

Flash flood inundation map preparation for wadis in arid regions

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Abstract Flood inundation maps are dependent on the topographic and geomorphologic features of a wadi (drainage basin) in arid regions, which are most susceptible for potential flash flood occurrences, such as in the southwestern part of the Kingdom of Saudi Arabia. It is not possible to control the potential flood hazards by using only technological instruments that forewarn the occurrences or imminence. Additionally, it would be better to prepare flood risk maps so as to delineate the risky areas to educate the administrators and local settlers. The availability of these maps is the key requirement for any urban development that entails land use allocation, identification of dam, tunnel, highway, bridge sites, and infrastructure locations for sustainable future. This paper suggests the necessary steps in flood inundation map preparation after determining the possible flood discharge. For this purpose, a set of critical cross-sections along the possible flood plain are taken in the field with surveying methods and measurements. The calculation of the average flow velocity in each section is calculated according to the cross-section geometric, hydraulic, and material properties. Synthetic rating curves (SRC) are prepared for each cross section, which are very useful especially in arid and semi-arid regions where there are no perennial surface water flows for natural rating curve measurements. All the SRCs appear in the form of power function which relates the flow depth to discharge in a given cross section. It

is then possible to calculate the flood depth in the cross section through its SRC. Depending on the cross-section shape, the flood width can be calculated. The connection of a series of widths on a scaled topographic map delineates the flood inundation area. If digital elevation map (DEM) is available, then the SRCs can be integrated with these maps and the flood inundation delineation can be achieved automatically. Since DEMs are not available, the topographic maps are used for this purpose in order to delineate flood inundation areas within wadis Hali and Yiba from the southwestern Kingdom of Saudi Arabia.

Keywords Arid region · Cross section · Flash floods · Inundation · Saudi Arabia · Synthetic rating curve · Wadi

Introduction

Flash floods are not uncommon in arid regions and present potential hazards to life, personal property, and structures such as small dams, bridges, culverts, wells, and dykes along the wadi courses. After a short period of intensive rainfall, flash floods are formed rapidly and they flow down over extremely dry or nearly dry water channels at speeds more than 1.5 m/s, faster than a person can escape from the rough and sandy wadi channels (Dein 1985). Herein wadi is defined in the sense that they have emerged in arid region hydrology context as distinct scientific areas within the last decade. The wadi hydrology is very different from that of humid regions and raises its important scientific, technical, and linguistic challenges. Hence, a special methodological basis is essential to meet current and future needs of water management.

Although flash floods are among the most catastrophic phenomena, especially for arid regions, the volume of the infiltration from these floods is a major source of groundwater

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replenishment to aquifers, which are hydraulically connected with surface water channels. The groundwater recharge volume can be significantly increased by impoundment behind surface dams or successive dykes. Importance of flood studies, other than dealing with surface and subsurface water interactions, includes flood influences on land-use practices, urban developments, and engineering structures, such as dams, bridges, culverts, and spillways.

The absence of detailed records on major floods is noticeable in arid region basins, which are wadis. In general, comparatively sufficiently recorded data exist on normal rainfall. The set of available rainfall data together with the drainage basin characteristics facilitate the use of empirical equations to estimate relevant flood discharges (Şen 2005). Because floods are in general flashy, the problem of defining the peak level accurately by water level record or maximum level is aggravated by siltation of inlet pipes (Farquharsen et al. 1992).

In this study, aerial photographs are utilized to delineate drainage boundaries, while a set of cross sections along wadi channels are measured in the field by surveying instruments. Also observations of the highest flood level marks in the field are gathered, and other relevant information was obtained from local inhabitants. The collected information is used to construct synthetic rating curves (SRC) in control sections by developing empirical formula. The data pertaining for the formulation, such as the geometrical and hydraulic variables including the cross-section shape, area, perimeter, hydraulic radius corresponding to a pre-selected set of depths, and cross-section material specifications, Manning coefficients, and the slope, are obtained from extensive field surveys and relevant maps.

Although a number of water balance studies have been conducted for a variety of watersheds throughout the world (e.g. Flerchinger and Cooley 2000; Scanlin 1994; Yin and Brooks 1992; Kattelmann and Elder 1997; Mather 1979), the rainfall–runoff studies in addition to the water balance of the arid and semi-arid lands present some interesting challenges. These watersheds, which are dominated by precipitation and evaporation, exhibit a high degree of variability in vegetation communities on scales much smaller than addressed by most hydrologic modeling. Thus, arid region wadis (catchments) pose a unique set of problems for hydrologic modeling.

The southern parts of the Kingdom of Saudi Arabia receives the maximum rainfall amounts within the Kingdom and, consequently, has regionally rich surface and subsurface groundwater resources in addition to quite frequent flood occurrences. Water potential of the area requires detailed morphologic, climatologic, and geological aspects and maps (Al-Suba'i 1992).

Unfortunately, only engineering structural protections cannot serve the community, but more significantly the pre-flood warning through the flood inundation maps are very helpful for future planning by local and central authorities. The main rule considered in this study is that rather than to trust an engineering structure and expansion of the activity within the flood plain, it is wiser to depend on the flood inundation maps in planning for future developments in flood-prone areas.

The flood hazard potentiality in the Kingdom of Saudi Arabia may have adverse effects on urban, industrial, infrastructure, and agricultural areas. This view emerges from the past experiences and, therefore, urges preparation of flood inundation maps. Availability of such maps is the key requirement in any urban development including dams, tunnels, highways, and bridges and industrial and agricultural areas for sustainable future.

The main objective of this study is to present the steps toward the preparation of inundation maps starting by measurements in Wadi Hali and Wadi Yibah in the southwestern part of the Kingdom of Saudi Arabia. The completion of such maps is achieved with the view of perspective for effective planning, protection, operation, construction, and maintenance against dangerous flood events. Although the main objective is, after the flood calculations, to show the inundation boundaries on digital elevation map (DEM) of each wadi, since DEMs are not available, such a task could not be achieved in this paper. Instead, classical topographic map contours around some representative cross sections are presented as inundation boundary delineations. In the future, once DEMs become available, then the calculations in this paper provide ready information for the implementations.

Dangerous flood levels

The major rule, which is considered in this paper, is that no intensive land use should ever occur on floodplains for flood hazard intact human activity sustainability. Unfortunately, this ideal rule is corrupted as a result of pressures of population and the growing shortage of land for development. The development of floodplain land can produce a net economic benefit if the additional benefits derived from locating on the floodplain (i.e., benefits over and above those available at the next best alternative flood-free site) outweigh the average annual flood losses. Throughout the history although the human beings were aware of flood danger, floodplains have always been attraction centers for human activities with the least investment cost. Economic growth and population redistribution have always

tempted greater degree of floodplain encroachment, which is also taking place today within the major wadis in the Kingdom of Saudi Arabia. It is not unnoticeable that the urban areas are expanding year by year toward the floodplains with no early warning. It is expected that the result of this study will provide an early warning message to local and central planners. By looking at the flood inundation map at different risk levels, one can decide the location of its property with a certain risk acceptance. In this paper, the flood inundation levels corresponding to the following categories are classified as:

1. Absolute protection zone (90 % risk): This is the most dangerous zone, which will be definitely under flooding whatever the flood intensity is. The local and central authorities must forbid the construction of any building or human activity within this zone.
2. Significant protection zone (90–80 % risk): This is the area where some human activities must be allowable such as small story building construction. A general rule might be accepted in this zone as the allowance of 10 % of the owned area for light building constructions. However, these buildings must not include significant activities such as schools, hospitals, general public services, etc.
3. Moderate Protection Zone (80 % – 70 % risk): About 30 % of the areal property must be opened for human activities such as agriculture, irrigation, storage buildings, etc.
4. Weak protection zone (70–50 % risk): These areas can be opened for public use at 50 % construction rate.

If any floodplain is already urbanized even at small scales, then there is an inevitable demand from the local community for flood protection. Furthermore, past experience has shown that the engineering structures fail in many cases due to either insufficient calculation and construction or the record-breaking behavior of natural events, such as floods. Despite of the fact that a progressive shift in recent

years toward more regulatory controls on floodplain development, it has been difficult to shake off the massive structural legacy even in modern societies. It is also sad to state that especially big cities undergoing economic recession are also prone to increased hazard since the local authorities are so desperate for investment that they are willing to attract floodplain development rather than no development at all. Unfortunately, in such conditions, even the prepared flood inundation maps cannot be salvages but at least they stand open to each individual, local, and central administrators, and consequently, such undesirable situations can be avoided to a great extend.

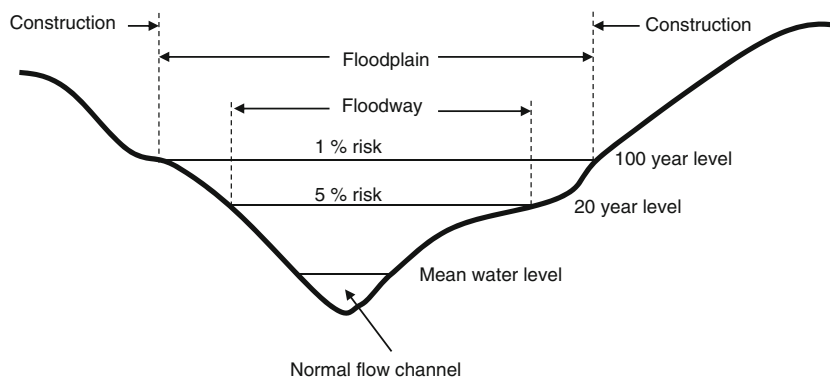
Smith (1992) gave the following three reasons for the circular link between flood control works and floodplain investment and encroachment:

1. The greater the amount of floodplain development and the greater the existing investment, the greater the economic benefits to be obtained from flood control structures. Thus, flood protection schemes are more likely to be implemented on cost–benefit grounds.
2. The cost–benefit ratio also weights in the favor of construction when land can be protected from risk and freed for development. The higher land values in the “protected” area then make further floodplain invasion more likely.
3. Above all the real cost of protection (and encroachment) typically has not been born by the parties most directly involved.

One can view any cross section in a flood-prone area as consisting of three major parts including the no-construction, only flood-proofed construction, and proper construction zones as in Fig. 1.

In this figure, ‘floodway’ term is used for 5 % annual probability which corresponds to 20-year level of probable flood water. Likewise, ‘floodplain’ is employed for 1 % annual probability corresponding to 100-year flood water level.

Fig. 1 Schematic delimitation of hazard planning zones on a cross section



Study area

Wadis Hali and Yibah are located in the southwestern part of the Kingdom of Saudi Arabia, and they run toward the Red Sea coastal lands reaching the sea. They are included in the quadrangle area between the longitudes 18°N and 19°N and latitudes $40^{\circ}30'\text{E}$ and 42°E . The headwater area lies at about 2,000-m elevation above the mean sea level (m.s.l.) and extends toward the west (Fig. 2).

High elevations are along with the Asir Escarpment (Sarawat mountains), which reaches more than 2,000 m above m.s.l. This region receives rainfall especially during winter period when the Mediterranean air masses penetrate the mid-western parts of the Kingdom, but due to the Red Sea trough, they penetrate further south and reach the study area. In spring months, the southwestern monsoon air pattern penetrations also provide rainfall.

Hence, the area is under these two frontal rainfall effects. However, due to the high elevations at the upstream locations, orographic rainfall occurrences may also take place.

Some flood estimation methods are based on theoretical considerations, whereas others are purely empirical. In general, flood discharge is a function of climatic and watershed characteristics. The main climatic variable is defined by the rainfall amount and its intensity, distribution, and duration, while the watershed features include the drainage area, density, shape, slope, main channel length, etc. The latter factors act as an operator to convert a time sequence of naturally occurring precipitation into a time sequence of runoff (Seyhan 1977). The rainfall–runoff relationship becomes even more complicated as the distribution of the vegetation; geological formations, soil condition, and spatial and temporal variation of climatic factors are considered.

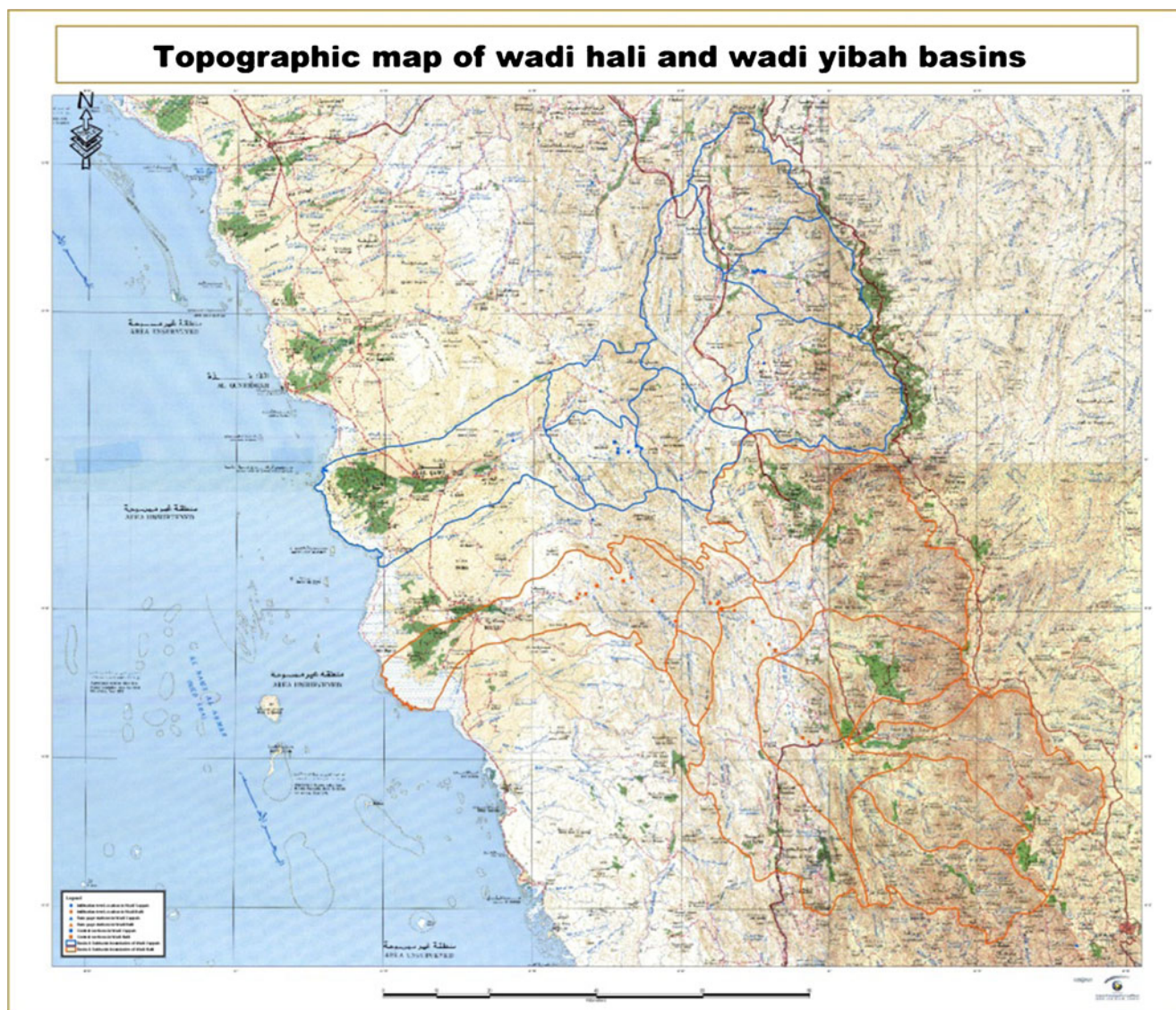


Fig. 2 Location map of the study area

Materials and methodology

There is not any specific hydrologic software used in this study except commonly available Excel Sheets and Matlab for simple program writings. Among the important materials are the field instruments such as theodolite for better refinement of digital elevation model (DEM), cross-section data generation and slope measurements in the field, Infiltration test double rings, cross-section material identification for Manning coefficient allocation, land use, and geological maps. Reconnaissance and detailed field trips along the wadi helped to identify a set of representative cross sections, which are the basic elements in any flood control or early warning works and applications. Detailed background material and information concerning hydrology of wadis Hali and Yibah are already presented in two reports by Saudi Geological Survey (SGS) (Khiyami et al. 2005). Therefore, herein hydraulic calculations are given rather simply, effectively, and explicitly presented because these are the basic principles in any flood inundation map preparation and they give systematic idea about the procedure for any flood calculations as they are in any software.

Hydrometric pattern

In general, hydrometrical studies include the measurement of flow velocity in a selected control cross section for the purpose of constructing the depth or better stage and discharge relationship. In perennial rivers, the discharge calculation is possible directly after the cross-sectional and velocity measurements. These calculations provide the relationship between the discharge and the depth or stage, and such graphs are referred to natural rating curves (NRC). Once such curves are prepared and then it is a matter of measuring the depth or stage, and the discharge can be easily read off from the relevant NRC. Its preparation requires the velocity, V , and cross-sectional area, A , measurements at a set of depths, D . The discharge corresponding to a given depth has, in general, a mathematical form, as a power function,

$$Q = aD^b \quad (1)$$

where a and b are the cross-section rating curve parameters that must be determined from the scatter diagram of discharge versus depth values. The procedure to obtain a NRC is presented in many textbooks on surface hydrology (Maidment 1993).

The rating curve gives the opportunity to predict the discharge amount that corresponds to any water depth or stage level. Besides, each cross section has different rating curves than others depending on the cross-sectional shape

and the upstream catchment area as well as morphological features within the area.

Unfortunately, none of the aforementioned measurements cannot be made in arid regions where there is no perennial surface flow. In cases of flash floods, however, such measurements cannot be done due to the power of surface flow.

Control cross sections

In order to prepare flood inundation map, it is necessary to know the corresponding possible discharge depths at a set of cross-sectional areas along the main wadi channel. Since the flood hazard potential is more common in the downstream part of catchment, most of the cross sections are taken at downstream locations. In the selection of cross sections, the following guidelines are considered:

1. It is preferable to select three best representative cross sections along each wadi branch. However, this is not possible due to time and budget restrictions, and therefore, most often two cross-sections are selected one in the upstream and the other in the downstream portion of each reach,
2. The selection of cross sections should be more intensified at the downstream branches of a drainage basin. Another useful guidance is a preliminary reconnaissance inspection through a quick field trip, if possible. This will identify the most flood inundation subjected areas by expert views and with information support from the local settlers.
3. The cross sections must be selected on rather stable portions of the wadi course and if possible at more or less straight-line reaches. This is a requirement for the simplicity of calculations.

In order to determine the cross-section geometry field, surveying applications are carried out across each section perpendicular to the wadi longitudinal extension. For this purpose, the surveying instrument is located over a point almost in the middle of the section, and a sequence of right and then left height readings is taken at points of appropriate distances from the instrument location. The appropriateness of the points is selected during the field observations as points of surface feature and texture changes. For instance, along the cross-section boundary, if there is a change from fine sand to gravel or to vegetation or to rock, then a measuring point is adopted. In this manner, the depth of each point from the common horizon of the instrument is recorded with distance. Finally, the plot of distances and these depths lead to the profile of the cross section as representatively shown in Fig. 3.

In both wadis Hali and Yibah convenient cross-sections are selected at possible dam sites, downstream of confluence

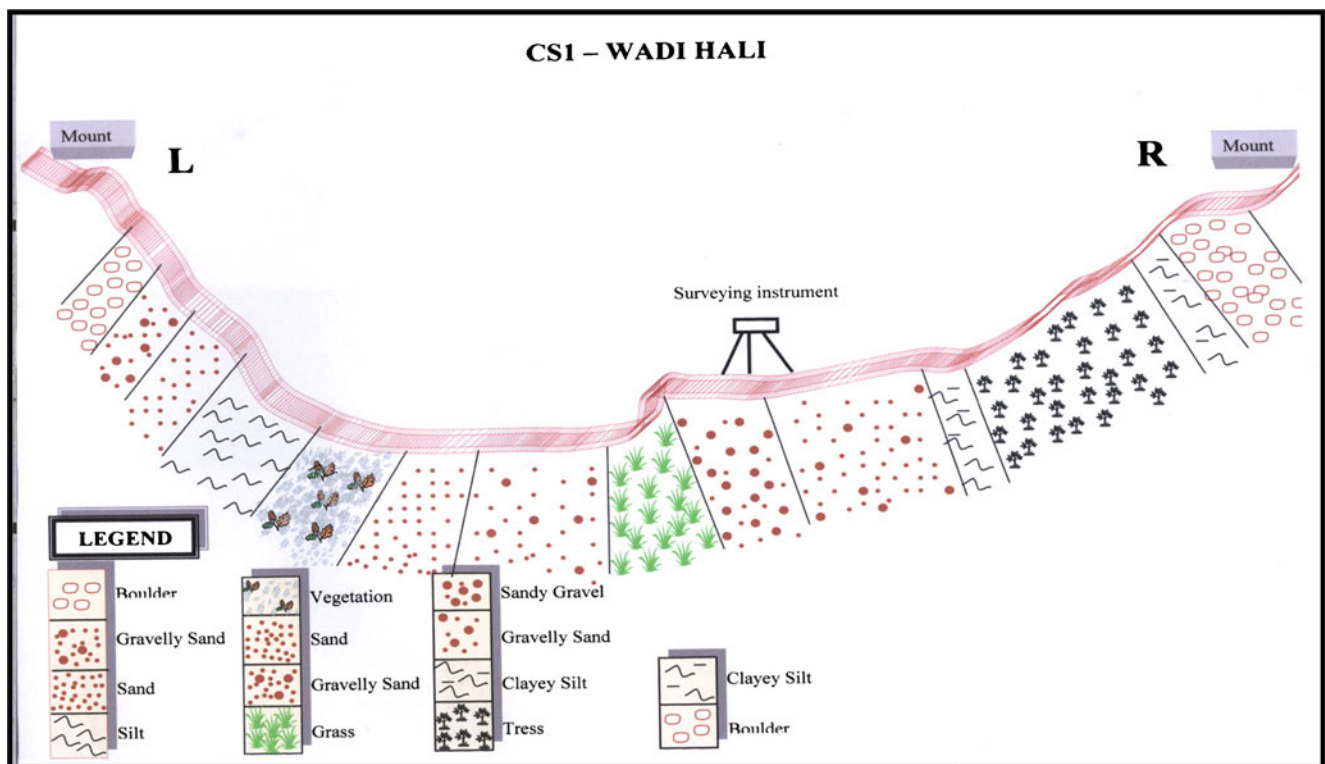


Fig. 3 Representative cross-section profile

points, significant cross-section width change locations, etc. The possible peak discharges corresponding to various risk levels are calculated through the SGS hydrograph method (Şen 2005).

Cross-section hydraulic quantities

The wetted perimeter of cross section is important for the friction between the water and natural wadi bed. Such a friction affects the cross-section velocity, which is very important in the calculation of SRCs. For necessary discharge calculations, also the nature of the material variations along the perimeter is required. The material type plays a dominant role selecting friction coefficient related parameters in the empirical velocity expressions, such as the Manning formula. The more the roughness of the material, the more will be the friction and hence hydraulic losses, and accordingly, reductions in the flow velocity will be more. In Figs. 4 and 5, the wetted perimeter variation with the flow depth is shown with simple regression models for wadis Hali and Yibah. It should be noted that the total length of the wetted perimeter changes depending on the water level in the cross section.

The wetted perimeter can be approximated as the summation of width, *W*, of flow area in the cross section with

twice water depth, *D*, as $P = W + 2D$. In surface flow, most often the width is many times greater than depth, which is valid especially at downstream portions of wadis in arid regions, and hence, it is possible to write

$$P = W \left(1 + \frac{2D}{W} \right)$$

Since $W \gg D$, one can practically conclude that $P \approx W$. On the other hand, since by definition the hydraulic radius, *R*, is the ratio of cross-sectional area, *A*, to the wetted perimeter, it can be written as,

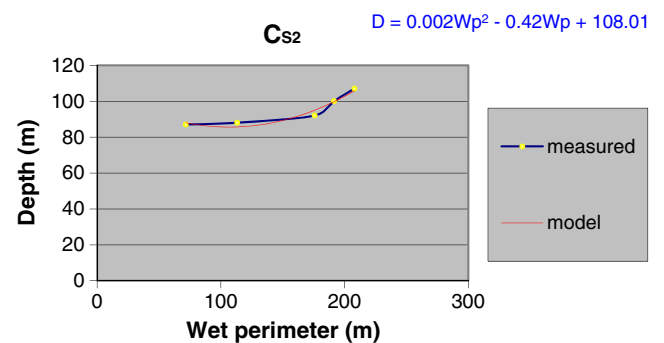


Fig. 4 Wetted perimeter in wadi Hali cross-section profile

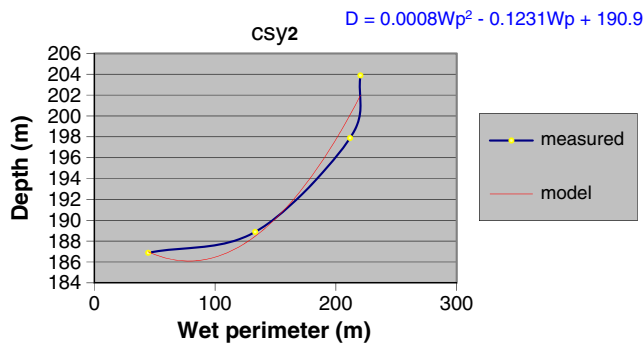


Fig. 5 Wetted perimeter in wadi Yibah cross-section profile

$$R = \frac{A}{W}$$

and since again by definition $A=WD$, the hydraulic radius becomes approximately equal to the flow depth, i.e.,

$$R \approx D \tag{2}$$

It has the dimension of length, and the greater its value, the greater will be the flow velocity. The hydraulic radius values are calculated for each set of selected flow depth.

Finally, although the cross-section velocity, V , can be calculated according to different empirical formulations, herein Manning formulation is adopted because it is extensively used in hydraulic empirical calculations for surface flow in natural or man-made channels. The Manning approach expresses the surface water velocity as,

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{3}$$

where R is the hydraulic gradient, S is the surface water slope (this is assumed as equal to the channel longitudinal slope), and n is the Manning coefficient. This expression becomes for extensively wide catchments under the light of the Eq. (2) approximately as,

$$V = \frac{1}{n} D^{2/3} S^{1/2} \tag{4}$$

Table 1 Wadi Hali CS-H1 discharges

Depth (m)	Q (m ³ /s)
1	293.691
4	567.735
6	704.012
9	851.031
12	1,096.824

Table 2 Wadi Yibah CS-Y1 discharges

Depth (m)	Q (m ³ /s)
1	153.995
4	394.658
6	515.816
9	3,046.391

Results and discussions

Since DEM is not available for the region, it is preferred to indicate the flood inundation marks on each cross section and then show their approximate positions on a piece of magnified 1/50,000 scale topographic map by use of a computer software. Calculations for wadis Hali (CS-H1) and Yibah (CS-Y1) cross sections are presented in Tables 1 and 2, respectively.

On the other hand, the maximum peak discharge calculated with the SGS hydrograph methodology (Şen 2005) is about 1,213.63 m³/s for Wadi Hali and 728.48 m³/s for Wadi Yibah, respectively. Comparisons of these discharges with respective cross-section discharges from Tables 1 and 2 indicate that in Wadi Hali, the peak discharge goes over more than 12 m, whereas in Wadi Yibah, the cross section is capable of passing the peak discharge at less than 9 m.

The plot of depth versus discharge from these tables on double-logarithmic paper results in straight lines, which imply power law relationship on ordinary domain. Figures 6 and 7 provide such relationships for respective wadis, which are graphical representation of the SRC for each cross section.

It is found that the SRCs in control sections appear in the form of straight line on double logarithmic papers, which is the case in natural flow and cross sections. For instance, in control section CS-H1, the mathematical equation of this line is

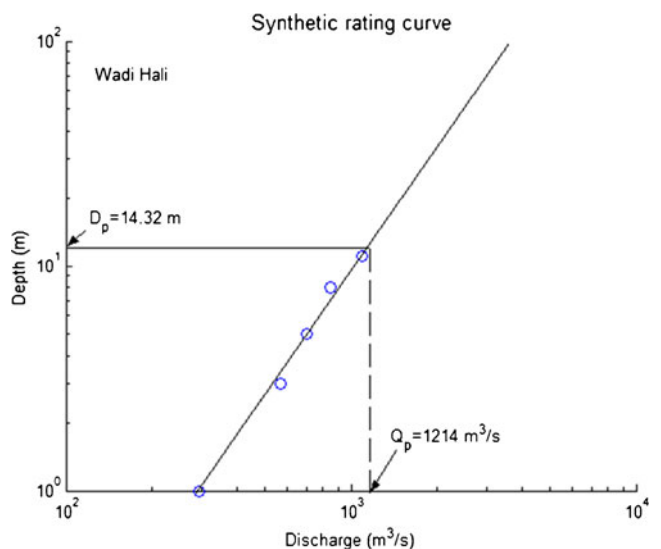
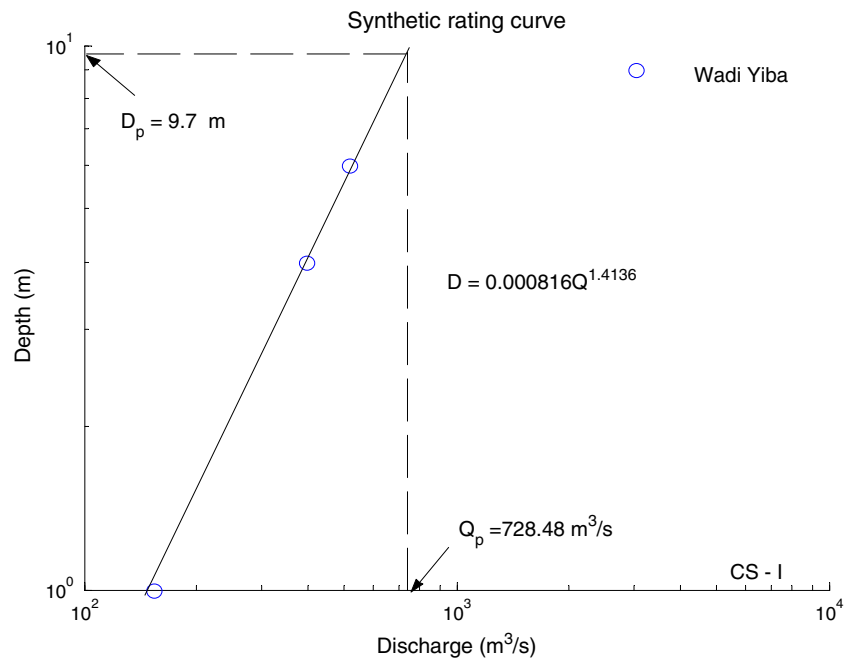


Fig. 6 SRC for Wadi Hali (CS-H1)

Fig. 7 Synthetic rating curve for Wadi Yibah (CS-Y1)



$$Q = 294D^{0.55} \tag{5}$$

or

$$D = 3.25 \times 10^{-5} Q^{1.83} \tag{6}$$

The substitution of the peak discharge into this expression yields the corresponding depth as $D=14.32$ m for CS-H1.

Likewise, in the control section CS-Y1 in Wadi Yibah, the rating curve expression becomes

$$D = 0.0008 Q^{1.4136} \tag{7}$$

This can be converted into discharge as subject

$$Q = 154.7D^{0.707} \tag{8}$$

The implementation of these depths on the topographic map around the CS-H1 and CS-Y1 locations leads to the flood inundation zones indicated in red in Figs. 8 and 9. The calculated maximum depths corresponding to the peak discharge, Q_p , values for a set of cross sections in wadis Hali and Yibah are presented in Tables 3 and 4 with all details.

Conclusions

Flood inundation maps are prerequisites for any agricultural, land use, urban development, highway, culvert, etc. design purposes. In general, humid regions have relevant hydrological measurements for the study, but arid regions lack necessary basic data, and therefore, it

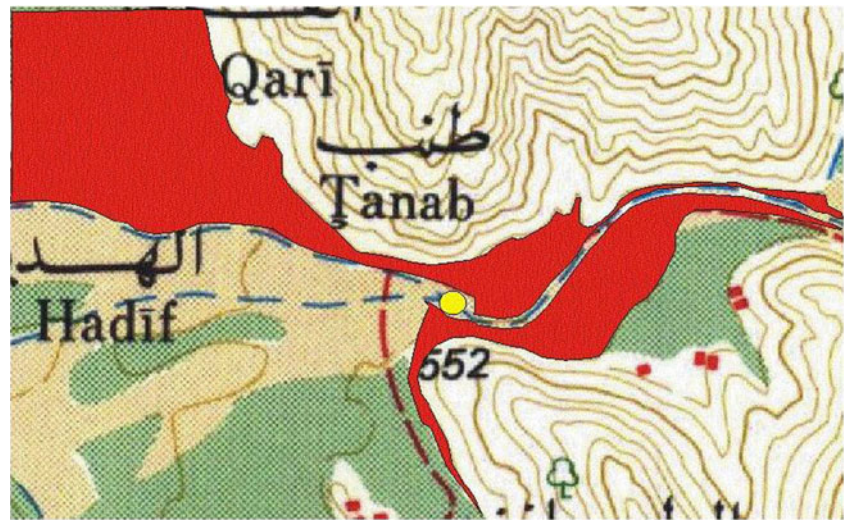
is necessary to employ empirical field methods and measurements for obtaining the inundation maps. In the preparation of inundation maps in arid regions, first SRS are obtained and then the flood levels at different cross sections are calculated. During the course of this study including office, field, and computer calculation stages, the following general and specific conclusions can be drawn:

1. The wadis that run from the Hijaz and Asir Escarpment (Sarawat Mountains) toward the Red Sea coast has occasional flash flood potential which may at times cause human life losses and property damages.



Fig. 8 Flood inundation boundaries around CS-H1

Fig. 9 Flood inundation boundaries around CS-Y1



2. In arid and semi-arid regions and especially in the study area of wadis Hali and Yibah, the floods are consequences of individual storm rainfalls.
3. The upstream portions of wadis are subject to intensive rainfalls, but the flood hazards appear mostly in the middle-stream and especially in the downstream portions. This is partly due to the fact that most of the settlement and urban areas are concentrated in the middle-stream and downstream sectors.
4. Demographically, the major towns and cities are located at the downstream area and most often the drainage basins are directed toward these centers. This is one of the reasons why surface drainage channels are constructed in some city surroundings for collection of these waters together with the surface waters and their discharge to the sea in the most rapid manner.

In general, the Kingdom of Saudi Arabia is within the subtropical climate belt, and hence in particular, its

Table 3 Wadi Hali cross sections

Cross-section number	SRC expression	Water depth (m)
CS-H1	$D=0.0000325Q_p^{1.83}$	14.32
CS-H2	$D=0.000632Q_p^{1.40}$	13.14
CS-H3	$D=0.0012Q_p^{1.19}$	5.82
CS-H4	$D=0.0034Q_p^{1.32}$	40.05
CS-H5	$D=0.000113Q_p^{1.77}$	32.30
CS-H6	$D=0.0020Q_p^{1.32}$	23.56
CS-H7	$D=0.031Q_p^{1.22}$	18.60
CS-H8	$D=0.017Q_p^{1.02}$	23.95
CS-H9	$D=0.0033Q_p^{1.32}$	37.52
CS-H10	$D=0.0518Q_p^{0.858}$	22.93
CS-H11	$D=0.0057Q_p^{1.03}$	8.74

arid and semi-arid regions are prone to occasional floods due to unexpected weather and geomorphologic effects. In addition to these natural effects, the human settlement and urbanization, highway network planning, etc. may also increase the flood hazard potential due to inconcise or mis-planning without flood hazard and inundation maps availability. Under the light of this paper, it is possible to deduce general and specific recommendations for flood awareness studies, hazards, and inundation areas:

1. Surface runoff measurement stations at a set of control cross sections must be established because worth of even a single runoff measurement is very high for arid regions.
2. Humid region flood assessment formulations as available in the literature must be used with care, and it must be born in mind that they are not directly applicable in arid and semi-arid regions. It is necessary either to modify them according to the features of arid region and the availability of data or new approaches must be developed for these regions.
3. High-resolution topographic maps (preferably digital elevation maps) must be prepared for the region in order to implement the flood inundation boundaries at different risk levels.

Table 4 Wadi Yibah cross sections

Cross-section no.	SRC expression	Water depth (m)
CS-Y1	$D=0.000816Q_p^{1.4136}$	9.7
CS-Y2	$D=6.3112 \times 10^{-25}Q_p^{7.553}$	0.2
CS-Y3	$D=0.0000184Q_p^{3.7106}$	14.6
CS-Y4	$D=1.25 \times 10^{-6}Q_p^{2.1403}$	2.5
CS-Y5	$D=0.1108Q_p^{0.5967}$	5.65
CS-Y6	$D=3.49 \times 10^{-10}Q_p^{3.3321}$	1.2

References

- Al-Suba'i KAMG (1992) Erosion-sedimentation and seismic considerations for dam siting in the central Tihamat Asir region. Unpublished Ph.D. thesis, King Abdulaziz University, Faculty of Earth Sciences, Kingdom of Saudi Arabia, 343 pp
- Dein MA (1985) Estimation of floods and recharge volumes in wadis Fatimah, Na'man and Turabah. Unpublished M.Sc. thesis, Faculty of Earth Sciences, King Abdulaziz University, Saudi Arabia, 127 pp
- Farquharsen FAK, Meigh JR, Sutcliffe JV (1992) Regional flood frequency analysis in arid and semi-arid areas. *J Hydrol* 138:487–501
- Flerchinger GN, Cooley KR (2000) A ten-year water balance of a mountainous semi-arid watershed. *J Hydrol* 237(1–2):86–99
- Kattelmann R, Elder K (1997) Hydrological characteristics and water balance of an alpine basin in the Sierra Nevada. *Water Resour Res* 27:1553–1562
- Khiyami HA, Şen Z, Harthy SG, Ammawi FA, Balkhi AB, Zahrani MI and Hawsawy HA (2005) Flood hazard evaluation in wadi Hali and wadi Yibah. Saudi Geological Survey, technical report SGS-TR-2004-6
- Maidment DR (1993) Handbook of hydrology. McGraw-Hill, New York
- Mather JR (1979) Use of the climatic water budget to estimate streamflow. Water Resources Center. University of Delaware, technical research report, July, Dept. Geography Newark DE, 528
- Scanlin BR (1994) Water and heat flux in desert soils: 1, field studies. *Water Resour Res* 30:709–719
- Seyhan E (1977) Regression of morphometrical variables with Synthetic Hydrograph parameters. Series B, no. 65, 18p. Geographic Institute, Utrecht
- Smith K (1992) Environmental hazards assessing risk and reducing disaster. Routledge, London, 324 pp
- Şen Z (2005) The Saudi Geological Survey (SGS) hydrograph method for use in arid regions. Technical report, Saudi Geological Survey, SGS-TR-2004-5, 20 pp
- Yin ZY, Brooks GA (1992) Evaporation in the Oketenokee Swamp watershed: a comparison of temperature and water balance methods. *J Hydrol* 131:293–312