width (m^2s^{-1}), r is the rainfall intensity (ms^{-1}), f is the direct runoff rate, t is the time (s), x is the distance from the upstream edge (m), d is the equivalent water height on saturation (m), Al and A are a subscription referring to land use and layer A respectively, m_b is constant concerning frictions, n is the equivalent roughness ($m^{-1/3}s$), k is the hydraulic conductivity (ms^{-1}), d is the saturation pondage (m), λ is the porosity (%), D is the layer thickness (m), and $\sin\theta$ is the slope gradient.

The kinematic wave model is employed also to describe the water behavior in the river channel using manning equation as following:

$$\frac{\partial A_r}{\partial t} + \frac{\partial Q_r}{\partial x} = q_r \qquad \text{(Eq. 3-4)}$$

$$Q_r = \alpha_r A_r^{m_r} \text{, where, } m_r = \frac{4}{3} \qquad \text{(Eq. 3-5)}$$

$$\alpha_r = \left(\frac{\sqrt{I}}{n}\right)\left(\frac{m}{\left(2\sqrt{1+m^2}\right)^2}\right)^{\frac{1}{3}} \qquad \text{(Eq. 3-6)}$$

where, A_r is the river cross section area (m^2), Q_r is the river discharge rate (m^3s^{-1}), q_r is the total river inflow rate per unit width (m^2s^{-1}), I is the river channel gradient, n is the channel roughness ($m^{-1/3}s$), m

is the river slope gradient. Each mesh has river channel, and its geometry (depth and width) identified using the upstream area the measurement of the channel geometry at standard locations as following:

$$H_i = H_{std}\left(\frac{A_i}{A_{std}}\right)^f \quad \text{(Eq. 3-7)}$$

$$B_i = B_{std}\left(\frac{A_i}{A_{std}}\right)^b \quad \text{(Eq. 3-8)}$$

where *H* is the channel depth (m), *B* is the river width (m), *std* is shortcut for standard point, *i* is referring to the target point, A_i is the upstream catchment area (m^2), *f* and *b* are constants and in Wadi Qena case are equal to 0.36 and 0.55 respectively. The subsurface layers (B, C and D layers) are modeled using the linear storage mode (Fig. 3-7-c) as following:

$$\frac{dS}{dt} = I - O \quad \text{(Eq. 3-9)}$$

$$O = (k_1 + k_2)\cdot S \quad \text{(Eq. 3-10)}$$

where *S* is the storage amount (m), *I* is the inflow (ms^{-1}), *O* is the outflow (ms^{-1}) and k_1, k_2 are outlet coefficients. The model estimate the initial, transmission losses using Natural Resources Conservation Service (NRCS) method (SCS, 1997) and Walter's equation (Walters, 1990) respectively as following:

$$V_1 = 0.0257V_A^{0.872} \quad \text{(Eq. 3-11)}$$

a) Hydro-BEAM model calibration

For several reasons, the calibration of rainfall-runoff models in wadi systems is hampered by a lack of data (Lange et al., 1999; Pilgrim et al., 1988). Flow measurement is particularly difficult in arid zones for several reasons as indicated by many researchers (e.g., Lange et al., 1999; Pilgrim et al., 1988; Rodier and Roche, 1978) and could be summarized as following: 1) The quick rise and fall of the water level during wadi flood; 2) Lack of suitable natural control sections in streams with movable beds, and high cost of artificial control; 3) Harsh climatological and physical conditions; 4) Sediment transport, moving rocks and debris may damage instruments placed in the wadi; 5) Access difficulty due to few drivable roads, especially during the flood; 6) Usually low population density at the wadi system.

To our knowledge, no flow rate data have ever been recorded in Wadi Qena. In this study, the model parameterization is performed based on the calibrated model parameters conducted by Saber et al. (2015) in Wadi Al-Khoudh in Oman. Applying a calibrated hydrological model from another wadi to a

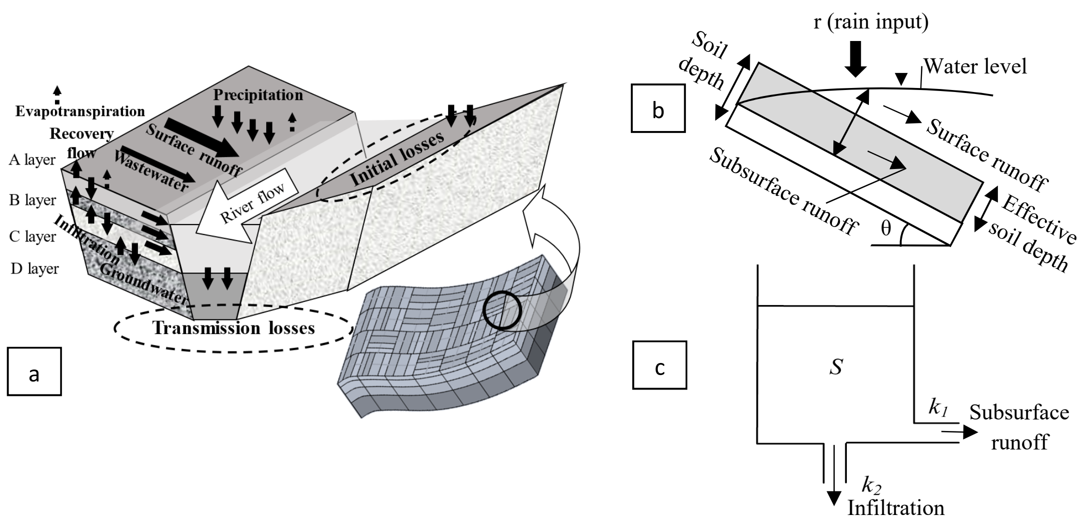

Fig. 3-7 Hydro-BEAM schematic diagram (after Kojiri et al. (1998)): a) Hydro-BEAM basic structure; b) surface layer kinematic wave model; c) simple representation of subsurface storage tank layers.

wadi under similar conditions has been done by some researchers, such as Milewski et al. (2009), who transferred the SWAT model calibration in Wadi Girafi in Palestine to all major wadis in the Saini Peninsula and the Eastern Desert in Egypt.

Both Al-Khoudh and Qena wadis record arid conditions with high average potential evapotranspiration values. However, the mean annual rainfall is higher in Wadi Al-Khoudh (150 mm). Topographically, the relief in Wadi Al-Khoudh ranges from 0-2460 m, while the relief in Wadi Qena ranges from 70-1930 m. Their land use settings are very similar; both areas mainly consist of desert and bare mountain land (comprising 90-95% of the total area) with very few houses and agricultural activities mainly existing in the downstream regions (5-10%). Both wadis have three main outcrop/soil type units: Quaternary alluvium (comprising 20-30% of the total area); sedimentary rocks, which are mainly limestone (40-55%); and volcanic or metamorphic rocks (25-30%). Therefore, these similar outcrop units and land use, topography, and climatic conditions could support the application of the Wadi Al-Khoudh parameter settings to Wadi Qena.

To verify this approach, the available rainfall and discharge volume data for the Nov. 1994 flood, as determined by Gheith and Sultan (2002), were used. These data indicated that the received flood volume at the Wadi Qena outlet was $9*10^6$ m^3, with a runoff percentage of 3.7% of the total rainfall volume. Using the same rainfall input, our model predicted a flood volume of $10*10^6$ m^3 with a runoff percentage of 4.5%, which are very consistent with the reference values.

Table 3-2 Summary of target flood events simulated at Wadi Qena.

Simulation results	1994	2010	2013	2014	3 hour synthetic homogenous storm		
					40 mm	60 mm	80 mm
Total rain volume (*10^6 m^3)	237	124	153	393	628	942	1256
Peak discharge (m^3/s)	109.5	42.67	12.0	101.1	1,230.9	5,564.6	14,964
Total outlet discharge volume (*10^6 m^3)	10.6	5.6	1.79	10.9	139	327	588
Outlet discharge percent (%)	4.49	4.57	1.17	2.76	22.21	34.72	46.91
Total transmission losses volume (*10^6 m^3)	14.6	6.9	1.4	13.8	102	212	328
Total transmission losses percent (%)	6.16	5.47	0.92	3.52	16.27	22.0	26.22

3.4 Results and discussion

3.4.1 Hydrological modeling of the wadi flash floods

The Nov. 1994, Jan. 2010, Jan. 2013 and Mar. 2014 flash flood events had severe impacts on many wadis throughout Egypt. The simulation results (Fig.3-8) described below focus on the assessment of surface runoff and transmission losses in order to determine their implications for flood disasters and groundwater recharge potential. Four locations on the main channel of the wadi (Fig. 3-8-a) were selected to characterize the spatiotemporal variability of flash floods in the wadi system (Fig.3-8-b to -e).

The simulated hydrographs of the target flood events show the flow features of WFFs, in which it takes only a few hours to reach the peak discharge value, Q_p, before gradually decreasing to return to a zero-flow status (Fig.3-8). Variations can be observed in the values of the hydrograph Q_p, T_p as well as in the shape of the hydrograph from one event to another due to differences in the rainfall spatial patterns and intensities of each event. The maximum and minimum Q_p values were observed in the 1994 flood (110 m^3/s) and the 2013 event (12 m^3/s), respectively (Table 3-2 and Fig. 3-8). The behavior of the hydrograph is directly linked to the pattern of the hyetograph. Even within the same storm, the discharge rate can vary between locations due to the spatiotemporal variability of rainfall and the geomorphologic parameters of the upstream catchment.

The geographic distribution maps of rainfall input and the simulated discharge values of the target flood events are shown in Fig. 3-9. Despite being affected by significant rainfall, the Wadi Qena sub-catchments do not record any surface runoff due to their high losses. Fig.3-9 shows that the 1994 and 2014 storms have more homogeneous distributions than the 2010 and 2013 storms, which have local rainfall distributions. The discharge distribution maps and simulated hydrographs record different

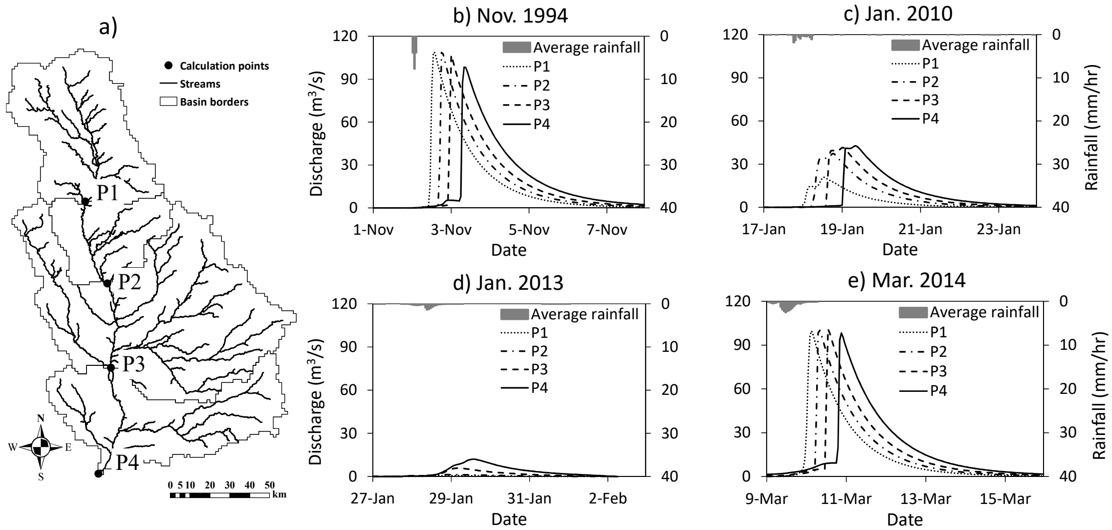

Fig.3-8 a) Wadi Qena watershed and locations where the simulated floods hydrographs are shown; for the b) Nov. 1994, c) Jan. 2010, d) Jan. 2013 and e) Mar. 2014 flood events.

patterns for each event, especially in their upstream regions, due to the spatiotemporal variability of rainfall. In the 1994 flood, the upstream area recorded higher discharge than the downstream area due to the greater rainfall intensity in the upstream region, in contrast to the 2013 event. However, there is no substantial difference between the downstream and upstream regions for the 2014 flood events because the 2014 storm covered a wider area of Wadi Qena than the other flood events, especially within the central part of the wadi.

It is clear from Table 3-2 that a significant amount of water could only be received by one event in such an arid environment and should thus be efficiently managed. Comparisons of the target flood events reveal that the 2014 event has a much greater total rainfall volume ($393*10^6 m^3$) than the other events (which range from $124\text{-}237*10^6 m^3$). However, the 2014 flood outlet discharge percentage is lower than that of the 2010 flood, which has a total rainfall amount that is one-third of that of the 2014 flood, because the duration of the 2014 event was longer.

Although the simulated flash flood event discharge rates are small, especially for a basin as large as Wadi Qena, these flash floods are risky and have caused substantial amounts of damage, as surveyed by Moawad et al. (2016). One of the unique features of WFFs is that the dry natural wadi channel does not have a consistent geometry like humid rivers, where the drainage network can be enhanced and maintained to receive water without flooding. Conversely, wadi channels can be flooded by any amount of discharge (Shamir et al., 2013). Furthermore, the absence of efficient mitigation strategies and unmanaged development, as discussed in the introduction, could increase the flood vulnerability and risk, even for low-stage floods.

To clearly assess the effect of rainfall variability on WFFs, nine synthetic storms (with total rainfall amounts of 40 mm, 60 mm and 80 mm and durations of 1 h, 3 h and 5 h) were uniformly applied throughout all the Wadi Qena sub-basins. The resulting outlet discharge values are presented in Fig. 3-11. The rainfall intensity has a direct effect on the surface runoff amount, as indicated by the results, in which there are substantial differences between the hydrograph shapes and values of Q_p and T_p between the results obtained using different total rainfall amounts. Q_p and T_p have direct and indirect relationships, respectively, with the applied rainfall amount; thus, the 80 mm storm has the highest Q_p values and the lowest T_p values. Despite the constant 20 mm interval between each rainfall group, the simulated Q_p values have inconsistent differences due to variations in the losses and runoff percentages with variations in total rainfall, as indicated in Table 3-2. For instance, the majority of the 40 mm storm is consumed by soil saturation and initial losses, which causes it to yield a small outlet discharge volume percentage (22%). In contrast, in the 80 mm storm, the percentage of consumed water losses from the

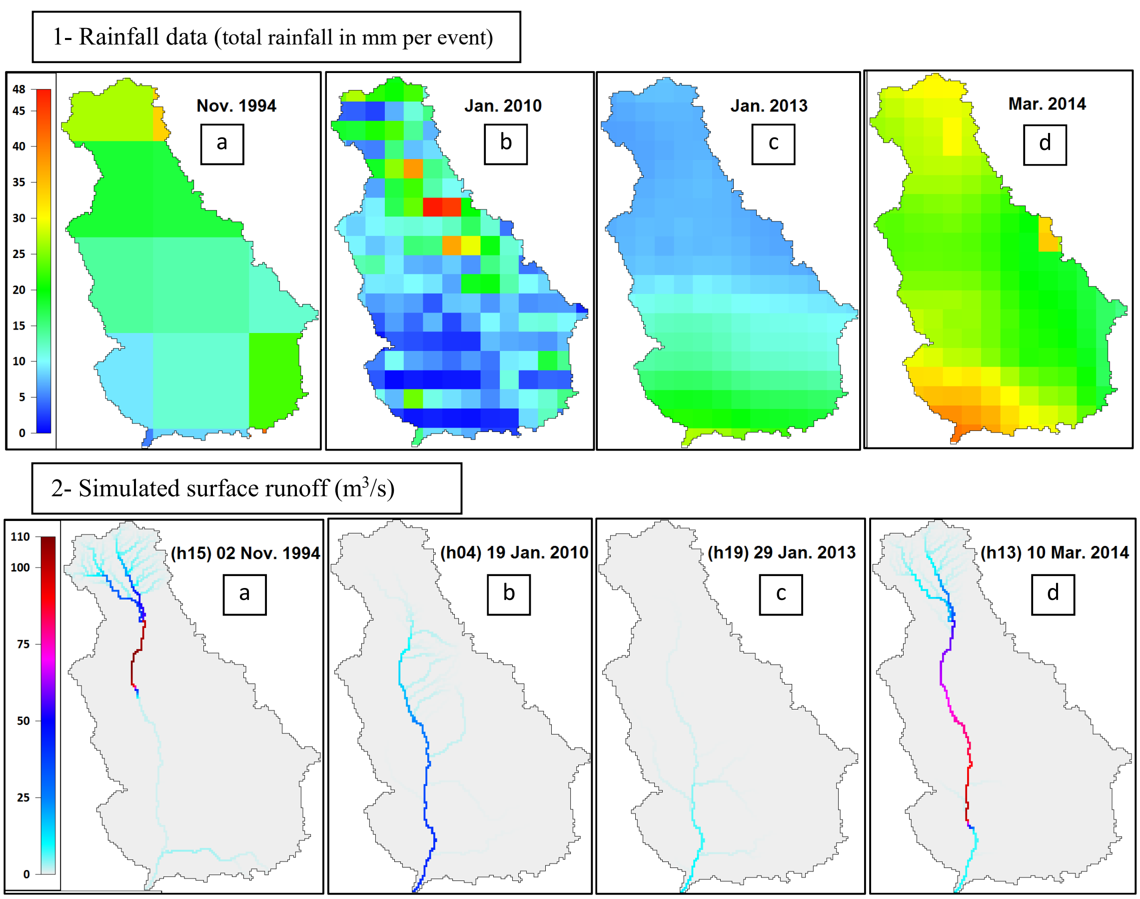

Fig.3-9 Geographical distribution maps at Wadi Qena for 1) total rainfall input; 2) simulated peak surface runoff for the a) Nov. 1994, b) Jan. 2010, c) Jan. 2013 and d) Mar. 2014 flood events. The rainfall data of Nov. 1994 event were used form Geith and Sultan [47] with a resolution of 0.5 degree whereas the GSMaP data of 0.1 degree resolution were used for the other events.

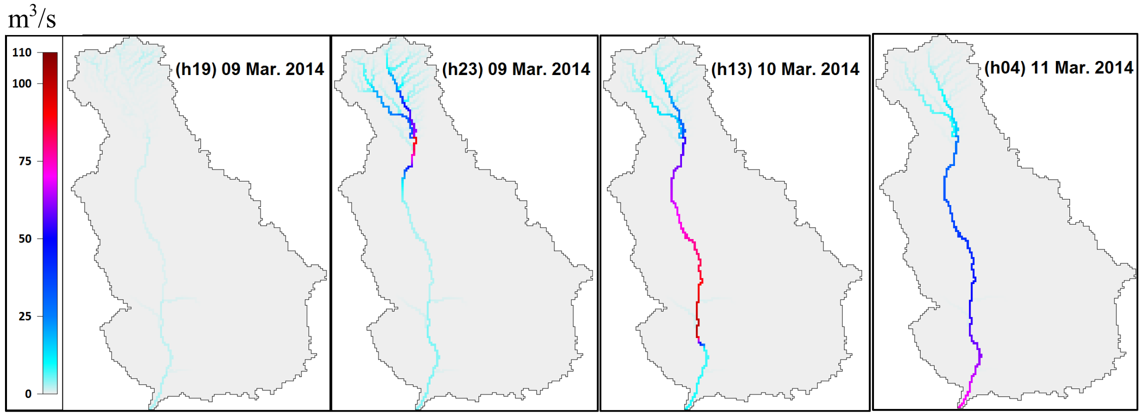

Fig. 3-10 Mar-2014 flash flood surface runoff geographical distribution maps showing the different flash floods stages.

total rainfall is smaller and the outlet discharge volume percentage is higher (47%) due to the high possibility of saturation excess flow.

Furthermore, for the same amount of rainfall, the storm duration variation resulting in variant hydrographs features. Most of the sub-basins show that a 1 h storm can generate greater Q_p values than a longer storm with the same total amount of rainfall. However, within the entire Wadi Qena catchment, using the longest storm duration (5 hours) for the same total rainfall amount can produce higher Q_p values (Fig. 3-11). Therefore, higher rainfall intensity does not always yield higher Q_p. As indicated in Fig. 3-11, the storm duration effect becomes more significant as the total rainfall intensity increases. Therefore, the 80 mm storm exhibits more distinguishable differences between different storm durations, while the 40 mm storm does not exhibit substantial differences between the applied storm durations. This is due to the increased fraction of surface runoff (either hillslope or channel surface runoff) with increasing rainfall amount, which could represent a clear impact of the storm duration. The hydrologic response differs for each storm type within each sub-basin (Fig. 3-11) due to variations in the scale, slope and other factors of the sub-basins. The highest Q_p is not obtained in the largest sub-basin; for example, sub-basin 7 yields higher Q_p than sub-basin 11 in the 1 h-80 mm storm, although sub-basin 7 has half the area of sub-basin 11. This reflects the significant impacts of the other basin characteristics, which are studied in detail in the following sections.

The assessment of transmission losses is important not only due to their effect on channel flow reduction but also due to their influence on recharging the groundwater of alluvial and Quaternary aquifers in wadi systems. The results of the estimated transmission losses (Table 3-2) indicate that they are affected by the volume of surface runoff as a translation of Walter's equation. In real flood events, the volume and percentages of total transmission losses are usually bigger than the outlet discharge total volume; for example, the 2014 flood has $13.8*10^6$ m^3 of transmission losses and an outlet discharge total volume of $10.9*10^6$ m^3 (Table 3-2), which indicates how significant transmission losses are as processes in wadi systems. For synthetic storms that have much higher rainfall than real events, the volume and percentages of transmission losses are smaller than those of the outlet discharge; their percentage increasing rate is smaller than the outlet discharge increasing rate as the rainfall intensity increases. The 40 mm storm transmission losses percentage is 16% of the total rainfall volume, whereas that of the 80 mm storm is 26%; thus, this value exhibits just a 10% difference, whereas the outlet discharge value increases by 24%. This is likely because the surface runoff increases with increasing rainfall, however, the channel bed capacity for surface water infiltration is limited and more surface runoff will pass without losses.

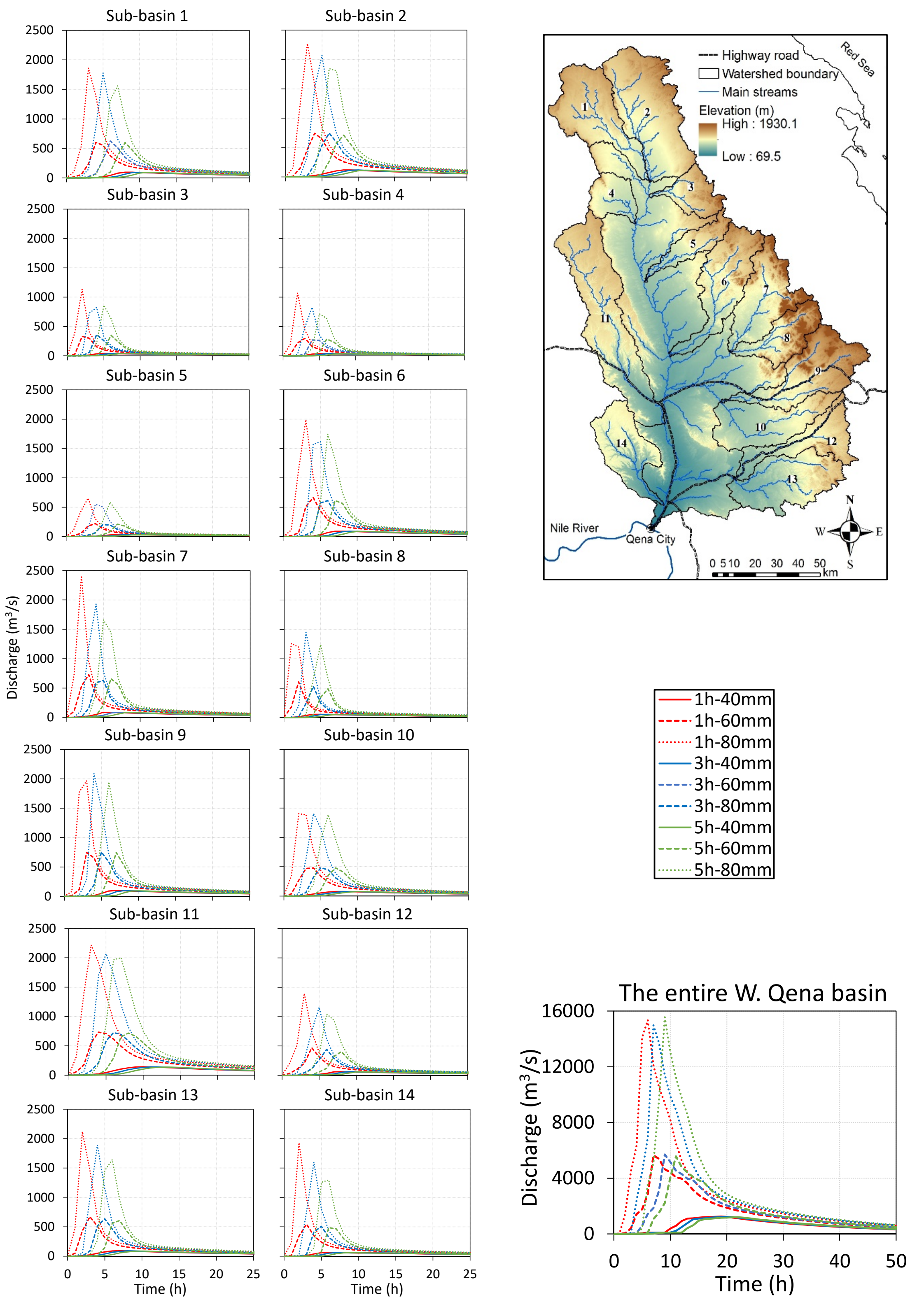

Fig. 3-11 Simulated hydrographs at the different sub-basins outlets (sub-basin1-14) and the entire Wadi Qena basin for the nine applied synthetic storm types based on total rainfall amount and duration.

3.4.2 The impact of geomorphometry and rainfall variability on flash flood generation

The extracted geomorphologic parameters (Table 3-1 and Fig. 3-4) were classified into four categories: scale, topographic, shape and drainage network parameters. Statistical correlations were established between the geomorphometric measures and the values of peak discharge (Q_p), Q_p standardized by the basin area (Q_p/A) and the time to peak (T_p). To examine only the effects of basin geomorphology, the pre-simulated real events were replaced by spatially homogenous synthetic storms of varying intensities (40 mm, 60 mm and 80 mm) that each lasted 1 h. The other storm durations did not cause any significant variations in the values of T_p between the different sub-basins.

a) Scale parameters

Scale metrics, such as the basin area (A), basin perimeter (P), basin length (L_b) and time of concentration (T_c), are the main factors to determine the flood magnitude. If there are two basins with similar characteristics and different scales, the bigger basin will receive more rainfall and will consequently produce more discharge. In this study, T_c is a scale parameter and is estimated by a formula that is applicable to large target sub-basins (Johnstone and Cross, 1949). Fig. 3-12 indicates that there is a strong relationship between the estimated hydrological indices and scale metrics.

Basin area (A) may be the most commonly used parameter for estimating stream discharge (e.g., Howard, 1990; Patton and Baker, 1976; Sen, 2008a). Q_p and T_p are directly proportional to scale parameters, whereas A exhibits the strongest correlation with Q_p. Other scale parameters (P, L_b or T_c) record less strong correlations with Q_p because basins with smaller areas can sometimes have larger values of P, L_b or T_c when they are compact, elongated or gently sloping, respectively. Therefore, the standardized Q_p/A index was used, which generally exhibits good correlation with scale parameters other than A and is indirectly proportional to them (in contrast to Q_p and T_p). As the basin scale increases, the area unit contribution to the outlet Q_p (Q_p/A) decreases due to the increasing potentiality of losses. If a raindrop falls at the farthest point of a relatively large-scale basin, its probability of reaching the mouth of the basin is lower than that of another raindrop falling in a smaller-scale basin. Thus, for T_p, A exhibits the lowest correlation with the scale parameters and, as expected, T_c exhibits the strongest correlation with T_p.

The magnitude of the effect of scale metrics on Q_p, Q_p/A and T_p is different for each applied storm (Fig. 3-12). For Q_p, the correlation degree, R^2, decreases with increasing rainfall intensity. Sub-basins 14 and 2 have the biggest scale metrics, producing the highest Q_p values for the 40 mm storm; however, for high intensity storms and higher effective rainfall, lower Q_p values may be obtained for larger sub-basins than for smaller-scale sub-basins (e.g., sub-basin 7), as is shown in Fig. 3-11. This finding is consistent with the work of Costa (1987), who found that there could be a greater risk of floods in smaller basins. Therefore, using only scale parameters cannot fully represent the likelihood of the occurrence of a WFF; thus, other basin characteristics, such as topography or drainage networks, should also be considered. For Q_p/A and T_p, the degree of correlation R^2 generally increases with increasing rainfall intensity, which indicates that scale parameters become more significant with increasing rainfall intensity. This could be interpreted in line with the results of previous hydrological modeling, which have shown that the surface runoff percentage of the total rainfall amount increases with increasing rainfall intensity.

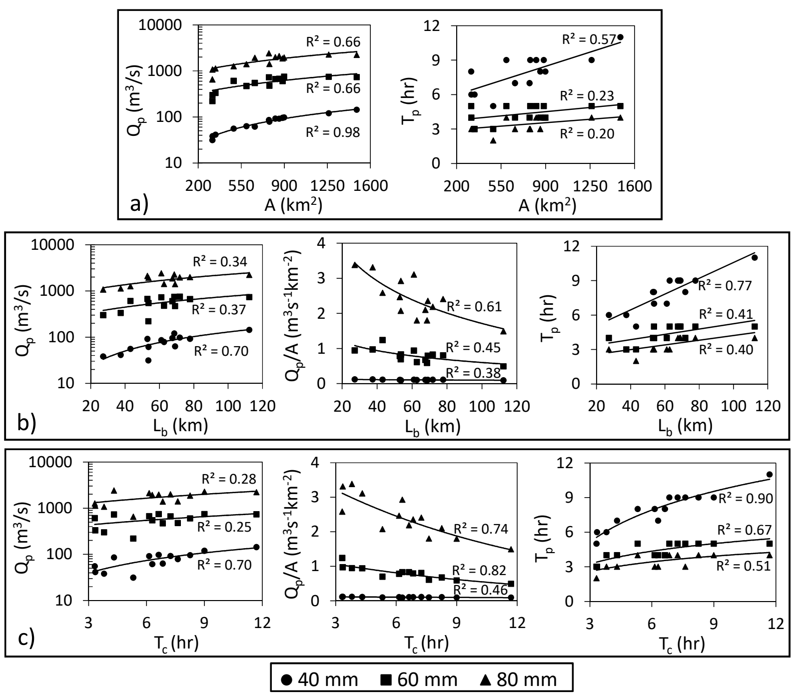

Fig. 3-12 Relationship between the estimated hydrological indices and basin scale parameters: a) area (A), b) basin length (L_b) and c) time of concentration (T_c) for the different applied storm intensities at all sub-basins.

b) Topographic parameters

The basin relief (R) and slope metrics, such as the main stream slope (S_{ms}), are considered to be important parameters by many researchers, such as Howard (1990), who reported that these parameters play significant roles in determining hydrologic response. In this study, Q_p did not exhibit good correlation with any of the topographic metrics (except for the slope ratio (R_s)), potentially because the topography effect is clouded by the basin scale. Therefore, in this study, only Q_p/A (which exhibits better correlation with topographic parameters) and T_p will be used to express the relationship between basin topography and flood response, which is depicted in Fig.3-13.

R shows weak to very weak correlation with Q_p/A and T_p under the variant applied storms, which is consistent with the results of other studies (Shamir et al., 2013). However, R and Q_p/A are directly proportional, whereas R and T_p are inversely proportional. This indicates that greater R values reflect higher flood potentiality, which was also reported by Patton and Baker (1976). The relief ratio (R_r) and Melton relative relief (R_M) are the dimensionless ratios of relief and L_b or A, respectively, which are used to compare values of relief, regardless of the scale. R_r was used by Howard (1990) to estimate Q_p and T_p. R_r showed the best correlation (good to strong) between the relief parameters and Q_p/A and T_p.

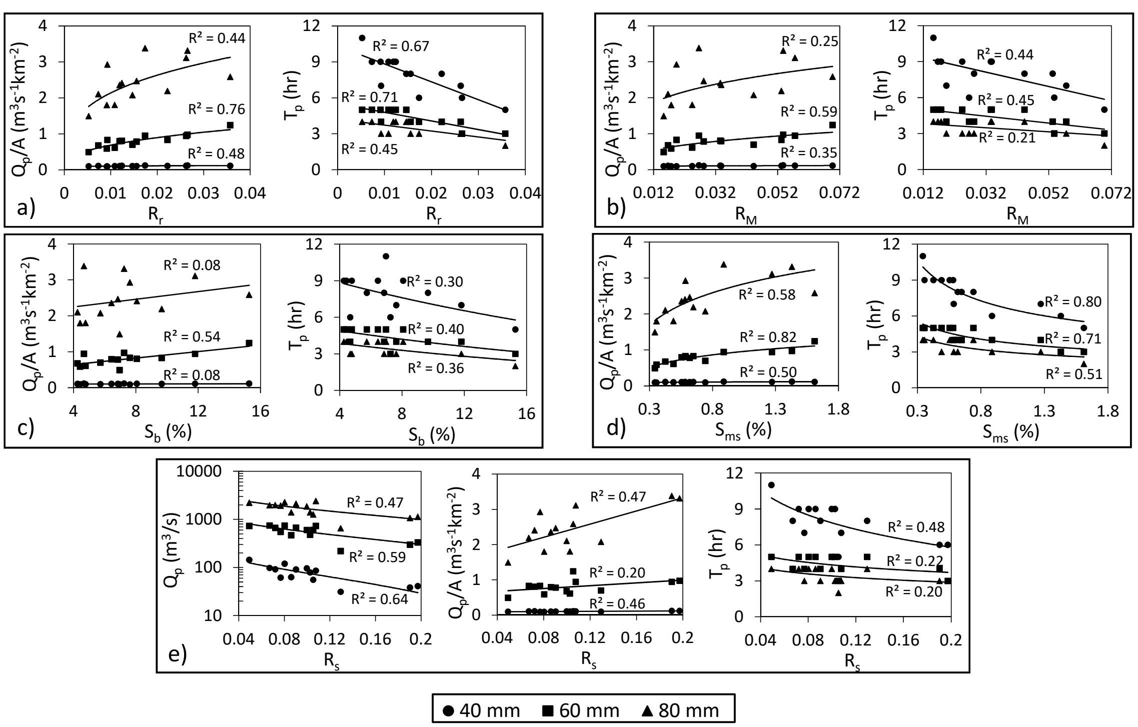

Fig.3-13 Relationship between the hydrological indices and significant basin topographic parameters: a) relief ratio (R_r), b) Melton relative relief (R_M), c) mean basin slope (S_b), d) mainstream slope (S_{ms}) and e) slope ratio (R_s) under different storm intensities.

Because R_M also exhibits better correlation than R, it is recommended to use the relative relief, not the absolute R, for the purposes of flood prediction or risk assessment, due to its elimination of scale effects.

The hypsometric integral (HI) exhibits weak correlation with the hydrologic indices. It is recommended to estimate more complex hypsometric forms than the HI, as hypsometric skewness, density skewness and density kurtosis have been found to have significant correlations with T_p (Harlin, 1984). The ruggedness number (R_n) shows weak correlations with Q_p/A and T_p. This may be because of the weak relationship between drainage density (used for the estimation of R_n (Table 3-1)) and the hydrological indices, which will be discussed later. The mean elevation of the basin (H_{mean}) and the dissection index (D_i) have weak to very weak correlations with the assessed hydrologic indices, because they do not adequately reflect variations in the topography and have weak correlations with the slope parameters, as is depicted in Fig.3-5.

The relationship between the slope, Q_p and T_p is well known and has been widely approved. Black (1972) reported that the slope has the most profound effect on Q_p. The basin mean slope (S_b) only exhibits a good correlation with Q_p/A under the conditions of the 60 mm storm. However, S_b still exhibits a direct relationship with Q_p/A for all storms. T_p displays a good to weak indirect correlation with S_b, which is compatible with the results of Schmidt et al. (2000).

The other important slope metric is the mainstream slope (S_{ms}), which exhibits the best correlation between all the slope metrics and the hydrological indices (Fig.3-13). S_{ms} has a stronger impact on the hydrologic response than S_b because S_b affects the hillslope runoff that is subsequently also controlled by S_{ms}, which has a direct effect on the channel water velocity that translates to Q_p and T_p. Nouh (1990) and Al-Rawas and Valeo (2010) used the S_{ms} (wadi slope) in their mean annual peak flow assessments. However, Schmidt et al. (2000) found a strong correlation between the longest stream slope (S_{ls}) and Q_p. The present results indicate that it is better to represent the stream slope using S_{ms}, which is estimated by using the stream path that has a greater upstream area, regardless of the stream length, and is sometimes different than S_{ls}. The slope ratio (R_s), which is the ratio of S_{ms} and S_b, shows good correlation with Q_p, Q_p/A and T_p, in which the powerful S_{ms} parameter enforces the impact of S_b on the hydrologic response.

c) Basin shape parameters

Dimensionless shape measures, such as the form factor (F), compactness (C), the circularity ratio (R_c) and the elongation ratio (R_c) were estimated (Table 3-1 and Fig.3-4). These calculated shape measures reflect the dominance of the elongated shape of all the study sub-basins, except for sub-basin 4. It appears that compact, circular and not elongated wadis are likely to yield greater Q_p and smaller T_p values. However, all shape metrics generally show weak correlation with the estimated hydrological indices (Fig.3-14), which is consistent with the results of Nouh (1990) and Al-Rawas and Valeo (2010), who claimed that the basin shape has a less significant effect on the hydrologic indices

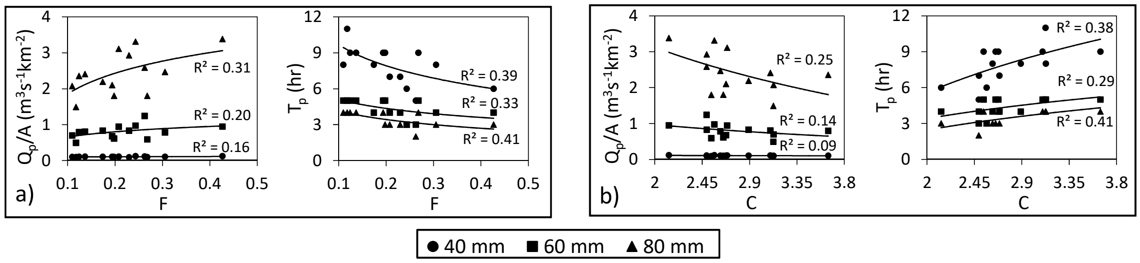

Fig.3-14 Relationship between the hydrological indices and some basin shape parameters: a) form factor (*F*) and b) compactness (*C*) with different storm intensities.

than the scale and slope of the basin. Nevertheless, there is a direct relationship between Q_p/A and the F, R_c or R_e of the basin and an inverse relationship between Q_p/A and C that is in agreement with the results of Patton and Baker (1976) and Costa (1987), which indicate that basins with larger elongation ratios and equidimensional basins (such as circular basins) tend to have greater flood peaks. Furthermore, Fig. 3-14 shows better correlation between shape metrics and T_p than the other hydrological indices.

According to laboratory experiments, basin eccentricity (τ) is an effective measure of the hydrologic response of a basin (Black, 1972). However, our results revealed a very weak relationship between τ and all the estimated hydrological indices, potentially because of the complexity of the real catchment, especially the wadi system, or because eccentricity only represents the shape of the basin from its center to its outlet (the lower half of the basin) and thus may not yield an accurate representation of the entire basin shape. Therefore, other watershed eccentricity calculation methods should be tested.

Notably, the degree of correlation of all shape metrics with Q_p/A is directly related to rainfall intensity. The best relationships are obtained by using the 80 mm storm (100 yr return period), which means that as the surface water runoff increases, the basin shape metrics will have more contribution for Q_p. However, T_p relationship with the basin shape parameters, does not exhibit a clear connection to the applied rainfall intensity. It is recommended to use a new parameter that can provide a link between basin shape and drainage network symmetry, where a circular basin shape does not necessary imply a symmetric drainage network due to geological factors such as tectonic control. For example, in sub-basin 2, the main channel is not located around the central axis of the basin and is instead located at the left edge of the basin; consequently, most of the water falling into the basin takes a relatively longer time to reach the main channel and to contribute to the values of Q_p and T_p.

d) Drainage network parameters

The drainage network of the Wadi Qena is strongly asymmetrical (Fig.3-4-v); the eastern half and the southern half of the wadi drainage represent 70% and 80% of the total drainage area, respectively (Abdelkareem and El-Baz, 2015). The values of total stream number (TN_s) and total stream length (TL_s)

are strongly correlated with *A* (Fig.3-5); thus, the relationships of TN_s and TL_s with the hydrological indices, as indicated in Fig. 3-15, exhibit the same behavior as *A* and the other scale metrics. Additionally, their correlation with Q_p decreases with increasing rainfall intensity, whereas the opposite is true for T_p.

The mainstream length (L_{ms}) exhibits a better correlation (strong to good) with the hydrological indices than the longest stream length L_{ls}. This good correlation that was observed for L_{ms} with Q_p and T_p may also be related to its strong correlation with *A*. However, Q_p/A still has a good indirect relationship with L_{ms}, because as L_{ms} becomes longer, the area unit contribution to the outlet Q_p decreases due to the increasing potentiality for losses. The R^2 value between L_{ms} and Q_p/A increases from 0.42 to 0.66 as the rainfall intensity increases from 40 mm to 80 mm. This might be because the water quantity in the channel increases as the rainfall intensity increases, which consequently allows the L_{ms} to have a greater impact on the resulting Q_p/A. Sen (2008a) used the product of L_{ms} and the stream length from the basin centroid to its outlet (L_{cs}) to express the values of T_p and Q_p; however, based on our analysis, the correlation of L_{ms} with the hydrological indices is better than the correlation of the product of L_{ms} with L_{cs}.

Stream sinuosity may have a relationship with the water movement time because the water flow speed decreases with channel sinuosity. However, in our analysis, mainstream sinuosity (Si_{ms}) and the longest stream sinuosity (Si_{ls}) exhibit weak correlation, which may be due to the minor effects of sinuosity compared to those of channel slope and length or because using a mesh resolution of 1 km for hydrological modeling cannot represent the real channel sinuosity.

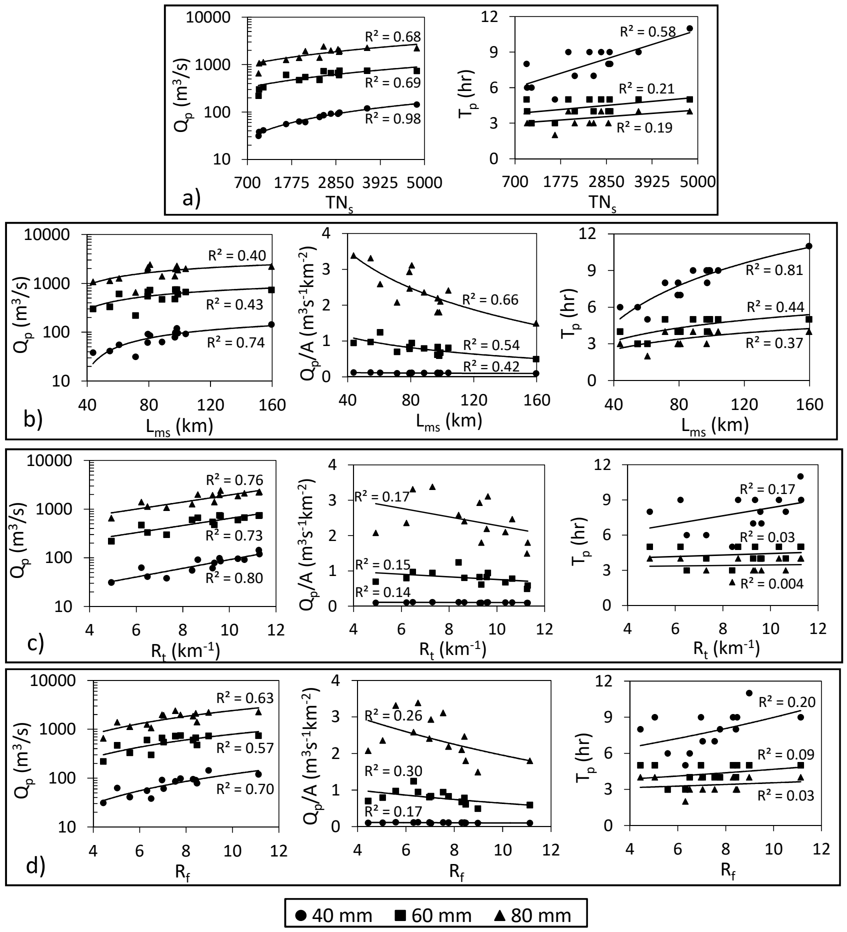

Fig.3-15 Relationship between the hydrological indices and significant basin drainage parameters: a) total stream number (TN_S), b) mainstream length (L_{ms}), c) texture ratio (R_t) and d) fineness ratio (R_f) under different storm intensities.

The variations in the drainage system intensity parameters, such as drainage frequency (D_f), 1st order streams frequency ($F1$) or drainage density (D_d), are due to the effects of climate, topography, infiltration capacity, land use, weathering resistivity and the total upstream area. The D_d for the Wadi Qena sub-basins varies from 2.42 at sub-basin number 14 to 2.85 at sub-basin number 10 (Fig. 3-4-r). According to the classification of Strahler (1957), low D_d values are related to Carboniferous and sandstone geological types, which is consistent with the fact that the major rock type in Wadi Qena is limestone, especially in the eastern region of Wadi Qena. However, the basins that are underlain by igneous and metamorphic rocks, such as sub-basin number 8, have lower D_d values than those defined by Strahler (1957). This may be because the values of D_d are lower in arid environments with low rainfall frequency than in humid areas (Moglen et al., 1998). These estimated D_d values are consistent with estimates from other studies of arid environments (e.g., Al-Rawas and Valeo, 2010; Subyani et al., 2012). The relative similarity of the D_f, $F1$ and D_d values of the Wadi Qena sub-basins is probably due to their existence in the same wadi and the fact that they have been developed under relatively similar climatological conditions.

The drainage intensity metrics could reflect the possibility of collecting hillslope water into channels, that is, the drainage efficiency. Thus, basins with higher drainage intensities might feature faster surface runoff to their outlets with fewer losses, which could translate to higher values of Q_p and lower values of T_p. Hence, Melton (1957) reported that D_f, $F1$ and D_d could be used to estimate the water delivered from upstream areas to basin outlets. The use and importance of drainage network parameters (such as D_d and D_f) in runoff prediction were reviewed by Wharton (1994), who demonstrated the dynamic natures of drainage networks and their importance in rainfall-runoff modeling. In this study, D_f, $F1$ and D_d exhibit weak to very weak correlations with the hydrological indices. Consequently, other D_d or D_f-based parameters, such as the channel maintenance constant (C_m), the length of overland flow (L_o) and drainage texture (T), also display weak correlations with the estimated hydrologic indices. We will try to explain this unexpected behavior, especially for D_d, considering the results of previous studies in the following sections.

In addition to A and stream slope, D_d was suggested by Horton (1945) to be highly correlated with the flood Q_p. Gregory and Walling (1968) suggested that both peak flow and base flow are related to D_d, and that its value is dynamic and should be correctly derived in order to be consistently related to the suitable flow type (e.g., base flow, average flow or peak flow). However, Black (1972) found that Q_p decreased with increasing D_d (the same behavior was observed in the results of the present study) and stated that a conclusion based on this relationship is untenable and that the accurate impact of D_d on the hydrograph remains a mystery because D_d could be correlated to annual rainfall, evapotranspiration, extreme flood events, the map scale or the basin shape. Baker (1977) revealed that higher D_d values are related to basins with higher flood potential. However, Costa (1987) found that D_d is not dominantly representative of flood-prone areas. Harlin (1984) stated that D_d behaves unpredictably in hydrologic models and can often change many hydrologic characteristics. Al-Rawas and Valeo (2010) found a weak correlation between the measured mean wadi flood peak and drainage density. However, Price et al. (2011) used D_d and $F1$ as variables to interpret low flow variability (i.e., not flood flow or Q_p). From this review, it can be concluded that drainage network parameters, such as D_d, are very complex and can be affected or masked by many other factors.

In this study, drainage network intensity parameters, such as D_d, exhibit weak correlation with the estimated hydrological indices, likely due to their very small range or the basic structure of the Hydro-BEAM model, which assumes that every mesh has a river channel (with its width and depth calculated by the upstream area) in addition to the hillslope process. This assumption may be suitable for the current 1 km modeling mesh, but may not adequately represent the accurate situation of the natural basin. Despite the fact that drainage network parameters that are calculated using the basin area, such as D_d or D_f, exhibit weak correlations with the hydrologic indices, other parameters calculated using the basin perimeter as a textural ratio (R_t) or a fineness ratio (R_f) show better (but still weak) correlations with Q_p/A and T_p, as is depicted in Fig.3-15. They also show good to strong correlation with Q_p, due to their strong correlation with A, as indicated in Fig.3-5.

Stream order-based drainage network metrics

Stream order (S_u) designation is the first step in performing drainage basin analysis (Strahler, 1957). The S_u analysis is shown in Fig.3-4-v, where the main trunk of Wadi Qena is of the 9th order, with a total length of 88 km that reflects the widely contributing watershed areas and the vast drainage network of Wadi Qena. Other studies, such as those performed by Abdelkareem and El-Baz (2015) and Abdel Moneim (2014), estimated that Wadi Qena was a 6th order wadi. Their use of a lower DEM spatial resolution and incomplete drainage network generation may be the source of this discrepancy. The maximum S_u frequency is obtained for first-order streams, and the stream frequency decreases as S_u increases.

The values of the well-known Horton's ratios, namely, the bifurcation ratio (R_b), length ratio (R_l), and area ratio (R_a), and the maximum-order stream length (L_{umax}) exhibit correlations with Q_p/A and T_p that are weak to good (Fig.3-16) but stronger than those of other drainage metrics, such as D_d or D_f.

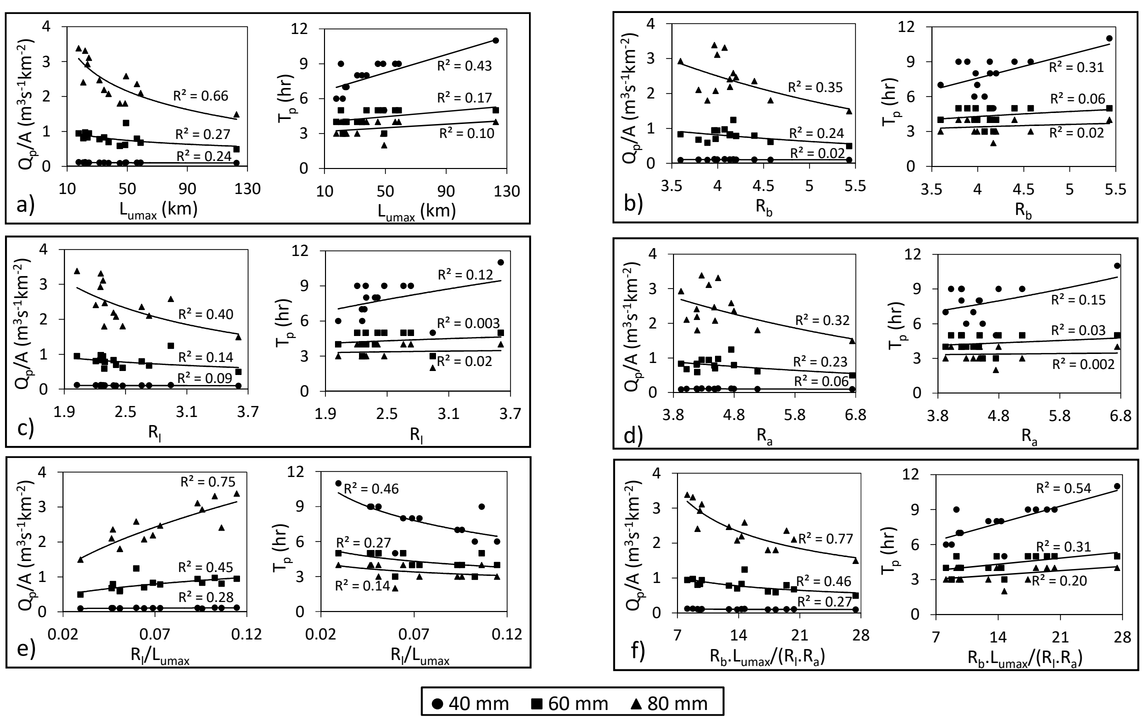

Fig.3-16 Correlation between the hydrological indices and drainage network measures based on stream order: a) maximum order stream length (L_{umax}), b) bifurcation ratio (R_b), c) length ratio (R_l), d) area ratio (R_a), e) R_l/L_{umax} and f) $Rb.L_{umax}/(R_l.R_a)$ under different storm intensities.

These results are consistent with those of Howard (1990), who suggested that basin-scale-based parameters mainly affect the hydrologic response and that the parameters related to the basin shape or network arrangement, such as R_b, R_a and R_l, are less significant. To study the effects of the combinations of these parameters on their relationships with the hydrologic response, we followed the methodology of Rodríguez-Iturbe and Valdes (1979), in which their unit hydrograph Q_p was directly proportional to R_l and $1/L_{umax}$ and their T_p was directly proportional to L_{umax}, R_b, $1/R_a$ and $1/R_l$. The use of these combinations yields better correlations with Q_p/A and T_p, as is indicated in Fig.3-16-e and Fig.3-16-f. Therefore, it is recommended to use these combinations instead of individual measures to represent the impacts of the drainage network on the hydrologic response. The relationships between all the stream order-based parameters and the hydrological indices improve as the rainfall intensity increases, potentially because a greater percentage of rainfall will be transferred to the drainage network in the form of surface runoff as the rainfall intensity increases, allowing the drainage network parameters to have a greater impact on the resulting hydrologic response. This observation was also noted by Rodríguez‑Iturbe and Valdes (1979), but only for R_l; that is, when the rainfall duration increases at a constant L_{umax} value, the influence of R_l will increase.

Overall, the geomorphometric parameters that revealed the most consistent impacts on the WFF indices, such as Q_p and T_p, were the scale parameters and topographic parameters. The majority of the geomorphometric parameters record less correlation with T_p than with other hydrological indices, which is consistent with the results of Schmidt et al. (2000), except for the shape metrics that record better correlations with T_p than other hydrologic measures. Q_p, only, could be a misleading index for determining the relationships between the WFF response and some geomorphometric measures; thus, it is more representative to assess its relationship with Q_p/A in addition to Q_p and T_p.

It can be concluded that the approach proposed here is an efficient, simple, applicable and cost-effective methodology that can be used in arid wadi systems, especially those in which insufficient or no data are available. This analysis could also be performed entirely by using remote sensing data that was proved to be effective either in hydrological modeling or geomorphometric analyses. Here, the specific application to Wadi Qena offers diverse data sets with which decision-makers can assess and manage the increasing flood risk as well as manage precious water resources. Using the distributed hydrological model provides a physical and reasonable representation of the geomorphometry of the wadi system and its hydrological response.

In general, the main challenges of this study are the limitations of the measured data and the need for a broader range of geomorphometric parameters, especially for the drainage network measures. It is recommended to obtain more data in order to validate this method and to apply the same approach in more wadis with a wider range of basin characteristics. For the Hydro-BEAM model, kinematic wave flow routing was used, which may be more physical than other simple lumped models. However, in natural hillslopes and channel networks, more complex routing techniques, such as dynamic or diffusive wave models, may provide more appropriate representation. Transported sediments also represent a significant problem that increase the risk of a WFF and decrease the efficiency of flood mitigation structures. Therefore, it is important to study this factor and to link it to wadi geomorphometry. Accordingly, this study should be updated and improved for the enhanced assessment of WFFs. Although the key factors controlling WFFs and their behaviors under different storm intensities and patterns were highlighted, it is recommended that this method should consequently be used in basin-based classifications of WFF risk and water resource potentiality. Additionally, future work will require a comprehensive study providing more clarification of the independent parameters using further statistical analysis.

3.5 Conclusions

This chapter revealed some of the characteristics of WFFs through a case study of Wadi Qena. Several hydrological and geomorphometric aspects were addressed to provide an integrated approach for the deeper understanding of WFFs in terms of its geomorphometric and rainfall characteristics, thus demonstrating the practicality and versatility of the proposed approach for its use in arid and ungauged wadi systems. The hydrological Hydro-BEAM model has been used to predict and simulate recent flash flood events. A series of virtual, spatially homogeneous storms with different total rainfall amounts and durations were proposed and simulated. The results reveal the unique characteristics of WFFs, such as the rapid increase in its discharge from its zero-flow status to the flood peak. The amounts of water that were assessed should be sustainably managed in such arid and vital areas, based on a deep understanding of the processes controlling WFFs. For instance, the estimated outlet discharge and the total volume of transmission losses in the 2014 flood were estimated to be 11 and 14 million m^3, respectively. The relationships between the estimated hydrological indices and the geomorphometric features of the target basins were also investigated, and it was confirmed that the wadi system floods bear the signatures of their geomorphometric properties. The impacts of the most effective geomorphometric parameters on the WFF generation process were highlighted (e.g., area, slope ratio, shape factor and Horton ratios), and the impact of rainfall variability was also studied. Generally, all of the geomorphometric parameters, except for the topographic parameters, have greater impacts on the hydrologic response of the wadi as the rainfall intensity increases. The complex geomorphometric parameters could be more strongly related to the WFF indices than the simple individual parameters, especially the topographic and drainage network metrics. As an extension of this study, we plan to use the assessed wadi geomorphology and hydrological relationships to further classify the wadi sub-basins based on their flood risk and water resource potentiality.

Chapter 4 Wadi flash flood risk assessment

4.1 Introduction

In wadi system, flash floods are among the most devastating natural hazards in terms of human losses and economical damages (Abdel-Fattah et al., 2015). However, the flood is an important source of water for such arid environments as wadi system. The characteristics of a flood and the vulnerability of the elements in the floodplain to the particular flood events appear to determine the risk to the elements (Shah et al., 2015). Defining flood hazards through meteorological, hydrological and hydraulic investigations, as well as determining the vulnerability of elements, by estimating the impact of floods, can be carried out separately (Shah et al., 2015), however, then, both hazard and vulnerability have to be combined for the final risk analysis (Shah et al., 2015). The estimation of direct flood damage is a complex process involving a large number of hydrologic and socioeconomic factors (Jongman et al., 2012).

Flash flood is characterized by its quick occurrence resulting in a very limited opportunity for warnings to be prepared and issued (Collier, 2007). Oman is an arid country, where the average annual rainfall, throughout most of the country is less than 100mm varying from less than 20 mm in the internal desert regions to over 350 mm in the mountainous areas (MRMWR, 2008). Recently in the arid region, Wadi Flash Floods (WFFs) are frequently occurring. Oman is one of examples where various raising challenges to manage this devastating natural hazard.

Oman WFFs mainly are in the coastal drainage systems. There are different causes for WFFs in Oman as thunderstorms and tropical cyclones. Records show that severe damages occurred in Oman in 1989, 1997, 2002, 2003, 2007, 2010, 2015 and 2016 (Al Barwani, 2015) due to WFFs. The extremist rainfall events occurred in Oman are due to Gonu-2007 and Phet-2010 tropical cyclones (Al Barwani, 2015; MRMWR, 2015), where both cyclones caused 56 fatalities with 6 billion USD of economic losses in Oman. W.Aday, W. Kabir and W. Samail are the main wadis that have experienced flash floods with major damage to people and property (Al-Rawas and Caterina, 2006). Detailed hydrological studies are urgently needed to evaluate WFFs risk in Oman and propose efficient mitigation measures.

Natural hazards related concepts such as hazard, vulnerability and risk have been extensively used in various disciplines with a different meaning and assessment procedures, hindering cross-disciplinary cooperation for facing hazardous events (Pistrika and Tsakiris, 2007). Hazard, risk and vulnerability are commonly used terms to describe the potential threats that natural disasters pose to human life, the environment and the infrastructure used to question the capacity of various structural and non-structural measures, which are applied for protection from these threats(Pistrika and Tsakiris, 2007). Additionally, quantification of these terms is not an easy task, where it is probable that some parameters affecting the above concepts are beyond quantification and also that these parameters vary in space and time (Brauch, 2005; Pistrika and Tsakiris, 2007; Thywissen, 2006).

Disaster risk could be defined as "The potential disaster losses in lives, health status, livelihoods, assets and services, which could occur in a particular community or to a society over some specified future time period" (UNISDR, 2009). Consequently, the food risk is the likelihood of a flood event together with the actual damage to human health and life, the environment and economic activity associated with that flood event (CEO, 2006; Pistrika and Tsakiris, 2007). A risk measure is defined as a mathematical function of the probability of an event and the consequences of that event (Jonkman et al., 2003). The risk (*R*) can be expressed as following:

$$R = H \times V \qquad \text{(Eq. 4-1)}$$

where *H* and *V* are hazard and vulnerability respectively. Hazard is a source of potential harm (Pistrika and Tsakiris, 2007). Vulnerability could be defined as "a set of conditions and processes resulting from physical, social, environmental and economical factors, which increase the susceptibility of a community to the impact of hazards" (ISDR, 2004; Pistrika and Tsakiris, 2007). Another componet of risk is included in Crichton (1999) risk triangle, which is exposure (*E*) and refers to the people/infrastrucuters that are exist at the location involved and the vulnerability indicates the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (Li et al., 2016). The flood risk can be expressed as:

$$R = H \times E \times V \qquad \text{(Eq. 4-2)}$$

If countermeasures (*C*) is existed it could be included in the disaster risk equation as following (Takara, 2013):

$$R = H \times E \times V \;/\; C \qquad \text{(Eq. 4-3)}$$

Flood risk and damages assessment is not only important factor for disaster management but also it is a substantial parameter in evaluation of mitigation strategies according to the type and size of measures (Heidari, 2009). Overall, four phases are stated by Jonkman (2003) on the quantitative risk assessment:

- Qualitative analysis: Definition of the system and the scope, identification and description of the hazards, failure modes and scenarios;
- Quantitative analysis: Determination of the probabilities and consequences of the defined events. Quantification of the risk in a risk number or a graph as a function of probabilities and consequences;
- Risk evaluation: Evaluation of the risk on grounds of the results of the former analyses. In this phase, the decision is made whether or not the risk is tolerable;

- Risk control and risk reduction measures: Depending on the outcome of the risk evaluation, measures may have to be taken to reduce the risk. It should also be determined how the risks can be controlled (for example by inspection, maintenance or warning systems).

Some effective and finite parameters employed by authors to evaluate flood risk include: land use, lithology, soil type, drainage density, distance from river, topographic wetness index, altitude, slope aspect, slope angle and plan curvature (Haghizadeh et al., 2017).

Thieken (2005) revealed that the most flood impact variables for building and for content damage, were particularly water level, flood duration, and contamination. Flood losses can be classified into direct and indirect losses (Thieken et al., 2005). Direct losses are those which occur due to the physical contact of the flood water with humans, property or any other objects (Thieken et al., 2005). Indirect losses are induced by a flood, but occur, in space or time, outside the actual event. Examples for indirect losses are disruption of traffic, trade and public services (Thieken et al., 2005).

Flood damage depends on the hydraulic factors which include characteristics of the flood such as the depth of flooding, rate of the rise in water level, propagation of a flood wave, duration and frequency of flooding, sediment load, and timing (Islam and Sado, 2000).

There are several hydrological models developed over the years to predict rainfall-runoff processes and simulate flood routing through the river networks. Most of these models are suitable for humid regions only. Rainfall-runoff modeling in Wadi systems is a complicated and challenging problem since we have to consider various interconnected variables and processes. Most of WFFs related studies are usually hindered by unsuitable models for arid regions and ungagged wadi (limited data). Hence, the need to evaluate the suitability of alternative modelling approaches for wadi system and its scarce dataset arises. Flash flood basin based risk assessment deduced from the geomorphological characteristics and distributed hydrological modeling is of great interest in disaster risk assessment and hydrology.

In that regard, Rainfall-Runoff-Inundation (RRI) Model (Sayama et al., 2012) was further selected in this study to evaluate its applicability and performance in WFFs prediction. It is the first time to apply RRI model in wadi system where it is usually applied in more humid areas as Kabul River (Sayama et al., 2012) or Thailand (Sayama et al., 2014). Wadi Samail (W. Samail), the costal wadi in Oman was selected for this research. Computation is carried out using sophisticated techniques where remote sensing data used with RRI model to simulate extreme flash flood events at W. Samail. As fare we know, and after a detailed literature review, this is the first time for RRI model to be applied in wadi system, so this study is very important to test the applicability of RRI model in wadi system and arid or semi-arid environments.

4.2 Target study area

Wadi Samail in Oman was selected for flood hazard (inundation) simulation in wadi system, while wadi Qena geomorphometric parameters were utilized for flash flood susceptibility assessment in wadi system. Oman's wadis may be classified into those that drain to the coast and those that drain to the interior desert (Al-Qurashi et al., 2008). W. Samail is one of the costal wadi, situated in the north of Oman; its outlet is 40 km of Muscat, Oman's capital city (Fig. 4-1). Muscat is the fastest growing city in Oman. Due to its geographic location, which is surrounded by mountains, and the horizontal expansion of the urban areas, most of the wadis and the main channels have been occupied by urban

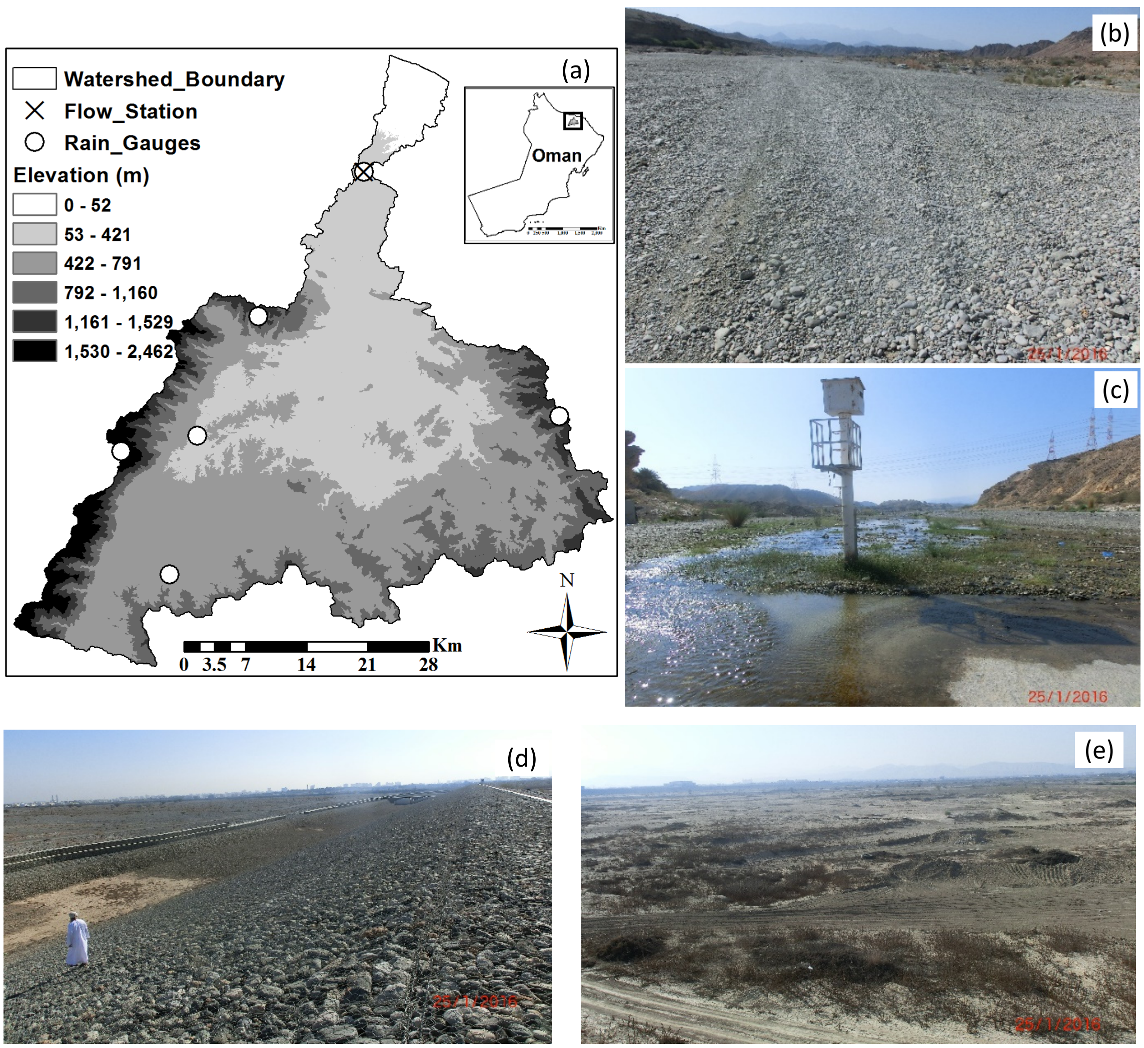

Fig. 4-1 W. Samail location map in Oman, its digital elevation model and the measurements stations, (b) main channel showing the wadi bed materials and its dry condition, (c) Al-Khoudh water flow measurement station and wadi week base flow at the downstream part, (d) Al-Khoudh Dam and (e) Al-Khoudh Dam reservoir showing its dry condition and siltation problem of it.

development (Al-Rawas and Caterina, 2006). W. Samail total area is 1741 km^2. The study area is characterized by high range of relief with elevation ranges from 2462 a.s.l. at the upstream, to sea level at the downstream, and generally slopes towards the North discharge the flow into the Arabian Gulf as shown in Fig. 4-1.

The main geological units in the target catchment are: Ophiolite, Hajar Super group, Hawasinah, Aruma Huqf and Hadhramaut group interspersed with alluvial wadi deposits. The wadi channels bed materials are mainly gravel and sands with weak base flow mainly at the downstream part originated the subsurface water flow. Land cover is mainly bare rock and desert with sparse vegetation cover. The terrain is mountainous, with slopes reached to 76% at the hill slope (estimated from a 30 m resolution DEM).

Comparing to much of the Arabian Gulf area, availability of rainfall and flow data for W. Samail is reasonable (Al-Qurashi et al., 2008; Nouh, 2006). There are 6 rainfall gauges with annual average rainfall ranges from 90 mm at Samail Station to 212 mm at Jabal Al-Hayl Station (MRMWR, 2015). The used measured surface runoff is measured at the downstream at Al-Khoudh station 13 km from the sea and before Al-Khoudh dam.

Al-Khoudh Dam is a recharge-flood protection dam which was constructed in 1988 at the downstream part of W. Samail with a design capacity of approximately 11.5 million m^3 (Al-Ismaily et al., 2015). The dam is an earthen type with 5,100 m crest length, up to 11 m high, a spillway section of 3,000 m long (Al-Ismaily et al., 2015). The dam reservoir area is 3.2 km^2. The top soils of the dam reservoir bed are experiencing the formation of a relatively low-permeability cake or siltation (Al-Ismaily et al., 2015). This siltation process decrease the dam reservoir capacity, decrease water infiltration to groundwater and increase the evaporation losses. Due to limitation of Al-Khoudh dam (in terms of its capacity and location) the Omani government start to construct more dams in such important wadi.

The target area studied by many authors SUCH as Al-Rawas and Caterina (2006) who explored the main challenges that are hindering progress on flash flood research and used a physically-based GIS supported modeling to assess and predict flash floods. Saber (2010) simulated different flash flood events at W. Samail using Hydro-BEAM model and apply the calibrated model to other wadi systems. Al-Housni, et al. (2014) use a lumped tank model to simulate flash floods in W. Samail. Al-Ismaily (2015) make a hydropedological study to investigate the impact of the of Al-Khoud dam construction on soil development in W. Samail.

As result of increasing pressure of population, and unmanaged development, people started cultivation of new lands even building their houses at more prone areas for flash floods in W. Samail. Therefore there are increasing risk of flash floods in W. Samail and more hydrological studies to asses this rising risk are highly needed.

4.3 Data and methods

Remote sensing data as well as Geographic Information Systems (GIS) techniques have been used for data input, preprocessing and visualization of the results. Rainfall Runoff Inundation model (RRI) has been utilized to simulate several WFFs events. RRI model is a hydrological model (Sayama et al., 2012), which developed for humid areas (Sayama et al., 2012; Sayama et al., 2014) and it is first time to be applied in wadi system.

A Sensitivity analysis is implemented to evaluate the weight of the several controlling parameters. The parameter setting range is based on the field investigation and literature review. This model has been calibrated using Al-Khoudh flow gauge station (Fig. 1). Due to data limitation further calibration for inundation output is still required.

4.3.1 Input data

Several data set were employed including the wadi flow data (MRMWR, 2015) measured at the downstream of Wadi Samil, just before Al-Khodh dam and the following data:

a) Rainfall data

As mentioned before we have 6 rainfall stations (Fig. 4-1) at W. Samail that cover Gonu-2007 and Phet-2010 cyclones and Thiessen method was used to interpolate these rainfall measurements all over

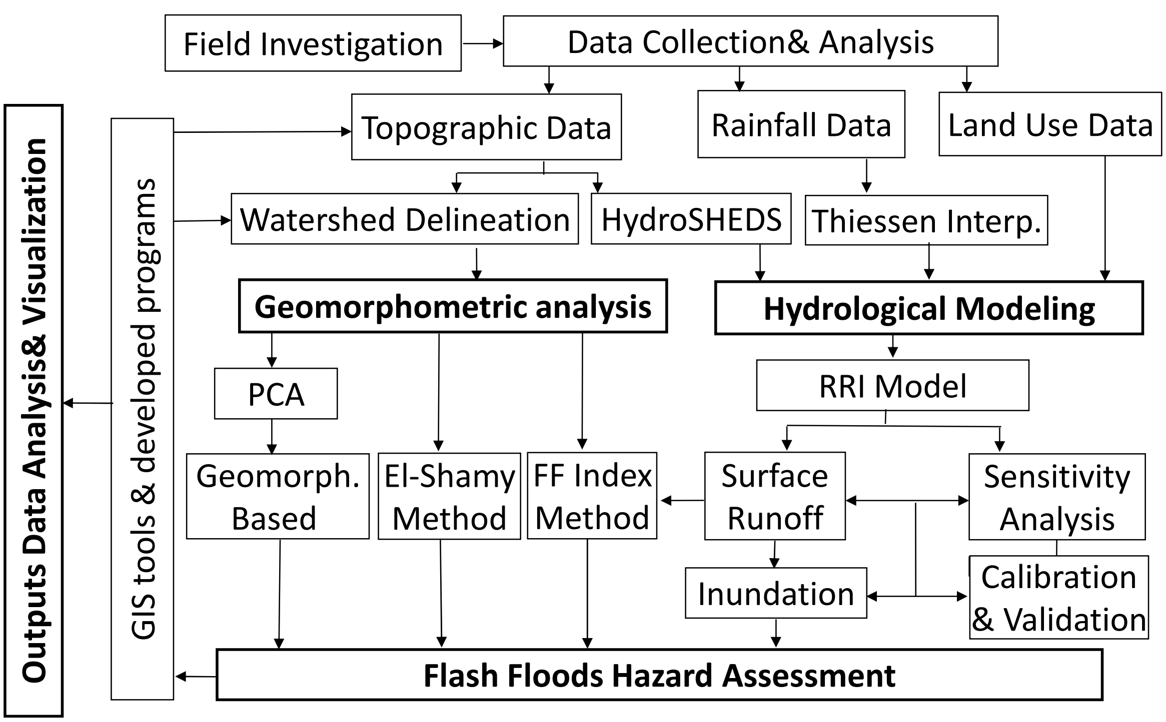

Fig. 4-2 The proposed approach for wadi flash flood risk assessment is this chapter.

the watershed. The GSMaP data have been tested also, where high discrepancy was found between both data types. The GSMaP data is highly underestimated the rainfall value as indicated in Fig. 4-3.

b) Topographic data& Watershed delineation

Topographic data were obtained by the Shuttle Radar Topography Mission (SRTM) data (USGS, 2008). The catchment can be subdivided into two areas; Samail South (upstream of the Al-Khoudh flow gauging station and 8 km north Al-Khoudh Dam, with elevation above sea level (a.s.l) ranging from 74 m to 2462 m, area 1669 km^2) and Samail North (from Al-Khoudh flow station to the coast, including Al-Khoudh Dam and Samail Alluvial fan, ranging from sea level to 109 m a.s.l., area 62 km^2).

This study used HydroSHEDS (Lehner et al., 2008) data including its flow-direction and flow-accumulation products. These data sets are utilized for identifying the streams location and watershed boundary. They are also considered one of the best topographic data sets that are globally available for

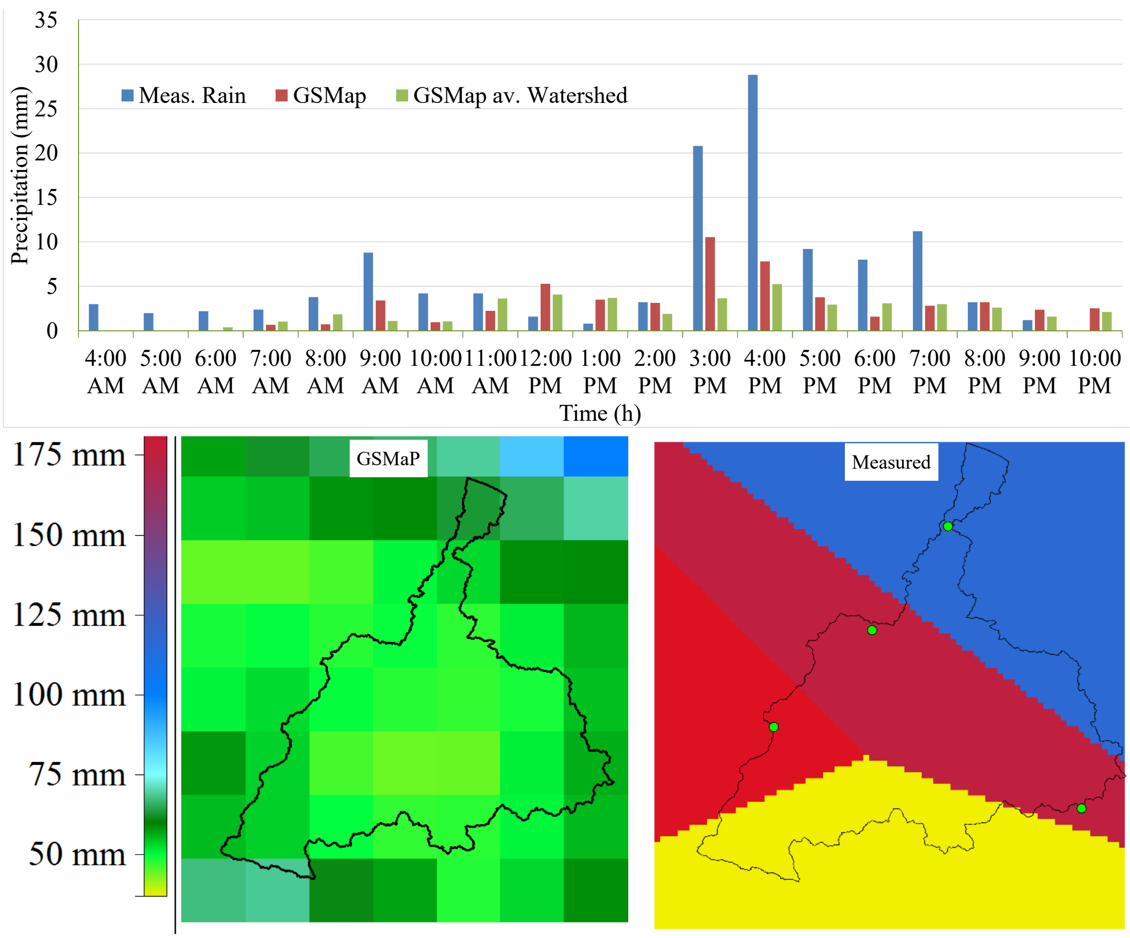

Fig. 4-3 Comparison between the measured and GSMaP rainfall data in Wadi Samail during Gonu 2007 event.

flood inundation simulation (Inomata, 2010). The used topographic and HydroSHEDS data are 30-s resolution.

c) Land use data

Land use classification is based on the study area geology (MRMWR, 2015) as uindicated in Fig. 4-4, where it is classified to three land use classes. Two classes are igneous rock (mainly ophiolite) and sedimentary rock (mainly limestone) that have high relief and slope with very shallow soil depth. The third land use class is Alluvium land use that mainly located in the downstream part with low slope and higher soil depth.

4.3.2 RRI model basic structure

The used model is 2D Rainfall-Runoff-Inundation (RRI) model, which is capable of simulating rainfall–runoff and flood inundation simultaneously (Sayama et al., 2012). Fig. 4-5 shows a schematic diagram of the RRI model. The model deals with slopes and river channels separately. Lateral flows are simulated on slope cells on a 2D basis, at a grid cell on which a river channel is located, the model assumes that both slope and river are positioned within the same grid cell.

A channel is discretized as a single vector along the center line of the overlying slope grid cell. The channel represents an extra flow path between grid cells lying over the actual river course (Sayama et al., 2012). The model calculations are based on the following mass balance (Eq. 4-1) and momentum equation (Eq. 4-2,3) for gradually varied unsteady flow:

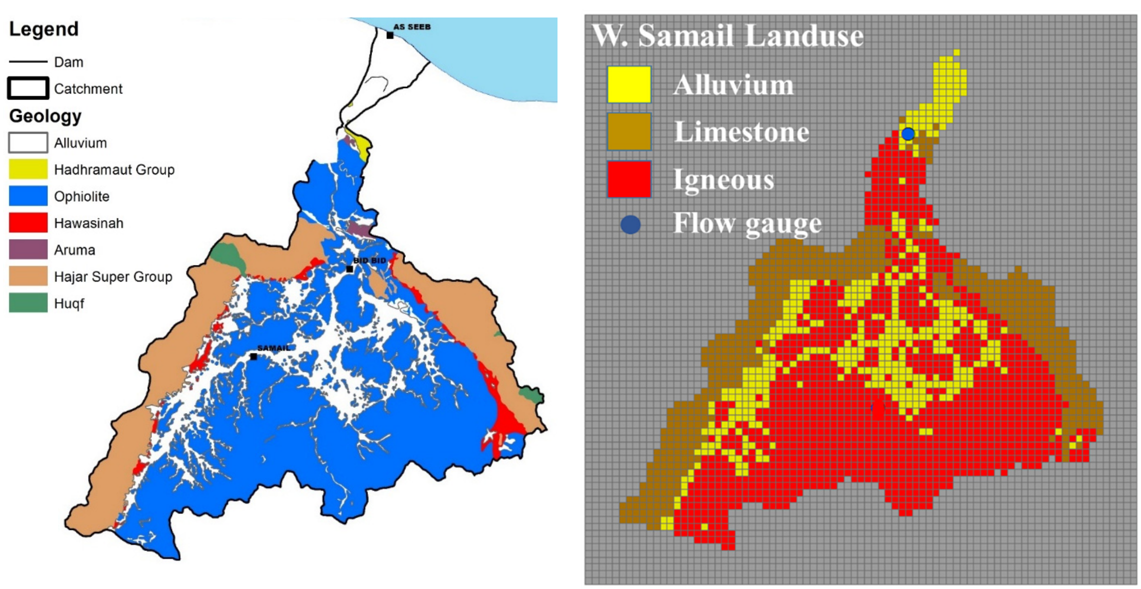

Fig. 4-4 Wadi Samail: a) geology and the extracted land uses.

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r \quad \text{(Eq. 4-4)}$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_y}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho_w} \quad \text{(Eq. 4-5)}$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho_w} \quad \text{(Eq. 4-6)}$$

where h is the height of water from the local surface, q_x and q_y are the unit width discharges in x and y directions, u and v are the flow velocities in x and y directions, r is the rainfall intensity, H is the height of water from the datum, ρ_w is the density of water, g is the gravitational acceleration, and τ_x and τ_y are the shear stresses in x and y directions and can be calculated using Manning's equation:

$$\frac{\tau_y}{\rho_w}=\frac{gn^2u\sqrt{u^2+v^2}}{h^{1/3}} \quad \text{(Eq. 4-7)}$$

$$\frac{\tau_y}{\rho_w}=\frac{gn^2u\sqrt{u^2+v^2}}{h^{1/3}} \quad \text{(Eq. 4-8)}$$

where n is Manning's roughness parameter. Under the diffusion wave approximation, inertia terms (the left side terms of (Eq. 4-2 and Eq. 4-3)) are neglected. Moreover, by separating x and y directions (i.e. ignoring v and u terms in equations Eq. 4-2 and Eq. 4-3, respectively), the following equations are derived:

$$q_x=-\frac{1}{n}h^{5/3}\sqrt{\left|\frac{\partial H}{\partial x}\right|}\,\mathrm{sgn}\left(\frac{\partial H}{\partial x}\right) \quad \text{(Eq. 4-9)}$$

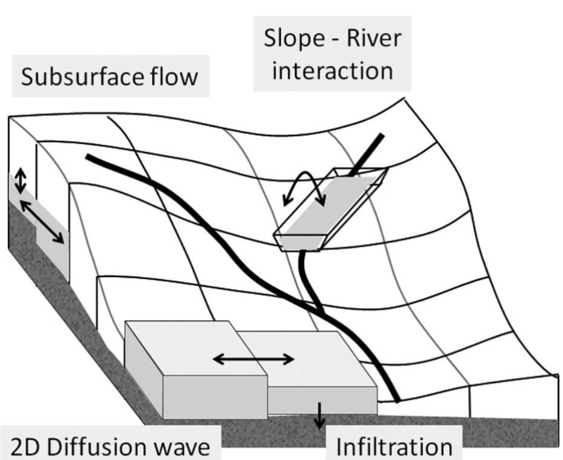

Fig. 4-5 Schematic diagram of RRI model (Sayama et al., 2012).

$$q_y = -\frac{1}{n} h^{5/3} \sqrt{\left|\frac{\partial H}{\partial y}\right|} \operatorname{sgn}\left(\frac{\partial H}{\partial y}\right) \qquad \text{(Eq. 4-10)}$$

where sgn is the signum function. For the subsurface calculation the RRI model replaces equations (Eq. 4-6) and (Eq. 4-7) with the following equations (Eq. 4-8) and (Eq. 7-9). The first parts of these equations describes the saturated subsurface flow based on Darcy's law, while the second parts describes the combination of the saturated subsurface flow and the surface flow (Sayama et al., 2012):

$$q_x = \begin{cases} -kh\dfrac{\partial H}{\partial x} & (h \le d) \\ -\dfrac{1}{n} h^{5/3} \sqrt{\left|\dfrac{\partial H}{\partial x}\right|} \operatorname{sgn}\left(\dfrac{\partial H}{\partial x}\right) - k(h-d)\dfrac{\partial H}{\partial x} & (d < h) \end{cases} \qquad \text{(Eq. 4-11)}$$

$$q_y = \begin{cases} -kh\dfrac{\partial H}{\partial y} & (h \le d) \\ -\dfrac{1}{n} h^{5/3} \sqrt{\left|\dfrac{\partial H}{\partial y}\right|} \operatorname{sgn}\left(\dfrac{\partial H}{\partial y}\right) - k(h-d)\dfrac{\partial H}{\partial y} & (d < h) \end{cases} \qquad \text{(Eq. 4-12)}$$

where k is the lateral saturated hydraulic conductivity and d is the soil depth times the effective porosity.

Streamflow was also calculated with the diffusion wave approximation. The form of streamflow equations was same as Eq. 4-6 and Eq. 4-7, but one-dimensional ($q_y = 0$). The shape of the channel was assumed to be rectangle, whose geometries were defined with three parameters, width (W), depth (D) using these equations: $W=C_W A^{S_W}$ & $D=C_D A^{S_D}$, where A is upstream catchment area.

The inflow–outflow interaction between the slope and river is calculated based on different overflowing formulae depending on water-level and levee-height conditions (Sayama et al., 2012). Green–Ampt infiltration model (Sayama et al., 2012) is used by RRI model to consider vertical infiltration as following:

$$f = k_v \left[1 + \frac{(\phi - \theta_i) S_f}{F}\right] \qquad \text{(Eq. 4-13)}$$

where f is the infiltration rate, kv is the vertical saturated hydraulic conductivity, ϕ is the soil porosity, θ_i is the initial water volume content, S_f is the suction at the vertical wetting front and F is the cumulative infiltration depth.

4.3.3 RRI model parameter setting

RRI model has been applied for extreme flash floods simulation in W. Samail after its calibration and validation. Flood estimation was performed on hourly basis to be able reproduce the rapid WFFs events. For the river cross-sections settings, we used surveyed data at two locations one is at the upstream and the other is in the downstream in addition to Google Earth images and SRTM-1s DEM to estimate the following channel geometry parameters, C_W=1.0, S_W=0.68, C_W=0.525 and S_W=0.24. The other model parameters were suggested after making sensitivity analysis to detect the weight of each parameter on the calculated results and the most sensitive parameters. More than 1000 manual runs using trial-and-error approach have been done. Later Gonu 2007 and Phet 2010 tropical cyclones are used for RRI model calibration and validation respectively.

Major sensitive RRI model parameters setting is indicated in Table 4-1, where the mountainous land use including the igneous and sedimentary rocks are governed by subsurface and surface flow assumption (Eq. 4-8 and Eq. 4-9). The Alluvium land use is governed by Green-Ampt model (Eq. 4-10).

To evaluate their effects on the predicted river discharges, we used the following five indices: Relative hydrograph peak (PE), Coefficient of determination (squared correlation coefficient) (r^2), Percent bias (PBIAS), Nash-Sutcliffe efficiency (NSE) (Nash and Jonh, 1970), Kling-Gupta efficiency (KGE) (Gupta et al., 2009) as following:

$$PE = \frac{\left(Y_{\max}^{obs} - Y_{\max}^{sim}\right)*100}{Y_{\max}^{sim}} \quad \text{(Eq. 4-14)}$$

$$r^2 = \frac{\sum_{i=1}^{n}\left(\left(Y_i^{sim} - Y_{mean}^{sim}\right)\left(Y_i^{obs} - Y_{mean}^{obs}\right)\right)^2}{\sum_{i=1}^{n}\left(Y_i^{sim} - Y_{mean}^{sim}\right)^2 \sum_{i=1}^{n}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2} \quad \text{(Eq. 4-15)}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)*100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \quad \text{(Eq. 4-16)}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2}\right] \quad \text{(Eq. 4-17)}$$

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad \text{(Eq. 4-18)}$$

where r is the linear correlation, Y_i^{obs} and Y_i^{obs} are observed and simulated discharge at time step i, Y_{mean}^{obs} and Y_{mean}^{sim} are the mean observed and simulate discharge, α is a measure of relative variability and equal to the ratio of standard deviation of the simulated and observed discharge and β represents the bias and equal to the ratio of the mean simulated and observed discharge.

Table 4-1 RRI model major parameter setting for the different land uses showing its default values and ranges.

Parameter (default)	Range	Alluvium	Igneous	Sedimentary
n_{river} (0.03m$^{-1/3}$s)	0.015 ~ 0.04	0.022	0.022	0.022
n_{slope} (0.3 m$^{-1/3}$s)	0.15 ~ 1.0	0.3	0.35	0.3
d (0.471 m)	0.15 ~ 1.0	-	0.14	0.3
k (0.1ms^{-1})	0.01-0.3	-	0.05	0.05
k_v(5.56*10^{-7} ms^{-1})	6.54*10^{-5} ~ 1.67*10^{-7}	4*10^{-6}	-	-
φ	0.3 ~ 0.5	0.475	-	-
S_f(0.3163 m)	0.0495 ~ 0.3163	0.15	-	-

4.3.4 Principal component analysis of the geomorphometric parameters

Watershed characterization included the pervious used 36 metrics from chapter 3, where the established correlation analysis further used to identify strongly inter-correlated variables, of which only one was retained. Preference was given to variables with strong correlation with the estimated hydrological indices. Principal components analysis (PCA) was used to examine the data structure of the 9 remaining explanatory variables. This method reduces redundancy and correlation among the independent variables and provides an objective means of variable selection (Morris et al., 2009; Price et al., 2011; Singh et al., 2009). More specifically, the first principal component is that linear combination of the original variables which contributes a maximum to their total variance; the second principal component, uncorrelated with the first, contributes a maximum to the residual variance, and so on until the total variance is analyzed (Singh et al., 2009). The PCA rotated factor loadings were used to further reduce the data to four candidate variables for inclusion in flash flood susceptibility analysis as indicated in Table 4-2, Table 4-3, Fig. 4-6, Fig. 4-7 and Fig. 4-8.

Table 4-2 Principal component loading matrix of the entire geomorphic parameters before screening

Parameter	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
A	-0.235	-0.006	-0.110	0.198	-0.039	0.046	0.035	0.030	-0.081	-0.111	-0.002	0.126	-0.105	-0.070
P	-0.247	-0.083	0.023	0.084	-0.042	0.104	0.036	0.027	-0.172	-0.143	0.139	0.195	0.177	-0.145
L_b	-0.250	-0.101	0.038	0.036	-0.042	-0.017	-0.008	0.115	-0.022	0.058	0.008	0.029	0.269	0.062
T_c	-0.260	0.058	0.011	0.032	-0.036	-0.018	-0.022	-0.042	0.045	-0.051	0.041	-0.154	0.136	0.135
H_{mean}	0.065	-0.211	0.009	0.248	-0.171	-0.271	-0.199	-0.225	-0.004	-0.480	0.144	-0.194	0.279	0.035
R	0.093	-0.293	-0.005	0.204	-0.063	0.102	0.123	-0.007	-0.053	0.080	-0.031	-0.199	-0.039	0.069
R_r	0.198	-0.196	-0.049	0.158	0.098	-0.053	0.076	-0.042	0.018	-0.074	0.063	0.016	-0.039	0.107
R_M	0.170	-0.257	0.042	0.105	0.004	-0.067	0.097	-0.026	0.083	-0.016	0.006	-0.052	-0.176	0.001
HI	-0.160	0.025	-0.166	-0.339	-0.010	-0.153	-0.097	0.015	0.011	-0.268	-0.019	-0.226	0.094	-0.153
R_n	0.096	-0.283	0.021	0.221	-0.075	0.101	0.140	0.011	-0.037	0.053	-0.039	-0.241	-0.053	0.023
DI	-0.011	-0.271	-0.063	-0.139	0.025	0.238	0.374	0.192	0.139	-0.015	0.037	-0.118	-0.126	-0.110
S_b	0.081	-0.301	-0.154	0.065	0.082	0.029	0.096	-0.117	0.088	0.186	0.108	0.276	0.238	-0.010
S_{ms}	0.207	-0.164	-0.062	0.071	0.145	-0.160	0.009	0.049	0.016	-0.107	-0.282	0.505	0.101	-0.031
R_s	0.209	0.119	0.082	0.016	0.111	-0.245	-0.111	0.272	-0.151	-0.155	-0.249	0.069	0.038	0.029
S_{ls}	0.202	-0.190	0.016	0.092	0.034	-0.062	0.040	0.217	-0.303	-0.284	-0.205	-0.156	0.075	-0.088
F	0.146	0.189	-0.202	0.148	0.152	0.064	-0.001	0.017	-0.314	0.057	0.463	0.019	-0.022	-0.019
C	-0.129	-0.157	0.280	-0.174	-0.073	0.042	0.060	-0.045	-0.183	-0.182	0.321	0.338	-0.001	0.102
R_c	0.144	0.183	-0.251	0.125	0.107	-0.064	-0.050	0.019	-0.086	0.258	-0.028	-0.280	0.310	0.007
R_e	0.147	0.180	-0.220	0.165	0.141	0.089	0.004	-0.018	-0.262	-0.036	0.303	0.012	-0.008	-0.077
τ	-0.018	-0.055	0.323	-0.120	0.019	0.209	0.187	-0.488	-0.490	0.123	-0.235	-0.151	0.109	0.001
TN_S	-0.236	-0.030	-0.106	0.184	-0.004	0.089	-0.009	0.069	-0.076	-0.089	0.006	0.079	-0.123	-0.048
TL_S	-0.231	0.014	-0.087	0.225	-0.052	0.045	0.057	0.003	-0.059	-0.128	-0.003	0.146	-0.085	0.084
L_{ms}	-0.258	-0.060	0.010	0.052	0.007	-0.017	-0.015	0.115	0.061	0.061	-0.101	-0.098	0.244	0.033
L_{ls}	-0.257	-0.066	0.005	0.054	0.020	-0.012	-0.015	0.095	0.080	0.060	-0.049	-0.072	0.233	-0.017
Si_{ms}	-0.001	0.260	0.083	-0.079	0.261	0.279	0.165	0.099	-0.195	-0.349	-0.241	0.011	0.050	0.119
Si_{ls}	0.076	0.110	-0.100	-0.023	0.423	0.138	0.203	-0.437	0.422	-0.245	-0.007	0.037	0.205	0.089
D_f	0.032	-0.066	0.230	0.187	0.103	0.168	-0.558	-0.140	-0.037	0.259	-0.149	0.164	0.077	0.043
$F1$	0.014	-0.203	0.013	-0.121	0.256	0.330	-0.384	0.225	0.071	-0.147	0.095	-0.142	-0.197	0.403
D_d	0.027	0.199	0.297	0.225	-0.052	-0.092	0.138	0.023	0.151	-0.020	0.024	-0.048	-0.051	-0.114
C_m	-0.026	-0.190	-0.305	-0.234	0.049	0.086	-0.116	-0.038	-0.128	0.031	-0.077	0.027	0.077	-0.466
L_o	-0.026	-0.190	-0.305	-0.234	0.049	0.086	-0.116	-0.038	-0.128	0.031	-0.077	0.027	0.077	0.130
T	0.041	-0.016	0.319	0.150	0.222	0.317	-0.179	0.133	0.184	-0.102	0.132	-0.107	0.107	-0.572
R_t	-0.159	0.030	-0.248	0.255	0.016	0.209	-0.058	-0.032	0.022	-0.024	-0.253	-0.028	-0.149	0.002
R_f	-0.150	0.113	-0.184	0.317	-0.059	0.107	0.054	-0.094	0.027	-0.061	-0.236	0.046	-0.068	0.035
L_{umax}	-0.209	-0.056	0.029	0.025	0.256	-0.264	-0.078	-0.200	-0.137	-0.010	0.021	-0.130	-0.362	-0.044
R_b	-0.163	-0.077	0.117	0.078	0.373	-0.138	0.168	0.226	-0.073	0.144	0.154	-0.086	0.264	0.255
R_l	-0.169	-0.139	-0.006	-0.001	0.306	-0.267	-0.130	-0.260	0.014	-0.024	0.041	-0.078	-0.236	-0.102
R_a	-0.154	-0.066	0.070	0.035	0.396	-0.264	0.165	0.167	-0.059	0.180	-0.107	0.054	-0.102	-0.147
Standard deviation	3.767	2.790	2.236	1.892	1.606	1.339	1.197	0.838	0.596	0.520	0.398	0.327	0.233	0.000
Proportion of variance	0.373	0.205	0.132	0.094	0.068	0.047	0.038	0.019	0.009	0.007	0.004	0.003	0.001	0.000
Cumulative proportion of variance	0.373	0.578	0.710	0.804	0.872	0.919	0.957	0.975	0.984	0.992	0.996	0.999	1.000	1.000

Table 4-3 Principal component (PC) loading matrix of the four finally screened out geomorphic parameters

Parameter	PC1	PC2	PC3	PC4
$\boldsymbol{A}$	**-0.572**	0.299	-0.409	**-0.645**
$\boldsymbol{S_{ms}}$	0.479	**-0.634**	-0.299	-0.529
$\boldsymbol{F}$	0.454	0.461	**-0.715**	0.264
$\boldsymbol{R_l}$	-0.486	-0.545	-0.481	0.484
Standard deviation	1.472	0.973	0.810	0.480
Proportion of variance	0.542	0.236	0.164	0.058
Cumulative proportion of variance	0.542	0.778	0.942	1.000

The value in bold italics for each PC is the highest loadings corresponding to that PC.

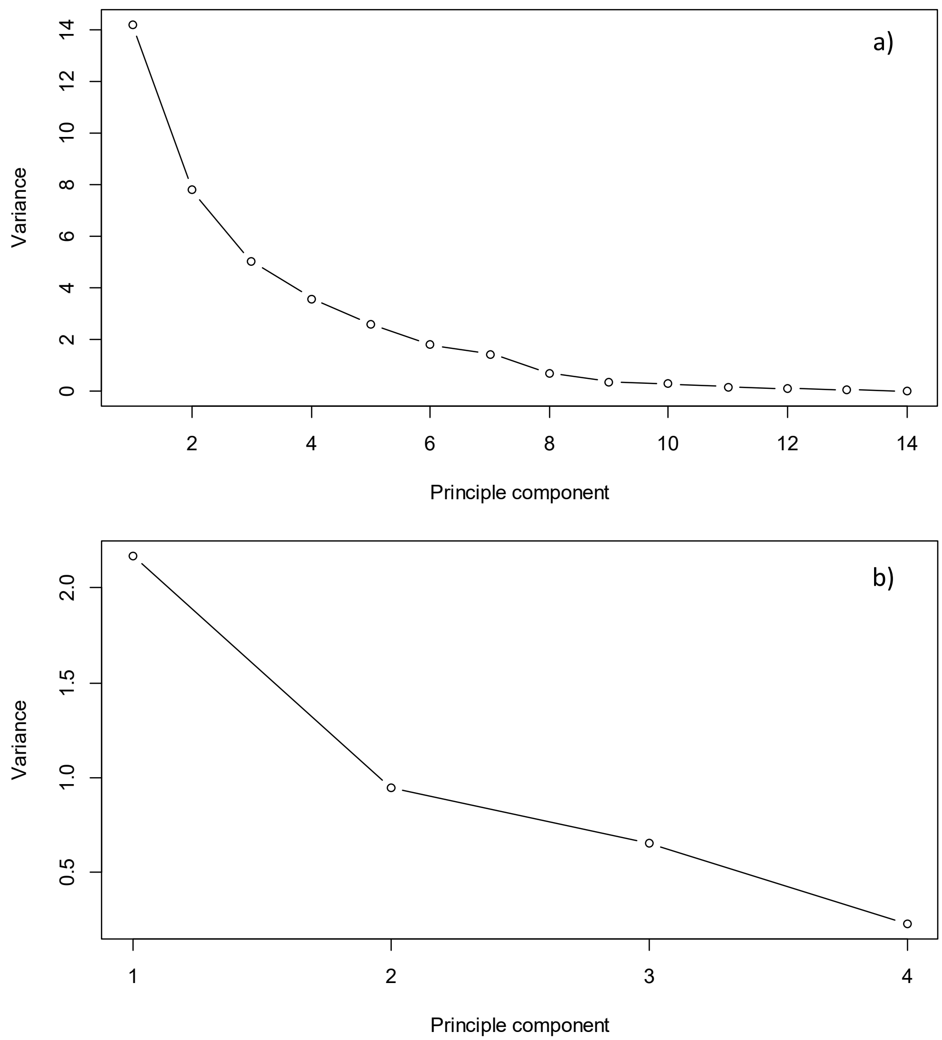

Fig. 4-6 Scree plots of the eigenvalues or variance for each Principal component (PCs) of: a) the entire geomorphic parameters before screening and b) the four finally screened out geomorphic parameters.

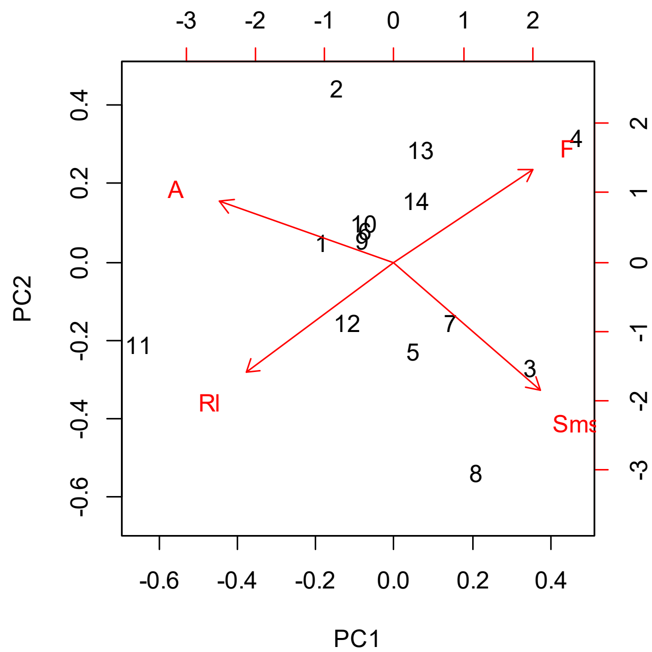

Fig. 4-7 Principal component analysis biplot showing the significance of each geomorphometric parameter and basin on the first two principal component (PC).

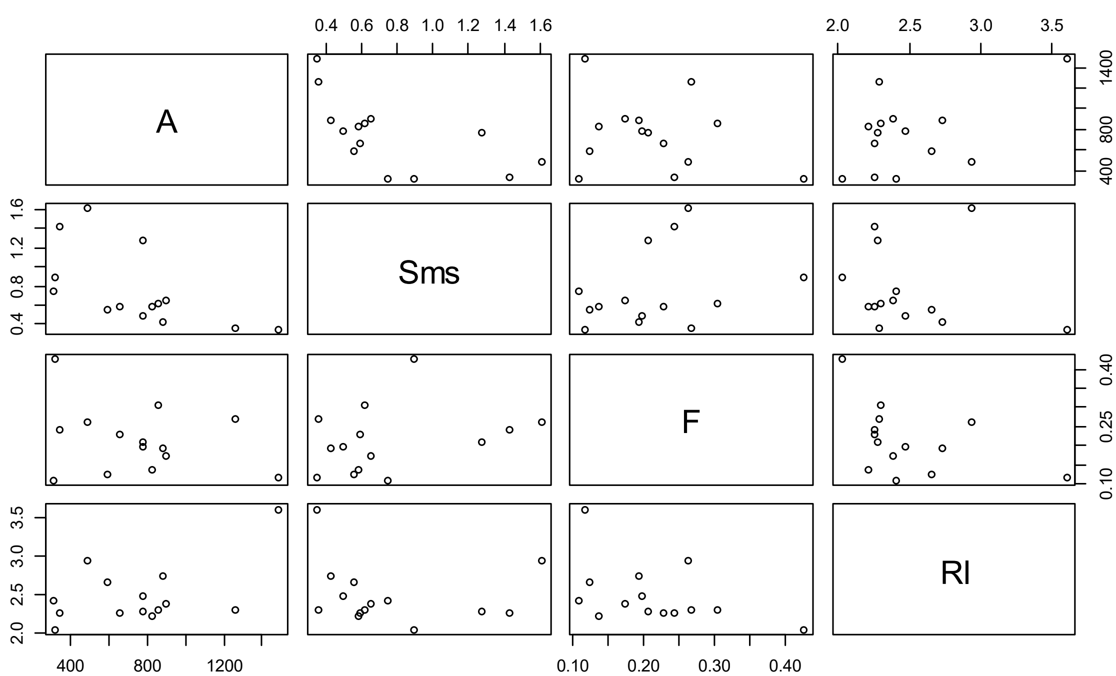

Fig. 4-8 The correlation matrix of the four finally screened out geomorphic parameters that are: Area (*A*), Main stream average slope (S_{ms}), Form factor (*F*) and Length ration (*Rl*) showing that the selected parameters are totally independent and there is no correlation between them.

4.3.5 Flood susceptibility assessment methods

Three methods to detect the flood susceptibility has been adopted as following:

a) Flood susceptibility based on Flash Flood Index

Flash flood events were identified by using the flash flood index (*FFI*) approach proposed by Bhaskar et al. (2000), who initially proposed the *FFI* to evaluate the severity of flood events using three variables including the rising curve gradient (*K*), the flood magnitude ratio (*M*), and the flood response time (*TP*) (Ahn and Merwade, 2016; Kim and Kim, 2014).

Rising Curve Gradient (K)

The rising curve of the hydrograph can be described by an exponential equation of this general form:

$$Q_t = Q_o e^{Kt} \quad \text{(Eq. 4-19)}$$

$$K=(ln(Q_t/Q_o))/t \quad \text{(Eq. 4-20)}$$

where Q_o is the specified initial discharge, Q_t is the discharge at a later time t (close to the time to peak, *TP*), K is the rising curve gradient (h^{-1}), and t is time in hours (Bhaskar et al., 2000). Basically, the rising curve gradient is a measure of the steepness of the rising limb of the flood hydrograph and, hence, flash floods would be associated with large values of parameter K (Bhaskar et al., 2000). To quantify the relative intensity of current basin K_i, maximum K_{max} and minimum K_{min} of all basins were used in this study to create the index of rising curve gradient RK as following:

$$RK=(K_i-K_{min})/(K_{max}-K_{min}) \quad \text{(Eq. 4-21)}$$

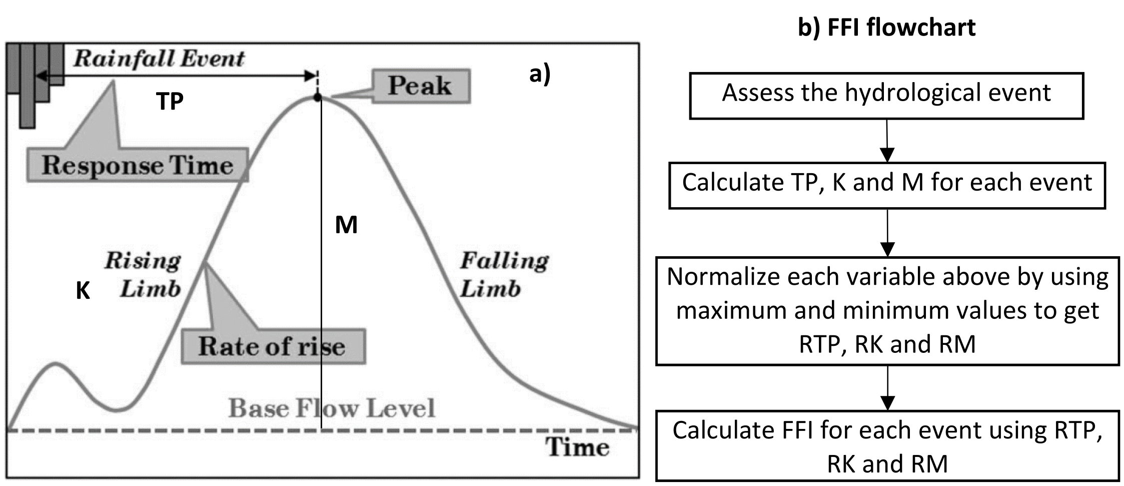

Fig. 4-9 a) Hydrograph showing the components of Flash Flood Index (FFI), including the rising curve gradient (K), flood magnitude ratio (M) and flood response time (TP); and b) flowchart summarizing the FFI estimation procedure (after Ahn and Merwade, 2016; Kim and Kim, 2014).

Flood Magnitude Ratio (M)

This parameter is an indication of the order of magnitude by which the peak flood discharge exceeds the long-term average discharge. The flood magnitude ratio, M, is defined as:

$$M=Q_{max}/Q_a \quad \text{(Eq. 4-22)}$$

where Q_{max} is the flood peak discharge and Q_a is the long-term average discharge (Bhaskar et al., 2000). In wadi special case where the is no base flow, Q_a is considered to be equal 1 and M is directly representing the peak flow. To quantify the flood event in a specific basin M_i, maximum M_{max} and minimum M_{min} of the other basins were used to create the relative flood magnitude ratio (RM) as following:

$$RM=(M_i-M_{min})/(M_{max}-M_{min}) \quad \text{(Eq. 4-23)}$$

Flood response time (TP)

The flood response time, TP, is measured directly from the flood hydrograph and is defined as the duration between the time the flood event starts and the time when the peak discharge occurs (Bhaskar et al., 2000). A low flash flood response time is associated with high runoff velocities typical of flash flooding. In view of this, low values of flash flood response time are assigned a higher RTP and FFI (Bhaskar et al., 2000). To quantify the current basin flood TP_i by relative intensity, maximum hour TP_{max} and minimum hour TP_{min} of all basins were used to generate the index of relative flood magnitude ratio (RT) as following:

$$RTP=(TP_i-TP_{min})/(TP_{max}-TP_{min}) \quad \text{(Eq. 4-24)}$$

Flash Flood Index (FFI)

In the case of rising gradient (K) and flood magnitude ratio (M) of runoff hydrograph, a relatively larger value means an increased likelihood of flash flood occurrence. In contrast, a smaller value of response or delay time (TP) means an increased likelihood of flash flood. By summation of relative intensity indices (RK, RM, RTP], it is possible to compute an FFI as follows:

$$FFI= RK+RM+RTP \quad \text{(Eq. 4-25)}$$

b) Flood susceptibility based on the geomorphometric parameters

The morphometric parameters were classified according to their risk potential to two main groups. Group I includes morphometric parameters such as Area (A), Form factor (F_f), Relief ratio (R_r), Average basin slope (S_b), and main basin slope (S_{ms}). These parameters were considered in many studies and as shown in Chapter 3, have direct proportion with the flash flood susceptibility in which a high value represents high susceptible for flooding (Abuzied et al., 2016; Youssef et al., 2011). Group II includes morphometric parameters such as Bifurcation ratio (B_r) and Elongation ratio (E_r). These parameters could considered inversely proportions with the flash flood susceptibility in that a high value relates to low flash flood susceptibility. The ranking score for each morphometric parameter was assigned based on its relationship to the flash flood susceptibility using simple statistically method according to the following steps (Abuzied et al., 2016):

- Determine minimum (X_{min}) and maximum (X_{max}) value of each morphometric parameter for all sub-basins of the study area
- Normalize all the values of each direct proportion parameters (X) based on the following equation.

$$(X - X_{min}) / (X_{max} - X_{min}) \quad \text{(Eq. 4-26)}$$

- Normalize all the values of each inversely proportion parameters (X) based on the following equation.

$$(X - X_{max}) / (X_{min} - X_{max}) \quad \text{(Eq. 4-27)}$$

- Sum the rank for the morphometric parameters to calculate the flood susceptibility value for each sub-basin.

In the current study, we adopted 4 morphometric and assumed that these morphometric parameters have the same weight according to the pre-mentioned equations (Abdelkareem, 2017; Abuzied et al., 2016; Youssef et al., 2011). The all used morphometric parameters are directly proportion and assigned 0 for the lowest value and 1 for the highest value. These parameters are Area (A), Mainstream slope (S_{ms}), Form Factor (F) and Length Ratio (R_l) and selected based on Principal Component Analysis (PCA) and correlation between the morphometric analysis and the flood indices that conducted in chapter 3. To come up with the flash flood susceptibility map, the sum of the rank values of these morphometric parameters in each sub-basin was classified using equal interval into 5 categories (very low, low, medium, high and very high) to evaluate the most critical sub-basins for flooding.

c) El-Shamy model

Integration of morphometric parameters could be used to characterize the risky flash-flooded sites. Because of wadi geology, drainage pattern and the morphological features controlling the flash flood risk and groundwater recharge of the flood plain, we adopt El-Shamy model who established two relation graphs to classify the catchment risk degree (El-Shamy, 1992a). This method based on the relations between bifurcation ratios versus the drainage frequency (D_f) and the relations between bifurcation ratio (R_b) and the drainage density (D_d). The location of any basin on the two relations designates its runoff/infiltration potentiality. The R_b-D_f and R_b-D_d diagrams are subdivided by two boundary lines into three main classes following and as shown in Fig. 4-10:

- A has high groundwater and low flooding potentiality
- B has high flooding and low groundwater potentiality
- C has intermediate groundwater and flooding potentiality

El-Shamy model have been adopted by several studies to assess flood and groundwater potentiality (Abdalla et al., 2014; Abdel-Lattif and Sherief, 2012; Arnous et al., 2011; El-Behiry et al., 2006; El-Shamy, 1992b; Geriesh et al., 2001; Taha et al., 2013; Youssef and Hegab, 2005; Youssef et al., 2009; Youssef et al., 2011).

4.4 Results and discussion

4.4.1 RRI model parameters sensitivity analysis

Sensitivity analysis for RRI model was conducted in Wadi Abadi to measure the relative significance of each model parameter in determining the output hydrograph peak and shapw, as indicated in Fig. 4-11, Fig. 4-12 and Fig. 4-13. According to results from sensitivity analysis, the most significant parameters are channel roughness coefficient (n_{river}), hillslope roughness coefficient (n_{slope}), soil depth, and soil porosity (ϕ). While vertical saturated hydraulic conductivity (kv) and lateral saturated hydraulic conductivity (k) have a medium impact on the generated hydrographs. The suction at the vertical wetting front (S_f) and the unsaturated subsurface flow parameters have minor impact on the model results.

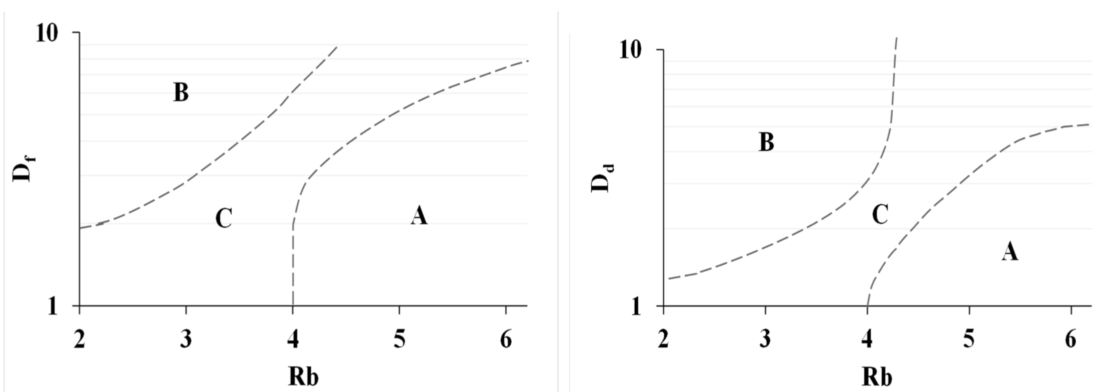

Fig. 4-10 El-Shamy model for flash floods risk and groundwater potentiality prediction (El-Shamy, 1992a).

Table 4-4 RRI model performance evaluation by using the following parameters for Gonu-2007 and Phet-2010 extreme flash floods.

Index (Ideal value)	Gonu 2007	Phet 2010
PE (0 %)	-1.18	-9.05
r2 (1)	0.96	0.89
PBIAS (0%)	-14.3	-12.04
NSE (1)	0.93	0.86
KGE (1)	0.81	0.74

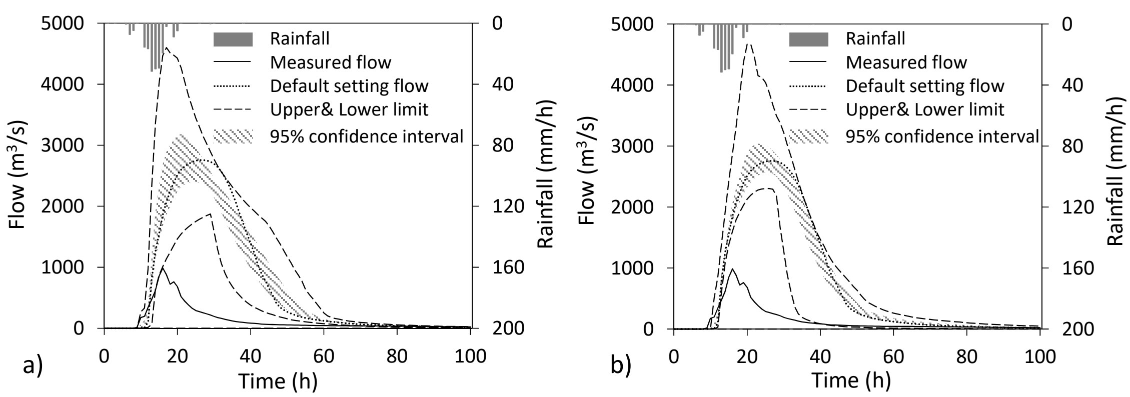

Fig. 4-11 Variations of simulated hydrographs in Wadi Samail during Gonu 2007 event under different RRI parameters setting: a) channel roughness coefficient (n_{river}) and b) hillslope roughness coefficient (n_{slope}) at the first flow case assumption in RRI model which is surface runoff only.

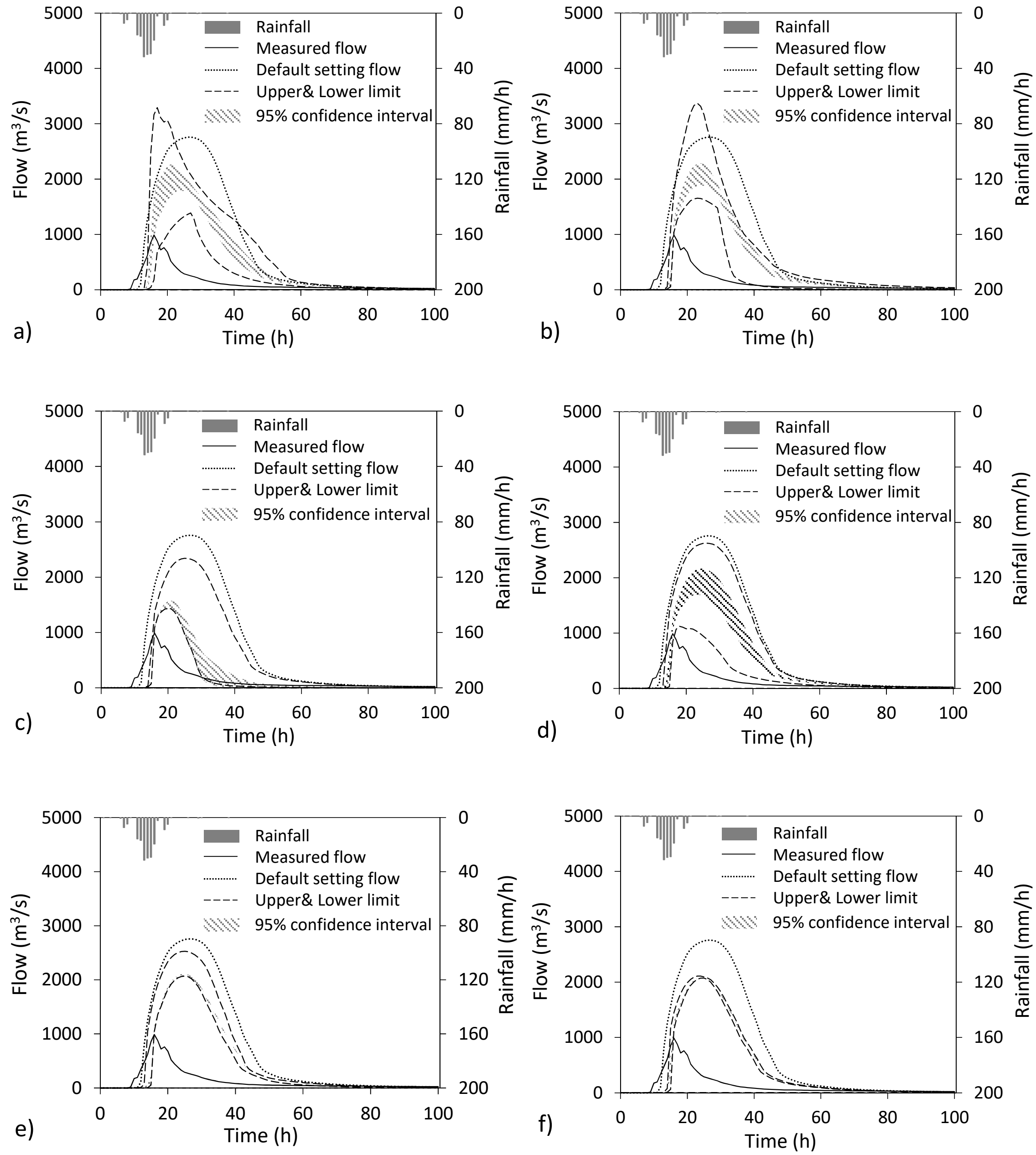

Fig. 4-12 Variations of simulated hydrographs in Wadi Samail during Gonu 2007 event under different RRI parameters setting: a) channel roughness coefficient (n_{river}), b) hillslope roughness coefficient (n_{slope}), c) soil depth, d) soil porosity (ϕ), e) vertical saturated hydraulic conductivity (kv) and f) suction at the vertical wetting front (S_f) at the second flow case assumption in RRI model which is infiltration excess surface runoff and vertical infiltration calculated using Green-Ampt model.

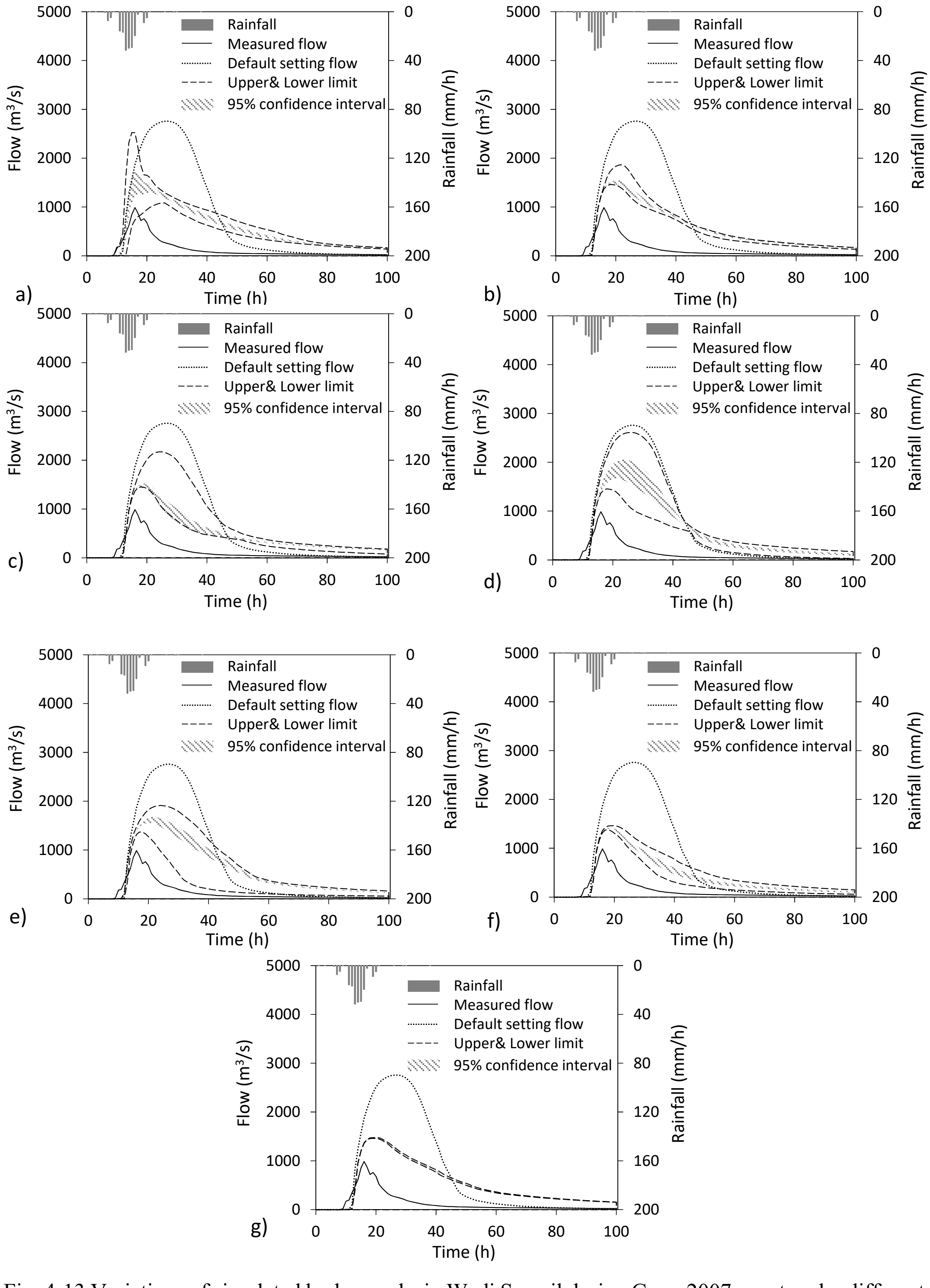

Fig. 4-13 Variations of simulated hydrographs in Wadi Samail during Gonu 2007 event under different RRI parameters setting: a) channel roughness coefficient (n_{river}) b) hillslope roughness coefficient (n_{slope}), c) soil depth, d) soil porosity (ϕ), e) lateral saturated hydraulic conductivity (k), f) unsaturation effective porosity and g) lateral unsaturated hydraulic conductivity at the third flow case assumption in RRI model (saturation excess surface runoff and unsaturated subsurface runoff.

4.4.2 RRI model application in Wadi Samail

The RRI model was applied to W. Samail and using the merit of the distributed models discharge of each mesh all over the basin is computed. Fig. 4-14 show the hydrographs and spatial distribution maps of the surface runoff for Gonu-2007 and Phet-2010 extreme events. WFFs special characteristics can be figured out from the results where it takes a few hours to reach to the peak discharge and then gradually decreasing until end of the event. Variation of hydrograph peak and spatial distribution can be noticed from one event to another. This is due to different rainfall intensity and pattern for each event. Results confirm that Gonu-2007 is more severe than Phet-2010 in terms of both discharge peak and geographical distribution.

The simulated hydrographs using the parameter setting that indicated in (Table 4-4) show good agreements with the measured data as shown in Fig. 4-14- a1 and Fig. 4-14-b1. RRI model has better performance with Gonu-2007 event, where it was used as the calibration event. The model has been

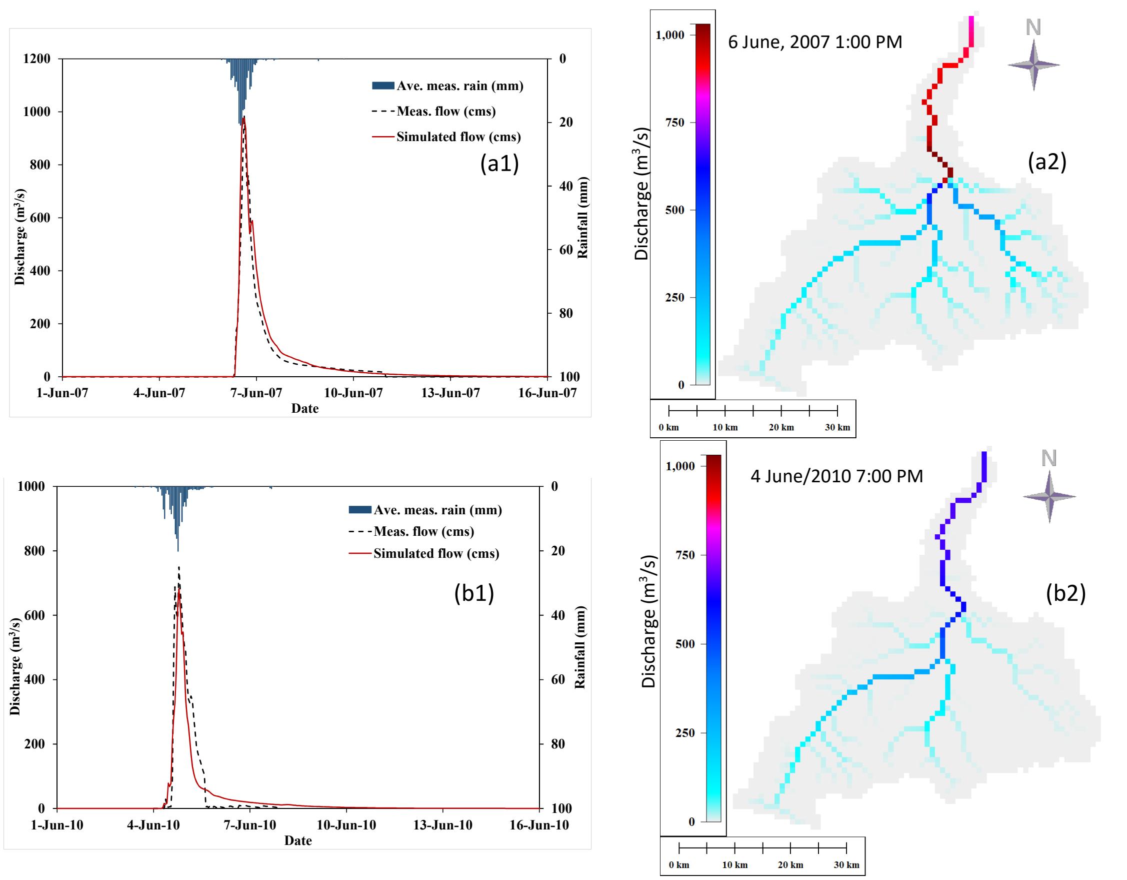

Fig. 4-14 RRI model: a) calibration results (Gonu-2007) and b) validation results (Phet-2007) for 1) flood hydrograph and 2) peak flow spatial distribution.

tested in the next extreme event (Phet-2010) and still has good performance and even better PBIAS. The peak generation is good for both events where the relative error in hydrograph peak is less than 0.02 and 0.1 of the measured peak flow in Gonu-2007 and Phet-2010 respectively. Hydrograph recession has reasonable behavior but it is the main source of the results bias. May be the main source of this error is the absence of stable groundwater module in RRI model, where still the groundwater part in RRI model is under development. Even the hydrological model has good generation for the

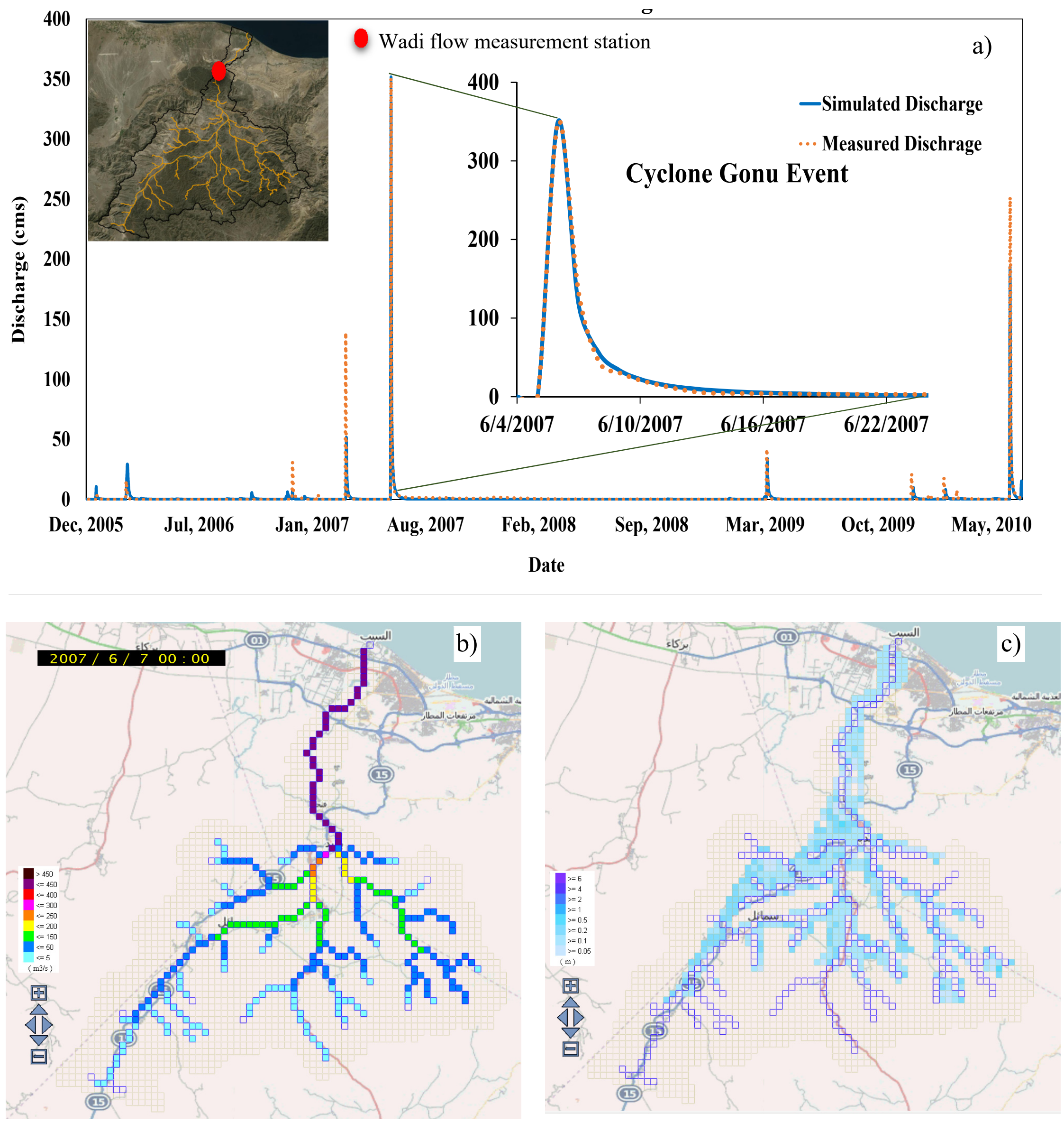

Fig. 4-15 Flash flood simulation at W. Samail using RRI model: a) long term measured and estimated hydrograph (average daily discharge m^3/s) from 2005 to 2010 highlighting Gonu 2007 flash flood event, b) peak estimated discharge distribution map, c) maximum estimated inundation distribution map.

hydrograph main peak in terms of value and time to peak, still the model cannot generate some small and minor peaks existing in the measured data. That may be normal in any model due to variant simplifications of the real complex hydrological system in terms of scale and rainfall. Due to data limitation and relative small area of W. Samail comparing to input data scale, RRI model inundation outputs were not calibrated and should be considered in the future.

The distribution maps (Fig. 4-14-a2 and Fig. 4-14- b2) can be helpful in flash floods, water resources, urban and land use management. Surface runoff zones can give signs of the potential groundwater

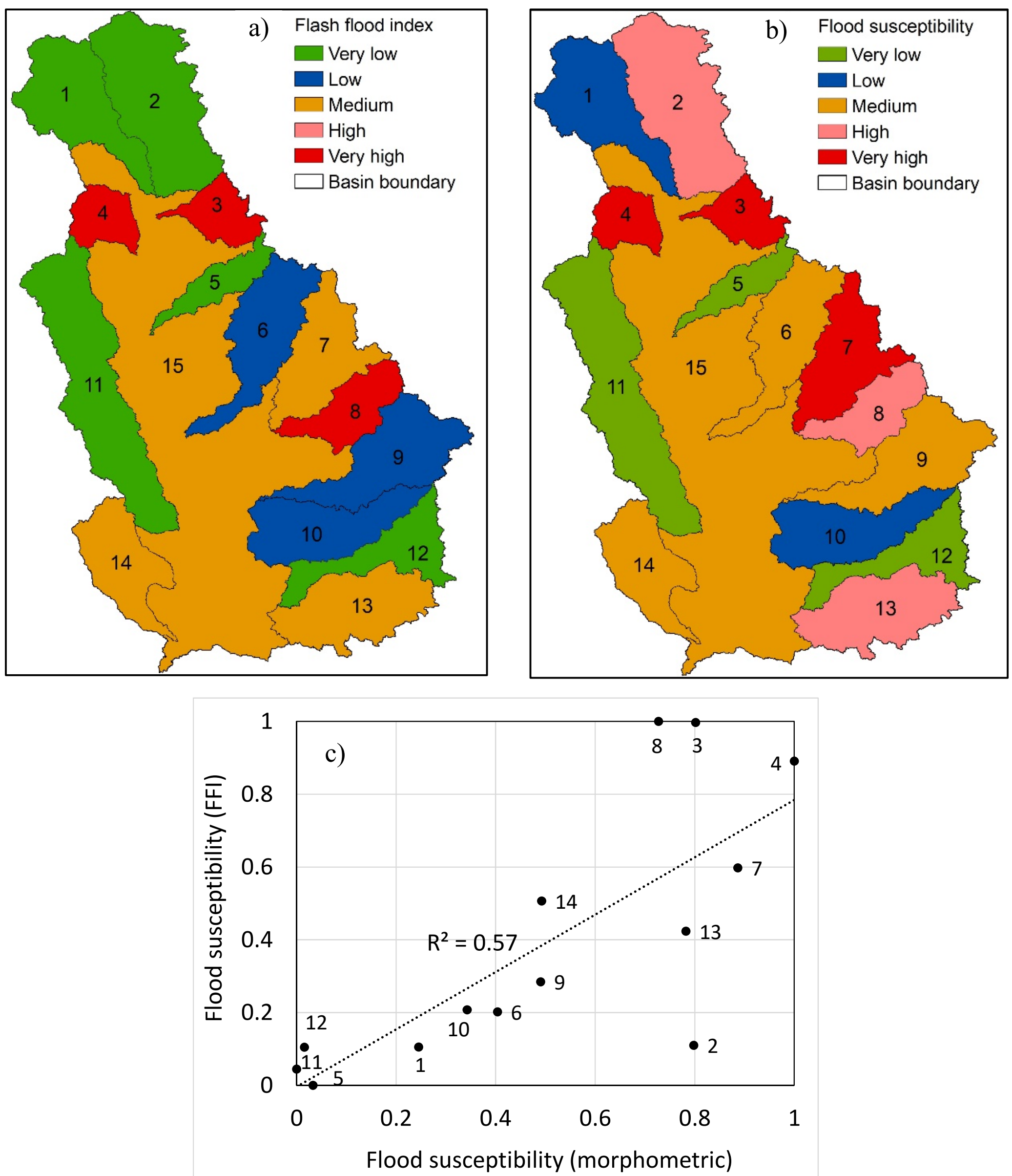

Fig. 4-16 Ranking of flash flood susceptibility of Wadi Qena catchments based on a) flash flood index, b) morphometric analysis and c) the relationship between both a) and b) methods.

locations, where the transmission losses and groundwater recharge are linearly related to surface runoff14).

4.4.3 Flash flood susceptibility assessment

Flash flood susceptibility for Wadi Qena sub-basins was determined according to the total rank values of the flash flood index, morphometric parameters in each sub-basin and El-Shamy model as indicated in Fig. 4-16-a, Fig. 4-16-b and Fig. 4-17-b respectively. The ranking values provide a relative measure to identify sub-basins of relatively high or low flood susceptibility in the study area. The flash flood susceptibility based on morphometric parameters and flash flood index has good correlation as indicated in Fig. 4-16-c. Results suggest that the sub-basins numbered 3, 4, 7 and 8 have the highest flood susceptibility rank, whereas sub-basins numbered 1, 5, 10, 11 and 12 have the lowest flood susceptibility rank. 6, 9, 13, 14 have medium flood susceptibility. However, sub-basin number 2 have high variation between the two methods as shown in Fig. 4-16. That discrepancy resulted from the network not symmetric in the case of sub-basin 2, so the water takes longer distance and time to reach the main stream, which was not reflected by the morphometric parameters while the flash flood index that based on the flood hydrograph, could figure out this issue. Generally, the flash flood susceptibility map shows Wadi Qena have medium possibility for flooding.

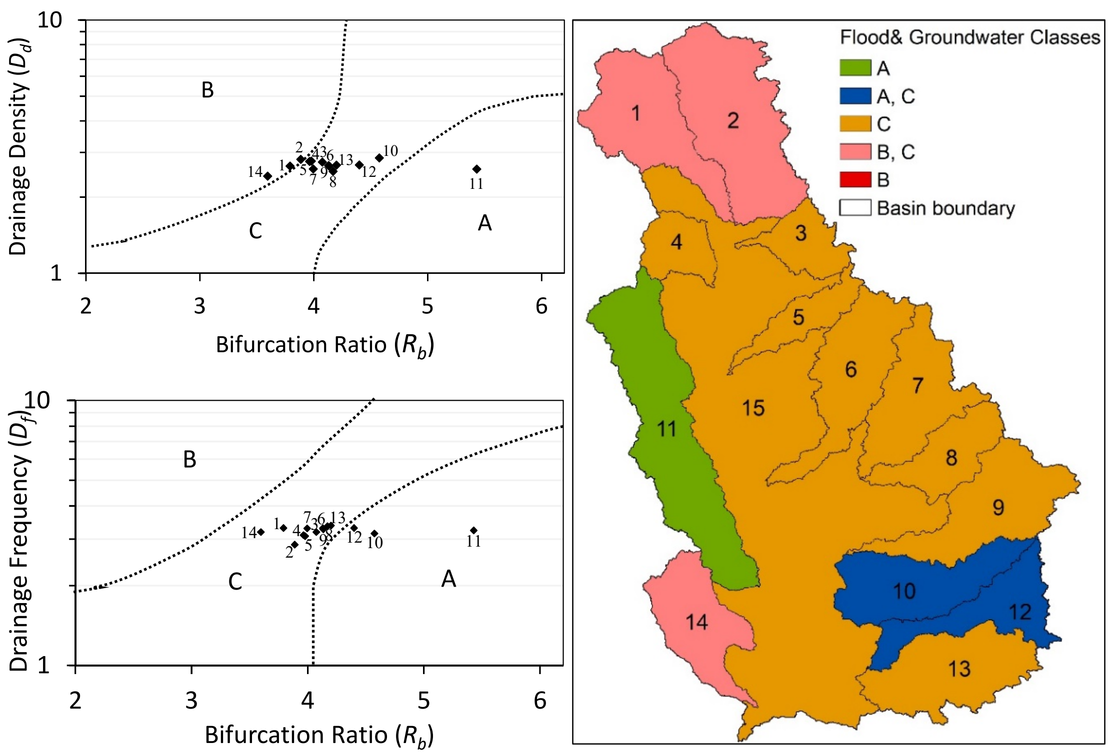

Fig. 4-17 Flash flood and groundwater possibility classification in W. Qena. Using El-Shamy method.

Although El-Shamy model was used in many studies, as mentioned before, it could not give compatible results with the other two methods in our case (Fig. 4-17), it might be because of using the drainage frequency and density that weren't have good correlation with the flash flood generation process (see Chapter 3). Therefore, it is recommended to conduct more evaluation for El-Shamy method in future using wide range of wadi basins.

4.5 Conclusion

In the arid region, WFFs are in fact common, but their occurrence and processes are poorly understood. There is an urgent need to mitigate and utilize floods water as a new supply to sustain a minimum water resources base in rural desert areas. The current study adopt a new methodology, which is applied for the first time in wadi system to simulate flash floods in arid regions. The first main chapter target was to evaluate RRI model applicability in wadi system for extreme flash floods events simulation using W. Samail at the Oman Coast as a case study. Remote sensing and measured data utilized beside RRI hydrological model as a main tool. The simulation results highlight the main features of WFFs

The RRI results show an acceptable agreements between the simulated results and measured data and approved by different statistical indices where for model calibration, NSE and PBIAS indices equal to 0.93 and -14.3 respectively and for model validation NSE and PBIAS equal to 0.86 and -12.0 respectively indicating that RRI model could simulate efficiently the extreme flash flood events in the arid wadi system. Groundwater and wadi channel transmission losses should be considered in future, where these processes are essential in wadi system. Due to data limitation the RRI inundation calculation was not covered by his research and should be further analyzed, calibrated and validated for more comprehensive evaluation of RRI model in the wadi system. The other main part covered in this chapter was to use the hydrological based method (Flash flood index) and geomorphometric based methods (e.g., El-Shamy method) for flash flood susceptibility in Wadi Qena.

Chapter 5 Evaluation of the structural wadi flash flood mitigation measures

5.1 Introduction

Regional extreme flash floods events (e.g., Jan. 2010, Mar. 2014 and Oct. 2015) have been frequently happened in Middle East, where flash floods are considered among the most severe disasters at the region in terms of fatalities and economical loss. Flash flood is a flood, which is characterized by its quick occurrence resulting in a very limited opportunity for warnings to be prepared and issued (Collier, 2007). In the arid desert environments, such as North Sahara, the flash floods usually occurred in ephemeral dry valleys, which are referred to as “wadis” in Arabic. The hydrology of arid wadi system, which is under increasing high water stress, is very different from that of humid areas raises significant challenges. The unique hydrological characteristics of the arid wadis includes high spatial and temporal storm variability, high evaporation rate, lack of vegetation cover, low infiltration capacity of the poorly vegetated soils and exposed rocks, absence of base flow, intermittent channel flow and significant transmission losses through the wadi channels (Abdel-Fattah et al., 2017; Lin, 1999; Pilgrim et al., 1988; Sen, 2008b; Wheater and Al-Weshah, 2002).

In addition to lack of rain gauge data, flow measurement is particularly difficult in arid zones for several reasons (Abushandi, 2011; Lin, 1999; Pilgrim et al., 1988) and could be summarized as following: 1) Access difficulty due to few drivable roads, especially during the rainy and flooding seasons; 2) Dominant low population density at the arid environments; 3) The quick rise and fall of the water level during flash floods; 4) Lack of suitable natural control sections in streams with movable beds, and high cost of artificial control; 5) Harsh climatological and physical conditions in arid environments; 6) Sediment transport, moving rocks and debris may damage instruments placed in the wadi. This condition of absence of data limit the ability of the rainfall-runoff model to regenerate the observed flow (Wheater et al., 2008). The magnitude and frequency of wadi flash floods are not clearly understood, zones of flood risk have not been clearly analyzed and mitigation strategies to protect the flood prone areas and guidelines for development in these areas have not been identified. Wadi flash floods in general have a high degree of spatial variability, coupled with poorly gauged rainfall data, which is a dominant situation in many arid basins, therefore, prediction of timing and magnitude of these floods is extremely difficult. The larger the disaster and the smaller the economy, the more significant is the impact will be, which is the case in the developing countries, where weak economies become even weaker afterwards (Hansson et al., 2008).

Egypt is one of the arid and developing countries that is frequently affected by several destructive flash floods in wadis located in the Sinai Peninsula and the Eastern Desert from 1975 to 2014. Various Egyptian governorates including Aswan, North Sinai, South Sinai, Red Sea, and Qena were exposed on

17 and 18 Jan. 2010 to strong flash floods causing 13 deaths, 49 injuries and 12401 victims (IDSC, 2010). It also caused major financial losses in terms of property damages as well as the impacted many vital sectors, services and facilities such as electricity, water, sanitary drainage, communications, roads, etc. (IDSC, 2010). The flash flood occurred in May 2014 caused economic losses of 125 million USD in Taba City only. In some wadis, there are already too many roads, buildings, electricity towers, and other infrastructures sited in the floodway. Rapid increase of population, urbanization and economic developments have forced construction in high disaster risk zones such as in the wadi's flood plains as will be discussed later in the case study application section.

Flood assessment in the arid environments and wadi system is hindered by limited or complete lack of data and resources for rainfall and channel flow measurements (Abushandi, 2011; Lin, 1999; Pilgrim et al., 1988). These conditions of absence of data limits the ability of the rainfall-runoff models to simulate the observed flow accurately. Although, there are some implementations of flash floods mitigation measures in Egypt such as obstacle and detention dams, artificial lakes and embankments exist, nonstructural mitigation measures such as early warning systems still very rare. Concurrent with the early warning and development of land-use suitability maps, new approaches for prediction and mitigation are needed for flash floods related disaster risk reduction.

Integrated management of wadi flash floods should involve development of a strategic methodology for evaluating the risk, mitigation, and water resource management (Kantoush et al., 2011; Sumi et al., 2013). The flood risk reduction can be achieved by decreasing the magnitude of flood or vulnerability of the flood prone area (Heidari, 2009), where the flood mitigation measures can be classified as non-structural and structural measures (Hansson et al., 2008; Heidari, 2009). Non-structural measures refer to non-engineering actions such as the use of insurance, increasing preparedness through early warnings, restricted development and land use planning and operation of flood control reservoirs, etc. (Hansson et al., 2008; Shah et al., 2015). Structural defense strategies are either traditional measures, such as use of levees or dams, or wider ecosystem specific measures, such as re-naturalization or restoration to natural conditions (Hansson et al., 2008). Controlled distribution of water, for instance through any structural measure, is essential to overcome the space and time variability of water and in controlling disastrous floods and managing droughts (Ho et al., 2017). The structural flood mitigation measures can be classified based on a spatial scale as: 1) distributed, scattered or watershed scale measures and 2) concentrated or localized flood mitigation measures at one location.

The concept of distributed structural measures for flood mitigation has been reported in several past studies (Andoh and Declerck, 1997; Emerson et al., 2005; Kurz et al., 2007; Montaldo et al., 2004; Ravazzani et al., 2014; Thomas, 2015). The aim of a distributed flood mitigation approach is to attenuate the flood peak or store excess floodwater in upstream sub-basins to reduce the accumulation of downstream discharge (Montaldo et al., 2004; Thomas, 2015). Application of distributed reservoirs either in series or in parallel have been assessed to reduce the magnitudes of the flood peaks throughout the basin using fully distributed models (Chennu et al., 2007; Del Giudice et al., 2014; Montaldo et al., 2004; Ravazzani et al., 2014; Thomas, 2015), semi-distributed models (Leblois et al., 2010; Ramireddygari et al., 2000) and analytic solutions (Del Giudice et al., 2014). Multiple studies in the past have also investigated flood mitigation scenarios using cost-benefit analysis (Heidari, 2009) or multi-criteria decision-making techniques (e.g., Ahmad and Simonovic, 2006; Mostafazadeh et al., 2017). Peak flow reductions in these studies (Emerson et al., 2005; Mostafazadeh et al., 2017; Ravazzani et al., 2014; Thomas, 2015) ranged widely from 0.3 % to 36 %, however in other cases of dry dams in the ephemeral streams, the peak reduction was lower than 50% (Chennu et al., 2007). The concentrated flood mitigation measures approach involves localizing the mitigation activities in one location usually upstream of the area aimed to be protected. Onusluel Gul (2010) has investigated the use of one single concentrated measure for flood mitigation impact assessment of single dam on the developed downstream area using a combination of hydrologic and hydraulic modeling efforts.

As discussed in chapter 4 the risk triangle is consisted of hazard, vulnerability and exposure (Crichton, 1999). Although it not possible to be completely protected from flood disaster but the natural disaster risk could be reduced by 1) reducing the exposure by preventing or move the development activities in areas where the hazards is high, such as floodplains, 2) reducing the vulnerability by having resilient infrastructure standards and design and sound disaster preparedness measure and 3) the hazard itself can be reduced, in some cases by the construction of flood mitigation measures. The mitigation plans application reduce the flood risk by decreasing the magnitude of flood or vulnerability of the flood prone area (Heidari, 2009). With increasing stress due to flash floods disaster and water resources limitation in Egypt, application of rainfall-runoff models can be a part of the solution to mitigate flash floods, and at the same time manage and sustain this water resource.

5.1.1 Facts Findings for wadi flash flood management in Egypt

In Egypt several measures are adopted to mitigate the flash flood as a combination of obstacle dams, and detention dams at upstream and artificial lakes at downstream leads to a better management of flood retention and groundwater recharge. A group of Kyoto University and Japan Dam Engineering Center (JDEC) made preparatory field investigations for several wadis in Egypt, from 22th to 29th of November 2014, for facts findings and selecting the type of suitable integrated flash flood measures and their design criteria. The main objectives of these field investigations were to obtain hydrological, geological, structural and operational conditions of existing flood mitigation dams at wadi basins in Red Sea coast and Eastern Desert, and clarify the possible cooperation on selected pilot project. During the trip, wadi basins were surveyed along Eastern Desert between Nile River and Red Sea coast, investigating flash flood mitigation and management strategies at Egypt.

Egyptian government make flash flood mitigation and harvesting master plan: (a) short-term plan for high-risk wadis and, (b) long-term plan for low risk wadis. There are different flash flood management structures at Egypt as storage dams, obstacle dam, artificial lakes, diversion dikes, embankments, and artificial drainage channel as indicted at Fig. 5-1. Selection and design of the best mitigation measures combination based on expected floodwater quantity, wadi risk degree, potential affected infrastructures and flash flood return period.

Fig. 5-1 shows the main flash flood mitigation and management structures at Egypt and their characteristics as following:

1. Obstacle dam: low dam (less than 4-6m), only for reducing flood impact (velocity reduction),

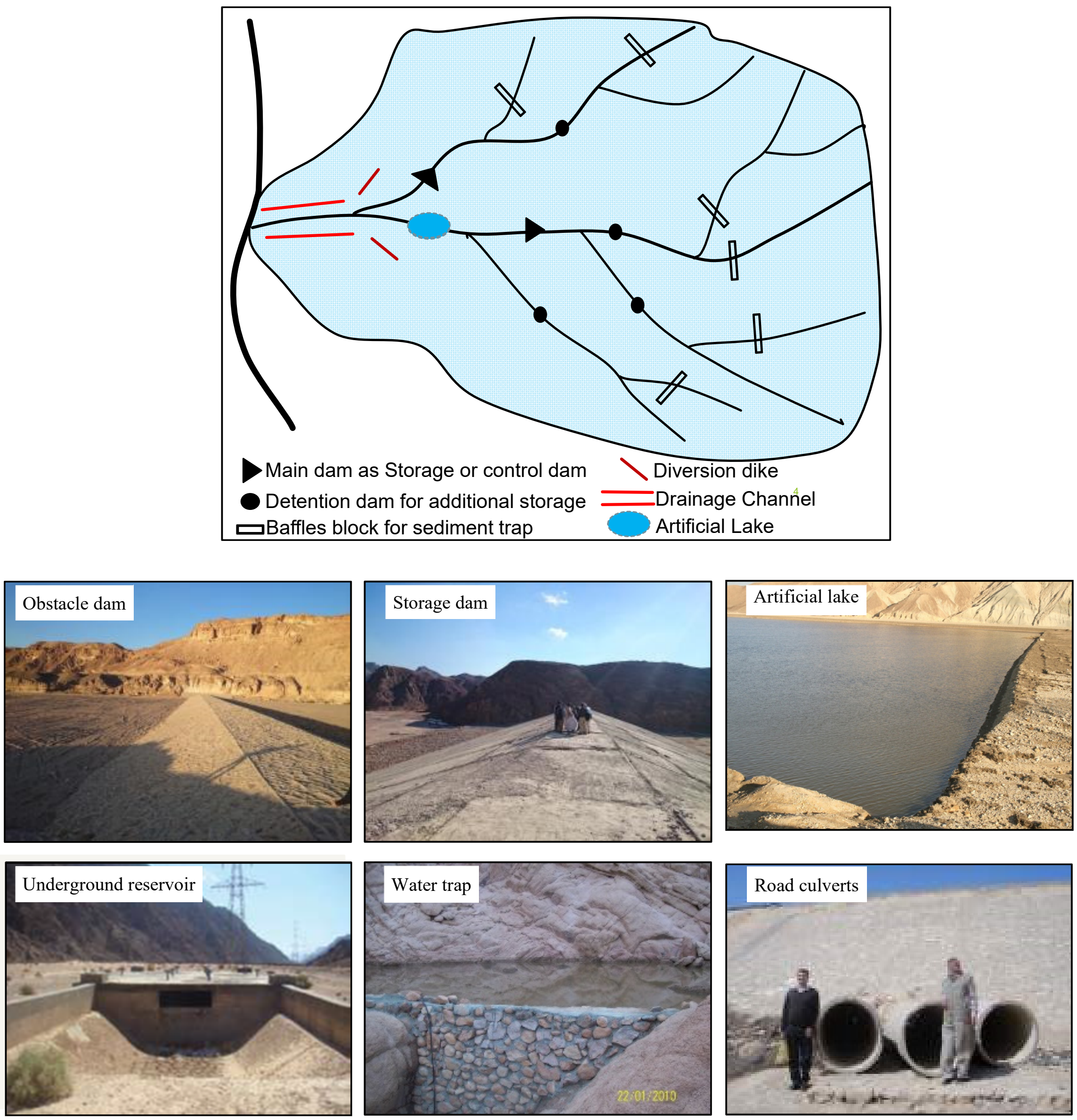

Fig. 5-1 Flash flood mitigation and management structures at Egypt (Abdel-Fattah et al., 2015)

2. Storage retention dam: middle height dam (around 10m), for flood retention and additionally water harvesting, and
3. Artificial lake: excavated, depth (2-4m), for flood retention and additionally water harvesting.

Accurate prediction and early warning for flash flood in a form that is readily understood by related authorities and common people is required so that they are prepared against such hazard before it become disasters (Khan, 2013). By doing so lives and property can be protected. However, warning system is a vital tool for forecasting the potential flash flood, there is only one system at Egypt. This system installed at W. Watier, South of Sinai Peninsula that considered as one of the most active wadis in Egypt with respect to flash floods. The Ministry of Water Resources and Irrigation in collaboration with Belgium has installed this early warning system called Flash Flood Manager (FlaFloM).

Limited studies exist in wadi systems, which have studied different alternatives of flash flood mitigation. One such study by Al-Weshah (1999) compared different combinations of mitigation measures such as afforestation, terracing and construction of check and storage dams using hydrological modeling tools in Jordan. The flood retention dam is one of the important structures due to its immediate benefits, therefore it is proposed in this study for the mitigation of wadi flash floods. This chapter objectives are to 1) propose an efficient methodology which face limited data coverage in the Egyptian wadis; 2) simulate and assess some recent events (Jan. 2010 and Mar. 2014); 3) develop a technique for dam location and reservoir volume estimation; and 4) to evaluate the mitigation scenarios by a single concentrated dam at the downstream and some geographically distributed dams by using a hypothetical design rainfall storm.

5.2 The study sites

Wadi Abadi in Egypt and Wadi Samail and Wadi Aday in Oman were selected as a case study to test and apply the proposed approach. Wadi Abadi is located at the southern part of Eastern Desert of Egypt, which is bounded by the Red Sea from the east, and the Nile River from the west as shown in Fig. 5-2 with area of 6810 km2. Wadi Abadi is cited with various names in the literature as Wadi Abbad or El-Btur. This vast wadi (6810 km2) basin, extending for 120 Km between the Red Sea to the east and the Nile River to the west. The general flow direction is NE-SW and at the end drain into the Nile River east of Idfu City. The downstream part of Wadi Abadi contains the delta of Wadi Abadi, where agriculture land cover is about 29 km2. The climatology of Wadi Abadi is characterized by a dominant arid climate with average annual rainfall of 25 mm and high annual average evaporation rate of 6 mm/day.

Wadi Abadi is classified as medium flash floods risk zone area by the Ministry of Water Resources and Irrigation at Egypt (MWRI, 2012) and it was affected by some irregular extreme flash floods that have happened in Oct. 1991, Nov. 1994, Oct. 1997 and Mar. 2014. The recent flash flood event of Mar.

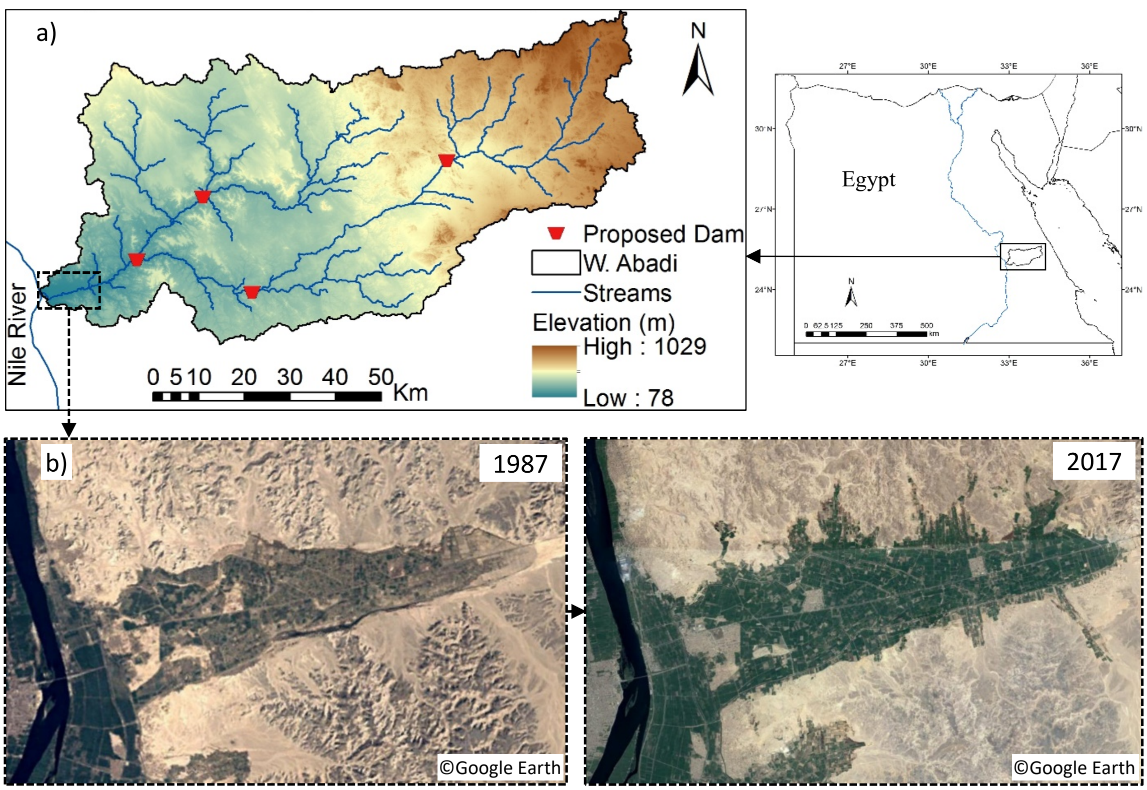

Fig. 5-2 Location of Wadi Abadi in Egypt sowing the proposed dam locations and topography b) The developed area expansion in the downstream of Wadi Abadi since 1987 until 2017.

2014 (one of the target events), was accompanied with severe impacts on many wadis in Egypt and wide area of Wadi Abadi Delta was flooded. The study area is crossed by one of the vital highways roads, Idfu-Marsa Alam road, was frequently damaged by these flash floods. Due to the increasing pressure of population growth and unmanaged development, people start to cultivate new lands and even build their houses in flash flood prone areas. For instance, in the downstream area of Wadi Abadi, the developed area increased by 40% over the last 30 years science 1987 till 2017 (Fig. 5-2-b). Flash flood disasters in the target area have been assessed by few recent studies (e.g., Milewski et al., 2009; Saber et al., 2015) and no studies related to flash flood mitigation and management in Wadi Abadi were found.

The basin of Wadi Aday is located in the Muscat governorate of Oman, which is the fastest growing part of the country (Al-Rawas, 2009), with a population of 1,288,300 according to a 2015 census made by the National Centre for Statistics and Information. The basin itself has an area of 372 km2 with a total urbanized area of about 85 km2, which represents about 22% of the total watershed area. Wadi Aday is bounded by coordinates 23°40’ of Latitude North and 58°35’ of East Longitude. Figure 4 shows the watershed delineation, and its geographical location in the Middle East, as well the rain gauges that were used for rainfall measurements in the basin.

5.3 Methods

The objective of this chapter is to simulate hydrological processes in a wadi system employing a variant of a Hydrological River Basin Environmental Assessment Model (Hydro-BEAM) and Rainfall

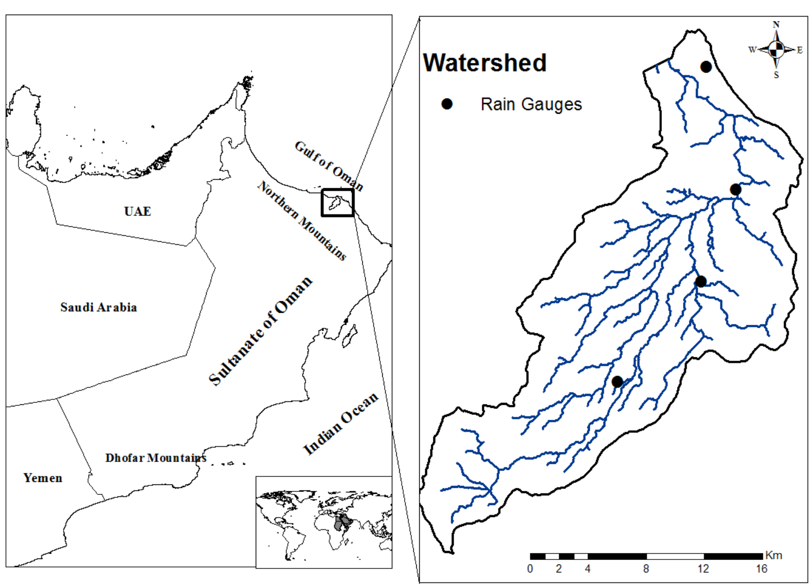

Fig. 5-3 Map of Wadi Aday basin in Muscat, Oman showing location of rain gauges (Moya, 2017).

Runoff Inundation (RRI) model, that considers multiple structural flash flood control measures using the proposed concept of distributed and concentrated dams and to evaluate the benefits of these measures for mitigating the flood risk. Different topographic datasets and geospatial analysis tools are used to provide input to the hydrological and hydraulic models. Hydro-BEAM model used for Wadi Abadi case while RRI model used for Wadi Samail and Wadi Aday cases. The Gonu Cyclone in June 2007 was the event chosen to calibrate using data from the MRMWR, measured from the rain gauges shown in Fig. 8. For validation, a major flood event that occurred in December 2006 and 2010 was taken, as the same sources of data were used. Fig. 5-4 presents the processed data and the proposed approach, which contains the following core steps and modules:

a) Simulate potential flash flood hazard using Hydro-BEAM for different flash flood scenarios of various return periods of design storms with respect to the available local rainfall data;

b) Propose suitable mitigation strategies through dam module that considers the runoff and computes the hydrographs with and without structures;

c) Evaluate and make decisions based on various criteria of flood mitigation; water resources; cost; operation and development potential.

To test and evaluate variant structural mitigation measures, the Hydro-BEAM model was upgraded to include dam module, as will be discussed later. RRI Model can also be used to simulate several mitigation measures such as dams, diversion channels and channel improvements. However, the dam module in RRI model is very simple where the dam outlet discharge should has a fixed rate regardless the water height above the outlet and it does not consider the evaporation effect.

There are other preliminary steps such as watershed delineation to detect the mainstream network, watershed and sub-basins boundaries by using spatial analysis tools (i.e. GIS) and Digital Elevation Model (DEM) data. The generated streams networks were cross-correlated and checked with the available satellite images, Google Earth and the local geological maps. Results of such comparisons confirmed that a reliable streams network for hydrologic modeling was obtained. To cover a wider range of return-periods, it is necessary to generate scenarios, including extreme events, with a possible spatial repartition of the input in the sub-catchments. Therefore, two separate extreme flash floods events that occurred on Jan. 2010 and Mar. 2014 in Egypt were simulated, in addition to several design storms were also evaluated in Wadi Abadi region.

5.3.1 Input data

Topographic data for the study area derived from the Shuttle Radar Topography Mission (SRTM) 1arc-second (~30 m) resolution DEM data (USGS, 2015). The study area is characterized by middle range of relief with elevation ranging from 1029 m at the upstream, where the basement outcrops are existed, to 78 m above the sea level at the downstream as shown in Fig. 5-2. DEM data were utilized for watershed delineation and detection of slope, identification of best locations for dams and estimation of reservoir volumes.

For Wadi Abadi case the Global Land Cover Characterization (GLCC) data were used to identify the different land use types(GLCC, 2008b). GLCC data are a 1-km resolution and have been used in a wide range of environmental research applications. Five land use types, desert, agriculture, urban, water and forest have been identified. More than 99% of Wadi Abadi area is desert and bare mountain and less than 1% of the total area, contains the Wadi Abadi Delta agriculture area and houses at the

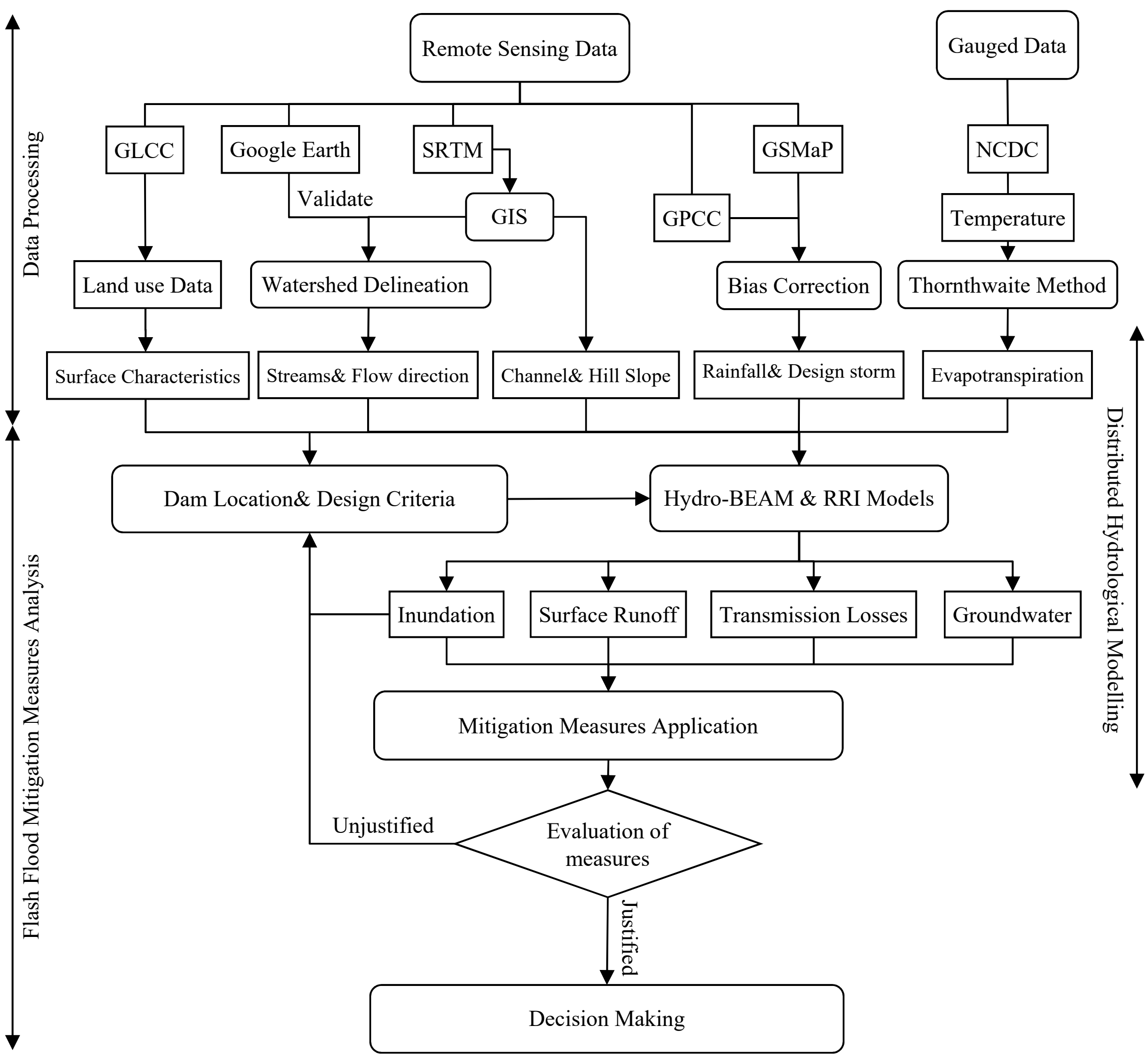

Fig. 5-4 Illustration of the developed approach including flowchart for: 1) input data processing, 2) hydrological modeling using Hydro-BEAM and 3) application and evaluation of the flood mitigation measures.

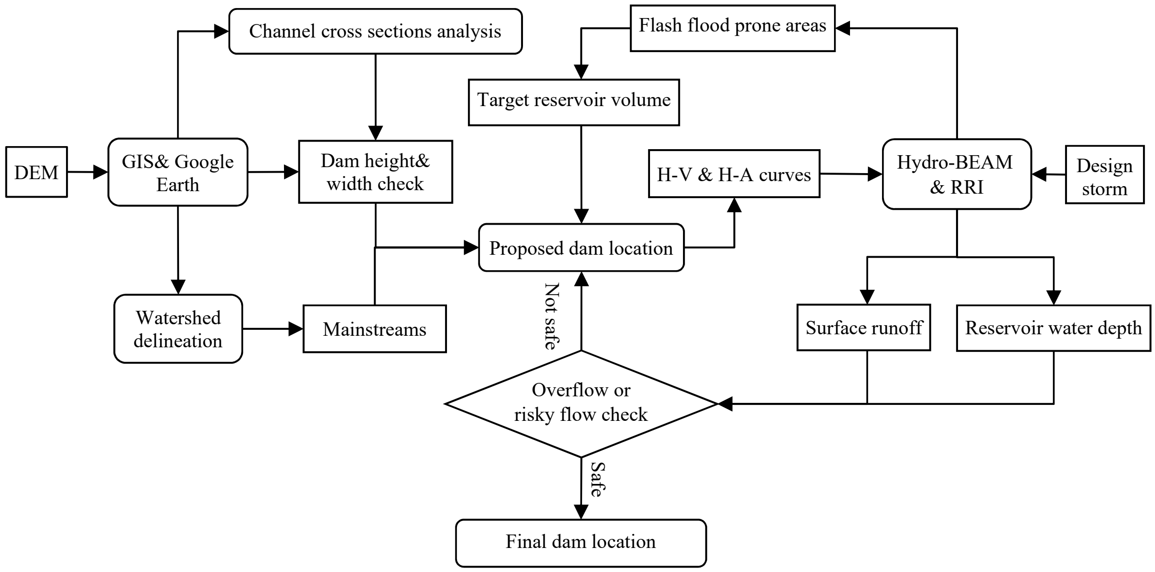

Fig. 5-5 Dam location and design criteria flowchart

downstream region of Wadi Abadi. In Wadi Samail and Wadi Aday, the main geologic base of the soil is made up of ophiolite, basaltic, limestone and sandstone rock according to data from MRMWR.

5.3.2 Climatic data and design storm

The Ministry of Water Resources and Irrigation (MWRI) in Egypt provides frequency analysis of the available rainfall data and the expected total rainfall amount for different return periods (MWRI, 2012). Three different return periods have been initially analyzed (50, 100 and 200 year return periods) and finally the 200 year return period storm (70 mm as total rainfall amount) was chosen because it has been recorded at Luxor station, 45 km from Wadi Abadi, on 4-May 1994 (TuTiempo, 2017). The storm events in the Eastern Desert and Northern Egypt are typically short, lasting from less than 1 hour to a few hours (Gheith and Sultan, 2002; Ghoneim and Foody, 2013), therefore the design storm duration was 3 hours and uniformly cover all area of Wadi Abadi. Moreover, Global Satellite Mapping of Precipitation (GSMaP) of 1-hour temporal resolution and 0.1 degree of grid resolution have been utilized to simulate the most recent rainfall events in Wadi Abadi (Jan. 2010 and Mar. 2014). Meteorological data from Integrated Surface Database (ISD) (Smith et al., 2011) were used to obtain potential evapotranspiration estimates by using Thornthwaite method (Thornthwaite, 1948). For Wadi Samail and Wadi Aday gauged rainfall data (MRMWR, 2015) used for the flood simulation and calculation of different rainfall intensities under different return periods.

5.3.3 Hydro-Beam model improvement and dam module

Hydrological River Basin Environmental Assessment Model (Hydro-BEAM) is an in-house developed distributed hydrological and environmental model, for humid areas (e.g., Kojiri et al., 2008;

Sato et al., 2013). Hydro-BEAM was modified by Saber et al. (2010) to account for different physical processes that are dominant in wadi system in the arid environment. In this study, a new development and upgrading for Hydro-BEAM model to be capable to consider the suggested mitigation scenarios by adding dam operation and reservoir routing routine, which can handle bottom outlet and reservoir water evaporation. Reservoir water infiltration and siltation processes were not considered in this version of Hydro-BEAM. The model was calibrated in a recent study (Saber et al., 2015) using the available measured flood discharges. Moreover, Abdel-Fattah (2017) verified the same model in another wadi region in Egypt (Wadi Qena, Chapter 3). In Hydro-BEAM model, the spatial domain of the watershed under investigation is divided into number of grids (i.e. unit mesh cells) (6800 mesh with an area of 1 km^2 in this study). Each grid mesh is divided into two pairs of rectangular hill slopes and one river channel and vertically it is represented by a combination of one surface layer (layer A) and three subsurface layers (B, C and D) as shown in Fig. 3-7.

The newly developed dam routine is suitable for the proposed mitigation measures with low dam height (less than 20 m) and rectangular shaped outlet. The key parameter that detects the operation stage is the dam outlet discharge, which is calculated based on the water depth behind the dam as follows:

$$Q_o = \begin{cases} CBH^{3/2}, & C = 1.456 + 0.185(H/L), \quad (H/D \leq 1.5) \\ CBD\sqrt{2gh}, & C = \sqrt{0.647 - 0.605(D/H)}, \quad (H/D \geq 1.5) \end{cases} \qquad \text{(Eq. 5-1)}$$

where Q_o is the dam outlet discharge rate (m^{3}s^{-1}), C is the state outlet coefficient calculated based on the water height and the dimensions of the outlet, B is the outlet horizontal dimension (m), H is the water depth above the dam bottom (m), L is the outlet length through the dam base (m), D is the outlet vertical dimension (m).

By using the established curves of reservoir volume-water depth above the dam bottom (V-H) and reservoir area-water depth above the dam bottom (A-H), dam operation status updated simultaneously within Hydro-BEAM model every time step (30 seconds in this study). Dam operation status corresponds to one of the following: (1) Reservoir filling if the inflow rate is higher than the current outlet discharge; (2) Reservoir water release if the inflow rate is lower than the current outlet discharge or (3) Overflow in case of the current water depth is higher than the maximum dam height.

5.3.4 Hydro-BEAM parameters calibration and sensitivity analysis

Calibration of the rainfall-runoff models in wadi system is difficult as discussed in the introduction. According to our knowledge and detailed literature review, no discharge rate data have ever been recorded in Wadi Abadi. In the present study, the model parameterization is done based on the calibrated model parameters conducted by Saber et al. (2015) at Wadi Al-Khoudh in Oman, that is similar in its arid climatic conditions with Wadi Abadi. The land use setting very similar also, where the majority of

Table 5-1 Input parameters description and results of the sensitivity analysis conducted in Hydro-BEAM (parameters with no appearance of sensitivity get rank of 15).

Name	Definition	Units	Calibrated	Min	Max	Process	SI[a]	Rank
DE	Layer A porosity	%	20	5	50	Soil	0.91	1
ASOD	Layer A thickness	m	0.355	0.1	2	Soil	0.86	2
FN	Hillslope runoff coefficient	%	0.617	0.3	0.8	Runoff	0.69	3
BHT	Layer B horizontal outlet coefficient	d^{-1}	0.83	0.1	1	Groundwater	0.58	4
SDR	Channel roughness coefficient	$m^{-1/3}s$	0.024	0.01	0.05	Channel	0.49	5
SDN	Hillslope equivalent roughness	$m^{-1/3}s$	0.024	0.02	0.1	Runoff	0.1	6
BVT	Layer B vertical outlet coefficient	d^{-1}	0.4	0.01	1	Groundwater	0.08	7
DK	Layer A hydraulic conductivity	ms^{-1}	$5*10^{-6}$	$1*10^{-7}$	$2*10^{-4}$	Soil	0.01	8
CHT	Layer C horizontal outlet coefficient	d^{-1}	0.004	0.001	0.1	Groundwater	0.004	9
CVT	Layer C vertical outlet coefficient	d^{-1}	0.001	0.0001	0.01	Groundwater	$4*10^{-7}$	10
BSOD	Layer B thickness	m	2.5	2	4	Groundwater	0	15
CSOD	Layer C thickness	m	3.5	3	8	Groundwater	0	15
DSOD	Layer D thickness	m	10	8	15	Groundwater	0	15
DHT	Layer D horizontal outlet coefficient	d^{-1}	0.03	0.001	0.1	Groundwater	0	15
DBCD	Subsurface layers (B-D) porosity	%	15	1	30	Groundwater	0	15

[a] Sinsetivity Index (SI) of the parameters to the flood peak discharge

both wadis are desert or bare mountains with very less urban or agriculture activities. Same concept of transferring calibrated hydrological model parameters from a specific wadi to be applied in a similar condition wadi has been also applied by Milewski et al. (2009), who employed the calibrated SWAT model in Wadi Girafi in Palestine to be use in rainfall runoff modelling for all main wadis in the Eastern Desert and the Saini Peninsula in Egypt.

Furthermore, Sensitivity analysis was conducted to evaluate the most sensitive parameters and to estimate the uncertainty range in the simulated flood hydrographs. Fifteen Hydro-BEAM parameters that relate to various hydrological processes simulated were considered as indicated in Table 5-1. The parameter ranges were detected based on the previous wadi hydrological studies. For each parameter, 20 to 40 values with uniform interval sampled using pseudo random number generator and tested through different storms of 50, 100 and 200-year return period with uniform variation across the geographical region. A total of 900 simulations were conducted and evaluated using a sensitivity index (*SI*) metric. *SI* is estimated by calculating the output percent difference when changing one parameter from its minimum value to its maximum value (Hoffman and Gardner, 1983). The most important factor in the process and mitigation of wadi flash floods is peak flow (Q_p), therefore it is used to detect the *SI* as following:

$$SI = (Q_{p\max} - Q_{p\min}) / Q_{p\max} \quad \text{(Eq. 5-2)}$$

where $Q_{p\ max}$ and $Q_{p\ min}$ are the maximum and minimum predicted peak flow (m^3s^{-1}), respectively per input parameter samples. Finally, the parameter sensitivity can be ranked according to *SI* value, where the most significant parameter, which has the highest *SI*, being given the first rank. The parameters, which have no effect on the model output given a rank equal to the total number of the model parameters (Table 5-1). Later the variation of the peak discharge and the standardized parameter values were established for evaluating the effect of the parameter on the resulting flood peak. Each standardized parameter value is expected to fall somewhere between 0 and 1 as given by equation 5-3:

$$x_{std} = (x - x_{\min}) / (x_{\max} - x_{\min}) \quad \text{(Eq. 5-3)}$$

where x is the applied parameter's value and x_{std}, x_{min} and x_{max} are the standardized, minimum and maximum parameter's value respectively. Using the generated hydrographs from the sensitivity analysis, a 95% confidence interval was established for the simulated design floods.

5.3.5 Flood mitigation measures

The structural measures of flood mitigation proposed in the study region are due to special characteristics of wadi system and the urgent necessity to address the flash flood challenges in the region. The non-structural measures, such as early flood warning system, social awareness and insurance systems etc., are not considered in this study; however, they are highly recommended to be investigated in further studies. Two approaches of long-term flood mitigation measures using dams are proposed for Wadi Abadi and they are:

a) Small or medium sized dams defined in terms of the dam height and reservoir capacity distributed all over the basin and;

b) Single relatively large concentrated dam at the downstream reach upstream of the developed area.

As for wadi Samail two scenarios have been analyzed 1) three distributed small dams allover over the catchment in the upstream, and 2) proposed large dam in the middle or downstream area of the wadi. The design storm in Wadi Samail is selected as Gonu 2007 cyclone which was the most severe rainfall event in the recent history of Oman and it has a return period of 1000 year at that time. In Wadi Aday there were four mitigation scenarios as follows: 1) with three concentrated dams and b) 6 distributed dams.

For reasonable evaluation and comparison between the two mitigation scenarios, the total reservoir volume based on accumulated volume from multiple small dams and one single large dam was made equal.

It is important to note that the main objective of this study is to test a methodology and compare between to mitigation approaches, not to obtain precise estimates of peak discharges. The latter is difficult due to limited hydrological and limited geospatial data. The criteria for the proposed locations of multiple dams and their characteristics are presented in Fig. 5-5 as following:

a) Flow directions of each cell and watershed boundary have been estimated using GIS and DEM data;

b) Hydrologic simulation was conducted using Hydro-BEAM and synthetically design storms to make a geographical distribution of the surface runoff and allocate the potential prone area for flash floods;

c) Estimations of the cross sections of the wadi drainage channels were carried out by using DEM and Google Earth images to detect the safe passing flow capacity of each channel;

d) Several dam locations were proposed according to the local topography and existing human activities;

e) Establishment of V-H (reservoir storage (V)-water depth(H)) and A-H (reservoir area(A)-water depth(H)) curves to be used in dam operation and the calculation of reservoir evaporation using the developed FORTRAN codes and DEM data;

f) Calculation of the expected design flood volume and the required dam height to mitigate this flood using the design storm and Hydro-BEAM model;

g) Outlet setting in each dam compatible with the downstream channel capacity and,

h) Comparative analysis between the different dams locations to decide the best option that can retain the flood volume with the lowest dam height and with a condition that surrounding developed areas for agriculture land or houses are not affected.

The proposed approach for evaluation are based on the analysis of five main aspects: 1) flood mitigation; 2) water resources management; 3) cost; 4) operation and 5) development potential. Hydro-BEAM was used to simulate and evaluate runoff hydrographs, peak reduction and expected protected areas with and without the variant mitigation scenarios to quantify the flood mitigation effectiveness for each scenario. Hydro-BEAM was further used to estimate the predicted stored water behind the dams, evaporation from the proposed reservoirs and recharge to the groundwater through the wadi channel transmission losses as indicator for the efficiency of each scenario from the water resources management point of view. As for construction, maintenance and operation cost calculations, help from local authorities in Egypt was sought to estimate the expected cost for each dam using the same dam type and construction materials. Finally, the relative advantage and disadvantage that related to accessibility, operation and development potential of each scenario have been discussed in light of the special and unique characteristics of wadi system.

5.4 Results and discussions

Wadi Abadi case results will be discussed only in this results section as the module case to present the proposed approach.

5.4.1 Hydro-BEAM model parameters sensitivity analysis

Sensitivity analysis for Hydro-BEAM model was conducted in Wadi Abadi to measure the relative significance of each model parameter in determining the output hydrograph peak and shape (Table 5-1). According to results from sensitivity analysis, the most significant parameters in detecting the flood peak are the surface layer A thickness and porosity, followed by the runoff coefficient, the layer B horizontal outlet coefficient and the channel roughness. The relationships between the peak discharge and the standardized parameter values are shown in Fig. 5-6. The surface runoff component in Hydro-BEAM model is based on saturation excess flow as indicated in Eq. 2 and Fig. 5-6-b, so the soil depth

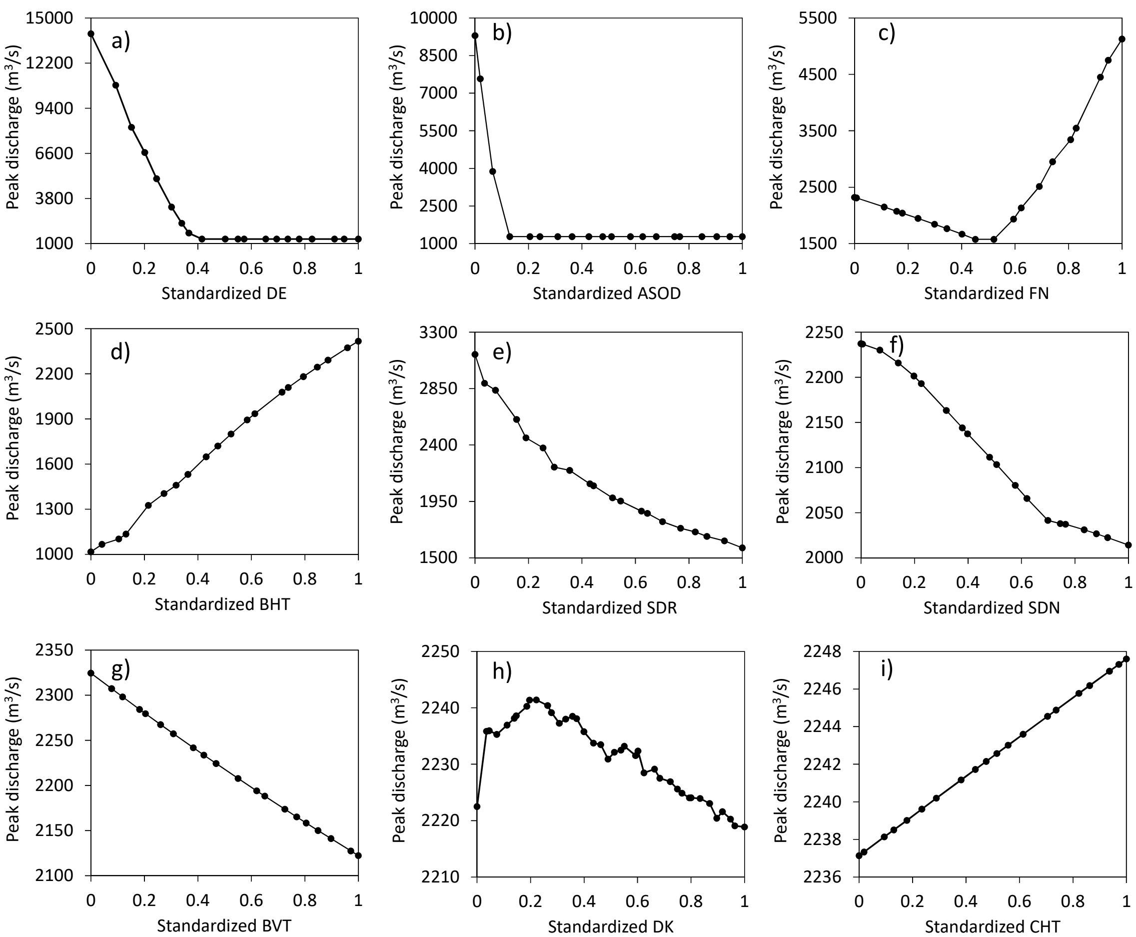

Fig. 5-6 Variations of standardized Hydro-BEAM parameters related to outlet peaks discharge computed in Wadi Abadi..

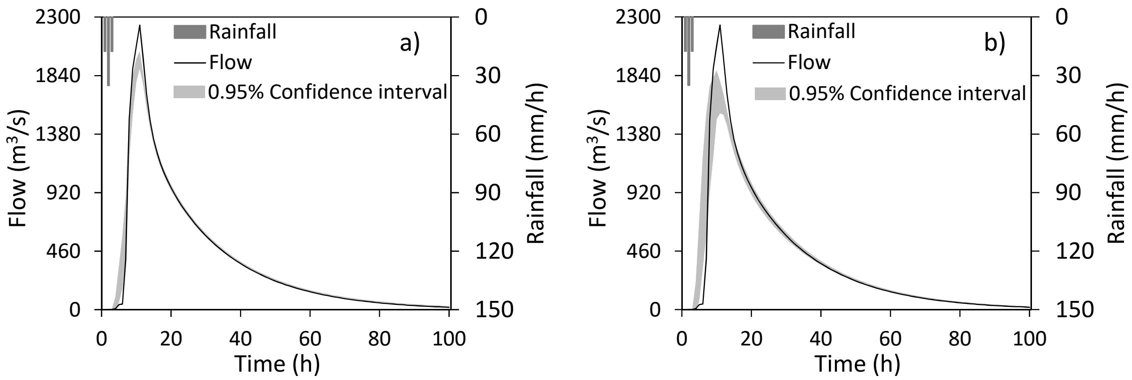

Fig. 5-7 Flow variability considering Hydro-BEAM model parameter sensitivity analysis in Wadi Abadi along with their 0.95% confidence interval for: a) all the parameters included and b) considering only the top five sensitive parameters.

and porosity are key factor to detect the effective rainfall amount and how much of the rainfall will transformed to surface runoff.

The soil depth and porosity have indirect high proportion with flood peak (Fig. 5-6-a and Fig. 5-6-b) until the soil effective porosity consumes all rainfall so it will produces the same peak. Runoff coefficient is the parameter, which partitions the rainfall amount between the surface and subsurface layers. As the runoff coefficient increased from its minimum value, the peak discharge decreases because the direct runoff infiltrates into the soil until the soil becomes saturated and the runoff coefficient will have a direct relation with the discharge (Fig. 5-6-c). Whereas, the channel and hillslope roughness coefficients have medium significance with indirect proportion with the peak flow (Fig. 5-6-e and Fig. 5-6-f), because it controls the channel water speed and consequently the flood response time and peak flow value. The horizontal layer B outlet coefficient has medium impact on the peak flow with direct relation with peak flow (Fig. 5-6-d), but exhibits stronger impact on the recession curve of the hydrograph.

There are some other less significant parameters mainly the outlet coefficients and thickness of the subsurface layers (other than layer B layer) as indicated in Table 3-1 and Fig. 5-6. These parameters are less sensitive because as the subsurface layer depth increases the layer porosity decreases and consequently its contribution to the flood decreases. In addition, as the applied rainfall intensity decreases, the variability of the hydrological model's outputs and sensitivity to the surface runoff related parameters (e.g., soil depth, runoff coefficient, hillslope roughness) also decreases.

The generated hydrographs from sensitivity analysis exercise were used to detect the uncertainty in the simulated hydrographs of different design storms for 95% confidence interval. We investigated the uncertainty range considering all the 15 evaluated parameters (Fig. 5-11-a) and also the top five

Table 5-2 Summary of target storms and other hydrological variables obtained from simulation at Wadi Abadi.

Simulation results	Jan. 2010	Mar. 2014
Total rain volume (*10^6 m^3)	37.0	207.8
Peak discharge (m^3/s)	4.16	78.36
Total outlet discharge volume (*10^6 m^3)	0.58	7.57
Outlet discharge percent (%)	1.59	3.64
Total transmission losses volume (*10^6 m^3)	0.67	4.97
Total transmission losses percent (%)	1.81	2.39

sensitive parameters (Fig. 5-11-b). For both estimations, the generation and recession parts of the hydrographs are approximately within the confidence interval identified, whereas the predicted peak flow is overestimated by 13 to 20%. These estimates are based on average of all sensitivity analysis runs and with the use of design storm of 200-year return period. Therefore, these results give considerable reliability for using of the validated Hydro-BEAM parameters to further investigate the objectives of this study. The sensitivity analysis results further allow some generalization of the significant parameters within the arid environments, which can be useful for the hydrological modelers who plan to investigate the hydrological processes in the arid wadi environments.

5.4.2 Recent flash flood simulation

Two storm events that occurred on Jan. 2010 and Mar. 2014, were used to simulate flood conditions using Hydro-BEAM in Wadi Abadi. The proposed dam locations (D1-D4) as indicated in Fig. 5-2-a, were selected to present the simulated hydrographs, which show the flow features of flash floods at wadi system, where the flood hydrographs have abrupt and quick generation of the peak discharge and then gradually decreasing until end of the event as shown in Fig. 5-8. The results record the high variability of discharge rate from one event to another and between the variant locations within the same event. For instance, in 2014 flash floods event at the upstream (i.e., D1 and D2) of Wadi Abadi, the flow rate is less than 10 m^3/s, but in the wadi downstream, the flow rate is higher than 70 m^3/s. In the 2010 event, the maximum recorded flow rate was 5 m^3/s because the maximum rainfall total amount was only 20 mm covered a small area of Wadi Abadi (Fig. 5-9-a). Hydrograph shape and time to reach the peak flow are also variable from one point to another because of the unevenness of precipitation, area and the geomorphologic parameters of the upstream catchment.

Spatial variations of the simulated discharges from both storm events (Fig. 5-9-2) show the differences in runoff patterns at Wadi Abadi due to high variability of rainfall spatial distribution in space and time. Where rainfall of Mar. 2014 event has more intensity, and covers a wider area of Wadi Abadi than Jan. 2010 event, which mainly concentrated on the upstream part of the region. Surface runoff maps confirm that for the same rainfall event, some parts of the watershed have experienced flash floods and on the other hand, some locations have no flow. It is confirmed also that Mar. 2014 flash flood was larger in terms of maximum peak flow and surface runoff area. These distribution maps can be helpful to detect the flash floods prone areas and consequently mitigate and mange flash floods at those areas. In addition, it can be valuable for wadi development and land use management to identify the best location for residential, touristic, industrial and agricultural activities. Surface runoff zones can give signs of the potential locations of groundwater, where the transmission losses and groundwater recharge are linearly related to surface runoff (Saber et al., 2010). Once sustainable groundwater resource is detected, especially at arid environment like wadi system, other development activities as land reclamation for agriculture can be constructed.

The simulation results summarized in Table 3-2, indicate the small outlet discharge percentage of the total rainfall amount (1.6 to 3.6 for 2010 and 2014 events respectively), where most of the water was consumed in the soil saturation process and other potential losses such as initial and transmission losses, which can have a total volume more than the outlet discharge total volume. At first glance, it can noted that the simulated flow could be considered as not risky flow, however at the arid wadis channel and the surrounding areas can be flooded by any amount of rainfall as stated also by Shamir et al. (2013), which is one of wadi system unique characteristics. The other critical factors are the unmanaged development activities of houses construction and land reclamation (that could be established directly within the wadi channel) and absence of sustainable management strategies for flash flood disaster. Structural mitigation measures (e.g., dam or embankment) could be part of an important component of the integrated management of flash floods, which is discussed and evaluated in the following section.

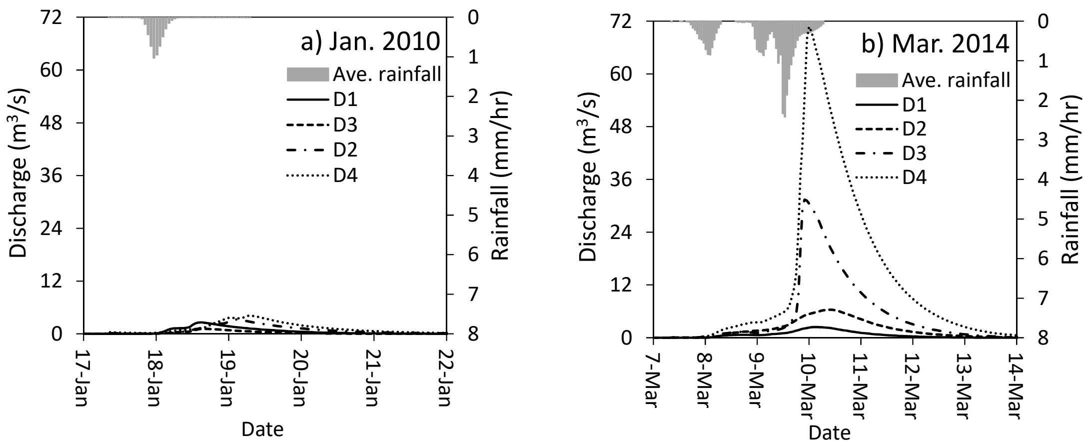

Fig. 5-8 Simulated hydrographs for a) Jan. 2010 event and b) Mar. 2014 flash floods in Wadi Abadi.

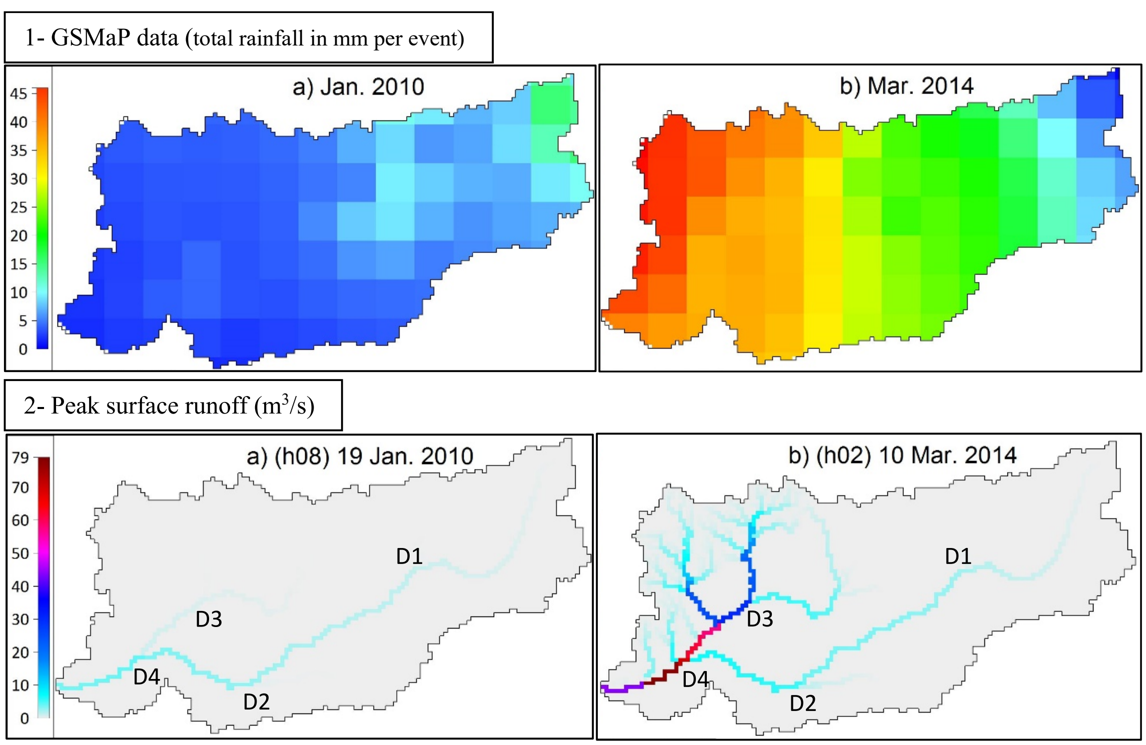

Fig. 5-9 Geographical variations different parameters of interest at Wadi Abadi for: 1) total rainfall input and 2) simulated peak surface runoff of the a) Jan. 2010, b) Mar. 2014 events and indicating the target locations (D1-D4).

5.4.3 Flash flood mitigation scenarios evaluation

Design storms of 50, 100 and 200-year return periods were initially assessed and finally the 200-year return period (70 mm of total rainfall amount, which was recorded in 1994 in near station to Wadi Abadi) was selected to test the proposed approach. The first investigated scenario is to apply four geographically distributed and watershed scale dams at D1, D2, D3 and D4 and the second scenario is to apply single concentrated dam at the downstream (D4). Both mitigation measures location and features were selected as discussed before in the methodology section (Fig. 5-5). The constructed V-H and A-H curves from DEM data are depicted in Fig. 5-10, in which the available storage volume and area are increasing as moving toward the downstream and the final proposed dams characteristics are indicated in Table 5-3 and Fig. 5-11. The suggested four distributed dams have dam height ranges from 11 m to 16 m and reservoir volume ranges from 24 to 39 million m^3 with total reservoir volume of 124 million m^3. The concentrated dam has higher dam height of 17 m and 118 million m^3, less than the total reservoir volume of the distributed dams scenario by 5%.

The proposed evaluation criteria are consisted of five main categories as following: 1) flood mitigation; 2) water resources; 3) cost; 4) operation and 5) development potential as depicted in Table 5-5. For the flash flood mitigation aspect, the design flood simulation was conducted for the two mitigation scenarios and without any mitigation measure as indicated in Fig. 5-13 and Fig. 5-14. It can be noticed that both strategies could be effective in flood mitigation at the downstream part, especially upstream of Wadi Abadi Delta that contains the most important agricultural, farmland and housing activities. The mitigation dams approach application decreases the surface runoff rate from 2197 m3/s to 228 m3/s and 304 m3/s with peak reduction percentage of 90% and 86% for the distributed and concentrated dam scenarios respectively. However, the distributed dams scenario has slightly better performance due to flood attenuation through the network of distributed dams, which prevent the flood water to be concentrated at the same time in the downstream. Furthermore, the distributed dams have potential flood mitigation for the upstream region in reverse to the concentrate dam which leave the upstream infrastructure as roads without protection and as indicated in Table 5-5 that the protected areas are much larger in case of the distributed dams (3018 km2) than the concentrated dam (488 km2). The peak flow reduction due to the proposed mitigation scenarios in this study were higher than the range of peak flow reduction (0.3 % to 36 %) indicated in some of the previous studies (Emerson et al., 2005; Mostafazadeh et al., 2017; Ravazzani et al., 2014; Thomas, 2015). That higher peak reduction may be due to the different capacities of the applied mitigation measures than the other studies and the dissimilar nature of wadi system, which has mainly dry and ephemeral channels.

With respect to water resources management, the distributed dams scenario has expected storage water in the reservoirs (91 10^6 m^3) and transmission losses to the groundwater (88 10^6 m^3) higher than the concentrated dam scenario, which expected to have 82 10^6 m^3 of reservoir water storage and 83 10^6 m^3 of transmission losses. Therefore, the distributed dams increase the reservoir water storage by 11%

and the transmission losses, which recharge the alluvium aquifer, by 5%. This relative merit of the distributed dams is expected to be more significant for events with lower rainfall amount such as those that have a 50 year of return period, because the potential losses percentage of the total rainfall amount will be higher and consequently the available surface runoff percentage for storage will be lower. In the case of the natural and not geographically homogenous storms, all the rainfall can be concentrated only in the upstream and not transported to the downstream so, only the distributed dams may be more efficient to harvest this precious water resource. However, the predicted total reservoir evaporation of the distributed dams of 0.6 10^6 m^3 is two times the evaporation from the concentrated dam reservoir (0.3 10^6 m^3), however it is not significant amount of water comparing to the total reservoir volume. The reservoir evaporation is expected to be more significant if the dam is storage dam without bottom outlet or the gate is closed.

The construction cost was estimated to be lower in the case of single dam (14.5 10^6 USD) than four distributed dams (23.3 10^6 USD). The cost of maintenance was difficult to be estimate due to the spatial and temporal variability of the wadi flash floods but the cost for operation and maintenance is predicted also to be higher in the case of the distributed dams scenario due to its larger accumulated reservoir area and the harder accessibility. Therefore, construction of a single concentrated dam will be more cost effective and may be more suitable for the developing countries with limited financial resources such as Egypt. Additionally, the operation of the concentered dam potentially could be easier with less cost due to the unique characteristics of the arid wadi systems where usually the development activities are located in the downstream region. The development potential and the final decision to implement a specific mitigation plan should be based on the strategic targets and plans. If the decision maker aiming to develop all the wadi area not only the downstream region, the distributed dams are necessary and can be used for local groundwater recharge and water use in addition to the extended geographic flood protection. If only the downstream zone has the highest priority for development or the total available budget is low, the concentrated dam can be the best option.

The development potential and the final decision to implement which mitigation plan is totally should be based on the strategic targets and plans. If the decision maker aiming to develop all the wadi area not only the downstream region, the distributed dams are necessary and could be used for local groundwater recharge and water use in addition to the extended geographic flood protection. If only the downstream zone has the highest priority for development or the total available budget is low, the concentrated dam could be the best option.

Table 5-3 Characteristics of the proposed dams for distributed (Dist.) and concentrated (Conc.) mitigation scenarios in Wadi Abadi.

Feature	D4 (Conc.)	D4 (Dist.)	D3 (Dist.)	D2 (Dist.)	D1 (Dist.)
Upstream area (km^2)	6322.3	1169.6	2103.5	1360.6	1688.4
Height (m)	17	11	13	13	16
Length (m)	1200	1200	600	700	750
Reservoir maximum volume ($*10^6$ m^3)	118.41	39.44	34.83	25.63	24.29
Reservoir maximum area (km^2)	16.94	6.76	6.74	4.71	5.36
Outlets number (with dimensions of 2.5*3 m)	3	3	1	2	1

Table 5-4 Characteristics of the proposed dams for distributed (Dist.) and concentrated (Conc.) mitigation scenarios in Wadi Samail.

Feature	Conc. Dam	Dist. Dam 1	Dist. Dam 2	Dist. Dam 3
Location: Y : X	23.554344 58.103665	23.554344 58.103665	23.371503 58.090958	23.368906 58.157186
Reservoir Capacity (*106 m3/s)	75	40	9.6	25.8
Height (m)	50	40	22	22

The current study recommends an additional detailed flash flood risk assessment study using two-dimensional hydraulic model to precisely predict the flooded or inundated zones and also to quantify the expected damages through evaluation of different land used types (urban or field land) for each mitigation scenario. Other criteria such as the structural measures impact on the society, environment, landscape and the habitat diversity suggested to be included in addition to the discussed factors. Gauging stations for wadi flow and rainfall measurements should be installed at the target are for accurate hydrological model calibration and precise prediction of the design storm. Additionally, the developed dam routine recommended to be further updated to assess the reservoir water infiltration. To detect the most sustainable management scenario, long-term siltation or sediment deposition evaluation is also recommended to be estimated for each mitigation scenario. In the case of real implementation of one of the mitigation strategies, the proposed methodology for the identification of the dam location and its characteristics (e.g., dam height or reservoir volume outlet dimension) using DEM data should be followed by a field survey for more accurate estimation of the area topography. To comply with integrated management concepts, the flood mitigation strategies evaluation recommended to take into account another measures such as channel enhancement or non-structural mitigation measures such as early warning system.

Table 5-5 Evaluation of the proposed mitigation scenarios using 200-year return period design flood in Wadi Abadi (relative advantage of a specific mitigation scenario comparing to the other scenario shown in bold font)

Aspect	Distributed dams	Concentrated dam	Without mitigation
Flood mitigation			
Peak flow at the entrance of Wadi Abadi Delta (m^3/s)	**228.0**	303.7	2197.3
Peak reduction at the entrance of Wadi Abadi Delta (%)	**89.6**	86.1	-
Protected area (km^2)	**3018**	488	-
Water resources management			
Total design reservoir volume ($*10^6$ m^3)	**124.2**	118.4	
Maximum reserved volume ($*10^6$ m^3)	**91.0**	82.1	-
Reservoir evaporation ($*10^6$ m^3)	0.57	**0.33**	-
Transmission losses (groundwater recharge) ($*10^6$ m^3)	**87.8**	83.4	79.7
Cost			
Construction cost ($*10^6$ USD)	23.32	**14.53**	-
Secondary	2nd priority	**1st priority**	-
Secondary	2nd priority	**1st priority**	-
Development potential	Based on the target	Based on the target	-

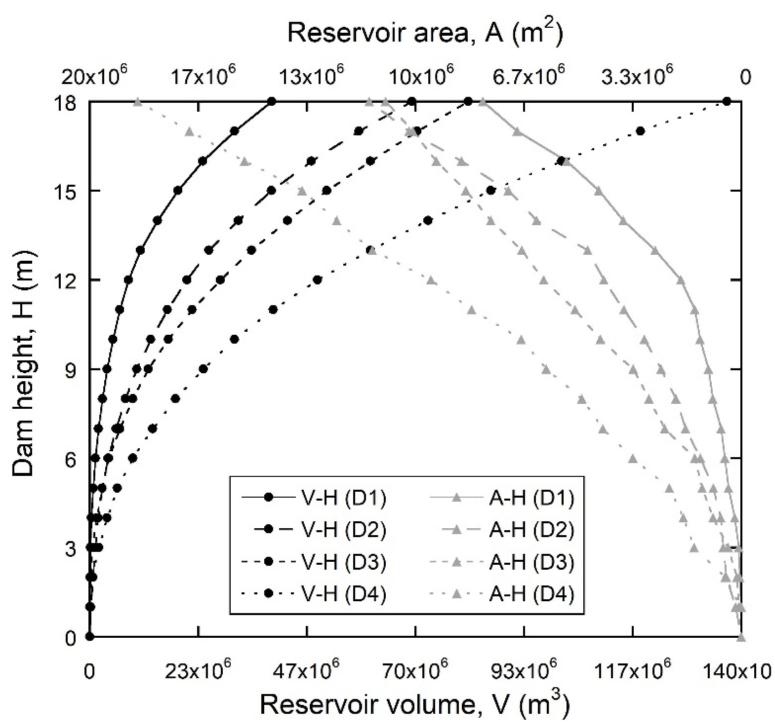

Fig. 5-10 Reservoir's storage capacity (V) and area (A) of the proposed dams (D1-D4) relations with dam height (H) using SRTM 1sec DEM data in Wadi Abadi.

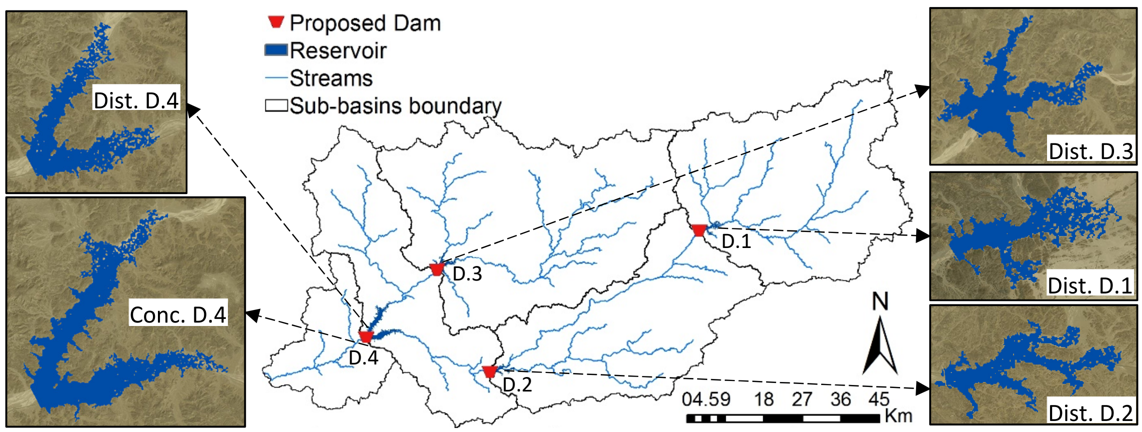

Fig. 5-11 Proposed dams (D1-D4) and reservoirs location constructed from SRTM 1sec DEM data for both distributed (Dist.) and concentrated (Conc.) mitigation scenarios indicating the upstream catchment in Wadi Abadi.

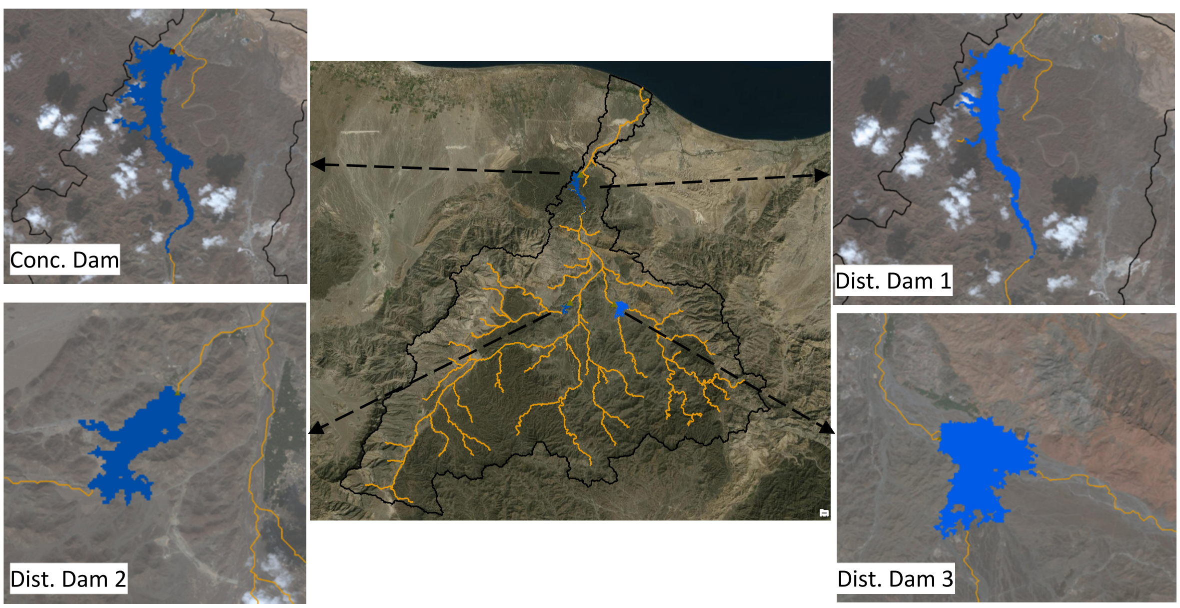

Fig. 5-12 Proposed dams (D1-D4) and reservoirs location constructed from SRTM 1sec DEM data for both distributed (Dist.) and concentrated (Conc.) mitigation scenarios in Wadi Samail.

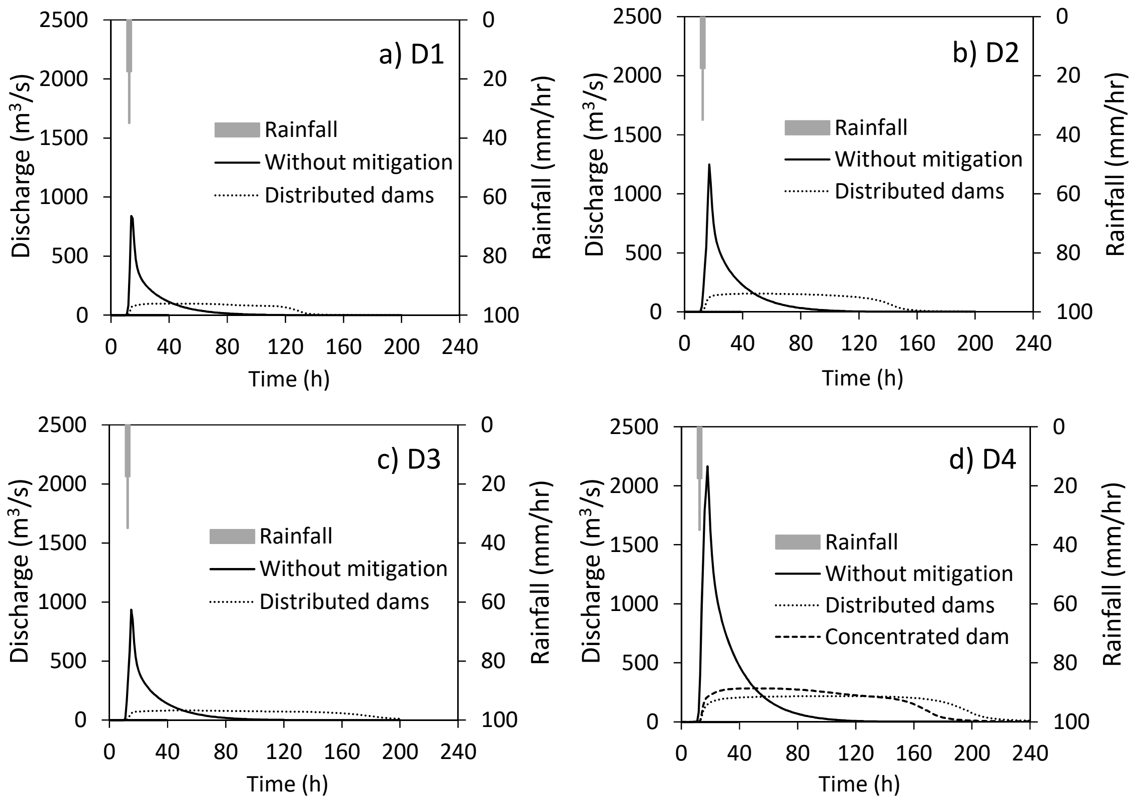

Fig. 5-13 Simulated hydrographs in Wadi Abadi before and after mitigation scenarios application at the target locations a) D1, b) D2, c) D3 and d) D4 under 200 yr. return period storm, which has been recorded in May 1994.

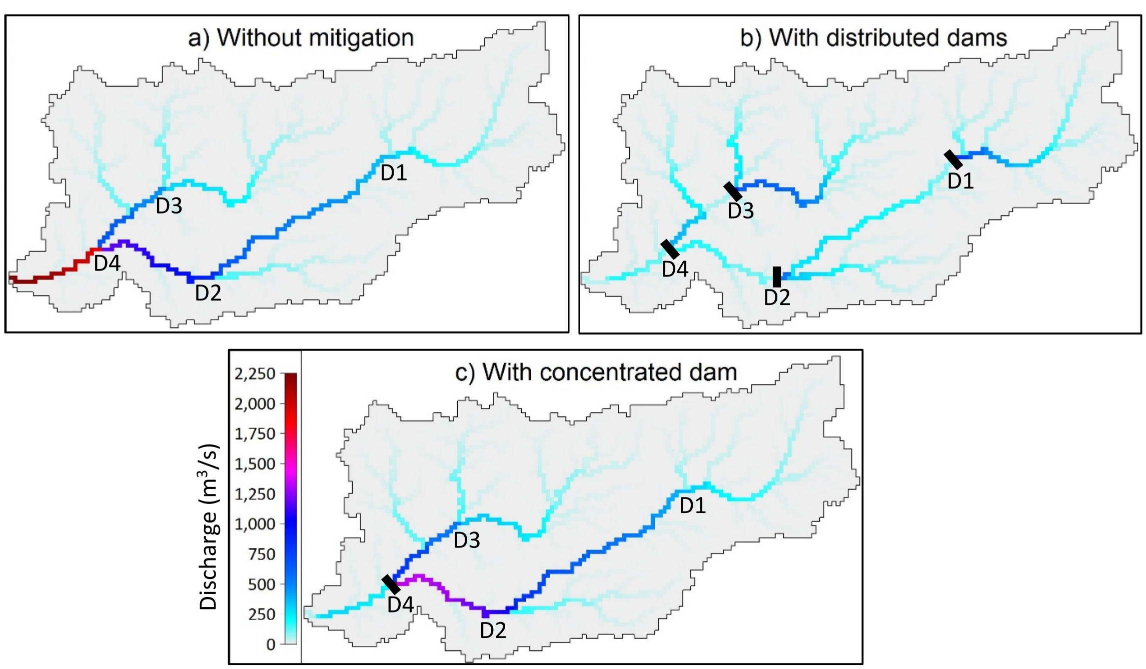

Fig. 5-14 Surface runoff distribution maps in Wadi Abadi: a) without mitigation, b) with distributed dams and c) with concentrated dam mitigation scenarios.

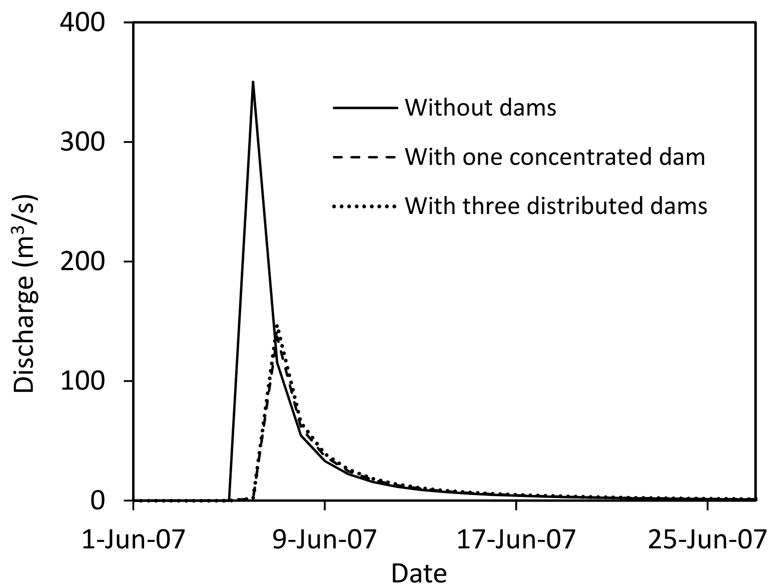

Fig. 5-15 Simulated hydrographs (daily average based) before and after mitigation scenarios application at the outlet of Wadi Samail for Gonu 2007 flash flood event.

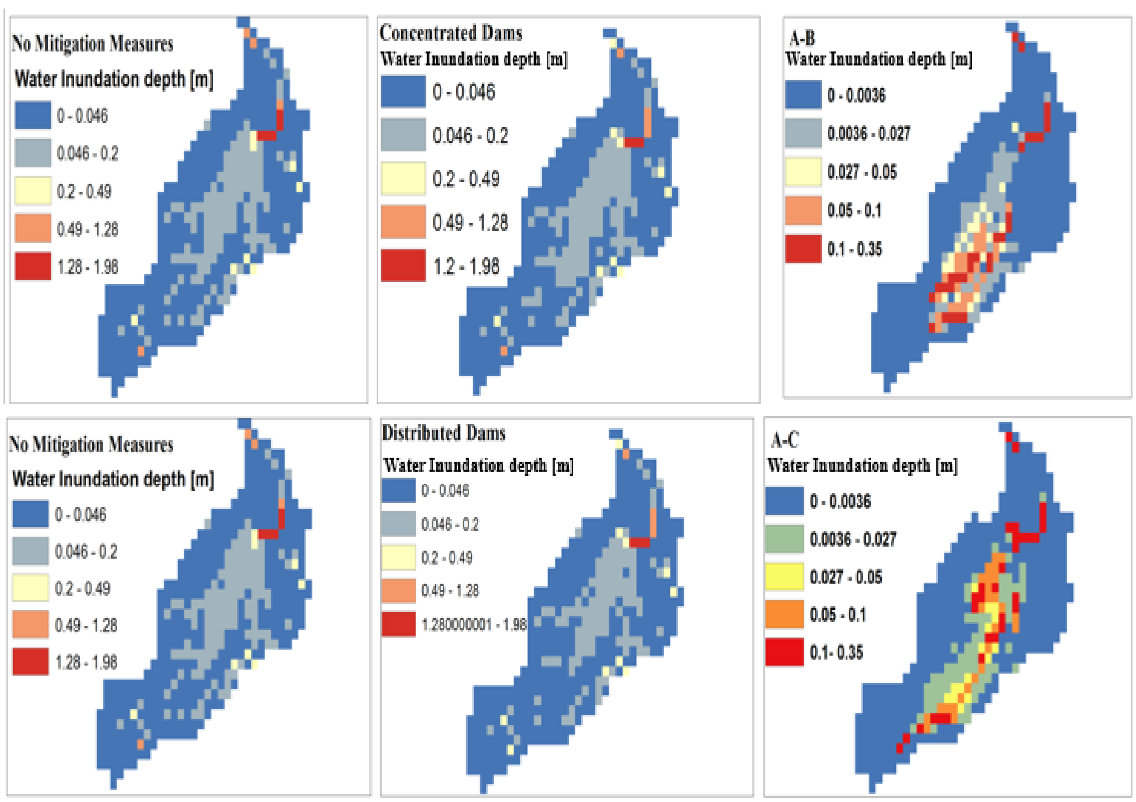

Fig. 5-16 Shows flood depth with concentrated and distributed dams in Wadi Aday for 100 year rainfall return period. A-B and A-C representing the difference between the flood depth with no mitigation measures and with concentrated and distributed dams respectively (Moya, 2017).

In spite of the above limitations, the proposed approach in this study represents an efficient and low-cost framework for the pre-analysis of the initial selection and evaluation of the suitable wadi flash flood structural mitigation measures using easily accessible global remote sensing data. Furthermore, this study also provides understanding of flash floods in wadi systems and provides advice on the key parameters in hydrologic simulation models to be considered in the arid environments. Using the methods and findings proposed above, this study recommends to develop guidelines for WFF mitigation based on variant categories including land use, morphometric, rainfall characteristics, wadi flash flood index and available resources. The developed guidelines will be much useful for the decision making process for the best mitigation option to be adopted.

5.5 Conclusions

Flash floods simulation and management in wadi system and evaluation of different methodologies for structural mitigation measures of flash floods is the main focus of this study. The proposed flash flood mitigation measures include geographically distributed dams and single concentrated dam strategically placed within a wadi region. The dam location and characteristics were identified using high-resolution DEM data and spatial analysis tools. Hydrological simulation model suitable for wadi systems referred to as Hydro-BEAM was applied to Wadi Abadi region in the Eastern Desert of Egypt to simulate two recent storm events. Results from sensitivity analysis conducted for different critical parameters of the Hydro-BEAM model indicated that the soil parameters are dominant in controlling the flash flood peak followed by the runoff coefficient, subsurface layer outlet coefficient and channel roughness. The simulation results also point to main feature of floods in the wadi region with steep and rapidly rising discharges contributing to peak flows with short durations of the order of hours after the storm events. This rapid rise in discharges contributes to increase in the risk of damage and destruction of flash floods compared to slow rising water levels of the normal floods. Wadi floods are also characterized by high spatial variability of runoff within the same event or from one event to another. The distributed dams strategy proposed in this study has relatively more advantages in the aspects related to flood mitigation and water resources management, compared to concentrated dam scenario. However, the concentrated dam approach is better when cost and operation issues are considered. Future studies should focus on sediment management and environmental impact assessment for better evaluation of the different management scenarios proposed in this study.

Chapter 6 Integrated management of the wadi flash floods

6.1 Introduction

Flood risk reduction is a prime concern for flood-vulnerable countries around the world and despite all international efforts and technological advancements, flood risk management remains a challenging task for many developed and developing nations (Shah et al., 2015), however in the most of the arid wadis, there is no comprehensive proper protection from flash floods proposed. That is mainly due to relative low flood frequency comparing to the humid regions. There is an urgent need to mitigate and utilize floodwater as a new supply to sustain a minimum water resources base in rural desert areas. With the progress in international collaboration and data sharing, flood management strategies and approaches could be transferred from other experience or country to be applied in the arid wadi system and customized for the unique characteristics of wadi system including the socioeconomic situation. In this chapter, a critical review for the concepts, strategies and practices of flood risk management, which could revealed new dimensions in developing and proposing sustainable and efficient management strategies in wadi systems.

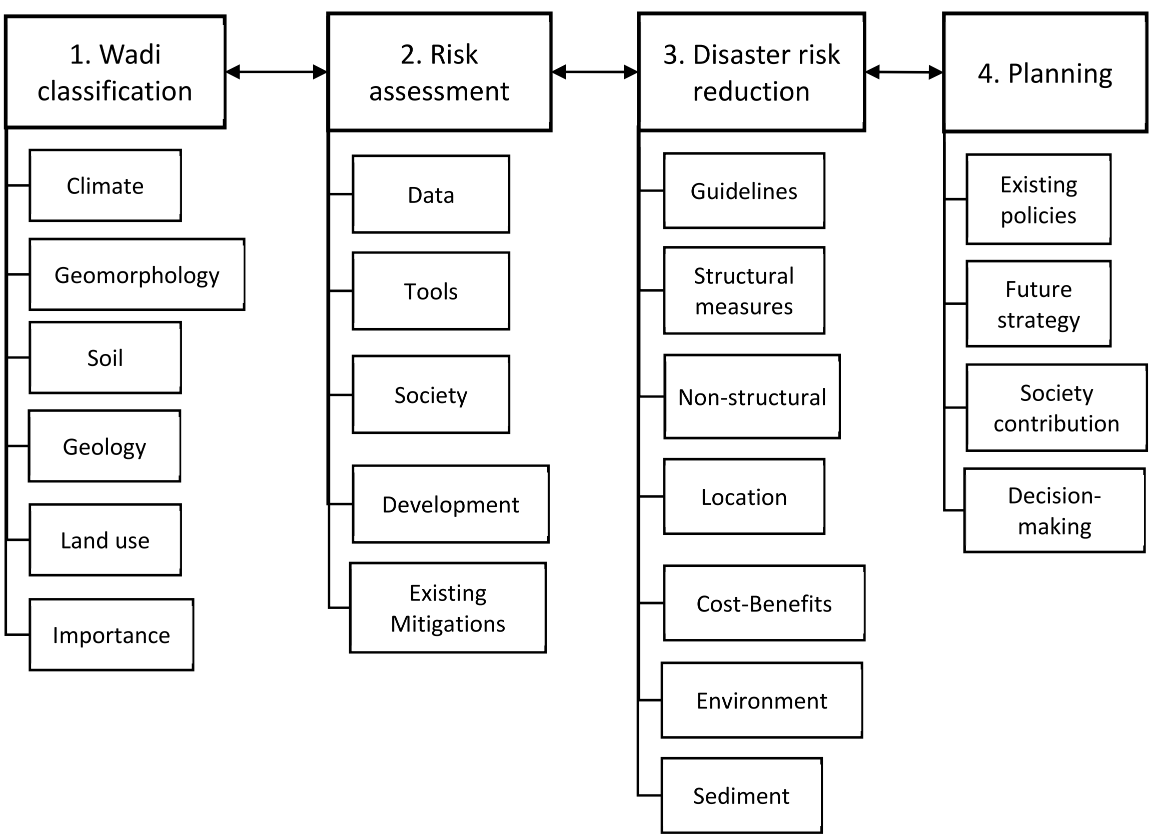

Fig. 6-1 The key components of the integrated wadi flash flood management.

Nevertheless, due to the multiple causes and hydrological uncertainties associated with climatic and morphological changes, to date, flood risk assessment has remained challenging. Also, currently practiced flood risk assessment processes seem to have gaps, which have led to improper planning and design of flood risk reduction measures, and consequently function ineffectively during various catastrophic flood events (Shah et al., 2015). Flood risk management processes, in general, include flood risk identification, flood risk assessment, and structural and non-structural interventions to reduce flood risk (McBain, 2012; Shah et al., 2015).

Flood risk reduction policies and strategies have shifted from localized, reactive and isolated approaches to regional, integrated and proactive approaches (Sayers et al., 2013; Shah et al., 2015), there regional management strategy should be planed and implemented through all the countries in the same region. Regarding to our case studies we recommend to have such concept of regional flash flood management between all countries of the East North Sahara countries (i.e., Egypt and Sudan) and the Arabian peninsula countries (e.g., Saudi Arabia, Oman, Qatar). The paradigm of flood risk management has shifted from a reactive approach, after having huge flood damage, to a proactive approach as the sea level rise management strategies (Shah et al., 2015; Tarrant and Sayers, 2012).

Although structural flood control projects have brought some benefits in flood mitigation, still the floodplain ecosystem appears to be largely destroyed and the ecosystem dependent livelihoods and economy are impacted (Shah et al., 2015). Taking into account the cost of irreversible change in the floodplain ecosystem, the benefits of flood mitigation would tend towards a negative position (Saha et al., 2012; Shah et al., 2015; Tapsell et al., 2002). The question of the sustainability of floodplains comes into focus when large-scale destruction has already taken place. Concepts of integrated river basin management or floodplain management were introduced in recent decades, in an attempt to reduce the impact of structural flood control measures (Sayers et al., 2013; Shah et al., 2015).

Scientists are now suggesting that modern flood risk management strategies should be embedded with a number of major aspects, such as the selection of management options through risk-based assessment, a consideration of the whole system approach to flooding and its effects, a portfolio-based integrated management by multiple organizations and stakeholders, multilevel analyses, evidence-based management options, adaptations to physical and socio-economic changes over time, a consideration of the uncertainties for the whole process, the engagement of all levels of stakeholders, and the integration of the sustainable development of river basins and coastal systems (Hall and Penning‐Rowsell, 2011; Sahin et al., 2013; Sayers et al., 2013; Shah et al., 2015).

As mentioned before flood risk management processes, in general, include flood risk identification, flood risk assessment, and structural and non-structural interventions to reduce flood risk, and we will try in the next sub-sections to give general guidelines for each main part on line with the identified challenges and applicable approaches in wadi system.

Table 6-1 Measures of flood damage reduction (HEC, 1998; Heidari, 2009)

Measures that reduce damage by reducing discharge	Measures that reduce damage by reducing stage	Measures that reduce damage by reducing existing damage susceptibility	Measures that reduce damage by reducing future damage susceptibility
Reservoir	Channel improvement	Levee or floodwall	Land-use and construction regulation
Diversion		Flood proofing	Acquisition
Watershed management		Relocation	
		Flood warning and preparedness planning	

6.2 Flood risk assessment

"What cannot be measured, cannot be managed". The first step in any disaster risk management activities is to assess the potential hazard and risk resulted from this disaster. However, the risk assessment is usually hindered by lack of data in the most of wadi systems, therefore many alternatives have been presented in Chapter 3 and Chapter to face this problem. For instance if the rainfall data are absent then one can use the corrected satellite products for rainfall such as GSMaP data. Furthermore, if the wadi flow is not available we can calibrate our model in a similar and condition wadi and transfer the calibrated model parameters to the target wadi basin, or to use a regional model to estimate the hydrological indices such as peak or average annual flow.

For the final risk assessment there are two option based on the data availability:

- To conduct simple flood susceptibility assessment using the flash flood index or the significant geomorphometric parameters (see Chapter 5). This option can give the relative flood hazard rank through the wadi basin;
- To conduct detailed risk assessment through the main components of the flood risk (hazard, vulnerability and exposure) which can be implemented using 2d hydraulic modeling and flood hazard damage curves data

6.3 Mitigation measures

The earliest civilizations settled along rivers or floodplains, with critical infrastructure and houses being located on higher ground. These settlements also adapted to floods by the population choosing flood-sensitive economic, social and cultural activities (McBain, 2012; Sayers et al., 2013). Since the early 20th century, structural engineering solutions have taken a key role in flood risk management, as the demand has continued for human safety, food security, and safe urban and rural development.

Investigations into the proportional contribution of structural and non-structural measures to reduce total flood risk could assist in better decision making (Shah et al., 2015). Relying on a 'levee only' option has been widened to the integration of other options, such as improvements in the channel, cut-offs of river bends (that were seen to be delaying the flow of waters), flood ways (to relief pressure in the channel during extreme flood events) and flood storage dams (Shah et al., 2015).

The structural and non-structural methods of flood mitigation could categorized as indicated Table 6-1 (HEC, 1998; Heidari, 2009). A flood mitigation plan should cover the following issues (Heidari, 2009):

- the best implementation method to control the flood;
- the most appropriate location to install the facilities;
- the most suitable size for the facilities;
- the best method for operation and maintenance of the facilities.

6.3.1 Structural mitigation measures

Structural defense strategies are either traditional measures, such as levees or dams, or wider ecosystematic measures, such as renaturalisation (Hansson et al., 2008). Despite the immediate benefit of structural flood control measures, over the long term, an improved and sustained performance of the structural measures cannot be justified, as many areas inside large flood control projects have flooded after only a few years of their establishment. Additionally, flood protection measures attract new development in floodplains, which can create a 'moral hazard', misleading a vulnerable community from a true appreciation of the risks associated with occupying the floodplain (McBain, 2012; Shah et al., 2015).

6.3.2 Non-Structural mitigation measures

Non-structural measures concern non-engineering actions such as the use of insurance and restricted development planning, regulating human activities in order to mitigate flooding (Hansson et al., 2008). Alongside structural measures, nonstructural measures have been used, including reducing the severity of flooding through land use changes in upstream catchments, increasing preparedness through early warnings, and reducing the consequence of flooding by reducing both exposure and vulnerability (Richards et al., 2008; Shah et al., 2015; Tapsell et al., 2002; White and Richards, 2007). Historical evidence suggests that flood risk management began and developed from a willingness to live with floods when there was limited technology (Shah et al., 2015). However, population pressures and food shortages have forced societies to utilize floodplains, and therefore to control floods with structures. In recent years, these strategies were followed by both increasing efforts to reduce flood damage and addressing whole risk management (McBain, 2012; Sayers et al., 2013).

Unlike the instant visualization of the benefits of structural flood defences, it is often difficult to quantify the effectiveness of non-structural flood management measures. Owing to non-structural measures, the response and adaptation to floods of the flood vulnerable communities vary widely and are impacted upon by various factors, such as community resilience and susceptibility to flood. Also, the effectiveness of the non-structural measures appears sensitive to socio-economic changes and governance arrangements (Dawson et al., 2011; Shah et al., 2015). Nevertheless, non-structural measures provide flexible flood management options for adapting to the ever-changing river basins, socio-economic and climate scenarios, and are in line with the spirit of environment-friendly and sustainable development (Kundzewicz, 2002; Shah et al., 2015).

a) Preparedness and emergency planning

The purpose of preparedness stage, is to provide the necessary decision support system for the case that the existing flood protection system has failed (Plate, 2002). It is evident that no technical solution to flooding is absolutely safe (Plate, 2002). Even if the system always does what it is supposed to do, it is hardly ever possible to offer protection against any conceivable flood (Plate, 2002). There is always a residual risk, due to failure of technical systems, or due to the rare flood which exceeds the design flood. The perception of flood risk and safety, and current risk communication methods, need to be improved for both the present and future generations (Shah et al., 2015).

6.4 Management strategies sustainability

The effectiveness and sustainability of both structural and non-structural flood control measures vary greatly according to the local context and planning processes (Shah et al., 2015). In the short term, many structural flood control projects have proved their performance by preventing flood; this outcome has led to a strong belief in our ability to protect ourselves from floods through engineering solutions (Shah et al., 2015). In the long term, however, some of these structural measures have been found to be inefficient during catastrophic flood events (Shah et al., 2015) due to unplanned developments, land use change and population growth and growing levels of production, consumption and transportation, which have lead to an increase of hazards and of the consequences of accidents (Jonkman et al., 2003). Flood losses have continued to increase; they have also required further risk assessment and risk management approaches in different ways (Hall and Penning‐Rowsell, 2011; Sayers et al., 2013; Shah et al., 2015).

As seen in the early decades of the 20th century, major flooding events have led to the transformation of local level flood control in the development of basin-scale flood control infrastructure and coordination policies for flood mitigation (Shah et al., 2015). Since flood risk management is recognized as a continuous adaptive management process (Hall and Penning‐Rowsell, 2011; Sayers et al., 2013), 'dynamic sustainability' concepts, approaches that involve adaptation of interventions for achieving best possible outcome through continuous learning and problem solving (Newman, 2005; Scoones et al., 2007) can be adopted.

6.5 Conclusion and recommendations

The single management strategy is not enough to reduce the flash flood risk; nevertheless, a combination of flood risk management approaches is required in all wadi systems. The proposed

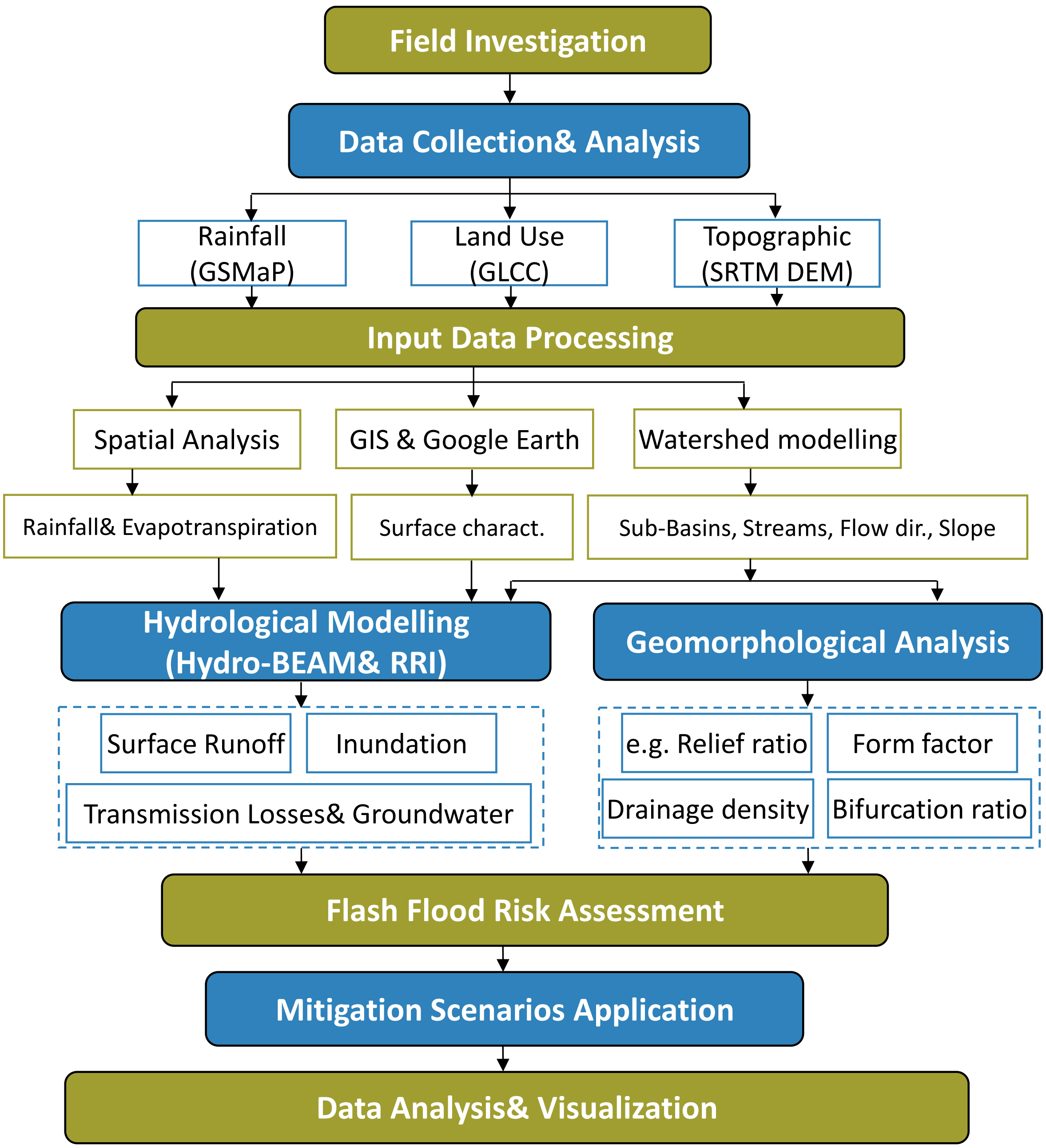

Fig. 6-2 The proposed wadi flash floods integrated management approach.

management approach (Fig. 6-2) focuses on developing a strategic methodology for evaluating wadi flash flood potential, mitigation, and floodwater resource management as well as a rainfall-runoff simulation model (Kantoush et al., 2011; Sumi et al., 2013). One of the flood mitigation measures, is constructing of flood retention structures such as dry dam by using innovative Japanese updated technology as CSG dam (Cement, sand and gravel dam) which developed by Japan Dam Engineering Center (JDEC).

Chapter 7 Conclusions and recommendations

Flash floods are destructive natural disasters and at the same time, an essential source of water, especially in arid areas, where flash floods could provide these regions with a renewable fresh water particularly for groundwater recharge. So using an appropriate decision support system based on effective methodologies could manage this infrequent but valuable resource. A flash flood can be generated during or shortly following a rainfall event, especially when high-intensity rain falls on steep slopes with shallow, impermeable soils, bare rocks and rare or sparse vegetation. The majority of the Great Sahara of North Africa and Arabian Peninsula are hyper-arid environment with very limited rainfall, where most countries suffer from water shortages.

Flash flood disaster at arid environment is associated with several challenges originated from many reasons that related to the features of the flash flood itself, arid environments characteristics, data and methodology limitation. The different dimensions of flash flood phenomena, reasons and resulted impacts have been discussed in detail as summarized at Fig. 1-1. In spite of these challenges, several hydrological, geomorphological and disaster management aspects have been covered in wadi system throughout this study.

This study is formulated into the following main four parts; the first one is declaration the wadi characteristics and its current problems, purpose of this research as well as the previous works which related to this study objectives as described in chapter one and two. The second part in chapter 3 is devoted to understanding the processes that controlling the generation of wadi flash floods, whereas the assessment and of wadi flash floods regarding different hydrological aspects discussed in the third part and chapter four. Finally, the fourth part is focusing on wadi flash floods mitigation and management as presented in chapter 5 and 6. Where, four wadis located in Egypt and Oman, capturing several wadi characteristics and wide range of challenges, were selected as study cases for this research, to discuss the flash flood phenomena at wadi system.

7.1 Conclusions

Accordingly, the findings and outcome of this study can be summarized as follows;

- Detailed discussion of flash flood at wadi system, their problems, important features of wadi basins in arid and semi-arid regions;
- An integrated approach for the deeper understanding of wadi flash floods in terms of its geomorphometric and rainfall characteristics was provided;
- Sophisticated methodologies using physically-based distributed hydrological models and GIS tools along with combination of the remote sensing data and ground observations were proposed;

- The distributed hydrological models could better represent the basin characteristics geographic changeability, for example its geomorphometry;
- Two hydrological models, Hydro-BEAM and RRI models was calibrated and verified in wadi system and simulation of some real virtual flash floods in target wadis under different basin and rainfall characteristics was successfully achieved. Sensitivity analysis was conducted for the hydrological models parameters indicating that the soil parameters are dominant in controlling the flash flood peak followed by the runoff coefficient and subsurface layer outlet coefficient and channel roughness.
- Wadi flash floods have unique characteristics such as the rapid increase in its discharge from its zero-flow status to the flood peak and the high spatial and temporal variability of the surface runoff;
- The amounts of water that were assessed are significant and should be sustainably managed in such arid and vital areas, based on a deep understanding of the processes controlling wadi flash floods;
- Detailed geomorphological analysis have been implemented suing high resolution topographic data and linked to the flood response;
- The impacts of the most effective geomorphometric parameters on the wadi flash flood generation process were highlighted (e.g., area, slope ratio, shape factor and Horton ratios), and the impact of rainfall variability was also studied;
- Generally, all of the geomorphometric parameters, except for the topographic parameters, have greater impacts on the hydrologic response of the wadi as the rainfall intensity increases;
- The complex geomorphometric parameters could be more strongly related to the wadi flash flood indices than the simple individual parameters, especially the topographic and drainage network metrics;
- The relationships between the estimated hydrological indices (e.g., peak flow and time to peak) and the geomorphometric features of the target basins were also investigated, and it was confirmed that the wadi system floods bear the signatures of their geomorphometric properties, where strong correlations between scale and topographic parameters and the hydrological indices of the wadi flash floods, while the shape and drainage network metrics have smaller impacts;
- Transmission losses are very important hydrological process in wadi system and should be considered in any hydrological modelling;

- Flash flood and groundwater potentiality classification for the different sub-basins have been implemented using Elshamy model;
- Different concepts of the structural mitigation measures of flash floods was evaluated, where The proposed flash flood mitigation measures were, applying some geographically distributed dams or single downstream concentrated dam. The distributed dams strategy has relative advantages than the concentrated dam in the flood mitigation and water resources management water aspects, however the concentrated dams scenario record more advantages in the cost and operation aspects;
- Remote sensing data are very effective in use either in hydrological modeling and geomorphometric analysis or the initial evaluation of the best mitigation measures to overcome the problem of data paucity in arid regions or under limited budget availability;
- Integrated concept of flash flood management was proposed;
- Database for the studied wadis have been collected and could be used in future in any related hydrological study. This dataset include wide spectrum of climatic, land use and topographic data. In addition to documentary record of flash floods.

7.2 Recommendations for future research

The current research has stand on the following gaps, where more research and development needs to be carried out to minimize the future wadi flash flood risk as following:

- The proposed approaches need further calibrations and validation in the ungauged wadis of Egypt using rainfall and wadi flow observations in addition to apply the same approach in more wadis with a wider range of basin characteristics;
- For the Hydro-BEAM model, kinematic wave flow routing was used, which may be more physical than other simple lumped models. However, in natural hillslopes and channel networks, more complex routing techniques, such as dynamic or diffusive wave models, may provide more appropriate representation. The current calculation time step of Hydro-BEAM model is identified manually, which could consume many of the computation resources (for instance, the mild slope areas do not need low value of time step like the sloppy area). Therefore it is recommended to have adaptive scheme for the setting of Hydro-BEAM time step;
- In the RRI model still not has a stable groundwater module in RRI model (under development) and it is recommended to be included and validated. Due to data limitation, the RRI model inundation outputs were not calibrated and should be considered in the future for more comprehensive evaluation of RRI model in the wadi system;

- Compare and assess more hydrological models performance to use the best option in wadi system;
- Fieldwork to investigate the infiltration capacity of the different land use types can be used for better calibration of the hydrological mod. Wadi channel transmission losses should be considered RRI model in future, where these processes are essential in wadi system;
- Over the years, the simple approach of defining flood events, with a return period through frequency analysis (Stedinger, 1993), has been transformed to more complex methods to determine probabilistic flood scenarios with consideration for exceedance probability (Merz and Thieken, 2004) and uncertainties (Merz et al., 2008; Wu et al., 2011) according to Shah (2015). Therefore the current flood risk assessment should, which based on return period should be updated;
- Other criteria such as the structural measures impact on the society, environment, landscape and the habitat diversity suggested to be included in addition to the discussed factors. Additionally, the developed dam routine recommended to be further updated to assess the reservoir water infiltration and siltation aspects;
- To evaluate the different method of water harvesting for effective and sustainable management of the vital water of wadi flash flood to improve the water situation;
- The proposed methodology for the identification of the dam location and its characteristics (e.g., dam height or reservoir volume and area) using DEM data should be validated using field survey;
- Long-term prediction of climate change and the anthropogenic (as land use change) impact on wadi flash foods;
- To more focus on the flood mitigation soft measures such as early warning system and social awareness to minimize the loss of human life and infrastructure damage caused by flash floods;
- Sediment transport evaluation during wadi flash flood is also recommended, where sediment has severe impact on the mitigation structure, which increases the flash flood risk and decrease the efficiency of flood mitigation structures. Therefore, it is important to study this factor and to be linked with the wadi characteristics such as geomorphometry and soil type;
- Detailed flood risk assessment based on more land use and geomorphological features it is highly advised;
- This study recommends an Integrated approach for all wadi systems that includes ‘dynamic sustainability’ concepts, for better flood management planning;

- By sharing knowledge and experiences throughout the world, stakeholders have multiple choices of technologies to apply to flood-prone communities (Shah et al., 2015). Therefore we highly recommended to have a database contains all the available data from all wadi systems and to be accessible for any researcher.

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Appendixes

Appendix 1 Geomorphometric characteristics of W. Qena

Table 1 The geomorphometric characteristics of Wadi Qena and it sub-basins.

Table 1 Wadi Qena morphometric parameters.

Basin ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**15**
A (km^2)	885.7	1261.7	341.2	316.4	314.9	826.4	774.4	487.8	898.3	779.0	1487.9	591.9	858.2	659.5	15606.5	5123.3
P (km)	282.4	319.4	168.0	134.5	196.8	315.6	265.0	195.0	307.0	262.3	427.3	314.5	272.3	226.9	1258.8	1272.9
L_b (km)	67.58	68.60	37.45	27.23	53.58	77.76	61.06	43.10	71.84	62.70	112.34	69.07	53.01	53.60	243.42	209.63
T_c (h)	8.2602	9.0008	3.3485	3.8044	5.3173	7.2426	4.3171	3.3246	6.6342	7.6215	11.6934	6.8445	6.1390	6.3004	20.6643	20.9505
H_{mean} (m)	628.0	621.1	669.9	481.7	569.3	561.5	634.0	727.4	705.3	442.3	526.6	534.9	436.6	426.9	496.2	351.8
h (m)	414.0	414.5	400.0	363.4	301.0	233.5	339.0	339.0	284.5	284.5	172.5	218.5	218.5	92.0	69.5	69.5
H (m)	898.0	1033.9	1386.9	828.5	1082.5	1187.1	1930.1	1868.1	1873.9	955.5	750.4	1037.0	1037.0	588.0	1930.1	1066.9
R (m)	494.5	627.4	992.4	472.5	785.3	962.6	1601.3	1539.1	1594.1	680.9	586.7	821.9	824.5	497.0	1860.6	1001.3
R_r	0.0073	0.0091	0.0265	0.0174	0.0147	0.0124	0.0262	0.0357	0.0222	0.0109	0.0052	0.0119	0.0156	0.0093	0.0076	0.0048
R_M (km^{-1})	0.0166	0.0177	0.0537	0.0266	0.0443	0.0335	0.0575	0.0697	0.0532	0.0244	0.0152	0.0338	0.0281	0.0194	0.0149	0.0140
HI	0.4421	0.3335	0.2735	0.2544	0.3433	0.3439	0.1854	0.2540	0.2648	0.2351	0.6127	0.3866	0.2664	0.6753	0.2293	0.2831
R_n	1.3093	1.7674	2.7258	1.3052	2.1775	2.5615	4.1313	3.8862	4.2280	1.9423	1.5124	2.1999	2.2029	1.2024	5.0070	2.7504
D_I	0.5390	0.5991	0.7116	0.5614	0.7219	0.8033	0.8244	0.8185	0.8482	0.7023	0.7701	0.7893	0.7893	0.8435	0.9640	0.9349
S_b (%)	4.2609	4.4231	7.2525	4.6661	5.7281	8.0675	11.807	15.279	9.6638	4.7732	6.9640	6.4418	6.8470	7.6215	6.4313	4.7732
S_{ms} (%)	0.4252	0.3556	1.4298	0.8882	0.7415	0.5815	1.2715	1.6110	0.6482	0.4897	0.3427	0.5550	0.6181	0.5855	0.2149	0.1534
R_s	0.0998	0.0804	0.1971	0.1904	0.1295	0.0721	0.1077	0.1054	0.0671	0.1026	0.0492	0.0862	0.0903	0.0768	0.0334	0.0321
S_{ls} (%)	0.4748	0.3963	1.6846	1.0053	0.8496	0.7009	1.5187	1.4234	1.2751	0.5235	0.3534	0.8839	0.7359	0.5976	0.2524	0.2967
S_{cs} (%)	0.2579	0.2339	0.6433	0.2849	0.5795	0.3447	0.3955	0.5596	0.5114	0.3647	0.2437	0.4640	0.5201	0.3387	0.1533	0.1529
F	0.1940	0.2681	0.2433	0.4268	0.1097	0.1367	0.2077	0.2625	0.1740	0.1981	0.1179	0.1241	0.3054	0.2295	0.2634	0.1166
C	2.6763	2.5369	2.5654	2.1331	3.1285	3.0970	2.6862	2.4909	2.8892	2.6506	3.1249	3.6471	2.6218	2.4923	2.8425	5.0167
R_c	0.1396	0.1554	0.1519	0.2198	0.1022	0.1043	0.1386	0.1612	0.1198	0.1423	0.1024	0.0752	0.1455	0.1610	0.1238	0.0397
R_e	0.4969	0.5842	0.5566	0.7372	0.3738	0.4171	0.5143	0.5781	0.4707	0.5023	0.3874	0.3975	0.6236	0.5406	0.5791	0.3853
τ	1.1598	0.7311	0.4820	0.6414	2.2679	0.9390	1.5894	1.0241	1.8275	2.8893	0.6032	4.9366	1.2225	0.5234	0.6369	0.9419
TNs	2924	3607	1088	982	970	2726	2549	1637	2938	2452	4812	1955	2897	2104	49139	15498
TLS (km)	2345.2	3554.1	937.1	873.9	873.2	2199.0	1997.8	1231.6	2382.6	2222.2	3835.6	1584.3	2293.0	1595.7	41998.2	14073.1

Table 1 Wadi Qena morphometric parameters.

Basin ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**15**
L_{ms} (km)	98.820	98.134	54.603	43.785	71.409	103.89	80.716	60.650	97.174	96.891	159.59	88.558	79.341	79.163	321.291	223.157
L_{ls} (km)	99.404	98.671	55.237	45.112	72.032	105.080	81.155	65.592	97.918	97.228	159.972	89.773	82.267	79.992	322.518	265.786
L_{cs} (km)	61.4894	49.7651	24.4045	22.8155	40.6765	38.8723	60.735	36.293	61.695	81.975	46.775	54.1199	37.0103	37.7882	124.5801	111.2187
Si_{ms}	1.6298	1.6564	1.7356	1.8393	1.5349	1.5685	1.4965	1.4317	1.4836	1.9196	1.6152	1.8063	1.9257	1.7159	1.5124	1.4540
Si_{ls}	1.6295	1.6649	1.7451	1.7823	1.5558	1.5543	1.5087	1.9587	1.5261	1.9209	1.6148	1.6996	1.9049	1.7921	1.5711	1.5705
Si_{cs}	1.6296	1.5382	1.6732	1.6138	1.5161	1.3794	1.5943	1.4390	1.4875	1.5366	2.1627	1.5428	1.3279	1.6705	1.3732	1.3731
D_f (km^{-2})	4.1096	3.7086	3.8428	3.8659	3.8582	3.9037	3.9439	3.8995	3.8718	3.8985	3.7898	3.9078	3.8895	3.5646	3.8241	3.7622
F_1 (km^{-2})	2.5877	2.2177	2.5179	2.4308	2.4419	2.5593	2.5440	2.5730	2.5381	2.4300	2.5351	2.5494	2.6229	2.4926	2.4551	2.3694
D_d (km^{-1})	2.6477	2.8170	2.7467	2.7623	2.7728	2.6610	2.5799	2.5250	2.6523	2.8526	2.5778	2.6766	2.6718	2.4194	2.6911	2.7469
C_m (km)	0.3777	0.3550	0.3641	0.3620	0.3606	0.3758	0.3876	0.3960	0.3770	0.3506	0.3879	0.3736	0.3743	0.4133	0.3716	0.3640
L_o (km)	0.1888	0.1775	0.1820	0.1810	0.1803	0.1879	0.1938	0.1980	0.1885	0.1753	0.1940	0.1868	0.1871	0.2067	0.1858	0.1820
T (km^{-1})	8.7407	8.0536	8.7595	8.5744	8.5406	8.7778	8.4925	8.4743	8.6747	8.9786	8.3368	8.8405	9.0190	7.7180	8.4731	8.3093
R_t (km^{-1})	10.356	11.292	6.477	7.302	4.929	8.637	9.620	8.394	9.571	9.350	11.261	6.215	10.640	9.273	39.036	12.175
R_f	8.3057	11.1265	5.5785	6.4975	4.4368	6.9677	7.5394	6.3154	7.7615	8.4733	8.9764	5.0367	8.4218	7.0328	33.3632	11.0559
L_{umax} (km)	58.867	45.094	22.020	17.673	37.549	20.786	24.463	49.239	34.579	48.561	122.662	56.463	31.515	23.551	83.434	83.434
R_b	3.7920	3.8874	4.0749	3.9639	3.9779	4.1307	3.9952	4.1699	4.1338	4.5753	5.4300	4.3996	4.2000	3.5959	3.8538	3.9703
R_l	2.7308	2.2918	2.2581	2.0238	2.4074	2.2080	2.2792	2.9435	2.3816	2.4716	3.6061	2.6584	2.2964	2.2537	1.9314	1.9989
R_a	4.0191	4.1925	4.5367	4.2666	4.4879	4.1851	4.3842	4.7516	4.1882	5.1838	6.7431	4.7973	4.4730	3.9282	4.0199	4.1866

A =Area, P_i =Perimeter, L_b =Basin length, T_c =Time of concentration, H_{mean} =Mean elevation, h =Minimum elevation, H =Maximum elevation, R =Relief, R_M =Melton relative relief, HI =Hypsometric integral, R_n =Ruggedness number, D_i =Dissection index, S_b =Basin mean slope, S_{ms} =Mainstream slope, R_s =Slope ratio, S_{ls} =Longest stream slope, S_{cs} =Slope of stream from basin centroid to its outlet, F =Form factor, C =Compactness, R_c =Circularity ratio, R_e =Elongation ratio, τ =Basin eccentricity, TN_s =Total Stream number, TL_s =Total Stream length, L_{ms} =Mainstream length, L_{ls} =Longest stream length, L_{cs} =Stream length from basin centroid to its outlet, Si_{ms} =Main stream sinuosity, Si_{ls} =Longest stream sinuosity, Si_{ls} =Stream from basin centroid to its outlet sinuosity, D_f =Drainage frequency, F_1 =1st order streams frequency, D_d =Drainage density, C_m =Channel maintenance, L_o =Overland flow length, T =Drainage texture, R_t =Texture ratio, R_f =Fineness ratio, L_{umax} =Main trunk length, R_b =Bifurcation ratio, R_l =Length ratio, R_a =Area ratio

List of publications

1-Journal papers

Abdel-Fattah, M., Saber, M., Kantoush, S. A. and Sumi T., 2017. A Geomorphometric and Hydrological Approach to Understanding the Generation of Wadi Flash Floods, Water, 9(7), 553.

Abdel-Fattah, M., Kantoush, S. A., Saber, M. and Sumi, T., 2017. Evaluation of structural flash flood mitigation measures in Wadi Abadi region of Egypt, Journal of Hydrologic Engineering (under review)

Saber, M., **Abdel-Fattah, M.**, Kantoush, S. A., Sumi, T., Galloway, D. L., 2017 Implications of land subsidence due to groundwater over-pumping: monitoring methodology using grace data, International Journal of GEOMATE (accepted)

2- Conferences

Abdel-Fattah, M., Kantoush, S. and Sumi, T., 2015. Hydrological Modelling of Flash Flood to Assess the Distributed Mitigation Structures in Wadi Abadi Case Study of the Eastern Desert in Egypt. 1St International Symposium on Flash Floods in Wadi Systems, 14-15 October 2015, Kyoto University, Japan (Abstract).

Abdel-Fattah, M., Saber, M., Kantoush, S. A. and Sumi T., 2016. Flash Floods Hazard and Groundwater Recharge Assessment at Wadi Qena, Egypt, 7th ICWRER, 5-9 June 2016, Kyoto, Japan (Extended Abstract).

Saber, M., **Abdel-Fattah, M.**, Kantoush, S. A. and Sumi, T., 2016. Exploring the Vulnerable Urbanized Regions for Flash Floods Hazard along the River Nile, Aswan, Egypt, 7th ICWRER, 5-9 June 2016, Kyoto, Japan (Extended Abstract).

Abdel-Fattah, M., Kantoush, S. A. and Sumi, T., 2016. Evaluating Flash Floods Mitigation Scenarios in Wadi Abadi, Egypt. 20th Congress of the Asia Pacific Division of the International Association for Hydro Environment Engineering & Research (IAHR APD), 28-31 August 2016, Colombo, Sri Lanka (Full Paper).

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Yusuke, O., **Abdel-Fattah, M.**, Saber, M., Sumi, T., and Kantoush, S. A., 2016. The Impacts of Extreme Flash Floods on the Archeological Sites: Case study, The Valley of the Kings, Luxor, Egypt. 2nd International Symposium on Flash Floods in Wadi Systems, 25-27 October 2016, Technische Universität Berlin, Campus El Gouna, Egypt (Abstract).

Abdel-Fattah, M., Kantoush, S., Saber, M., and Sumi, T., 2017. Flash Floods in the Arid Arabian Wadis: Processes, Hydrological Modeling and Mitigation. DPRI Annual Meeting Jan 2017, Kyoto, Japan (Abstract).

3- Reports

Abdel-Fattah, M., Kantoush, S. and Sumi, T., 2015. Integrated Management of Flash Flood in Wadi System of Egypt: Disaster Prevention and Water Harvesting. *京都大学防災研究所年報*, (58), pp.485-496.

Abdel-Fattah, M., Kantoush, S., Saber, M. and Sumi, T., 2016. Hydrological Modelling of Flash Flood at Wadi Samail, Oman. *京都大学防災研究所年報*, (59), pp.533-541.

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MOYA J., Kantoush, S., **Abdel-Fattah, M.**, Sumi, T. and Saber, M., 2017. A Comparative Study between Flash Floods in Arid and Semi-arid Basins with Respect to Economic Mitigation Measures. DPRI Annual Meeting Jan 2017, Kyoto, Japan (Abstract).

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