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Arid lands flood evaluation and mitigation measures using HEC-HMS model and best management practices (BMPs)

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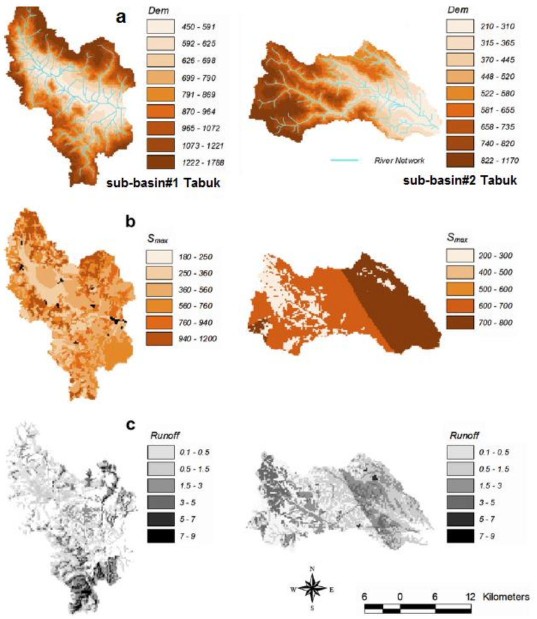
Graphical abstract



Abstract

This study emphasis on draining and slowing runoff volumes in arid and semi-arid landsregions using HEC-HMS model linked with various Best Management Practices (BMPs) alternatives. The proposed methods may help significantly in reducing flash flood precipitation and improving instream water quality. It provides facilities to increase flood retention times and infiltration rates. Recently, flash flooding in arid lands is occurring on almost every two-year basis and is threatening human lives and damaging properties. Modern urbanization of the cities has great impacts on flooding schemes, it increases peak streamflows and it reduces the time to peak. Eventually, major cities experienced newly developed areas to accommodate the increase of population, and thus surface runoff volumes would increase substantially. In addition to outflows from surrounding high desert lands which form a significant portion of flash flood volumes. This study proposed a modern and progressive flash flood management scheme that would emphasize on enhancing soil infiltration and runoff attenuation by construction facilities that would absorb runoff water. We formulated five proposals for flood mitigation derived from BMP techniques for the purposes of stormwater management. Rainfall-runoff natural disaster modeling was simulated using HEC-HMS (Hydrological Modeling Systems). The Geographic Information System (GIS) coupled with HEC-HMS was employed in this study to delineate the watershed line and to simulate streams discharges. Results for investigating the construction of dry dams' option showed a significant reduction in both peak volumes and time to peak and consequently, the mitigated flood spreads longer. Furthermore, downstream calculations prove the contributions of other events on increasing flood hazards downstream. Outlet bottom size and storage capacity are the major parameters that control flood hazards. Outcomes of this study would help water resources managers and decision-makers who need immediate action plans and operational responses when floods occur. Discharge outflow rates were assessed using HEC-HMS and CN methods, and modeling the studied area using Geographic Information Systems (GIS). This study reveals runoff volumes ranges of 0.04 to 0.77 cm/hr. Also, results shows that the HEC-HMS model is capable of simulating runoff-based event.

Keywords: flash flood, arid land, HEC-HMS model, best management practices, CN method

1. Introduction

Water-powered engineers' endeavors have been embraced for quite a long time to lessen flood harm. More often, the point was to forestall floods and guarantee a fast outpouring of runoff volumes. Streams were channelized, redirected, fixed, and corseted in levees, with next to zero ideas for waterway elements and biodiversity protection. This methodology is presently generally reprimanded (Loucks, 2006). Initially, speeding up the stream regularly brings about exasperating floods downstream. Besides, the interruption of the regular examples can upset the residue balance, thus causing disintegration or stores. Lastly, the results on biological systems are regularly terrible (Lowe *et al.*, 2020). The most effective method to both shield residents from floods and biodiversity from flood-the executives' plans is a hot issue (Jenkins *et al.*, 2017). We promote that ecologist and hydraulic practitioners should work intently together to supplement applicable flood mitigation solutions with eased effects on the environment.

In arid environments like the east region in Jordan, precipitation storms display solid spatial fluctuation, particularly during thunderstorms and localized torrential rainstorms (Almazroui, 2010). All through the most recent couple of years, flooding has been one of the most exorbitant calamities as far as both property harm and human setbacks in the Kingdom. In 2018 almost all of the kingdom witnessed heavy rain and flash floods. The hot springs the surroundings Dead Sea flood was the most influenced. Approximately 21 individuals are accounted for to have been killed and the number of missing people remains unknown. Many other cities in the country have witnessed streets were under a meter (two feet) of water on 26 October, and a large number of the casualties were accepted to have suffocated in their vehicles. No less than 1200 vehicles were cleared away or harmed.

The climatological dispersion of yearly precipitation saw by downpour measures across Saudi Arabia is displayed in Figure 1 and the 10-year climatological satellite image is displayed in Figure 2 (Habib and Nasrollahi, 2009). Dryness is the predominant climatic attribute of Saudi Arabia besides in the Asir district (shown in Abha in Figure 1), which gets yearly precipitation > 300 mm because of its special geological setup and the nearby mountains, and an optional pinnacle situated in the upper east, which is related with winter precipitation. Precipitation in the majority of Saudi Arabia is < 200 mm.

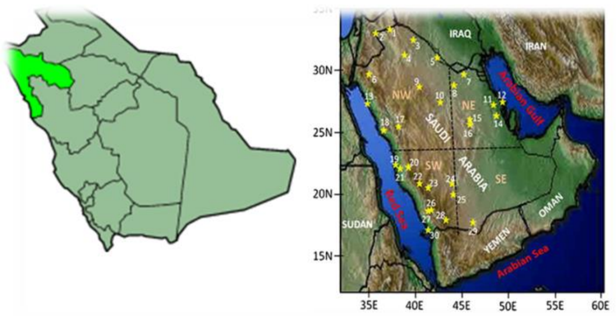


Figure 1. (a) Vicinity of Tabouk Region. (b) Rainfall gauge stations cover entire Saudi Arabia (after Almazroui, 2010).

In arid environment like Saudi Arabia and Jordan, rainfall patterns exhibit strong temporal and spatial variability, particularly during heavy rainfall storm event and localized flash floods (Almazroui, 2010). Throughout the last few decades, the kingdom has witnessed several flood events and it has been cost a lot of damages to public and private properties and deaths and human causalities. For example, the most intense flood was the 2009 event in Jeddah and other areas of Makkah Province (western coast of the kingdom) (Huffman, Bolvin, 2009). Civil defence officials described the flood as the worst in the 30 years.

Rainfall gauge stations are distributed across the kingdom as shown in Figure 1. Figure 2 shows 10-year climatology observed by satellite (Habib and Nasrollahi, 2009). Most areas of the kingdom have dry climate characteristics except Asir region in the southern part of the kingdom, where it has special topography and local mountains, which usually receives annual rainfall greater that 300 mm. On the contrary, most areas in Saudi Arabia receive annual rainfall less than 200 mm.

Meteorological parameters are critical for any hydrological studies. Rainfall intensities and distribution should be measured accurately for any application studies of rainfall data. Additionally, assessing runoff volumes and surface storage are important to supply domestic, agricultural, and industrial demands (Goodrich *et al.*, 2004).

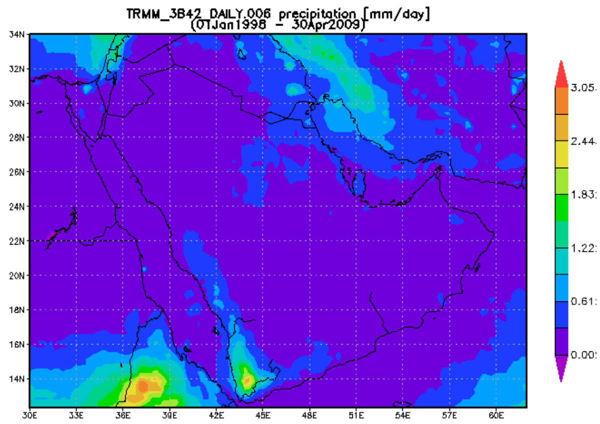


Figure 2. 10-year climatology observed by satellite for Saudi Arabia.

For the present study, the HEC-HMS model coupled with GIS is employed for better output data performance. GIS and remote sensing are well known tools for efficient input data preparation. HEC-HMS is a hydrological model offers various simulation scenarios of rainfall-runoff processes which has been used to understand the hydrological predictions in the studied watershed. The Soil Conservation Service Curve Number loss method and the Soil Conservation Service Curve Number unit hydrograph are employed, lag routing method and constant monthly base flow method. Various modeling scenarios shall provide an insight about various hydrological processes predictions, particularly rainfall and runoff storm events in Tabouk watershed.

Also, this study proposed a modern and progressive flash flood management scheme that would emphasize on enhancing soil infiltration and runoff attenuation by construction facilities that would absorb water such as rain gardens and bio swales, rainwater collection systems, and water reuse systems. We formulated five proposals for flood mitigation derived from BMP techniques for the purposes of storm water management. Various flood mitigation structural measures proposed by hydraulic engineers and biologists will be checked for the purpose of proposing operational plans responses to be implemented once flash flood occur. The implementations of these proposal required a coordinated effort between all parties involved and to be conducted on a long-term policy.

2. Research methodology

2.1. Data collection

2.1.1. Runoff volume calculations

Commonly, the Rational Method used for hydrological analysis of runoff. It uses the general form of the equation Q=CiA, in which Q is the runoff volume in acre-in/hr or cubic feet per second (cfs), C is the runoff coefficient for a given surface material and condition, i is the rainfall intensity in in/hr, and A is the catchment area in acres (Gupta, 2001). The runoff coefficient C is requiring accurate evaluation; hence, it depends on soil type, land use, surface cover and slop of drainage basin. Agricultural and forest land usually have low runoff coefficients in the range of 0.05-0.4 (Alsharhan *et al.*, 2001). On the contrary, paved and concrete surfaces have much higher runoff coefficients of about 0.9 (Alsharhan *et al.*, 2001).

NRCS TR-55 is another common method for estimating surface runoff, more complicated than Rational Method since it employs several equations to calculate runoff peak volumes (Gupta, 2001). CN is the most critical parameter that affect the runoff calculations, it is a function of land use and soil group. Similar to runoff coefficient, a higher CN value associated with high runoff volumes, and lower CN value indicates low runoff. Typical CN value for arid lands is 91, while for agricultural land CN ranges of 30 to 84, depending on soil surface conditions (Mays, 2001).

In this study, city area will be subdivided to assess runoff volumes and contributions in the overall flood. Also, soil infiltration capacity and infiltration rates will be evaluated. This analysis is necessary to identify areas where mitigation action plans should be focused.

2.2. Mapping and modeling

In this study, Geographic Information System (GIS) was employed to calculate the area of each surface group type. We coupled GIS with Hydrological Modeling System (HEC-GeoHMS) (Mays, 2001). HEC-HMS model was developed by US Army Corps of Engineers, Hydrological Engineering Center. The coupled version of these models contains Arc Hydro tool, which has been used to delineate two sub watersheds for Tabouk watershed. Inputs for GIS modeling are surface topography, land cover, land use, soil type, stream flows data, and physical characteristics of the watershed. Various HEC-HMS input models were created for Tabouk Sub watersheds. These models will be used later on to simulate rainfall and runoff volumes produced from storm water event.

The HEC-HMS model is built in this study from three historical storm event back on Jan 15th, 2011, Feb 26th, 2007, and Dec. 7th, 2004. Rainfall data were obtained from six discharge gauging station located in the study area on hourly bases. For the purpose of building the watershed model (basin model) several processes are executed as shown in Figure 3. The ArcGIS coupled with the extension HEC-GeoHMS and DEM are used to delineate and generate watershed parameters such as, elevations, stream network, stream lengths, flow paths, and slopes.

HEC-HMS model was used to identify the parameters value in the studied watershed. The model adjustment initially was done by trial-and-error procedures. Since commonly the first assumed value is true in the calibration stage and then the modeled parameter will be compared with measured ones for verification. Usually, the pre calibration values (assumed) can be adjusted if the conformity with the observed parameters is not satisfactory. Commonly, trial and error approach allow modeler to achieve a good agreement between modeled and observed hydrographs by adjusting the values of best parameters based on the results of the model runs.

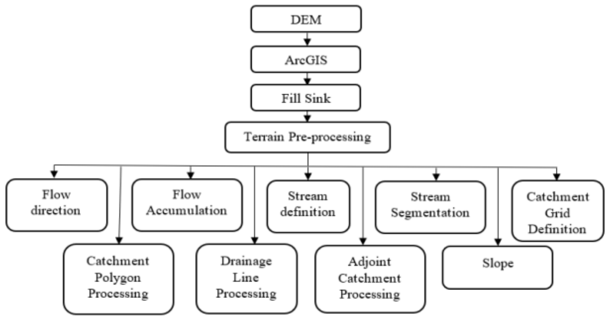


Figure 3. Schematic diagram for building watershed model processes.

2.3. Soil properties investigation

Soil infiltration rates in the study area are evaluated using Darcy's law. This law contains parameters of hydraulic conductivity, soil porosity, and hydraulic gradient. Such parameters are best described soil nature, land cover, porosity, and hydraulic conductivity of the soil column.

$$Qz = \frac{ka\Delta H}{nL}$$

In which Q_z is the volumetric seepage rate, k is the hydraulic conductivity, A is the area of watershed of interest perpendicular to the direction of flow, ΔH/L is the change in hydraulic head divided by the seepage depth, and n is the soil porosity.

3. Study area

3.1. Topography of the Tabouk Area

Tabouk city has a desert climate surrounded by low relief of local mountains from east, west, and south, while the city is open to the north. The city has an elevation of 700-800 m above main sea level. Mountains in the west of study area has an average elevation of 1200 m above main sea level. Most of the catchment drainage area is located in the north side of the city. Basically, the Tabouk basin is flat, drainage network extends southwards to Harrah, three main wadis are located in the basin, namely Wadi Al-Khader (east) and Wadi Abu Nishaiah (east), and Wadi Al-Baggar (west) (Al-Baradi, 2000). Tabouk city is underlain by a shale formation where silt and sandy soils are prevailed in several parts of the province. Figure 4 shows geological map of the study area (Masoud, 2009).

3.2. Climate of Tabouk

The climate of Tabouk city is dry most of the year, it has occasionally influenced by Mediterranean Sea climate. Mean annual temperature in summer is about 28 C° and 12 C° in winter. Average annual rainfall is about 20 mm as shown in Figures 5 and 6. Evaporation rates are high and is almost about 40 mm. In winter season, sometimes the penetration of cool Mediterranean air mass brings frontal rainfall events with high intensities (Alsharan and others, 2001).

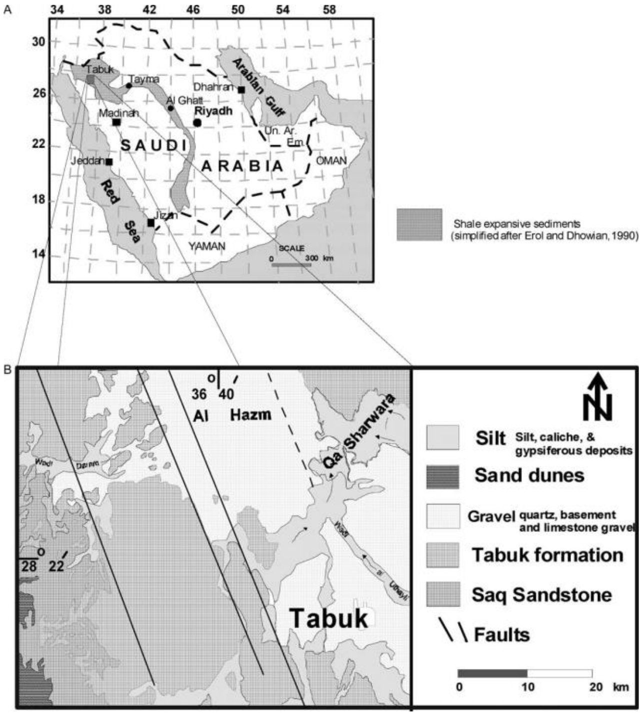


Figure 4. Geological map for the Tabouk area.

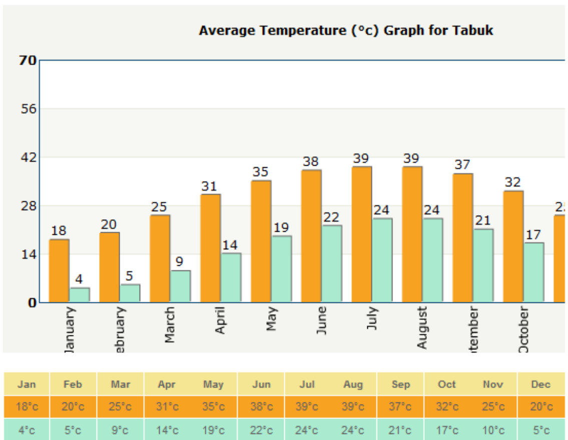


Figure 5. Average Temperatures for Tabouk city.

4. Results and discussion

4.1. HEC-HMS modeling

Nowadays engineers are capable to study and analyze impacts of various floods with various intensities on a hydraulic structure. The analysis involved calculations for all hydrological parameters like peak flows and flood hazards maps. In addition, modelers are able to do economical assessment by comparing several technical solution, estimating the costs of avoided damages. Various flood scenarios with different return period (different probabilities) can be tested. Such analysis is invaluable to predict flood occurrence and to protect human lives and their properties (Figure 7). Also, it helps in protecting flood mitigation structures by considering the safety check floods (i.e., maximum peak flow which the dam can withstand without risk of failure and low-probability but devastating dam-breaks).

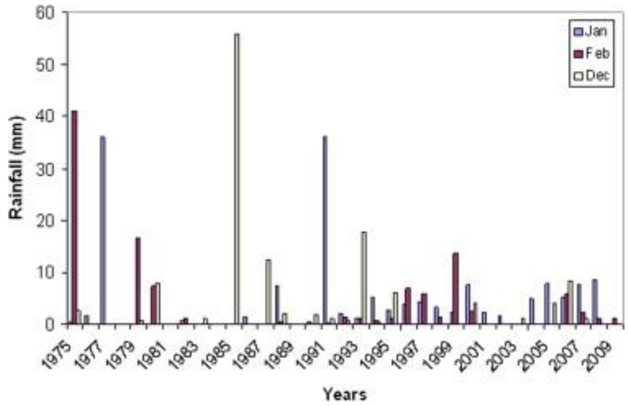


Figure 6. Annual rainfall values for Tabouk City in *mm* (1975-2019).

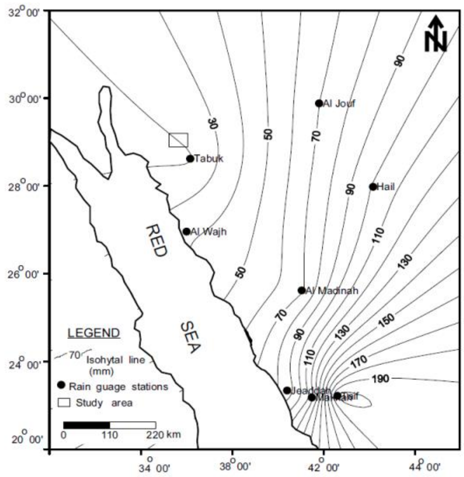


Figure 7. Isohyetal map shows average annual rainfall for Tabouk city.

In this project, HEC-HMS has been employed to estimate various runoff volumes resulted for the several scenarios we proposed. HEC-HMS is a commercial model developed by US Army Corps of Engineers, several sub-models are embedded inside the model to compute hydrological parameters such as channel routing values, rainfall losses, runoff generations, and base flows. HEC-HMS package comprises of three main model, namely basin model, precipitation model, and control; model (Romali *et al.*, 2018). Basin model calculates watershed and routing variables, and basin connectivity data as well. All rainfall data and computations are embedded in the precipitation model. Timing information are included in control model. Uses has the option to assign the proper data sets for each model, then the whole run is executed using all data sets from the basin model, precipitation model, and control model. Model structures and processes are given in the technical manual (USACE-HEC, 2000, 2008, and

2018). Follow to this section a brief description of the model employed in this project is provided.

As we've mentioned earlier to this section, the HEC-HMS model contains three main sub-models. The basin model provides watershed physical elements (i.e., subwatershed areas, reaches, junctions, diversions, reservoir, sources and sinks, and hydrologic model for each element as shown in Figure 13. Terrain processing module (ArcHydro) was used to delineate basin and sub-basin boundaries as networks as needed for the basin model. DEMs data was obtained using an existing contour map 1:100,000 scale. HEC-HMS model was employed to calculate initial model variables using model default values. HEC-GeoHMS then was used to develop soil maps and land use maps, CN for each grid was assigned (10 m x 10 m resolution). Averaging method linked within spatial analyst module of ArcGIS was used to evaluate the weighted CN values for each sub watershed. CN values were approximately in the range of 83-95 for studied sub watersheds.

This study shows that basin-hydraulic responses are in the form of runoff hydrographs and tables for hydrologic characteristics (such as, peak discharges, time to peak and lag time). Runoff, infiltration rates and interception are presented in the form of a numeric form. Table 1 display the main hydrological values used in this modeling. Repeated revisions for storms of return periods 2, 10, and 100 years at different durations of 0.75, 1.25 and 1.75 hours were employed and analyzed. Analysis proved that least frequent storms (large return period) bring rain more than the most frequent ones (small return period). HEC-HMS model calculate runoff volume rates in the range from 0.04 to 0.77 cm/hr. Figure 8 show the runoff distribution for two sub-basins within the study area.

Table 1. Primary values used in the HEC-HMS model runoff calculations

Variable	Value
Rain fall duration (hr)	2.20
Rainfall intensity (cm/hr)	0.87
Area ratio (R_A)	0.25
Length ratio (R_L)	2.00
Bifurcation ratio (R_B)	2.00

4.2. *Construction of dray dams*

This study analyzed and assessed the impacts of constructing a dray dam across floodplain, the dam has a bottom outlet for the purpose of discharging main channel flow. All hydraulic, hydrological, and civil engineering characteristics were described inconsistency with typology thus minimize impacts of river biodiversity. Outflows that exceed conduit capacity have been modified.

Figure 9a shows the dry dams' responses to various flood magnitudes differently. Two types of dry dams are proposed, dam#1 with H=2 m, h= 1.25 m, and dam32; H=4 m, h= 1.25 m. All calculations were taken at 1000 m downstream of the dry dams. Outflow discharges are shown in Figure 9b. Primarily, the existence dry dams affect the hydraulics of flash flood by delaying peak flows while it's obvious that flood waves last longer. The adverse impact of this response that in some cases of delayed peak may become associated with other runoff minor events which ultimately will increase flood hazards downstream. Commonly, two significant parameters in flood mitigation; size of bottom outlet and its storage capacity. Large runoff volumes can fill up storage capacity quickly and thus there is a great need for flow control structures (flow weirs and over spillway devices) to be provided to drain excess flows (Liu *et al.*, 2021). Usually, flood risks drop consequently after overflows happen (Lai *et al.*, 2020).

On the other hand, small flow outlet reaches faster the maximum storage capacity which permit earlier mitigation actions.

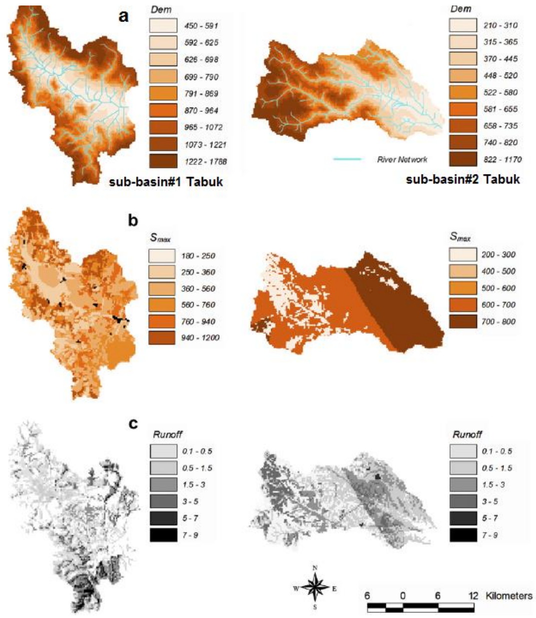


Figure 8. Physical characteristics for selected sub-basins considered in the HEC-HEM modeling. (a) Stream network, (b) Soil type and (c) Runoff values.

4.3. *Flood mitigation measures*

Low cost and nonstructural structures used in mitigation floods in urban settings are commonly known as Best Management Practice (BMP). Non-structural measures are used in rural areas. These structural measures are used to reverse the disturbances caused by urbanization, many of these structures proven promising efficiency for controlling and lessen damages caused by flash flooding and combined sewer systems (Glas *et al.*, 2020). Selection of these mitigation structures are usually considered entire watershed characteristics, technical feasibility, economical aspect, sustainability, environmental integrity, and public acceptance. Determination of the BMPs to propose will be based on past and practical experience gained upon the implementation and monitoring of these mitigation measures. In addition, theoretical and common engineering sense will be used for the purpose of the assessment. It is a learning by doing process based as shown in Figure 10. Two main principles are embedded in this practice, namely promoting natural drainage systems and urbanized surfaces. It combines both storm water components and flood control components (Bathrellos *et al.*, 2016).

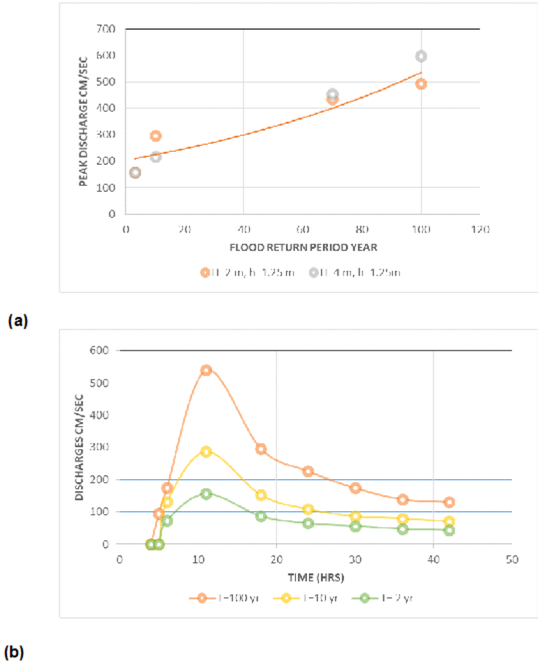


Figure 9. (a) dry dams construction effects; (b) computed hydrographs delay and attenuation.

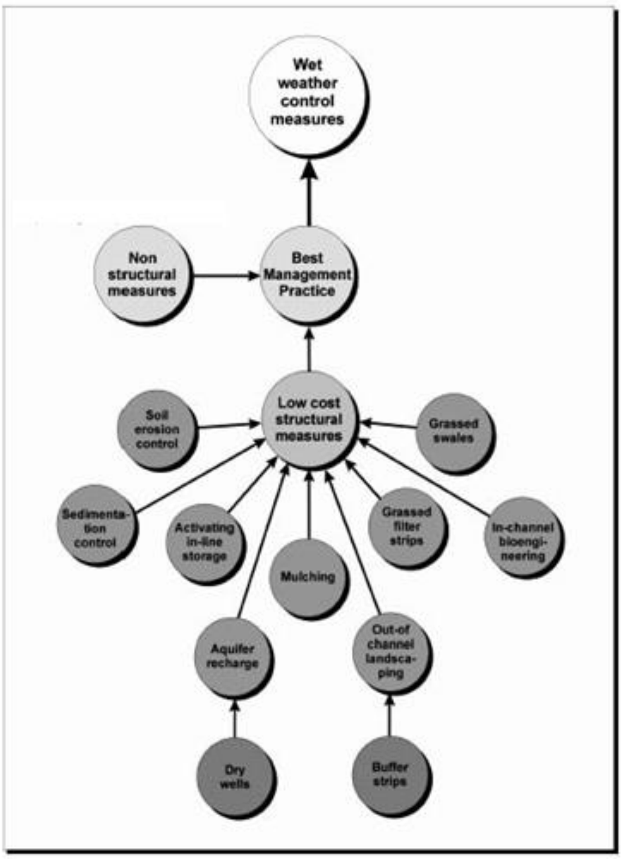


Figure 10. BMP low-cost structural measures.

Herein, we formulated five proposals for flood mitigation techniques for the purposes of storm water management.

4.3.1. An extended detention basins (EDB) design criteria

An extended detention basin is a structure that permit a temporal storage for runoff. The design of such structure with outlet device detains and attenuated the outflow runoff and allow settling of sediments. Usually, EDB has multistage facility for storage and attenuation. EDB provides a better management tool for storm water quantitatively and qualitatively. Expected removal of suspended solids varies from 40-70 percent, mainly depending on the designed settling time of the basin.

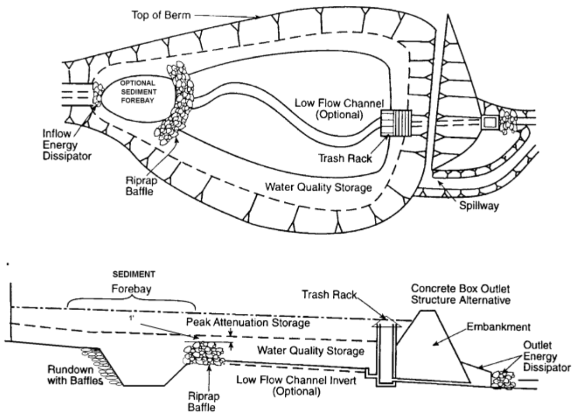


Figure 11. An extended detention basin basic Components.

Typical components of EDB are shown in Figure 11. Storage volume and detention time parameters must be designed carefully for an extended detention basin. Detention time usually defined as the time from maximum storage is reached in the basin till 10 percent of that storage remains in the basin. The combination of the two parameters would control the outflow runoffs velocities and travel times. Eventually, the construction of such structure must slowly drain outflows and consequently increase detention time. Furthermore, design should provide enough detention time to ensure the treatment of runoff volumes generated by storm event. Better efficiency can be achieved for orifice diameter greater than 9 cm.

4.3.2. Land erosion control

Sedimentation and soil erosion control measures should be coordinated with any construction of land undergoing development. Control measures like berms, mulching, silt traps and others are recommended to put into service in conjunction with infrastructure grading operations and before the construction of any increment of urbanization or land development. These measures are crucial for the removal of suspended sediments from runoff sormwaters draining from urban areas. Furthermore, stream banks should be maintained and stabilized, removal of vegetation covers and cut of trees should be prohibited. Construction of roads, drainage improvements work, and utility rights of way may consider as exceptional case. Pavement with concrete or asphalt within trees zones should not be allowed. Installation of permanent vegetation cover should be installed immediately as soon as all utilities are in place and final grading phase is achieved.

Runoff attenuation and retention structures should preserve natural topography and vegetation, where possible. All constructed mitigation measure (on-site) should be properly monitored and maintained by the owner of this site. This practice is important to operate these facilities appropriately and not become a source of nuisance to public. For example, Stagnant water and improper storage may result excessive algae growth and uncontrolled runoff volumes, respectively. Outlet's conduits should be designed to prevent or to minimize stream bed erosion.

4.3.3. Source control measures

In rural areas, where a natural and undeveloped watershed exists, the spatial distribution of runoff is in the form of mobilized small volumes which result in slowing down the runoff flow volumes. Usually, wetlands, flood plains, previous soils, and natural depressions are good storages for such small waters. Urbanization and development may cause serious damage to these natural ways of attenuation and cleaning storm runoff though decreasing permeability of soil, removing vegetation cover, altering this natural way and transforming into culverts and channels, and finally by leveling off the irregular natural ground surface (Poulard *et al.*, 2010).

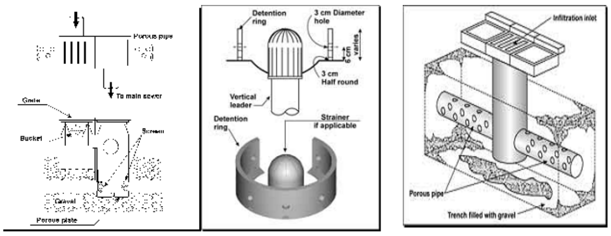


Figure 12. Examples on source control measures (Rooftop, infiltration inlet and trench).

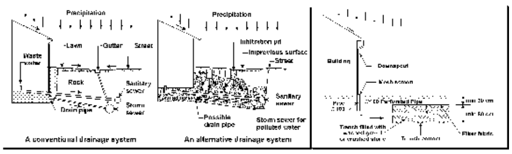


Figure 13. Infiltration trenches as an example on source control measures.

Source control measure are considered as an extra effort to improve methods of maintaining natural drainage system behavior. It's a supplementary tool and does not cancel the role of other conventional structural practices. Figures 12–14 represent number of urban low-cost effective structural measures that proved to be very efficient as flood mitigation measures.

5. Conclusions

The present study simulates basin-hydraulic responses using HEC-HMS hydrological modeling system based on the hourly rainfall data from Tabouk watershed. The Geographic Information System (GIS) coupled with HEC-HMS was employed in this study to delineate the watershed line and to simulate streams discharges. Simulation results proved that least frequent storms (large return period) bring rain more than the most frequent ones (small return period). HEC-HMS model calculate runoff volume rates in the range from 0.04 to 0.77 cm/hr. Also, results shows that the HEC-HMS model is capable of simulating runoff-based event.

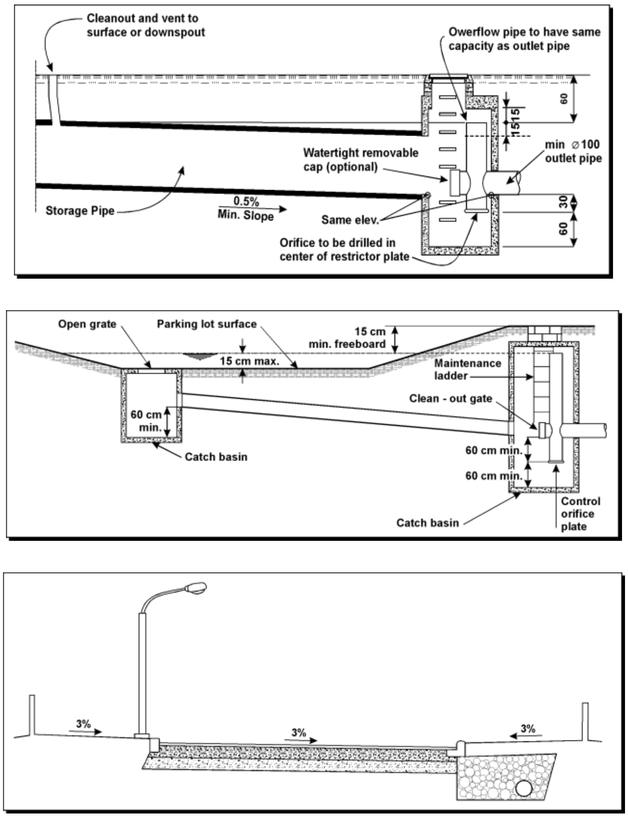


Figure 14. Source control measures examples (pipe storage, parking lot, porous pavement).

Moreover, this study assessed the watershed hydraulic response as a result of constructing a dray dam across floodplain, two types of dry dams were evaluated, dam#1 with H=2 m, h= 1.25 m, and dam32; H=4 m, h= 1.25 m. Analysis showed the existence dry dams affect the hydraulics of flash flood by delaying peak flows while it's obvious that flood waves last longer. The adverse impact of this response that in some cases of delayed peak may become associated with other runoff minor events which ultimately will increase flood hazards downstream. Results also proven that HEC-HMS model can be reliably used for flood modeling of the watershed.

Nonstructural flood control and mitigation measures provided useful tools for prevent or avoid serious damage consequences of flash floods in arid lands. Traditional plans treat the results of flood rather than focus on operational or action plans to avoid floods. Five proposals of BMPs were described in this study and general concepts were introduces, as follows:

- Optimal technical engineering solutions may not the best due to social and political constrains
- Urbanization should consider hydrological principles for planning in addition to the administrative instructions

- To prevent flood consequences in arid lands, the management plans should be comprehensiveness in terms of storm water drainage, pollution control, and flood mitigation as well.
- Public participation and data accessibility are key practices to build the trust between officials and the public to reach a successful management tool.

This study proposes multi-alternative tool which may help in applying flood mitigation measures using well defined structures/methods. Certainly, managers need immediate responses and operational plans – when a flood occurs, the demand for such action is robust. Managers and decision makers need quick and efficient plans to respond to flood prior to their occurrence. More research is needed on case-by-case bases to find the most appropriate and efficient management scheme. The linkage between conceptual approach and the operational plans is necessary to facilitate the transfer of knowledge and the exchange of technicalities from side to side and promote sharing progress developed by each side.

Acknowledgement

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

All data will be available upon the request of reviewers.

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