Flood prevention dams for arid regions at a micro-scale sub-catchment, case study: Tabuk, Saudi Arabia

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ABSTRACT

Unexpected flash flooding is one of the periodic hydrological problems affecting the city of Tabuk in Saudi Arabia. The region has high potential for floods as it suffers high rainfall intensity in a short time and also has high urbanization rates and topographic complexity. Constructing flood prevention dams is one option to solve this problem. A cost-effective design requires a detailed feasibility study and analysis for the selection of suitable sites. The aim of this study was to develop a method for selecting a suitable site for flood protection dams in the Abu Saba'a district, the most affected part of the city of Tabuk during the flash flood in January 2013. Spatial analysis was applied using Landsat Thematic Mapper images and Shuttle Radar Topography Mission digital elevation model to select a site in the Abu Saba'a area. A simple model using ArcGIS was built including all suggested parameters. The results showed the best site for a dam was 2 km distance backfrom the area, where all parameter values matched. The results showed that the dynamic properties of land cover can affect site selection. It is therefore suggested that more field and hydrological data should be gathered for greater accuracy.

Key words | arid regions, dams, flash flood, GIS, remote sensing, Tabuk

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INTRODUCTION

The Arabian Peninsula covers an arid area with limited rainfall rates and high temperature gradients. Surface water bodies in Saudi Arabia are very scarce and exist mainly in the form of dams (Table 1, after Al Hamid (2004)), increasing the pressure on the limited number of non-renewable groundwater reservoirs.

There is an obvious need to understand an arid region's flood behavior, particularly urbanized areas, in order to avoid human and economic losses. This can be achieved by applying an integrated plan to couple various types of data. Flash floods in arid regions are often unexpected (Abushandi & Merkel 2011; Katz *et al.* 2015), producing a high flood magnitude in a short time which destroys everything, especially in the catchment outlet. As noted by Bates *et al.* (2008), flood events are affected by several climatic parameters but mainly by precipitation and temperature patterns. In addition, floods are affected by basic conditions such as geology, topography, soil type, land cover and land use type, rate of urbanization, and drainage conditions such as stream network density. Local flash flood patterns are affected by rainfall intensity duration and timing (Poff *et al.* 1997). Flood magnitudes are also affected by stream network density. During the recent past, Tabuk like many other Saudi cities has been affected by unexpected flash floods causing human catastrophes and damaging infrastructure. From 25 to 29 January 2013, Tabuk city suffered a huge rainfall storm. This was the highest cumulative storm since 1978, and it caused flash flooding throughout the city. Figure 1 shows the rainfall amount for this particular storm.

The worst damage to infrastructure was in the Abu Saba'a district as it is the lowest part of the city (Figure 2) and is crossed by major stream called Wadi Al Baggar. The highest number of cloudy days in 2013 occurred from 25 to 29 January (Figure 3).

According to Cedar Lake Ventures (2015) most of the rain in 2013 fell on 28 January (14 hours). A total of 42 hours of rainfall occurred in that month (Figure 4).

Generally, the reasons for the floods are high rainfall intensity in a short time coupled with high population and construction rates (Elfaki *et al.* 2014), which increase the impermeable areas and decrease infiltration rates. In

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Table 1 | Types of dams and their storage capacity in Saudi Arabia

	Constructed dams				Dams under construction	
Dam type	**No.**	**%**	**Storage capacity × 10³ m³**	**%**	**No.**	**Storage capacity × 10³ m³**
Embankment dams						
Earthfill	87	40.47	141,895	17.04	10	93,435
Rockfill	39	18.14	42,228	5.07	2	20,000
Concrete dams						
Gravity	84	39.07	455,785	56.05	5	668,335
Buttress	2	0.93	53,130	6.369		
Arch	1	0.465	86,000	10.33		
Underground	2	0.93	42,800	5.139		
Total	215	100	832,838	100	17	781,770

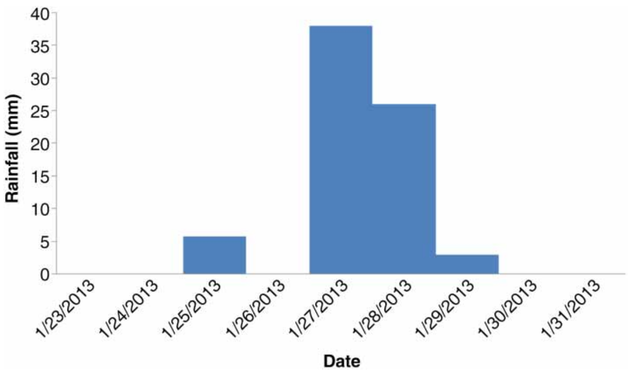

Figure 1 | Rainfall storm magnitudes in January 2013, causing massive damage in Tabuk.

particular, Tabuk is located in a hyper-arid area with relatively low altitude compared with the sharp topographic variation surrounding the city. Because of the potential for severe flash-flooding in Tabuk, flood control structures or dams should be planned to manage this problem. These kinds of structures are favorable in terms of efficiency and simplicity (Hansson and Nilsson 1986; Forzieri *et al.* 2008). However, flood estimations play a significant role in dam-siting from the perspective of water availability (Sen & Al-Suba'i 2002). Usually dams are constructed for purposes such as water storage and redistribution, ground water recharge, sediment and flood control, and municipal and industrial supplies. Common to most constructed dams is the reduction of flow and peak discharges (Brandt 2000). Yet not all dam types are suitable for arid regions (Gur & Spuhler 2015). Choosing a site for such structures in a micro-scale catchment is one of the main challenges facing decision-makers because of the cost of such projects.

Figure 2 | Flood event in Abu Saba'a district (January 2013) caused a massive bar of sediment (during and after) (Al-Enezi (2013), reproduced with permission).

Selecting the right location for a dam is important in terms of water resources planning and hence reducing the potentially harmful impact of flash floods on social, environmental and economic sectors. There are many challenges in selecting sites for such control structures in the particular case of Abu Saba'a:

(1) high population density and growth rates around the main wadis;

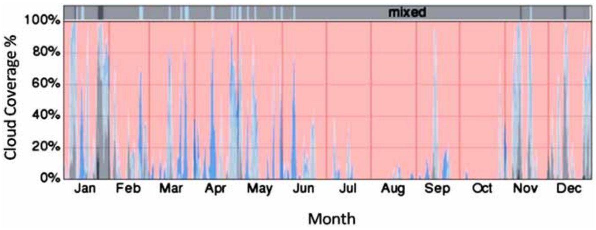

Figure 3 | Cloud coverage for the full year of 2013 over Tabuk city (data from the Regional Airport Weather Station) (Cedar Lake Ventures 2015).

(2) illegal domestic construction;
(3) high variability and irregular occurrence of flow;
(4) lack of a suitable natural control section in a stream with movable beds, and high cost of artificial controls;
(5) a series of mountains surrounding this particular area more than 1,450 meters above sea level (masl), while Abu Saba'a district is fewer than 665 m above sea level (Figures 5 and 6);
(6) difficulty of gathering data from different authorities;
(7) harsh climatological and biophysical conditions.

The choice of dam type is mainly based on the amount of rainfall and other considerations summarized in Table 2. It is an important component in the planning stage in order to reduce flood dangers.

The main objective of this study is use of a geographic information system (GIS) in order to select the optimal protection dam site for a single main wadi in Tabuk to guard

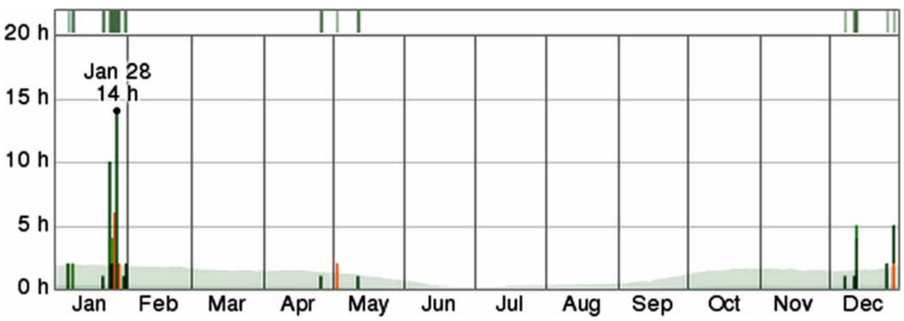

Figure 4 | Hourly observed rainfall for the full year of 2013 over Tabuk city (data from the Regional Airport Weather Station) (Cedar Lake Ventures 2015).

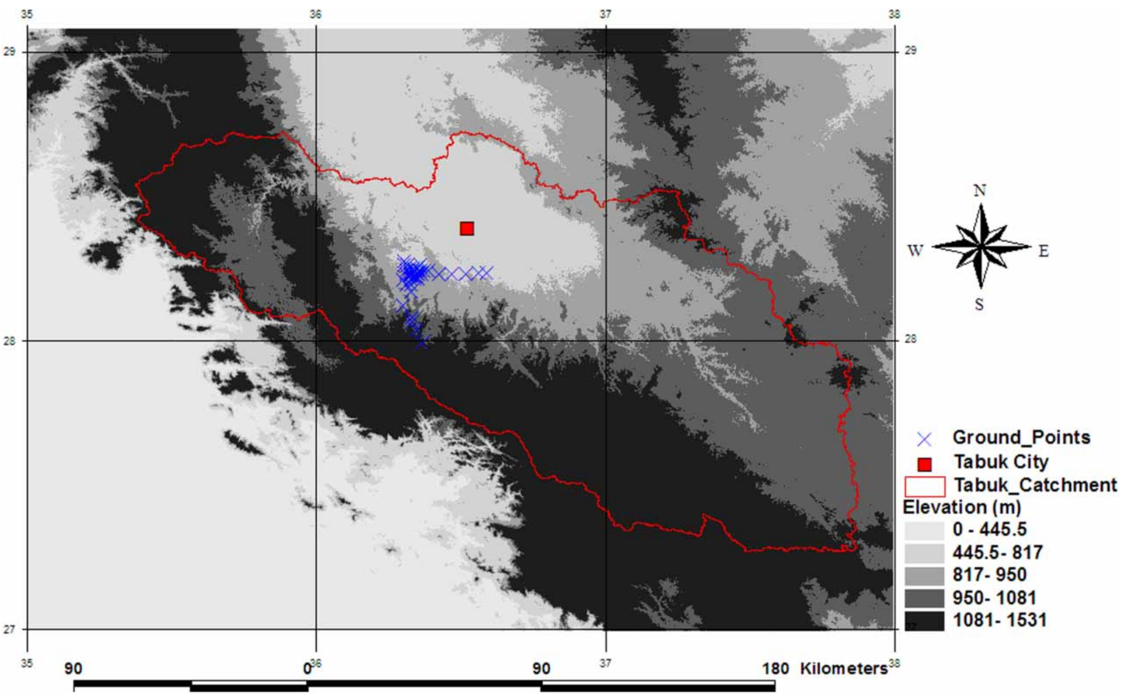

Figure 5 | The study area including GPS points (Alatawi & Abushandi 2015).

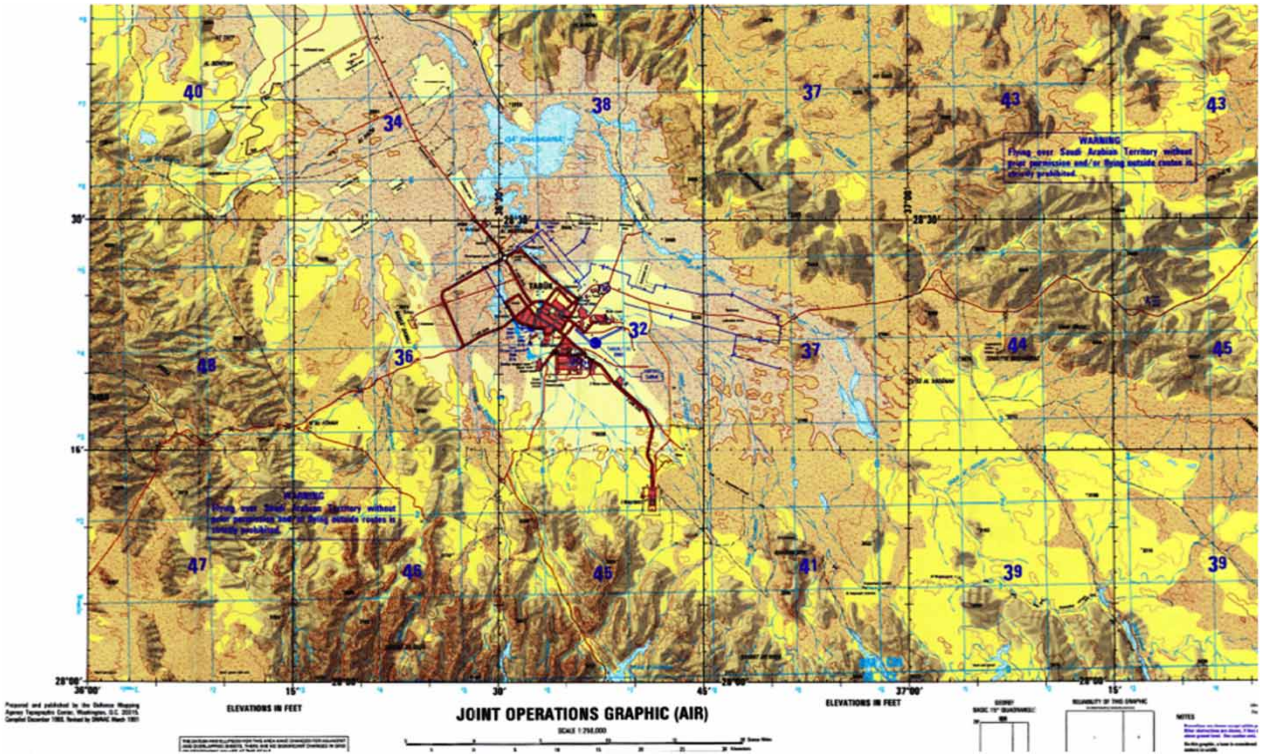

Figure 6 | Topographic map extracted at scale 1:250,000 (Saudi Ministry of Interior 1991).

Table 2 | Considerations and main focus for constructing dams

Consideration	Main focus
Site topography	Land altitudes
Stream network	Wadi shape and length
Geological structure	Foundation condition
Spillway	Size and location
Transportation	Roadway
Soil type	Soil physical properties (example: expansive soils) Groundwater recharge depends on the type and size of the granules and the permeability of the soil
Climatic condition	Maximum rainfall storm frequency and temperature variation
Dam life and overall cost	Construction material type and cost
Land cover type	Settlement zone and human impact on wadi morphology
Length and height of dam	Maximum dam capacity based on maximum rainfall and runoff
Environmental considerations	Earthquake Pollution

against flood hazards. In addition, the study aims to identify the main parameters that might affect site selection and hence improve water resources planning.

STUDY AREA

The area is characterized by a very sharp undulating topography with height varying between 658 masl in the north-east to 1,546 masl in the south-west. The biophysical characteristics of Tabuk are strongly influenced by agricultural activities. Because of the low rate of annual precipitation (under 33 mm/yr), the Tabuk area is classified as a hyper-arid area and strongly endangered because of drought. In addition, rainstorms are irregularly distributed in both space and time. Furthermore, several wadis cross the city of Tabuk, as described by Abushandi & Al Atawi (2015), including Wadi Damm, which connects with Wadi Al Baggar, Wadi Naam, Wadi Atanah, and Wadi Abu Nishayfah. These wadis converge at a single outlet called Qa'a Sharawra. This research focuses on Wadi Al Baggar as it crosses the Abu Saba'a district. Distinctive features of Tabuk's hydrology are as follows:

(1) sloping regions with an integrated stream network;
(2) plain lands with primitive or no stream networks;

(3) regions with major inputs of short-time surface water or groundwater from surrounding mountains, frequently with extensive irrigated agriculture.

METHODOLOGY

Information technology has recently been developed to convert maps into usable digital formats and allow the manipulation of both spatial and temporal data. In this context, a simple GIS model was built based on remote sensing data to select a suitable site (Figure 7).

The GIS process, data and parameters used in the proposed algorithm are described below.

(1) **Land cover type:** supervised classification was applied on Landsat Thematic Mapper Plus (ETM+) to extract land cover type. There is a significant value of using land cover classification using Landsat multispectral imagery (e.g. Özesmi 2000; Alberti *et al.* 2004; Yuan *et al.* 2005), in much more complicated and diverse wetland areas, where the accuracy reaches in some cases more than 90 percent. For an accurate land cover classification, the minimum level of interpretation accuracy in the identification of land use and land cover categories from the ETM+ image was at least 80 percent of the total pixels.

Land cover types were extracted by application of the supervised and maximum likelihood classification to an ETM+ image of Tabuk city from the year 2005. The classes can be statistically considered as a group or a cluster of pixels characterized by similar spectral signatures. To process and classify the image ERDAS Imagine version 11.05 was used. As a further step ArcGIS software was used to produce the maps. In this paper supervised classification was used to classify Landsat ETM+ images according to ground truth data as well as existing maps and personal experience for continuous and homogeneous groups of pixels. The supervised training sample was closely controlled by the operator by drawing polygon areas on the pixels that represent patterns of land cover features. Training sites are used by the system to record spectral or multi-band characteristics from the sample pixels to represent each class of interest (Tholey 2001).

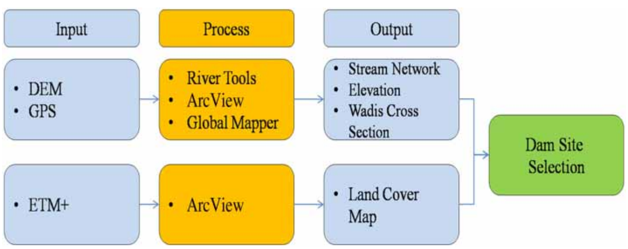

Figure 7 | Algorithm flow chart.

(2) **Wadi width and stream network:** wadi width was obtained from a Shuttle Radar Topography Mission digital elevation model (DEM) with a 90 m grid. The software used for network delineation process and extraction was RiverTools.

(3) **Wadi length:** a delineation process can estimate the longest continuous polyline to reach Abu Saba'a district area. Stratification for both DEM stream networks and land cover classification was applied and a geo-processing step was conducted in order to determine the crossed area.

(4) **Catchment area:** the catchment area was automatically calculated based on DEM.

(5) **Slopes:** the slopes of both the wadi and catchment area were obtained from DEM and global positioning system (GPS) field data. The GPS interpolation was based on 100 points. To determine the slope in each wadi the query builder in ArcView was used.

(6) **Hydrological data:** in a further step, hydrological data such as maximum rainfall and temperature should be taken into account in order to calculate the maximum capacity of the dam.

(7) **The flood coefficient** was calculated in order to find the highest value among the wadis. A simple equation was used which was developed by Sen and Al-Suba'i (2002) for a similar area in south-western Saudi Arabia called Tihamat Asir:

$$C_r = A^{-0.359}$$

where C_r is the flood coefficient and A is the area.

According to land cover classes, the pixels of both images are aligned using specific ground control points. Different software packages were used to extract required datasets for the model. The parameters of a suitable location are shown in Table 3.

RESULTS

Dam site selection depends on several parameters such as stream order, slope, land cover type, wadi cross-section, and maximum storage or volume. ETM+ and DEM results show most required data of the catchment area using automated procedures. The main wadi network was extracted

Table 3 | Determined values of model parameters

Parameter	Value
C_r	Less than 0.2
Land cover type	Low land (bare soil)
Slope	0
Stream order	3 or less (out of 7 orders), and not crossing settlement area
Area	100 km^2
Wadi length	More than 8 km
Wadi volume	More than 1,500 km^3

and shows that Wadi Al Baggar crosses Abu Saba'a district (Figure 8).

As part of the GIS model, the chosen slope values were generally flat; in other words, the slope was equal to zero degrees. The slope for the entire study area was automatically calculated from the DEM. Apart from the mountain series, the area is flat (Table 4). The C_r value varied from 0.16 to 0.38 with an average of 0.28.

The land cover map in Figure 9 shows the spatial distribution of land features in Tabuk. After supervised classification, five major land cover types were defined for the study area. This land cover classification was based on both spectral classes and the training statistics for each land cover type. It can be easily seen that Tabuk is a typical arid city with many agricultural activities. The greatest pixel confusion was between agriculture and settlement classes.

As a step of accuracy assessment for supervised classification, the accuracy percentages described for the ETM+ images are based on generated error matrix reports in ERDAS software (Figure 10). Furthermore, settlement class was separately classified as it was mixed with agriculture.

To prove that Abu Saba'a is the lowest-lying district in Tabuk, an interpolation technique using field GPS data was used (Figure 11).

All datasets were converted into vector data stratified within stream network and land use categories. The geospatial wizard in ArcView was applied based on the defined parameters in Table 3 to select all suitable points in the area (Figure 12).

The results of the geospatial process showed that Wadi Al Baggar crosses the city of Tabuk (Abu Saba'a district) in a single continuous point, and this point is highly dangerous in terms of flood zones. Therefore, the dam should be constructed backfrom this area to secure it from floods (Figure 13). Table 5 shows the specification of the proposed dam location whereby the stream delineation order was automatically fixed at three to meet other parameters. The area and the length were calculated based on pixel counts in the chosen site. The volume of the dam was basically based on the cross-sectional area multiplied by the length. The area of the chosen site should be flat, which means the slope is equal to zero degrees.

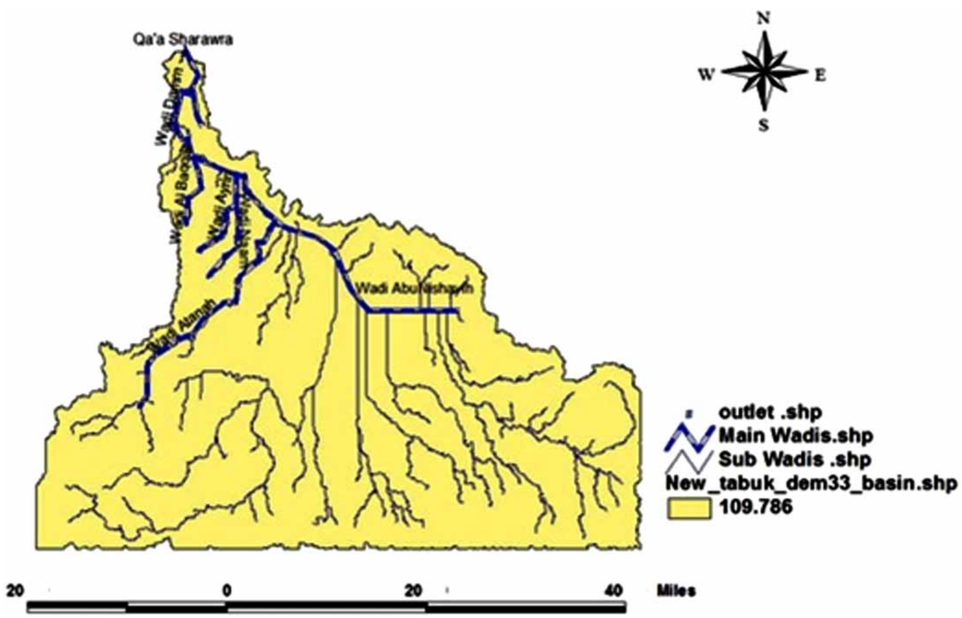

Figure 8 | Stream network crossing Tabuk (1 mile = 1.609 km).

Table 4 | Slope distribution for Tabuk

Slope %	Percentage %	Area in km^2	C_r
0–9.87	37.1	171.4527	0.16
9.87–19.74	3.3	15.1956	0.38
19.74–29.61	4.6	21.2706	0.33
29.61–39.48	5.1	23.5062	0.32
39.48–49.36	6	27.5481	0.30
49.36–59.23	7.1	32.7078	0.29
59.23–69.10	8.5	39.4551	0.27
69.10–78.97	12.6	58.0284	0.23
78.97–88.84	15.7	72.5355	0.21

For further earthwork and construction planning, the cross-section of the chosen site was selected using DEM (Figure 14).

DISCUSSION

Unfortunately, the importance of building flood control dams may not be recognized until significant flood events have already happened. The flood event in 2013 happened because of dynamic interaction between hydrological, natural and cultural forces.

Remote sensing and GIS tools solved various questions about geomorphology to aid selection of a suitable dam site. Satellite imagery provided data to examine a suitable location in a particular area in Tabuk on a fine scale. Satellite imagery and DEMs within the GIS umbrella were used to stratify surface parameters affecting the choice of flood control dams. Mapping the area has many applications such as updating the vegetation layer, evaluating human changes and understanding potential causes of floods over time. In addition, there are some algorithms in GIS software which enabled us to calculate slope and land cover type over the whole study area. In this study, the main goal of land cover classification was to localize flood risk zones in the city and produce an acceptable overall description. Because of available ground knowledge about land cover identity and distribution, supervised classification was successfully applied to estimate land cover type with high accuracy by referring to ground truth data. The result of combining the land cover type map, slope and wadi network in a single model shows a higher risk in Abu Saba'a district,

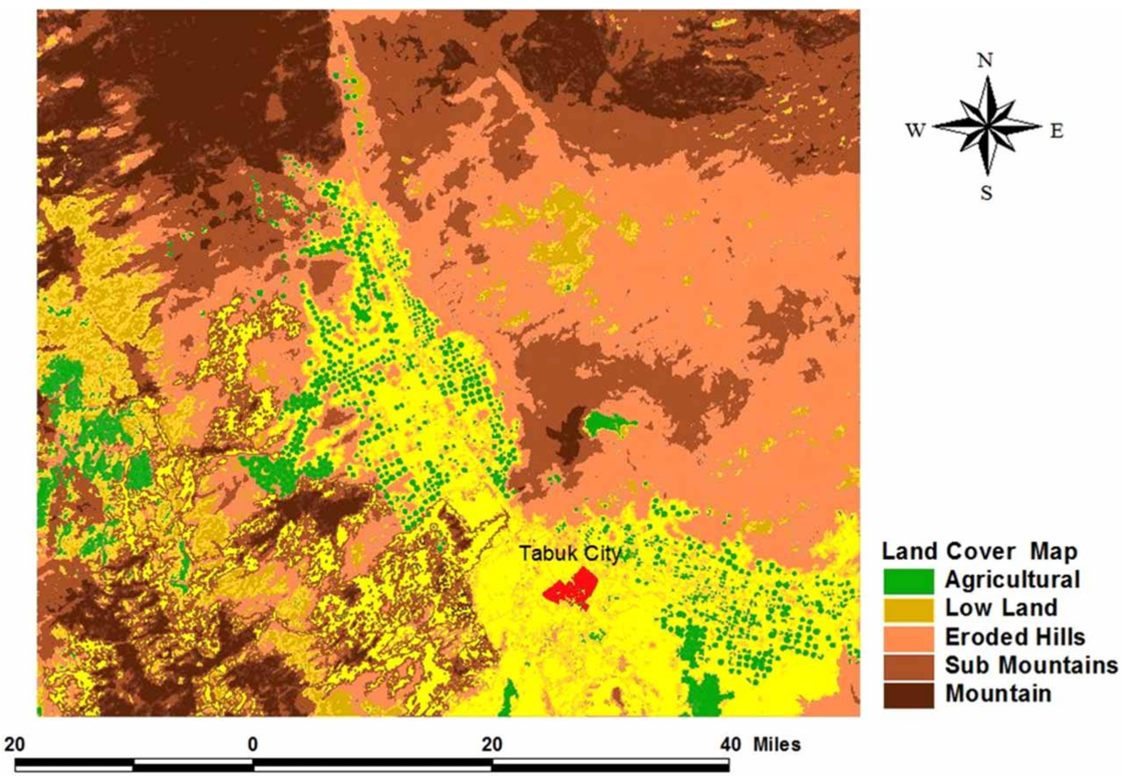

Figure 9 | Land cover and land use classification for Tabuk using maximum likelihood classification (1 mile = 1.609 km).

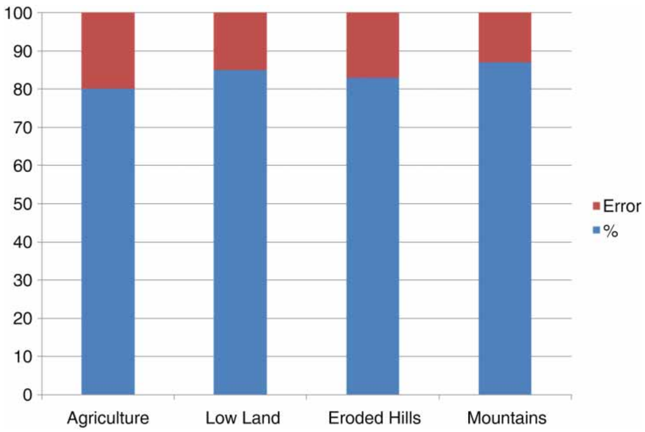

Figure 10 | Classification accuracy assessment for ETM+ image from 2005 based on error matrix report.

particularly in the south and west parts of the study area, including settlement as a land cover type, slope equal to zero, and the wadi stream order of 1, which means a major wadi. According to the results, the dam site can be selected under many parameters especially slope value and land cover type. Most pertinent to this study area is human activity, including land use and urbanization trends.

Because the Tabuk area is an agro-landscape area, seasonal or annual changes must be taken into account. These changes of land cover can be classified into two classes: reversible changes such as seasonal cultivation and irreversible changes such as construction projects. According to land cover data, mountains and sub-mountains are the major cover in the Tabuk study area (47%) and indicate a high risk of flood from those areas.

In addition, dam location in such a case should be planned for a flatter area (0 degree slope) which gives more stable slopes, especially on poorer foundations or where much sedimentation has gathered at times of hazard, thus, decreasing the infiltration rate and increasing the time of residence at the dam site. Therefore, taking this step into account will protect the dam structure against possible instability.

Apart from flood control purposes, Forzieri *et al.* (2008) highlighted that dams are able to store water during the rainy season and preserve it during the dry season, ensuring a stable water supply source. They gave a simple example of a surface small dam using gabions. Important advantages of gabions with respect to other construction materials are that they are very cheap and easy to make and they can be directly placed on any type of soil (Figure 15).

The cross-sectional measurements for selected sites are important as they can be used to:

(1) calculate construction cost;
(2) calculate dam storage;
(3) assess stability and risk.

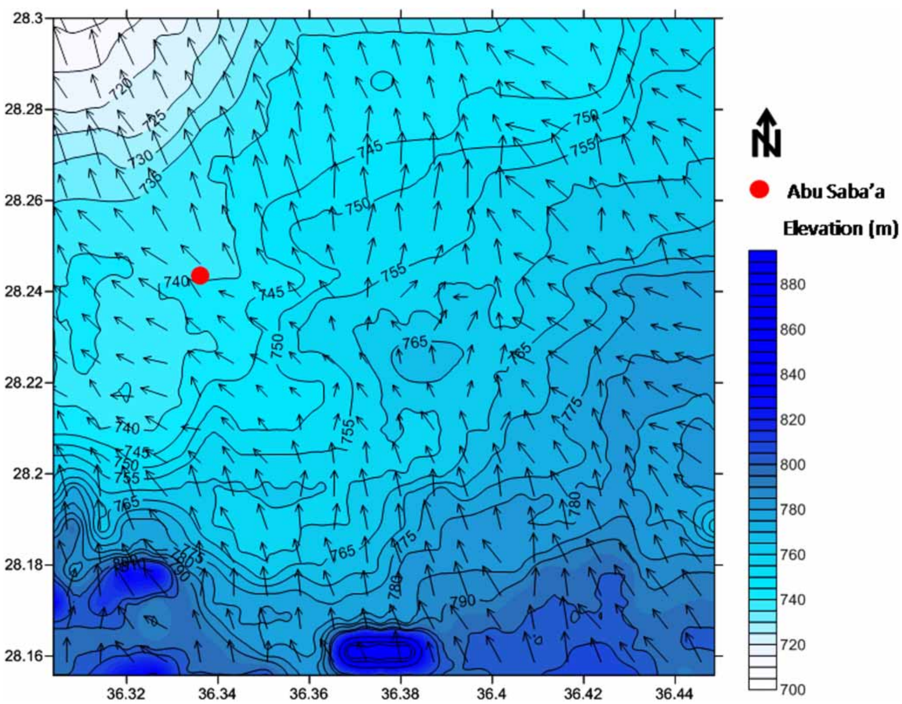

Figure 11 | Tabuk area flow direction map.

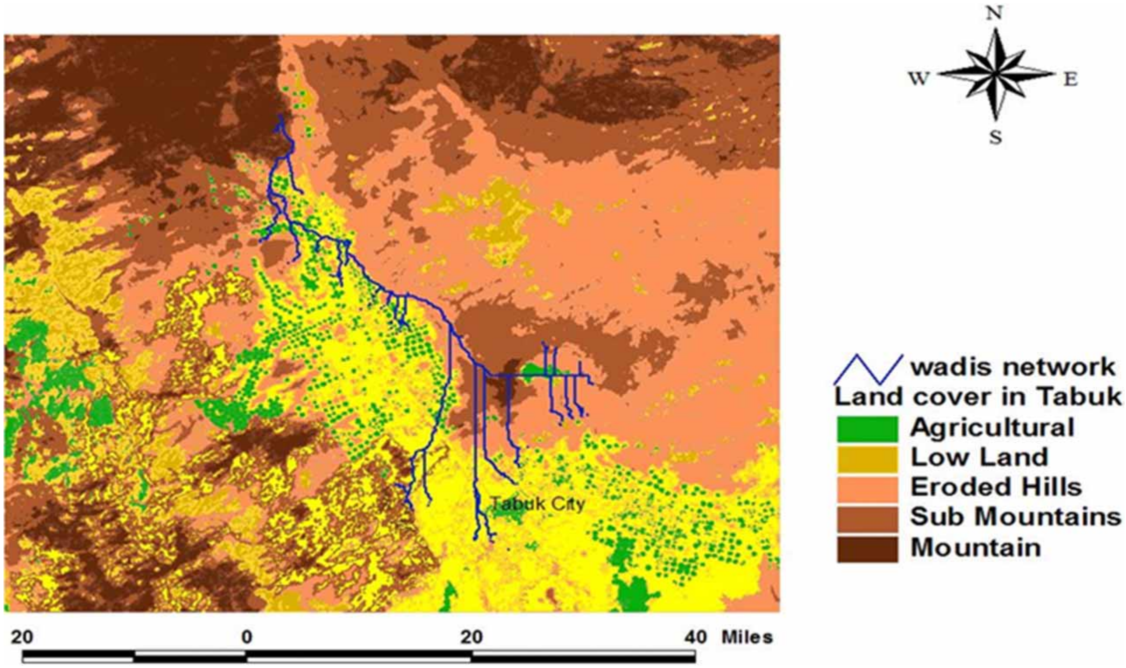

Figure 12 | Land use/land cover and wadi network stratification for Tabuk (1 mile = 1.609 km).

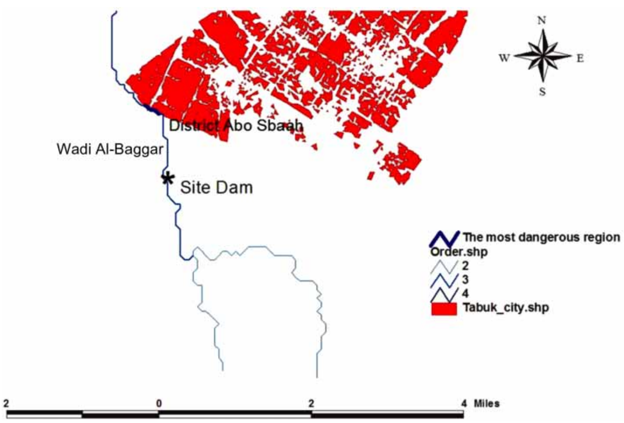

Figure 13 | Site for a flood control dam based on several parameters (1 mile = 1.609 km).

Table 5 | Dam specification based on the GIS model

Order	Area (km^2)	Length (km)	Volume (km^3)	Slope (%)	Land cover type
3	207.2	9.1	1,878	0	Low land

Adapting flood control structures for Tabuk will protect investments in a variety of sectors and infrastructure, including transportation, oil industry, and urban programmes. Further studies could include:

(1) tectonic nature of the region and seismic activity;
(2) hydrological changes in the region: the amount of rainfall and surface water hydrogeology (groundwater);
(3) geotechnical approach: measuring soil permeability and rock properties;
(4) calculating the storage capacity of the dam based on hydrological frequency;
(5) specifications of building materials.

This proposed method can be applied to different catchments. However, there is an urgent need to install modern hydrological and meteorological equipment to gather data and apply integrated remote sensing and GIS techniques.

Technically, the most serious problem for flood control dams in arid regions is the wadi's total sediment load captured by the dam which is called *trap efficiency*. Indeed, this is an important issue to be considered as it can affect the dam storage functionality, thus, losing the ability to prevent the floods for which it was built. Therefore, a regular removal of dam sedimentation is required in order to keep the dam functioning.

CONCLUSION

The paper describes a general method for selecting a suitable site for a flood protection dam at a single wadi. The

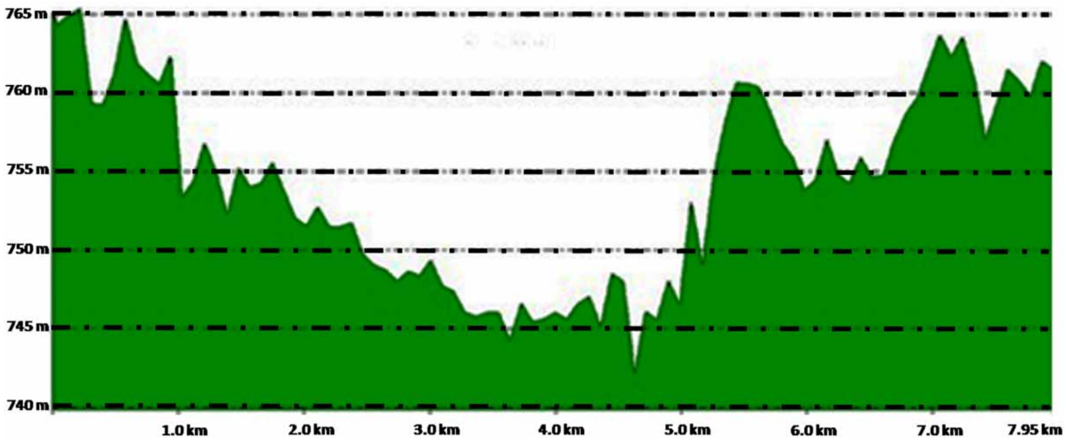

Figure 14 | Cross-section of selected location.

Figure 15 | Wadi Al Ahin desert dam, Oman (February 2016).

selection procedure is based on several defined parameters extracted from remote sensing data where ground data are not available. The methodology was applied to a small area in Tabuk city, Abu Saba'a district, where the greatest damage occurred during the flash flood in 2013. The study area is surrounded by mountains, which increases the potential of attracting flash floods. DEM data have been used to understand the drainage pattern and extract wadi networks and the boundary of the catchment area around Abu Saba'a. ETM+ images acquired in April 2005 with 15 m ground resolution were used to extract land cover types. GPS field data were used to find the lowest land in the area. Although the described method requires a series of assumptions, the results are sufficient for site selection. The collection of more field data and hydrological data such as rainfall, temperature, and flood frequency distributions is recommended for a more accurate feasibility study.

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