Evaluation of Structural Measures for Flash Flood Mitigation in Wadi Abadi Region of Egypt

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Abstract: Wadis, an Arabic term referring to a wadi, in the Eastern Desert of Egypt have undergone rapid unsustainable development in areas vulnerable to flash flooding and water scarcity. To reduce the risk of damage and loss of life from flash floods to a wadi's new residents, the priority is to develop mitigation strategies with distributed (watershed scale) or concentrated (localized) mitigation structures to promote sustainable development. The focus of this study is to develop a new approach that will help in assessing various flood mitigation scenarios in Wadi Abadi in the Eastern Desert of Egypt. The proposed approach considers the limited data availability in the wadi system and utilizes spatial analysis and an in-house developed distributed hydrological model, Hydrological River Basin Environmental Assessment Model (Hydro-BEAM), upgraded with a reservoir routing module. Sensitivity analysis of the key Hydro-BEAM model parameters indicated that the most significant parameters controlling the wadi flood peaks are soil thickness and porosity, runoff coefficient, subsurface layer outlet coefficient, and channel roughness. Digital Elevation Model (DEM) data and satellite imagery were utilized to propose the locations and derive design characteristics of the mitigation structures. The mitigation strategies evaluated in this study resulted in a peak flood reduction percentage of 90% and 86% for the distributed and concentrated dam scenarios, respectively. The results show that a group of distributed dams could outperform a single concentrated dam when flood mitigation and water resources management aspects are considered in the wadi region, where the distributed dams scenario has 600% more protected area and 21% more reservoir volume than the concentrated scenario (i.e., use of one dam). However, the concentrated dam scenario may have advantages due to the cost of construction and operations. The proposed approach can assess the flood risk reduction due to different mitigation measures and provide strategies for development and planning in wadi regions. **DOI:** 10.1061/(ASCE)HE.1943-5584.0002034. *© 2020 American Society of Civil Engineers.*

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Introduction

Regional extreme flash flood events (e.g., January 2010, March 2014, and October 2015) have been frequently occurring in the Middle East, where these types of floods are considered among the most severe disasters in this region in terms of fatalities and economic losses. The flash floods are generally characterized by their quick occurrence, leaving a very limited opportunity for warnings to be prepared and issued, and they are generally caused by steep slopes, sparse vegetation, poor soil development, impermeable soil, and high rainfall intensity (Collier 2007; Lin 1999). In arid desert environments, such as the North Sahara, the flash floods usually occur in ephemeral dry valleys, which are referred to as "Wadis" in Arabic. The hydrology of the arid wadi system, which is under increasing water stress, is very different from that of humid areas, which raises significant challenges for water resources and disaster management. The unique hydrological characteristics of the arid wadis include: (1) high spatial and temporal rainfall variability; (2) high evaporation rate; (3) lack of vegetation cover; (4) low infiltration capacity of the poorly vegetated soils and exposed rocks; (5) absence of baseflow; (6) intermittent channel flow; and (7) significant transmission losses through the wadi channels (Abdel-Fattah et al. 2017; Lin 1999; Sen 2008; Wheater and Al-Weshah 2002).

The magnitude and frequency of wadi flash floods are not clearly understood and therefore zones of flood risk have not been 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. Consequently, the prediction of the timing and magnitude of these floods is extremely difficult. Disaster impact in the developing countries is more severe, where the larger the disaster and the smaller the economy, the more significant the impact will be and the weaker the economies will become afterward (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 (Abdel-Fattah 2017). In the recent decade, various Egyptian governorates, including Aswan, North Sinai, South Sinai, Red Sea, and Qena, have been exposed to strong flash floods causing 13 deaths, 49 injuries, and 12,401 affected persons (IDSC 2010).

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Flood assessment in arid environments and wadi systems is hindered by limited or complete lack of hydrological data and resources for rainfall and channel flow measurements (Abdel-Fattah et al. 2018; Lin 1999). This absence of data limits the ability of the rainfall-runoff models to simulate the observed flows accurately. Although there are some implementations of flash flood mitigation measures in Egypt (such as obstacle and detention dams, artificial lakes, and embankments), nonstructural mitigation measures such as early warning systems are still very rare. If an appropriate warning system existed in Egypt, the severe flood from October 2015 in Alexandria could have been predicted at least one week in advance (Zevenbergen et al. 2017). Concurrent with the early warning and development of land-use suitability maps, new approaches for prediction and mitigation are needed for disaster risk reduction due to flash floods.

Integrated management of wadi flash floods requires the development of strategic methodologies for evaluating risk, mitigation, and water resource management (Sumi et al. 2013). Flood risk reduction can be achieved by decreasing the magnitude of the flood or the vulnerability of the flood-prone area (Heidari 2009) using nonstructural and structural measures (Hansson et al. 2008; Heidari 2009). Nonstructural measures refer to nonengineering actions such as the use of insurance, increasing preparedness through early warnings, restricted development, land-use planning, operation of flood control reservoirs, etc. (Hansson et al. 2008; Shah et al. 2015). Structural defense strategies are either traditional measures, such as the use of levees or dams, or wider ecosystem specific measures, such as renaturalization 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). 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 measure at one location.

The concept of distributed structural measures for flood mitigation has been reported in several previous studies (Andoh and Declerck 1997; Emerson et al. 2005; Kurz et al. 2007; Montaldo et al. 2004; Ravazzani et al. 2014; Thomas 2015). A distributed flood mitigation approach aims to attenuate the flood peak or store excess floodwater in upstream subbasins to reduce the accumulation of downstream discharge (Montaldo et al. 2004; Thomas 2015). Application of distributed reservoirs either in series or in parallel has been assessed to reduce the magnitudes of the flood peaks throughout the basin using fully distributed models (Cazares-Rodriguez et al. 2017; Chennu et al. 2007; Del Giudice et al. 2014; Montaldo et al. 2004; Ravazzani et al. 2014; Thomas 2015), semidistributed models (Cazares-Rodriguez et al. 2017; Leblois et al. 2010; Ramireddygari et al. 2000; Yazdi et al. 2018), 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 multicriteria 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 et al. (2010) has investigated the use of one single concentrated measure for flood mitigation impact assessment of a single dam on the developed downstream area using a combination of hydrologic and hydraulic modeling efforts.

Limited studies exist in wadi systems that explore different alternatives to flash flood mitigation. One such study by Al-Weshah and El-Khoury (1999) compared different combinations of mitigation measures such as afforestation, terracing, and construction of check and storage dams in Jordan. Abd-El Monsef (2018) assessed runoff water using a lumped hydrological model and estimated sediment yields to determine the impact of flash floods on the El-Qusier-Qena highway in Egypt. The study proposed some structural flood mitigation measures without quantifying the performance of these mitigation measures for reducing flood disaster risk. Alhumaid et al. (2018) proposed a framework to assess stormwater drainage options for urbanized regions in the arid wadis in Saudi Arabia.

The main objective of this study is to simulate and assess some recent wadi flood events (i.e., January 2010 and March 2014) and to propose an efficient approach that would reduce the risk from wadi flash floods by integrating structural mitigation scenarios such as concentrated dams and geographically distributed dams using a hypothetical design rainfall storm. The physical and institutional features of the rural regions, such as the target area, including the abundance of undeveloped land, prioritize structural over nonstructural flood mitigation measures (Consoer and Milman 2018). Also, the flood retention dam is an important structure due to its immediate benefits; therefore, it is proposed in this study for the mitigation of wadi flash floods.

Hydro-BEAM was used as a tool flood simulation and modified by adding a reservoir routing for evaluating flood mitigation strategies suitable for the arid regions. This modification can be considered as a variant to the widely used lumped modeling approach in wadi systems. Also, the sensitivity analysis of the hydrological model carried out in this study will be beneficial to the hydrologic modeling efforts in the ungauged arid wadis. After the hydrological model is calibrated and validated and several flood events were simulated, multiple dam locations were proposed according to the expected design flood volume, local topography, and existing human activities. Reservoir storage (V)–water depth (H) and reservoir area (A)–water depth (H) relationships were developed and DEM data is used in the developed dam module in the Hydro-BEAM model. The proposed flood mitigation scenarios were evaluated based on their efficiency in mitigating the flood hazard, securing required water storage, under cost, operation, and land development constraints.

Methodology

The objective of this study is to simulate hydrological processes in a wadi system employing a variant of a Hydro-BEAM that considers multiple structural flash flood control measures using the 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 Hydro-BEAM. Fig. 1 presents the processed data and the proposed approach, with the following core steps and execution of different modules:

1. Simulate potential flash flood hazards using Hydro-BEAM for different flash flood scenarios of various return periods of design storms concerning the available local rainfall data;
2. Propose suitable mitigation strategies through dam module that considers the runoff and computes the hydrographs with and without structures; and

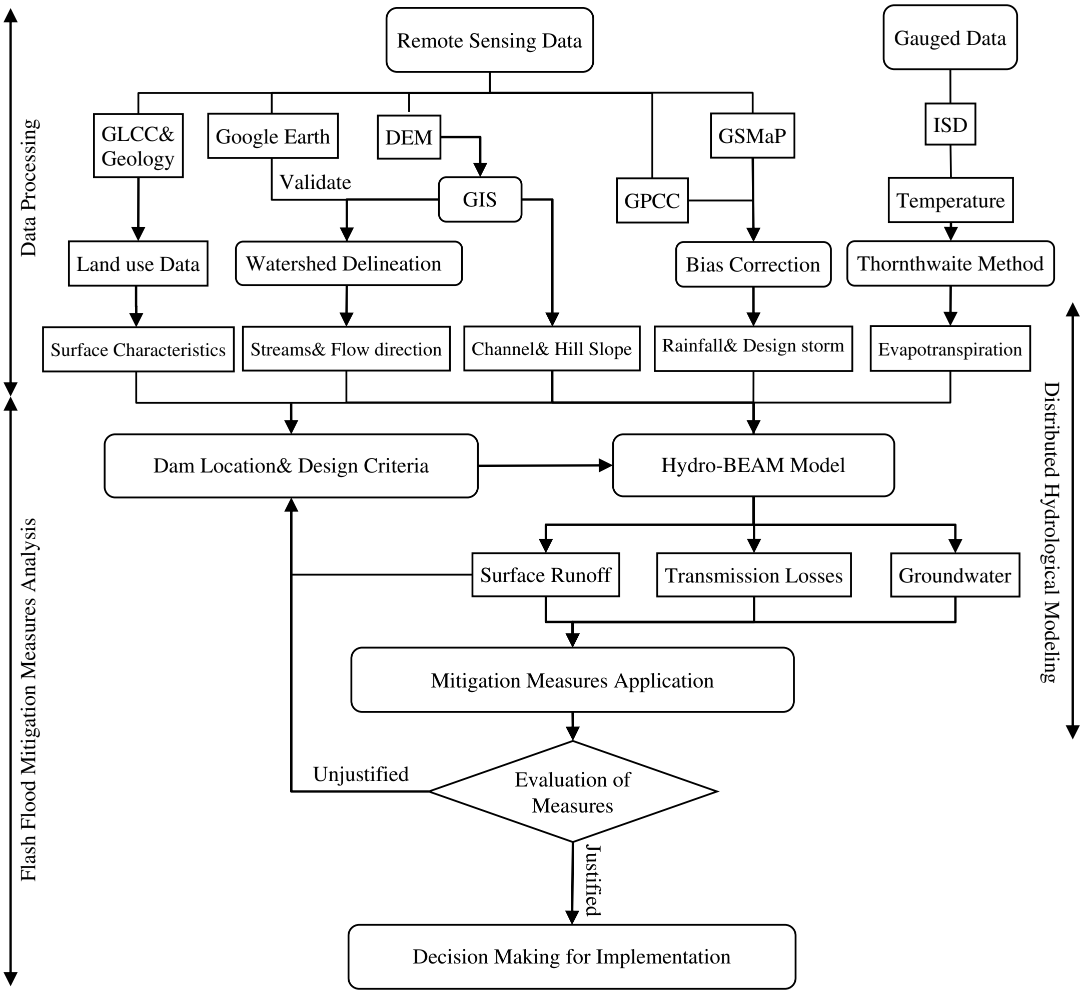

Fig. 1. Illustration of the developed approach including flowchart for input data processing that includes Global Land Cover Characterization (GLCC), Global Satellite Mapping of Precipitation (GSMaP), Integrated Surface Database (ISD), and Global Precipitation Climatology Centre (GPCC); hydrological modeling using Hydro-BEAM; and application and evaluation of the flood mitigation measures.

3. Evaluate and make decisions based on various criteria of flood mitigation, water resources, cost, operation, and development potential.

There are other preliminary steps such as watershed delineation to detect the mainstream network, watershed, and subbasins boundaries by using spatial analysis tools (i.e., GIS) and DEM data. The generated streams networks were cross-correlated and checked with the available satellite images from different sources (i.e., Google Earth and the local geological maps). The results of such comparisons confirmed that a reliable stream network for hydrologic modeling was obtained for the case study region. 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 subcatchments. Therefore, two separate extreme flash floods events that occurred in January 2010 and March 2014 in Egypt were simulated, in addition to several design storms were also evaluated in Wadi Abadi.

Hydro-BEAM Model

Hydro-BEAM is an in-house developed, distributed, and continuous 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 the wadi system in the arid environment. In the Hydro-BEAM model, the spatial domain of the watershed under investigation is divided into several grids (i.e., unit mesh cells) (6,800 mesh with an area of 1 km^2 in this study). Each grid mesh is divided into two pairs of rectangular hillslopes 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. 2.

An integrated kinematic wave model used to describe layer A considering the diverse surface characteristics of different land-use types. A kinematic wave model is also employed to describe the behavior of the water in the river channel using Manning's equation. The channel's geometry (depth and width) identified using the upstream area and related to reference locations with measured geometry. The subsurface layers (B, C, and D layers) are modeled using a linear storage mode. The model estimates the initial and transmission losses using the Natural Resources Conservation Service (NRCS) method (SCS 1997) and Walter's equation (Walters 1990), respectively (Saber et al. 2010). The parameters used in Hydro-BEAM are listed in Table 1 and reflect the components of the model. For each mesh, the rainfall, evapotranspiration, channel slope, hillslope gradient, downstream mesh, and land-use should be identified as inputs for the Hydro-BEAM model.

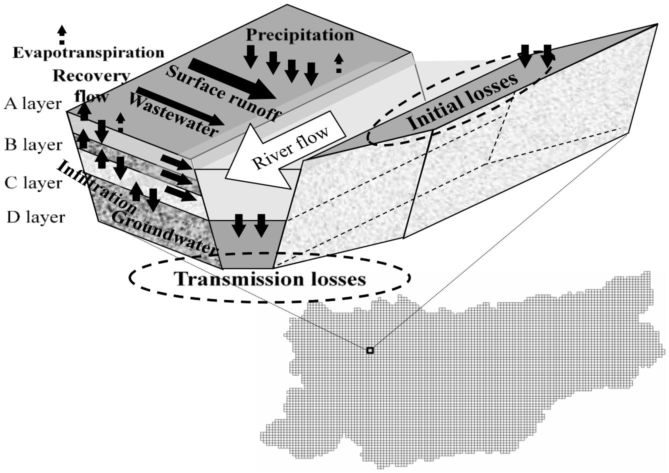

Fig. 2. Conceptual illustration of the Hydro–BEAM model and the considered hydrological processes.

In this study, new development and upgrades are applied to the Hydro-BEAM in order to consider the suggested mitigation scenarios by adding a reservoir routing routine, which can handle the bottom outlet and reservoir water evaporation. Reservoir water infiltration and siltation processes were not considered in this version of Hydro-BEAM. The Runge-Kutta method was adopted as a reservoir routing scheme to solve the following continuity equation:

$$\frac{dS}{dt} = I(t) - Q_o(H) \tag{1}$$

where S = reservoir storage volume; I = reservoir inflow; t = time; and $Q_o(H)$ = reservoir outflow as a function of the water head (H) in the reservoir. The reservoir storage volume, S, can be a function in the water head, H, and the reservoir area (A); therefore Eq. (1) can be expressed as

$$\frac{dH}{dt} = \frac{I(t) - Q_o(H)}{A(H)} \tag{2}$$

The last equation can be solved by small increments of the independent variable, t, using known values of the dependent variable H. The dam outlet discharge is calculated based on the water depth behind the dam as follows:

$$Q_o = \begin{cases} CBH^{3/2}, & C = 1.456 + 0.185(H/L), \quad (H/D \le 1.5) \\ CBD\sqrt{2gh}, & C = \sqrt{0.647 - 0.605(D/H)}, \quad (H/D \ge 1.5) \end{cases} \tag{3}$$

where Q_o = dam outlet discharge rate ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$); C = state outlet coefficient calculated based on the water height and the dimensions of the outlet; B = outlet horizontal dimension (m); H = water depth above the dam bottom (m); L = outlet length through the dam base (m); and D = 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 outlet discharge updated simultaneously within the Hydro-BEAM model at every time step. The newly developed dam routine is suitable for the proposed mitigation measures with low dam height (less than 20 m) and rectangular-shaped bottom outlet.

Model Verification and Sensitivity Analysis

The model was calibrated in a recent study (Saber et al. 2015) using the available measured flood discharges in Wadi Samail in Oman, which has comparable conditions of geology, topography, and land use to the study area. Moreover, Abdel-Fattah et al. (2017) verified the same model setting in another wadi region in Egypt, Wadi Qena, adjacent to the target wadi (75 km north of Wadi Abadi). To our knowledge, in most of the developing countries, few wadi basins are monitored that can be addressed by regionalization techniques, including transferring calibrated hydrological model from one wadi to another wadi under similar conditions. Milewski et al. (2009) regionalized the validated hydrological model at Wadi Girafi in Palestine to all major wadis in the Eastern Desert of Egypt. Abdel-Fattah et al. (2017) reported that the measured flood volume received at the Wadi Qena outlet was 9×10^6 m^3, with a runoff percentage of 3.7% of the total rainfall volume, which are very consistent with our model prediction for the flood volume to be 10×10^6 m^3 with a runoff percentage of 4.5%.

Sensitivity analysis was performed using the simple one-factor-at-a-time method to evaluate the most sensitive parameters and to estimate the uncertainty range in the simulated flood hydrographs. Therefore, the local response of the runoff is investigated by

Table 1. Input parameters description and results of the sensitivity analysis conducted in Hydro-BEAM model

Parameter name	Definition	Units	Calibrated	Minimum	Maximum	Process/medium	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	$\mathrm{m}^{-1/3} \cdot \mathrm{s}$	0.024	0.01	0.05	Channel	0.49	5
SDN	Hillslope equivalent roughness	$\mathrm{m}^{-1/3} \cdot \mathrm{s}$	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	$\mathrm{m} \cdot \mathrm{s}^{-1}$	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

Note: Parameters with no appearance of sensitivity get rank of 15.
[a]Sensitivity index (SI) of the parameters to the basin outlet's flood peak discharge.

varying one model parameter one at a time while holding the others fixed to a specific value. Fifteen Hydro-BEAM parameters that relate to various hydrological processes simulated were considered (Table 1). The ranges of the model's parameters were established from a detailed literature review and expert judgment. For each parameter, 20–40 values with uniform intervals were sampled using a pseudorandom 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 follows:

$$SI = (Q_{p\,\max} - Q_{p\,\min})/Q_{p\,\max} \tag{4}$$

where $Q_{p\,\max}$ and $Q_{p\,\min}$ = maximum and minimum predicted peak flow ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), 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, is given the first rank. The parameters, which do not affect the model output, were given a rank equal to the total number of the model parameters (Table 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. Using the generated hydrographs from the sensitivity analysis, a 95% confidence interval was established for the simulated design floods.

Flood Mitigation Measures

The structural measures of flood mitigation proposed in the study region are due to the special characteristics of the wadi system and the urgent necessity to address the flash flood challenges in the region. The nonstructural 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. The two approaches of long-term flood mitigation measures using dams are proposed in this study as follows:

1. Small or medium-sized dams defined in terms of the dam height and reservoir capacity distributed all over the basin and; and
2. A single relatively large concentrated dam at the downstream reach upstream of the developed area.

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.

Specifications and Location of the Proposed Structural Measures

It is important to note that the main objective of this study is to test a methodology and compare it to the two mitigation approaches, not to obtain precise estimates of peak discharges. The latter is difficult due to limited hydrological and limited geospatial data. To locate the optimum sites of construction more detailed studies must be carried out. Furthermore, all water stakeholders in the study region should participate in a broad discussion to identify the acceptable level of flood risk. The criteria for the proposed locations of multiple dams and their characteristics are presented in Fig. 3 as following:

1. Flow directions of each cell and watershed boundary have been estimated using GIS and DEM data;
2. A hydrologic simulation was conducted using Hydro-BEAM and synthetic design storms to make a geographical distribution of the surface runoff and allocate the potential prone area for flash floods;
3. 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;
4. Several dam locations were proposed according to the local topography and existing human activities;
5. Establishment of V-H [reservoir storage (V)–water depth (H)] and A-H [reservoir area (A)–water depth (H)] curves to be used in the developed dam module in Hydro-BEAM model

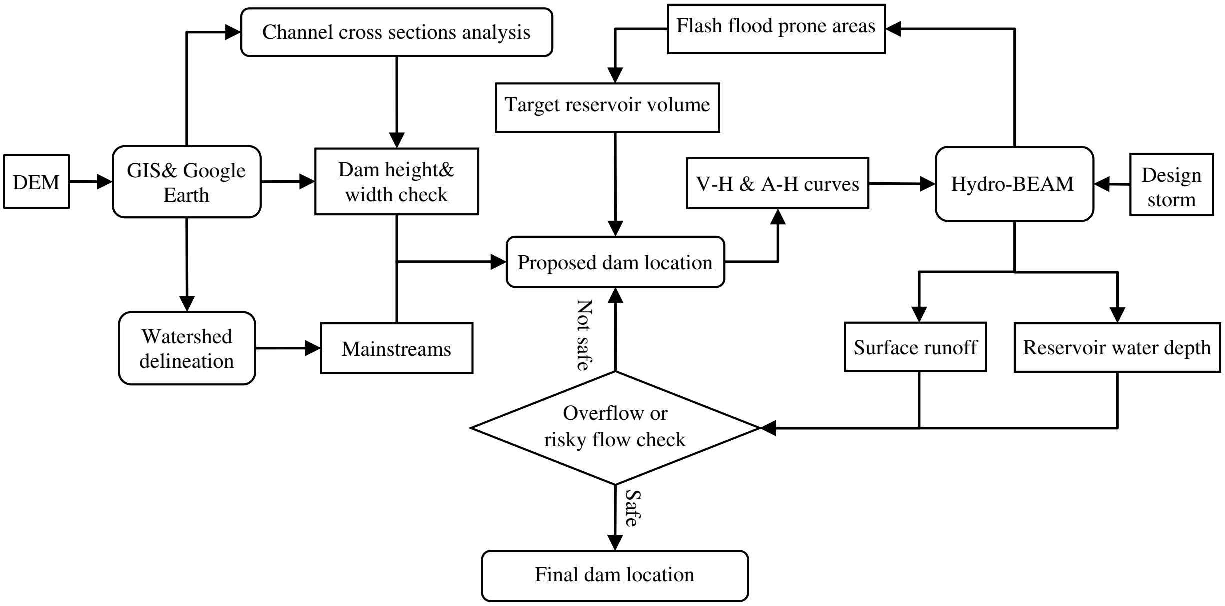

Fig. 3. Overview of the proposed procedure for the identification of the location and characteristics of the applied dams.

and the calculation of reservoir evaporation using the developed FORTRAN codes and DEM data;

6. Calculation of the expected design flood volume and the required dam height to mitigate this flood using the design storm and Hydro-BEAM model;
7. Outlet setting in each dam compatible with the downstream channel capacity; and
8. Comparative analysis between the locations of the different dams 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 agricultural land or houses are not affected.

Evaluation Methods for the Mitigation Measures

The proposed approach for evaluation is 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 an indicator of 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 the light of the special and unique characteristics of the wadi system.

Case Study Application

Watershed Description

Wadi Abadi, which is located in the southern part of the Eastern Desert of Egypt [Fig. 4(a)], was selected as a case study to test and apply the proposed approach. Wadi Abadi is cited in the literature as Wadi Abbad or El-Btur. This vast wadi (6,810 km^2) 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 agricultural land cover is about 29 km^2. The climatology of Wadi Abadi is characterized by a dominant arid climate with an average annual rainfall of 25 mm and a high annual average potential evaporation rate of 6 mm/day. However, Wadi Abadi is classified as a medium flash flood 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 happened in October 1991, November 1994, October 1997, and March 2014. The recent flash flood event from March 2014 (one of the target events) was accompanied by severe impacts on many wadis in Egypt and wide areas of Wadi Abadi Delta were flooded. The study area is crossed by one of the vital highways roads, Idfu-Marsa Alam road, and was frequently damaged by flash floods. Due to the increasing pressure

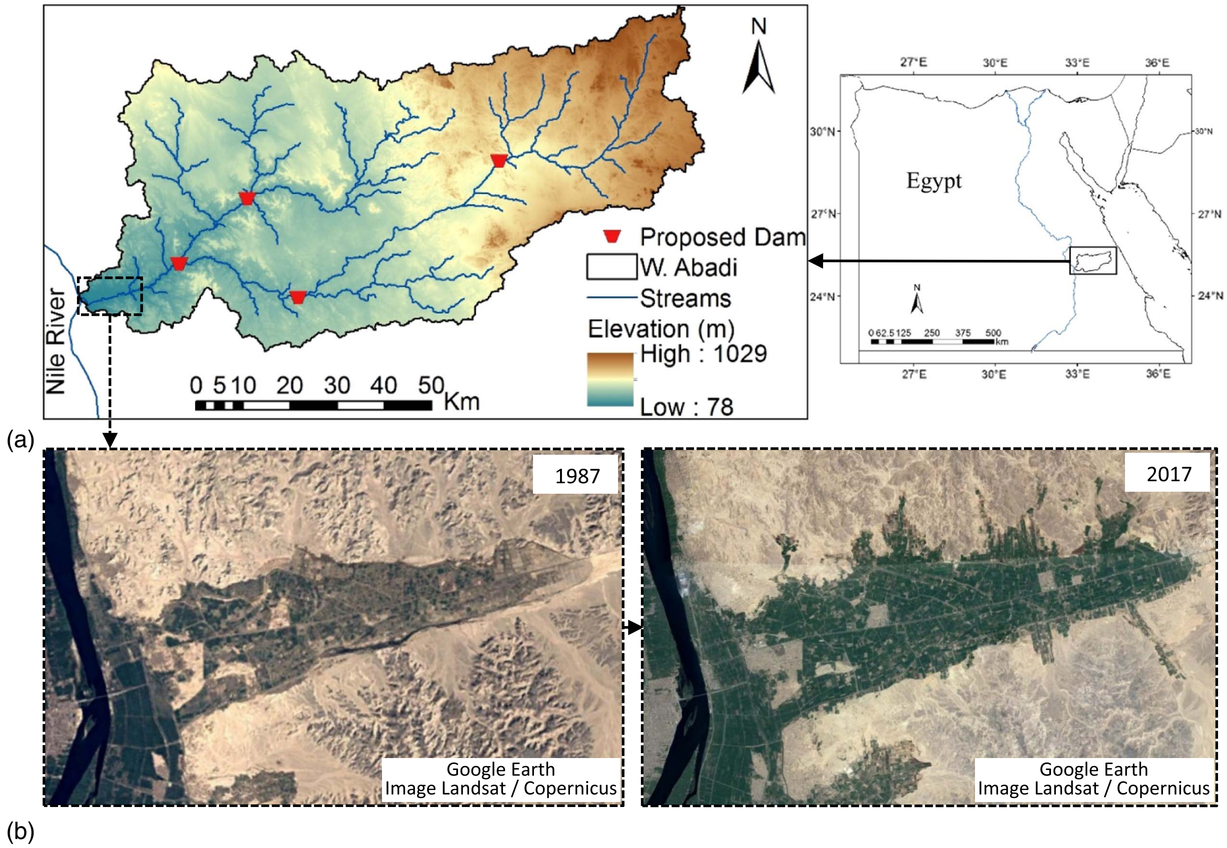

Fig. 4. (a) Location of Wadi Abadi in Egypt sowing the proposed dam locations and topography; and (b) the developed area expansion downstream of Wadi Abadi from 1987 to 2017 (map data © Google Earth, image Landsat/Copernicus).

of population growth and unmanaged development, people have started 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, from 1987 until 2017 [Fig. 4(b)]. Flash flood disasters in the target area have been assessed by a 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.

Input Data

Topographic data for the study area derived from the Shuttle Radar Topography Mission (SRTM) 1 arc-second (approximately 30 m) resolution DEM data (USGS 2015). The study area is characterized by a middle range of relief with elevation ranging from 1,029 m at the upstream, where the basement outcrops exist, to 78 m above the sea level at the downstream (Fig. 4). DEM data were utilized for watershed delineation, detection of the slope, identification of the best locations for dams, and estimation of reservoir volumes. Global Land Cover Characterization (GLCC) data (1-km resolution) were used to identify the different land-use types (GLCC 2008). The original GLCC types of land use were reclassified as desert, agriculture, urban, water, and forest, where the desert land use represents more than 90% of the total area of Wadi Abadi.

Climatic Data and Design Storm

The Ministry of Water Resources and Irrigation (MWRI) in Egypt provides a 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 the total rainfall amount) was chosen as a design storm because it has been recorded at Luxor station, 45 km from Wadi Abadi, on May 4, 1994 (TuTiempo 2017). The storm events in the Eastern Desert of Egypt are typically short, lasting from less than 1 h to a few hours (Gheith and Sultan 2002; Ghoneim and Foody 2013), and therefore the design storm duration was 3 h and uniformly cover all areas of Wadi Abadi. Moreover, Global Satellite Mapping of Precipitation (GSMaP) of 1-h temporal resolution and 0.1° of grid resolution have been utilized to simulate the most recent rainfall events in Wadi Abadi (January 2010 and March 2014). The Global Precipitation Climatology Centre (GPCC) data (Schneider et al. 2011) and gauge-based global rainfall data used to validate the GSMaP data. Meteorological data from the Integrated Surface Database (ISD) (Smith et al. 2011) were used to obtain potential evapotranspiration estimates by using the Thornthwaite method (Thornthwaite 1948).

Sensitivity Analysis for the Hydrological Model Parameters

Sensitivity analysis for the Hydro-BEAM model was conducted in Wadi Abadi to measure the relative significance of each model parameter in determining the basin outlet hydrograph peak and shape (Table 1). According to results from sensitivity analysis, the most significant parameters in detecting the basin outlet 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 basin outlet peak discharge and the standardized parameter values are shown in Fig. 5. The soil depth and porosity are the key factors to detect the effective rainfall amount and how much of the rainfall will be transformed to surface runoff; therefore, they have indirect high proportion with flood peak [Figs. 5(a and b)] until the soil effective porosity consumes all rainfall so it will produce the same peaks. The hillslope runoff coefficient is the parameter, which partitions the rainfall amount between the surface and subsurface layers. As the hillslope runoff coefficient increases from its minimum value, the outlet peak discharge decreases because the surface water is retained by the soil and the main contribution to the channel's runoff will be from the horizontal flow in the subsurface layers, which has an indirect relation with the hillslope runoff coefficient, until the soil becomes saturated and the hillslope runoff coefficient will have a direct relation with the discharge [Fig. 5(c)], whereas the channel and hillslope roughness coefficients have medium significance with indirect proportion with the peak flow [Figs. 5(e and 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 a medium impact on the outlet peak flow with direct relation with peak flow [Fig. 5(d)] but exhibits a 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 1 and Fig. 5. These parameters are less sensitive because as the subsurface layer depth increases the layer porosity decreases and consequently its contribution to the flood decreases. Also, 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 the sensitivity analysis exercise were used to detect the uncertainty in the simulated hydrographs of different design storms for a 95% confidence interval. We investigated the uncertainty range considering all the 15 evaluated parameters [Fig. 6(a)] and also the top five sensitive parameters [Fig. 6(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%–20%. These estimates are based on an average of all sensitivity analysis runs and with the use of a design storm of the 200-year return period. The confidence interval does not cover the peak of the calibrated hydrograph because it is established using the sensitivity analysis results where the peak time is different. Therefore, the hydrographs peak values are averaged by other lower hydrographs values at the final calculated confidence interval zone. This hydrograph timing shifting is more significant in the case of hydrological modeling with a fine temporal resolution, such as the flood simulations in this manuscript that conducted with a 1-h time step. These results provide considerable reliability when the validated Hydro-BEAM parameters are adopted 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.

Flash Flood Simulation

Two storm events that occurred on January 2010 and March 2014 were used to simulate flood conditions using Hydro-BEAM in Wadi Abadi. The proposed dam locations (Fig. 4) were selected to present the simulated hydrographs, which show the flow features of flash floods at the wadi system, where the flood hydrographs have an abrupt and quick generation of the peak discharge and then gradually decreasing until the end of the event as indicated in Fig. 7. The results record the high variability of discharge rate from one

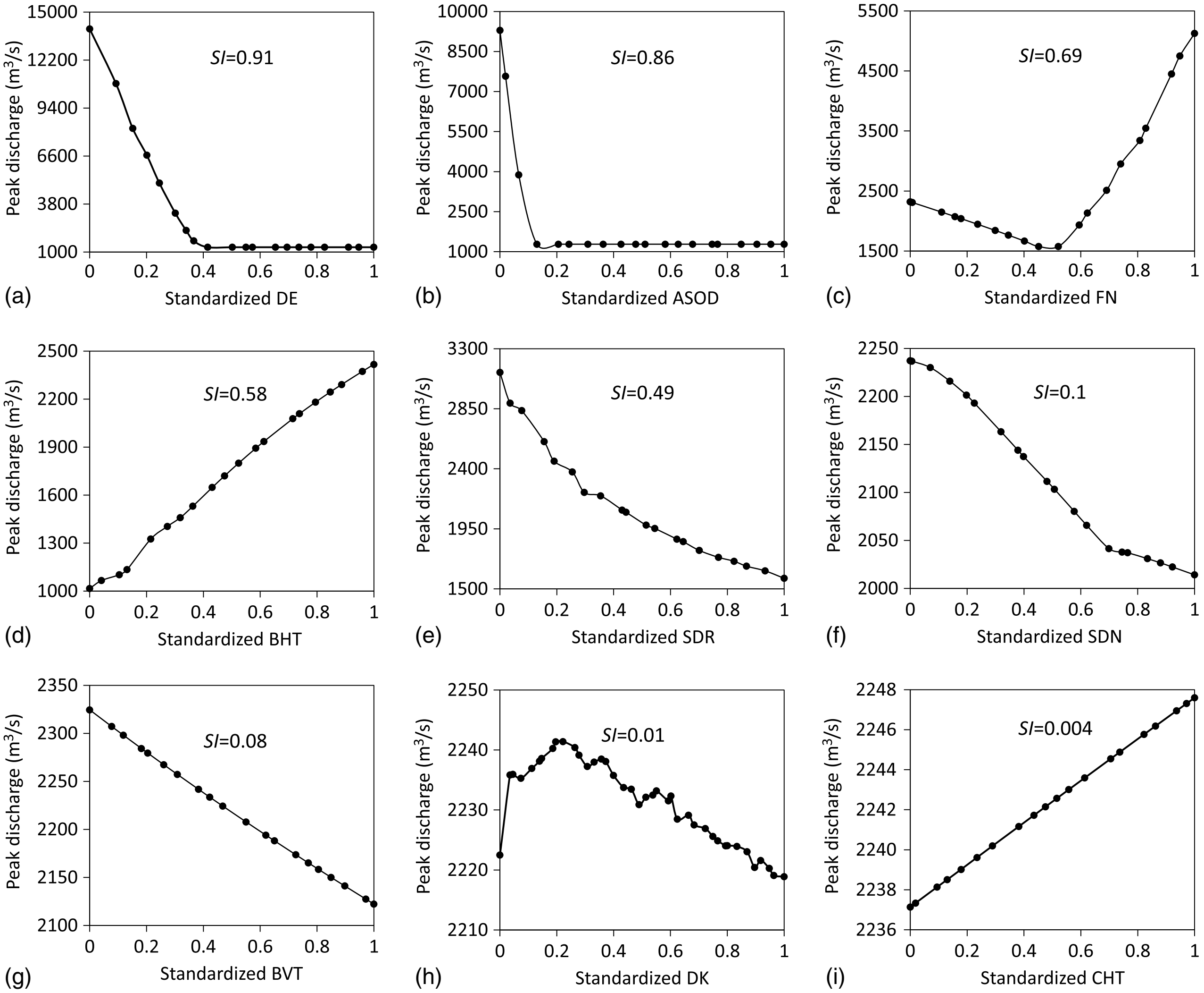

Fig. 5. Variations of standardized Hydro-BEAM model parameters related to outlet peaks discharge: (a) layer A porosity (DE); (b) layer A thickness (ASOD); (c) hillslope runoff coefficient (FN); (d) layer B horizontal outlet coefficient (BHT); (e) channel roughness coefficient (SDR); (f) hillslope equivalent roughness (SDN); (g) layer B vertical outlet coefficient (BVT); (h) layer A hydraulic conductivity (DK); and (i) layer C horizontal outlet coefficient (CHT). The sensitivity index (*SI*) values indicate the significance of each parameter on the predicted peak discharge.

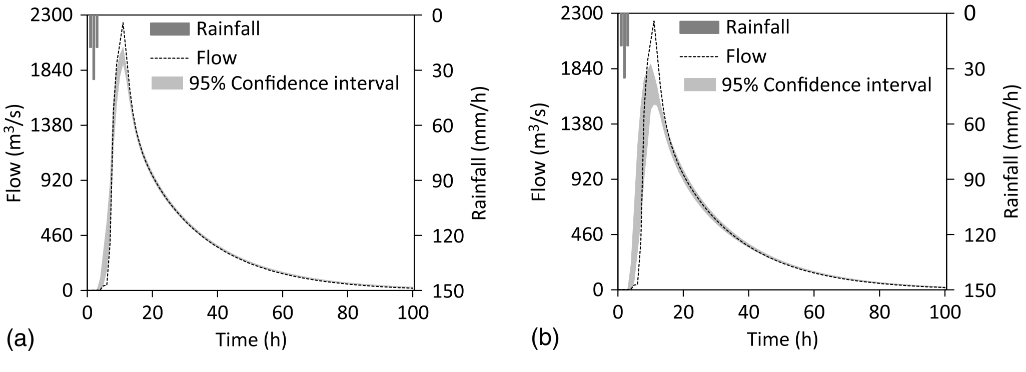

Fig. 6. Flow variability at the outlet of Wadi Abadi under the applied design storm considering the Hydro-BEAM model parameter sensitivity analysis along with their 95% confidence interval (gray shading) for (a) all the parameters included; and (b) considering only the top five sensitive parameters. The dashed line represents the final predicted flow using the calibrated model parameters.

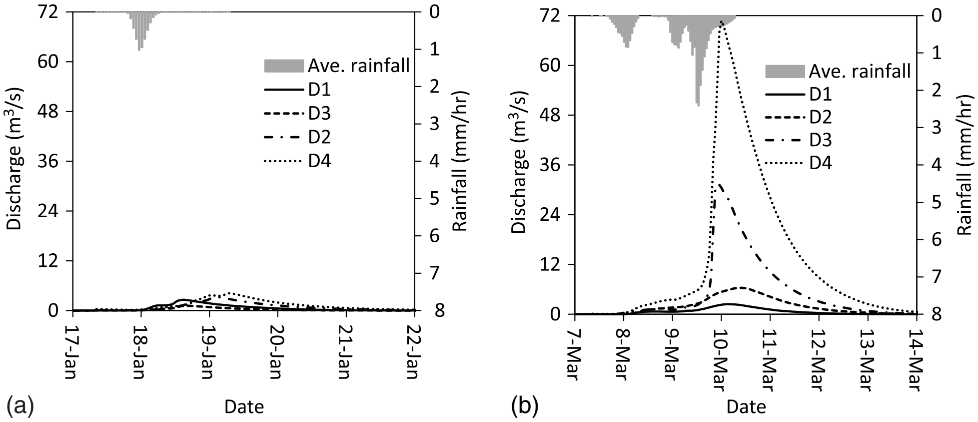

Fig. 7. Simulated hydrographs at the target control points (D1–D4) for (a) the January 2010 event; and (b) the March 2014 flash floods in Wadi Abadi.

event to another and between the variant locations within the same event. For instance, in the 2014 flash flood 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. 8(a)]. Hydrograph shape and time to reach the peak flow are also variable from one point to another because of the unevenness of precipitation, the area, and the geomorphologic parameters of the upstream catchment.

Spatial variations of the simulated discharges from both storm events [Figs. 8(c and d)] show the differences in runoff patterns at Wadi Abadi due to the high variability of the rainfall spatial distribution in space and time, where the rainfall of the March 2014 event has more intensity and covers a wider area of Wadi Abadi than the January 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 March 2014 flash flood was larger in terms of the maximum peak flow and surface runoff area. The distribution maps can be helpful to detect the flash flood–prone areas and consequently mitigate and manage flash floods in 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

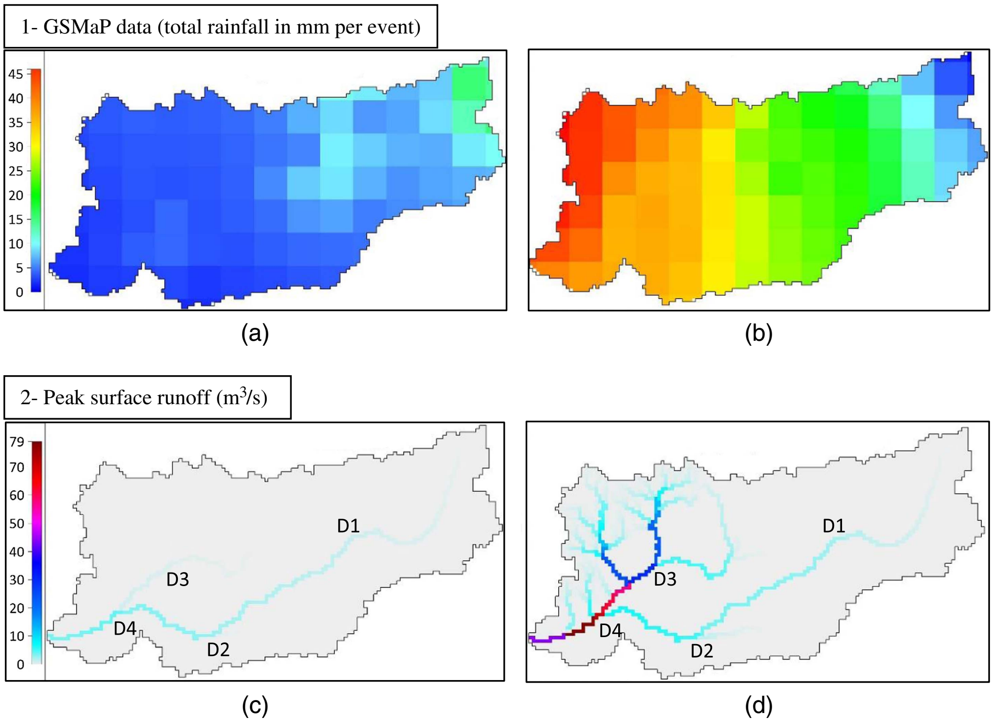

Fig. 8. Geographical variations for different parameters of interest at Wadi Abadi for total rainfall input of the (a) January 2010; and (b) March 2014 events, and the simulated peak surface runoff of the (c) January 2010; and (d) March 2014 events and indicating the target dams' locations (D1–D4).

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

Hydrologic variable	January 2010	March 2014
Total rain volume ($\times 10^6$ m^3)	37.0	207.8
Peak discharge (m^3/s)	4.16	78.36
Total outlet discharge volume ($\times 10^6$ m^3)	0.58	7.57
Outlet discharge percent (%)	1.59	3.64
Total transmission losses volume ($\times 10^6$ m^3)	0.67	4.97
Total transmission losses percent (%)	1.81	2.39

runoff (Saber et al. 2015). Once a sustainable groundwater resource is detected, especially in the arid environment as a wadi system, other development activities as land reclamation for agriculture can be constructed.

The simulation results summarized in Table 2 indicate the small outlet discharge percentage of the total rainfall amount (1.6–3.6 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 be noted that the simulated flow could be considered not risky; however, at the arid natural wadi channel, the surrounding areas can be flooded by any amount of rainfall, as stated by Shamir et al. (2013), which is a unique characteristic of wadi systems. 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 the 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.

Effectiveness of Flood Mitigation Scenarios

Design storms of 50-, 100-, and 200-year return periods were initially assessed and finally the 200-year return period (70 mm of the total rainfall amount, which was recorded in 1994 in a station near 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 a single concentrated dam at the downstream (D4). Both mitigation measures location and features were selected as discussed before in the methodology section (Fig. 3). The final proposed characteristics of the dams are indicated in Table 3 and Fig. 9 and the constructed *V-H* and *A-H* curves from DEM data are depicted in Fig. 10, in which the available storage volume and area is increasing as moving toward the downstream. The heights of the four distributed dams varied from 10.8 to 15.7 m and the reservoir volumes varied from 22.68×10^6 to 37.79×10^6 m^3 with a total reservoir volume of 118×10^6 m^3. The concentrated dam has a higher dam height of 17 m and reservoir volume the same as the total reservoir volume of the distributed dams.

The proposed evaluation approach consisted of five main categories as discussed previously: (1) flood mitigation, (2) water resources, (3) cost, (4) operation, and (5) development potential, as depicted in Table 4. For the flash flood mitigation aspect, the design flood simulation was conducted with and without mitigation measures, as indicated in Figs. 11 and 12. Both strategies could be effective in flood mitigation at the downstream part, especially upstream of the Wadi Abadi Delta, which contains the most important agricultural, farmland and housing activities. The mitigation dam application decreases the surface runoff rate from 2,197 to 228 m^3/s and 304 m^3/s with peak reduction percentages of 90% and 86% for the distributed and concentrated dam scenarios, respectively. However, the distributed dams scenario has slightly

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

Feature	D1 (Dist.)	D2 (Dist.)	D3 (Dist.)	D4 (Dist.)	D4 (Conc.)
Upstream area (km^2)	1,688.4	1,360.6	2,103.5	1,169.6	6,322.3
Height (m)	15.7	12.8	12.8	10.8	17.0
Length (m)	750	700	600	1,200	1,200
Reservoir maximum volume ($\times 10^6$ m^3)	22.68	24.69	33.48	37.79	118.41
Reservoir maximum area (km^2)	5.06	4.61	6.60	7.97	16.94
Outlets number (with dimensions of 2.5×3 m)	1	2	1	3	3

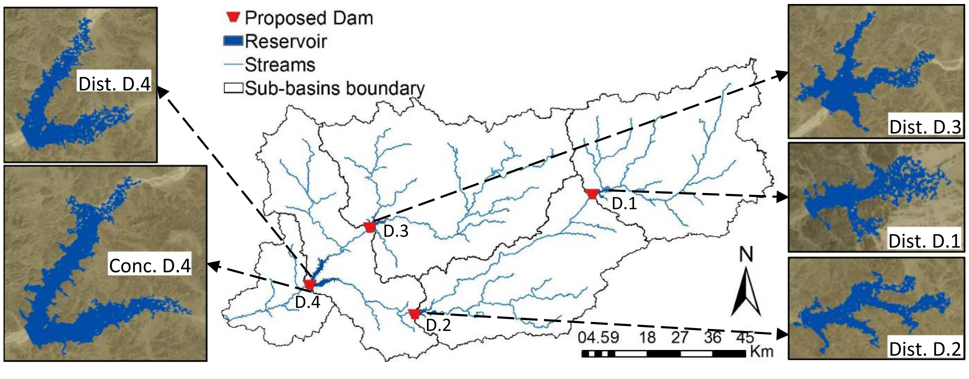

Fig. 9. Proposed dams (D1–D4) and reservoirs location constructed from SRTM 1-s DEM data for both distributed (Dist.) and concentrated (Conc.) mitigation scenarios indicating the upstream catchment for each dam.

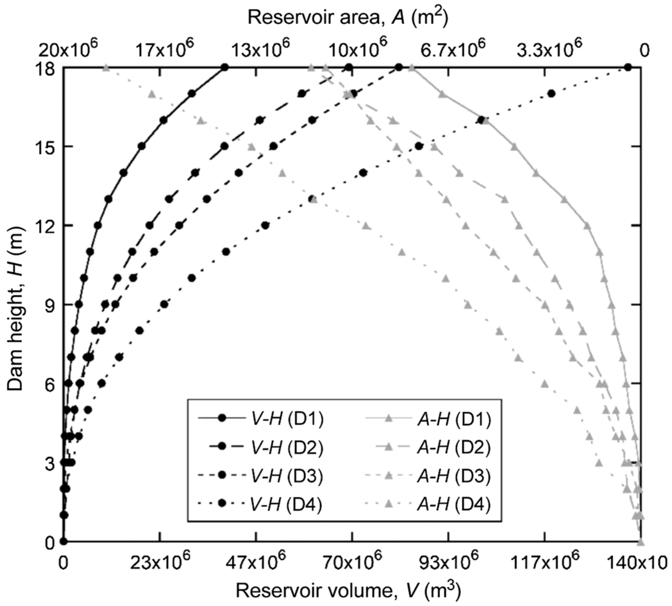

Fig. 10. Reservoir's storage capacity (V) and area (A) of the proposed dams (D1–D4) relations with dam height (H) using SRTM 1-second DEM data.

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 in the upstream region in reverse to the concentrate dam, which leaves the upstream infrastructure as roads without protection and, as indicated in Fig. 12, the protected areas are much larger in the case of the distributed dams (3,018 km^2) than the concentrated dam (488 km^2). The peak flow reduction due to the proposed mitigation scenarios in this study was higher than the range of peak flow reduction (0.3%–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 the 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 (106.1×10^6 m^3) and transmission losses to the groundwater (87.8×10^6 m^3) higher than the concentrated dam scenario, which was expected to have 87.7×10^6 m^3 of reservoir water storage and 83.3×10^6 m^3 of transmission losses. Therefore, the distributed dams increase the reservoir water storage by 21% 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 amounts, such as those that have a 50-year 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 nongeographically homogeneous 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 0.63×10^6 m^3 is around two times the evaporation from the concentrated dam reservoir (0.35×10^6 m^3); however, it is not a significant amount of water compared to the total reservoir volume. The reservoir evaporation is expected to be more significant if the dam is a storage dam without a bottom outlet or the gate is closed.

The construction cost was estimated to be lower in the case of a single dam (USD 14.5×10^6) than four distributed dams (USD 23.3×10^6). The cost of maintenance was difficult to estimate due to the spatial and temporal variability of the wadi flash floods, but the cost of 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 harder accessibility. Therefore, the construction of a single concentrated dam will be more cost-effective and may be more suitable for developing countries with limited financial resources, such as Egypt. Additionally, the operation of the concentered dam potentially could be easier with less costs where usually the development activities are located in the downstream region of the arid wadi systems. 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 intends to develop all the wadi areas and 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 current study recommends an additional detailed flash flood risk assessment study using a two-dimensional (2D) hydraulic

Table 4. Proposed mitigation scenarios using a 200-year return period design flood

Assessment parameter	Distributed dams	Concentrated dam	Without mitigation
Flood mitigation			
Peak flow at the entrance of the Wadi Abadi Delta (m^3/s)	**227.8**	303.8	2,197.3
Peak reduction at the entrance of the Wadi Abadi Delta (%)	**89.6**	86.2	—
Protected area (km^2)	**3,018**	488	—
Water resources management			
Total design reservoir volume ($\times 10^6$ m^3)	**124.2**	118.4	—
Maximum reserved volume ($\times 10^6$ m^3)	**106.1**	87.7	—
Reservoir evaporation ($\times 10^6$ m^3)	0.63	**0.35**	—
Transmission losses (groundwater recharge) ($\times 10^6$ m^3)	**87.8**	83.3	79.7
Cost			
Construction cost (USD)	23.32×10^6	**14.53×10^6**	—
Running cost	2nd priority	**1st priority**	—
Operation	2nd priority	**1st priority**	—
Development potential	Based on the target	Based on the target	—

Note: Bold font represents relative advantage of a specific mitigation scenario compared to the other scenario.

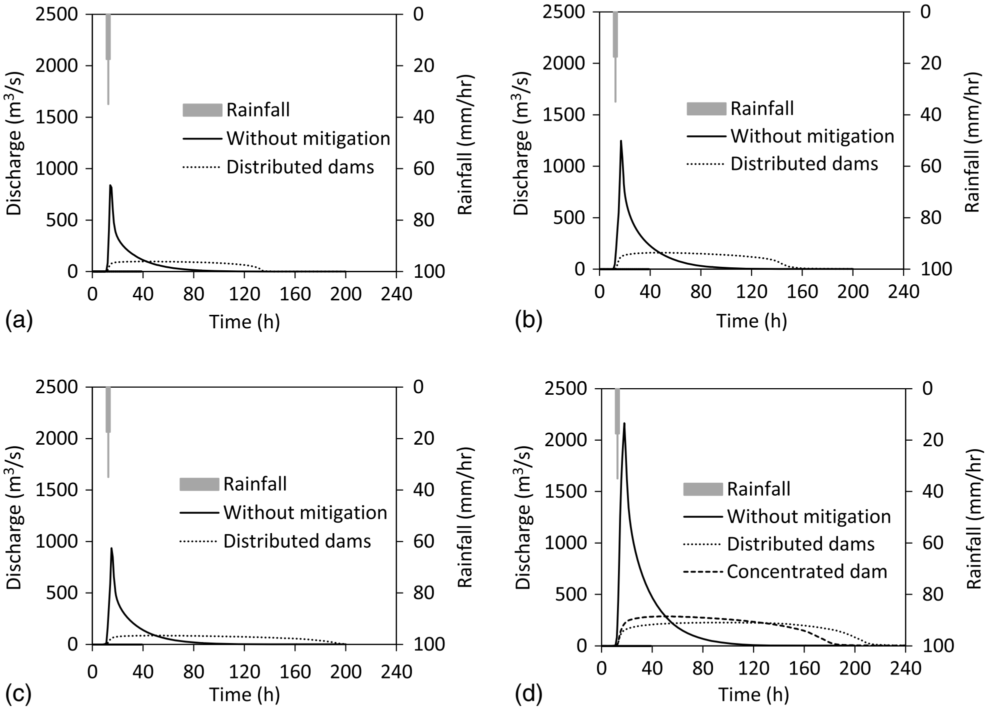

Fig. 11. Simulated hydrographs before and after mitigation scenarios application at the target dam locations: (a) D1; (b) D2; (c) D3; and (d) D4 under a 200-year return period storm, which was recorded in May 1994.

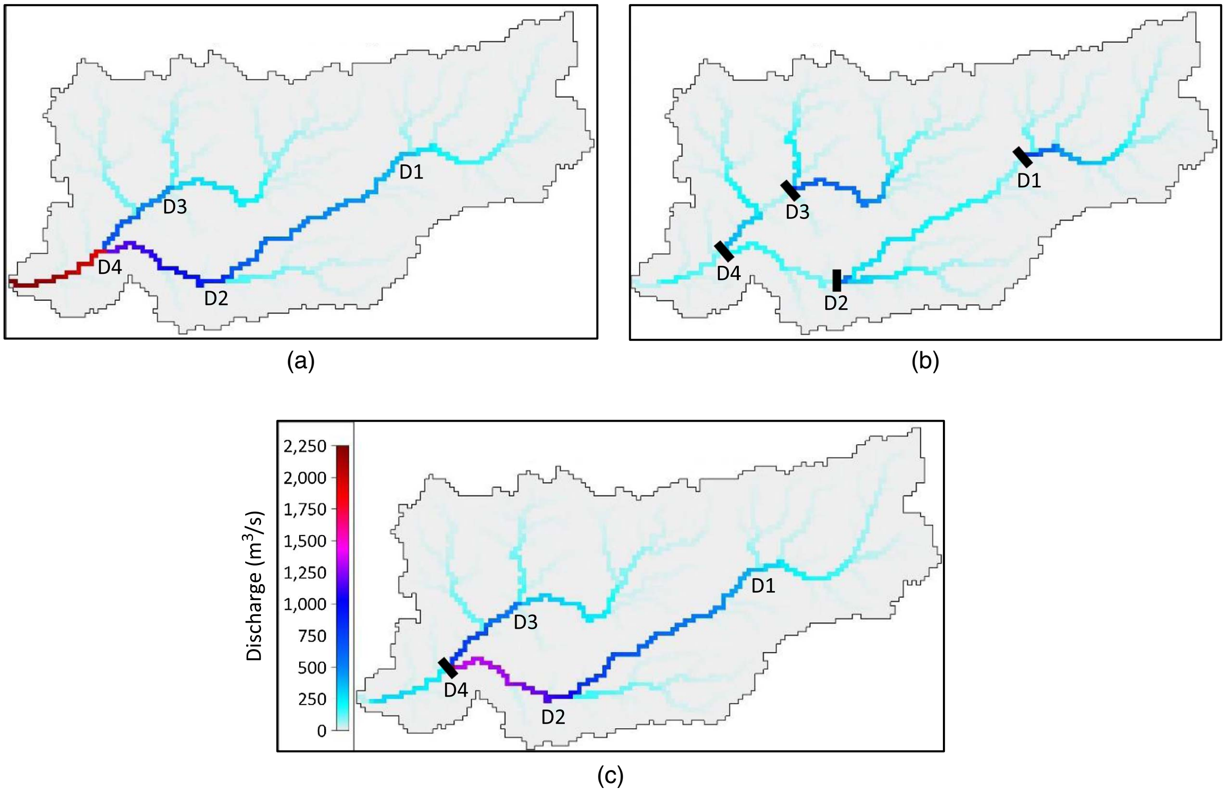

Fig. 12. Surface runoff distribution maps: (a) without flood mitigation; (b) with the application of distributed dams scenario; and (c) with the application of concentrated dam mitigation scenarios.

model to precisely predict the flooded or inundated zones and also to quantify the expected damages through evaluation of different land-use types (urban or field land) for each mitigation scenario. Other criteria, such as the impact of the structural measures on the society, environment, landscape, and habitat diversity, are suggested to be included in addition to the discussed factors. Gauging stations for wadi flow and rainfall measurements should be installed at the target area for accurate hydrological model calibration and precise prediction of the design storm. Additionally, the developed dam routine is 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 recommend taking into account other measures such as channel enhancement, groundwater recharge techniques, or nonstructural mitigation measures such as early warning systems. Groundwater recharge structures can be an efficient approach for water resources management in this arid and dry region.

Despite the preceding limitations, the proposed approach in this study represents an efficient and low-cost framework for the preanalysis 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 an understanding of the flash floods in wadi systems and provides advice on the key parameters in hydrologic simulation models to be considered in arid environments.

Summary and Conclusions

Flash flood simulation and management in the wadi system and evaluation of different methodologies for structural mitigation measures of flash floods are the main focus of this study. The proposed flash flood mitigation measures include geographically distributed dams and a 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. A hydrological simulation model suitable for wadi systems referred to as Hydro-BEAM was applied to the Wadi Abadi region in the Eastern Desert of Egypt to simulate two recent storm events. The Hydro-BEAM model was modified to include reservoir routing based on the Runge-Kutta method to evaluate various flood mitigation scenarios considering the evaporation losses from the reservoir water.

Results from the 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 Hydro-BEAM model was calibrated and verified in another wadi basin with similar climatic, geologic, and land-use properties. The simulation results also point to the 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 an 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 proposed flood mitigation measures provided an average of 88% peak flow rate reduction under the 200-year return period storm, which was recorded in 1994. The simulation also showed that the distributed dams scenario has better performance because it prevents the flood water to be concentrated at the same time in the downstream. The protected areas are much smaller in the case of the concentrated dam than the distributed dams, which implies that the last mitigation scenario will secure more safe zones for the development activities in promising regions. The distributed dams have more reservoir water volume by 21% and transmission losses by 5%; therefore, it can sustain more water resources than the concentrated dam scenario. However, the construction cost is 62% less than the concentrated dam scenario. Generally, the distributed dams strategy proposed in this study has relatively more advantages related to flood mitigation and water resources management compared to the concentrated dam scenario. However, the concentrated dam approach is better when cost and operational issues are considered.

Future studies should test the performance of the proposed approach in a region with a higher gauge density in terms of the resulting hydrological model accuracy. Sediment management and environmental impact assessment for the proposed flood management scenarios will also be a beneficial addition to the study. The effects of uncertainties, such as those originated from rainfall, should be considered in the dam design and site selection. We recommend an additional flood risk assessment study using a 2D hydraulic model to accurately predict the inundated zones and quantify the probable damages associated with the different land-use types for each mitigation scenario. However, there are very few previous studies dealing with flood mitigation in the arid wadi systems, and this paper presents a study to fill this research gap by considering the challenges of scare hydrometeorological data in many arid developing countries.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Abdel-Fattah, M. 2017. “Integrated hydro-geomorphological approach to flash flood risk assessment and mitigation strategies in Wadi systems.” Ph.D. thesis, Graduate School of Engineering, Kyoto Univ.

Abdel-Fattah, M., S. A. Kantoush, M. Saber, and T. Sumi. 2018. “Rainfall-runoff modeling for extreme flash floods in Wadi Samail, Oman.”

J. Jpn. Soc. Civ. Eng., Ser. B1 74 (5): 691–696. https://doi.org/10.2208/jscejhe.74.5_I_691.

Abdel-Fattah, M., M. Saber, S. A. Kantoush, M. F. Khalil, T. Sumi, and A. M. Sefelnasr. 2017. "A hydrological and geomorphometric approach to understanding the generation of Wadi flash floods." *Water* 9 (7): 553. https://doi.org/10.3390/w9070553.

Abd-El Monsef, H. 2018. "A mitigation strategy for reducing flood risk to highways in arid regions: A case study of the El-Quseir-Qena highway in Egypt." *J. Flood Risk Manage.* 11 (1): 158–172. https://doi.org/10.1111/jfr3.12190.

Ahmad, S., and S. P. Simonovic. 2006. "An intelligent decision support system for management of floods." *Water Resour. Manage.* 20 (3): 391–410. https://doi.org/10.1007/s11269-006-0326-3.

Alhumaid, M., A. R. Ghumman, H. Haider, I. S. Al-Salamah, and Y. M. Ghazaw. 2018. "Sustainability evaluation framework of urban stormwater drainage options for arid environments using hydraulic modeling and multicriteria decision-making." *Water* 10 (5): 581. https://doi.org/10.3390/w10050581.

Al-Weshah, R. A., and F. El-Khoury. 1999. "Flood analysis and mitigation for Petra area in Jordan." *J. Water Resour. Plann. Manage.* 125 (3): 170–177. https://doi.org/10.1061/(ASCE)0733-9496(1999)125:3(170).

Andoh, R. Y. G., and C. Declerck. 1997. "A cost effective approach to stormwater management? Source control and distributed storage." *Water Sci. Technol.* 36 (8–9): 307–311. https://doi.org/10.2166/wst.1997.0684.

Cazares-Rodriguez, J. E., E. R. Vivoni, and G. Mascaro. 2017. "Comparison of two watershed models for addressing stakeholder flood mitigation strategies: Case study of Hurricane Alex in Monterrey, Mexico." *J. Hydrol. Eng.* 22 (9): 17018. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001560.

Chennu, S., J. Grésillon, D. Dartus, C. Poulard, E. Leblois, J. Faure, and M. Maubourguet. 2007. "Efficiency of distributed flood mitigation measures at watershed scale." In *Proc., WaReLa Scientific Conf. on Integrated Catchment Management for Hazard Mitigation*, 16–19. Trier, Germany: Univ. of Trier.

Collier, C. G. 2007. "Flash flood forecasting: What are the limits of predictability?" *Q. J. R. Meteorolog. Soc.* 133 (622): 3–23. https://doi.org/10.1002/qj.29.

Consoer, M., and A. Milman. 2018. "Opportunities, constraints, and choices for flood mitigation in rural areas: Perspectives of municipalities in Massachusetts." *J. Flood Risk Manage.* 11 (2): 141–151. https://doi.org/10.1111/jfr3.12302.

Del Giudice, G., G. Rasulo, D. Siciliano, and R. Padulano. 2014. "Combined effects of parallel and series detention basins for flood peak reduction." *Water Resour. Manage.* 28 (10): 3193–3205. https://doi.org/10.1007/s11269-014-0668-1.

Emerson, C. H., C. Welty, and R. G. Traver. 2005. "Watershed-scale evaluation of a system of storm water detention basins." *J. Hydrol. Eng.* 10 (3): 237–242. https://doi.org/10.1061/(ASCE)1084-0699(2005)10:3(237).

Gheith, H., and M. Sultan. 2002. "Construction of a hydrologic model for estimating Wadi runoff and groundwater recharge in the Eastern Desert, Egypt." *J. Hydrol.* 263 (1): 36–55. https://doi.org/10.1016/S0022-1694(02)00027-6.

Ghoneim, E., and G. M. Foody. 2013. "Assessing flash flood hazard in an arid mountainous region." *Arabian J. Geosci.* 6 (4): 1191–1202. https://doi.org/10.1007/s12517-011-0411-7.

GLCC (Global Land Cover Characterization). 2008. *Global land cover characterization*. Reston, VA: USGS.

Hansson, K., M. Danielson, and L. Ekenberg. 2008. "A framework for evaluation of flood management strategies." *J. Environ. Manage.* 86 (3): 465–480. https://doi.org/10.1016/j.jenvman.2006.12.037.

Heidari, A. 2009. "Structural master plan of flood mitigation measures." *Nat. Hazards Earth Syst. Sci.* 9 (1): 61–75. https://doi.org/10.5194/nhess-9-61-2009.

Ho, M., U. Lall, M. Allaire, N. Devineni, H. H. Kwon, I. Pal, D. Raff, and D. Wegner. 2017. "The future role of dams in the United States of America." *Water Resour. Res.* 53 (2): 982–998. https://doi.org/10.1002/2016WR019905.

Hoffman, F., and R. Gardner. 1983. "Evaluation of uncertainties in environmental radiological assessment models." In Vol. 11 of *Radiological assessments: A textbook on environmental dose assessment*, 1. Washington, DC: US Nuclear Regulatory Commission.

IDSC (Information and Decision Support Center). 2010. *Cabinet information and decision support center in Egypt*. Cairo, Egypt: IDSC.

Kojiri, T., T. Hamaguchi, and M. Ode. 2008. "Assessment of global warming impacts on water resources and ecology of a river basin in Japan." *J. Hydro-environ. Res.* 1 (3): 164–175. https://doi.org/10.1016/j.jher.2008.01.002.

Kurz, B., X. Wang, L. de Silva, S. Hanson, M. Kurz, W. Peck, T. Simonsen, and E. Steadman. 2007. *An evaluation of basinwide, distributed storage in the red river basin: The Waffle concept*. Grand Forks, ND: Energy & Environmental Research Center, Univ. of North Dakota.

Leblois, E., C. Poulard, and J.-B. Faure. 2010. "Design of dry dams at watershed scale: Lessons learnt from sensitivity analyses using a simple but consistent rainfall-runoff model." In *Proc., Balwois 2010*, 10. Skopje, North Macedonia: Ss. Cyril and Methodius Univ.

Lin, X. 1999. *Flash floods in arid and semi-arid zones*. Technical Documents in Hydrology. Paris: UNESCO, International Hydrological Programme.

Milewski, A., M. Sultan, E. Yan, R. Becker, A. Abdeldayem, F. Soliman, and K. A. Gelil. 2009. "A remote sensing solution for estimating runoff and recharge in arid environments." *J. Hydrol.* 373 (1–2): 1–14. https://doi.org/10.1016/j.jhydrol.2009.04.002.

Montaldo, N., M. Mancini, and R. Rosso. 2004. "Flood hydrograph attenuation induced by a reservoir system: Analysis with a distributed rainfall-runoff model." *Hydrol. Processes* 18 (3): 545–563. https://doi.org/10.1002/hyp.1337.

Mostafazadeh, R., A. Sadoddin, A. Bahremand, V. B. Sheikh, and A. Z. Garizi. 2017. "Scenario analysis of flood control structures using a multi-criteria decision-making technique in Northeast Iran." *Nat. Hazards* 87 (3): 1827–1846. https://doi.org/10.1007/s11069-017-2851-1.

MWRI (Minisrty of Water Resources and Irrigation). 2012. *Flash flood atlas for Aswan governorate Wadis*. Cairo, Egypt: MWRI.

Onusluel Gul, G., N. Harmancioglu, and A. Gul. 2010. "A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures." *Nat. Hazards* 54 (2): 245–260. https://doi.org/10.1007/s11069-009-9464-2.

Ramireddygari, S. R., M. A. Sophocleous, J. K. Koelliker, S. P. Perkins, and R. S. Govindaraju. 2000. "Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and groundwater: The case of Wet Walnut Creek Watershed, Kansas, USA." *J. Hydrol.* 236 (3–4): 223–246. https://doi.org/10.1016/S0022-1694(00)00295-X.

Ravazzani, G., P. Gianoli, S. Meucci, and M. Mancini. 2014. "Assessing downstream impacts of detention basins in urbanized river basins using a distributed hydrological model." *Water Resour. Manage.* 28 (4): 1033–1044. https://doi.org/10.1007/s11269-014-0532-3.

Saber, M., T. Hamaguchi, T. Kojiri, K. Tanaka, and T. Sumi. 2015. "A physically based distributed hydrological model of wadi system to simulate flash floods in arid regions." *Arabian J. Geosci.* 8 (1): 143–160. https://doi.org/10.1007/s12517-013-1190-0.

Saber, M., T. Hamagutchi, T. Kojiri, and K. Tanaka. 2010. "Hydrological modeling of distributed runoff throughout comparative study between some Arabian wadi basins." *Annu. J. Hydraul. Eng.* 54: 85–90.

Sato, Y., T. Kojiri, Y. Michihiro, Y. Suzuki, and E. Nakakita. 2013. "Assessment of climate change impacts on river discharge in Japan using the super-high-resolution MRI-AGCM." *Hydrol. Processes* 27 (23): 3264–3279. https://doi.org/10.1002/hyp.9828.

Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, B. Rudolf, and M. Ziese. 2011. *GPCC full data reanalysis version 6.0 at 1.0: Monthly land-surface precipitation from rain-gauges built on GTS-based and historic data*. Berlin: Global Precipitation Climatology Centre. https://doi.org/10.5676/DWD_GPCC/FD_M_V5676_5050.

SCS (Soil Conservation Service). 1997. "Soil conservation service, chapter 5, stream flow data." In *Hydrology national engineering handbook*. Washington, DC: USDA.

Sen, Z. 2008. *Wadi hydrology.* New York: CRC Press.

Shah, M. A. R., A. Rahman, and S. H. Chowdhury. 2015. "Challenges for achieving sustainable flood risk management." Supplement, *J. Flood Risk Manage.* 11 (S1): 352–358. https://doi.org/10.1111/jfr3.12211.

Shamir, E., L. Ben-Moshe, A. Ronen, T. Grodek, Y. Enzel, K. Georgakakos, and E. Morin. 2013. "Geomorphology-based index for detecting minimal flood stages in arid alluvial streams." *Hydrol. Earth Syst. Sci.* 17 (3): 1021–1034. https://doi.org/10.5194/hess-17-1021-2013.

Smith, A., N. Lott, and R. Vose. 2011. "The integrated surface database: Recent developments and partnerships." *Bull. Am. Meteorol. Soc.* 92 (6): 704–708. https://doi.org/10.1175/2011BAMS3015.1.

Sumi, T., M. Saber, and S. A. Kantoush. 2013. "Japan-Egypt hydro network: Science and technology collaborative research for flash flood management." *J. Disaster Res.* 8 (1): 28–36. https://doi.org/10.20965/jdr.2013.p0028.

Thomas, N. W. 2015. "Simulating the hydrologic impact of distributed flood mitigation practices, tile drainage, and terraces in an agricultural catchment." Ph.D. thesis, Dept. of Civil and Environmental Engineering, Univ. of Iowa.

Thornthwaite, C. W. 1948. "An approach toward a rational classification of climate." *Geogr. Rev.* 38 (1): 55–94. https://doi.org/10.2307/210739.

TuTiempo. 2017. "Datos climáticos: Egipto." Accessed May 5, 2017. https://www.tutiempo.net/clima/egipto.html.

USGS. 2015. *The shuttle radar topography mission (SRTM) collection user guide*. Sioux Falls, SD: Land Processes Distributed Active Archive Center.

Walters, M. O. 1990. "Transmission losses in arid region." *J. Hydraul. Eng.* 116 (1): 129–138. https://doi.org/10.1061/(ASCE)0733-9429(1990)116:1(129).

Wheater, H. S., and R. Al-Weshah. 2002. "Hydrology of Wadi systems." In *Technical documents in hydrology*, edited by H. Wheater and R. A. Al-Weshah. Paris: UNESCO, International Hydrological Programme.

Yazdi, J., M. S. Moghaddam, and B. Saghafian. 2018. "Optimal design of check dams in mountainous watersheds for flood mitigation." *Water Resour. Manage.* 32 (14): 4793–4811. https://doi.org/10.1007/s11269-018-2084-4.

Zevenbergen, C., B. Bhattacharya, R. A. Wahaab, W. A. I. Elbarki, T. Busker, and C. Rodriguez. 2017. "In the aftermath of the October 2015 Alexandria flood challenges of an Arab city to deal with extreme rainfall storms." *Nat. Hazards* 86 (2): 901–917. https://doi.org/10.1007/s11069-016-2724-z.