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European Journal of Advances in Engineering and Technology, 2022, 9(8):1-9

Research Article ISSN: 2394 - 658X

Numerical Modelling of Flash Floods in Wadis from Rainfalls in an Arid Region

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ABSTRACT

Flash floods worldwide are now more frequent with higher intensity than in the past due to global warming. Flash floods cause significant loss of life and damages properties, ecosystems, businesses and other facilities. In this paper initially flash flood risks from intense rainfall were assessed for a seafront development site. Then numerical modelling of wadi flood flow modelling was carried out using the REC-RAS model and the flash flood modelling was carried out using the MIKE21 Flow Model. Both 1 in 10 year and 1 in 100 year return periods were considered in the study for rainfall duration of 0.5, 1 and 9 hours. Flooding extent and maximum flood water depths were extracted from the model results from which flood water volumes were calculated. Model results were used to select an appropriate site for the development. Model results were also used to derive a flood mitigation option to prevent flood water entering the project site. The methodology described in this paper for numerical modelling of flash flood adopted by Royal HaskoningDHV (RHDHV) could also be applied to similar sites around the world.

Key words: Flood, Flash Flood, Wadis, Rainfalls, Arid Region, Numerical Modelling, Royal HaskoningDHV

1. INTRODUCTION

Definition of a flash flood

A flash flood is a rapid flooding of low-lying areas which usually occur during intense rainfall associated with a severe thunderstorm, hurricane, tropical storm, or meltwater from ice or snow flowing over ice sheets or snowfields when the amount of water is too much for drains and sewers to deal with. Flash flood can happen very quickly without much warning.

Causes of flash floods

Flash floods are more frequent and with higher intensity due to global warming. It occurs when heavy rainfall exceeds the ability of the ground to absorb or drain it away fast enough. *Flash flood* occurs when water overflows on or inundates land that is normally dry. If there is more rain than the soil can absorb then the excess water quickly runs into rivers and creeks overwhelming storm drains and ditches causing a flash flood. A flash flood can cause water level to rise up significantly in a short duration of time.

The main causes of floods are heavy rainfall and conditions of catchment area, inadequate drainage or breach in flood control structures (such as embankments and levees). Constructions on riverbeds, poor planning and implementation, poor storm-water drainage and sewerage systems are the main causes of flash floods. Poor permeability of soil causes flash floods because flood water fails to seep down to deeper layers. Rapid urbanization and a growing tourism sector in the regions prone to flooding are also putting more people at risk.

Between 80-90% of all documented disasters from natural hazards during the past 10 years have resulted from floods, droughts, tropical cyclones, heat waves and severe storms [1]. Floods affected more than 2 billion people worldwide between 1998-2017 [1]. Drowning accounts for 75% of deaths in flood disasters [1]. An estimated 50 per cent of the world's population will live in coastal areas exposed to flooding, storms and tsunamis by 2030 [2].

Damages from flash floods

Flooding are possibly the most recurrent natural disaster impacting large areas. Heavy rainfalls may cause flash floods and submergence of low lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and damages to properties. The resulting floods, standing water and inundation pollute drinking water sources and spread water-borne diseases (such as cholera, typhoid or malaria) leading to outbreak of epidemics. Flash flood water can contain debris (such as trees, stones or even pieces of houses), pollutants and nutrients. Pollutants in flood water (such as bacteria and pesticides) can be carried far distances. Flash flood waters carry suspended sediments which can degrade water quality and lead to harmful blooms of algae.

Flash floods cause significant loss of life and damages properties, ecosystems, businesses and other facilities. Damages from flash floods also include injuries, chemical hazards, mental health effects, disrupted health systems, facilities and services and damage to basic infrastructure (such as food and water supplies, and safe shelters). Flash floods can tear out trees, roll boulders and destroy buildings, bridges and facilities (such as power, telephone and cable lines) and scour out new channels.

Applications of Numerical Modelling Results

Numerical modelling results of flash floods are used for deriving robust design conditions for structures and facilities. The numerical modelling results are also used for emergency planning and decision-making to estimate potential loss of life, damage to properties and other facilities and to develop rescue and mitigation measures and plan clean-up operations.

2. FLASH FLOOD MITIGATION MEASURES

Flash floods can be controlled either through constructing nature based soft defences (such as using vegetation, sandbags, geo-tubes and sand fences) or by constructing hard defences (such as floodwalls, levees, flood gates and embankments). Strict implementation of regulations for development in flood prone areas, efficient early forecasting and warning systems, building safe shelters and flood resistant structures and planning for evacuation and rescue are important mitigation measures to reduce the risk.

The Present Study

In this paper initially flash flood risks from intense rainfall were assessed for a seafront development site. The flood risk assessment suggested that 1D wadi flood flow modelling and 2D flash flood modelling are deemed to be necessary in order to flood risks and to determine drainage capacity required for off-site and on-site rainwater discharges.

The 1D wadi flood flow modelling was carried out using the HEC-RAS model and the 2D flash flood modelling was carried out using the MIKE21 Flow Model. Both 1 in 10 year and 1 in 100 year return periods were considered in the study for rainfall duration of 0.5, 1 and 9 hours. Flood extent and maximum flood water depths were extracted from the model results from which flood water volumes were calculated. Model results were used to select an appropriate site for the development. Model results were also used to derive a flood mitigation option to prevent flood water entering the project site.

The methodology described in this paper for numerical modelling of flash flood adopted by Royal HaskoningDHV (RHDHV) could also be applied to similar sites around the world. The flowchart in Figure 1 illustrates the key steps adopted in the present study for flash flood modelling and development of flood mitigation options.

Flash flood risk assessment

Literature search was carried out to identify the historical flash floods that affected the development site. It was found that the project site was affected by flash floods in the past. It was also identified that flash flood water might enter the development site from its three sides.

The flood risk assessment suggested that 1D wadi flood flow modelling and 2D flash flood modelling are deemed to be necessary in order to understand flood risks and to determine drainage capacity required for off-site and on-site rainwater discharges.

3. INPUT DATA

3.1 Rainfall data

Both short return period (1 in 10 year) and extreme long return period (1 in 100 year) were considered in the study. Rainfall duration of 0.5, 1 and 9 hours were modelled. The input rainfall scenarios are provided in Table 1.

Table -1 Rainfall scenarios modelled

Return periods	Rainfall duration	Rainfall intensity
1 in 10 year	½ hour	1380 mm/day
	1 hour	801 mm/day
	9 hours	144 mm/day
1 in 100 year	½ hour	3700 mm/day
	1 hour	2280 mm/day
	9 hours	380 mm/day

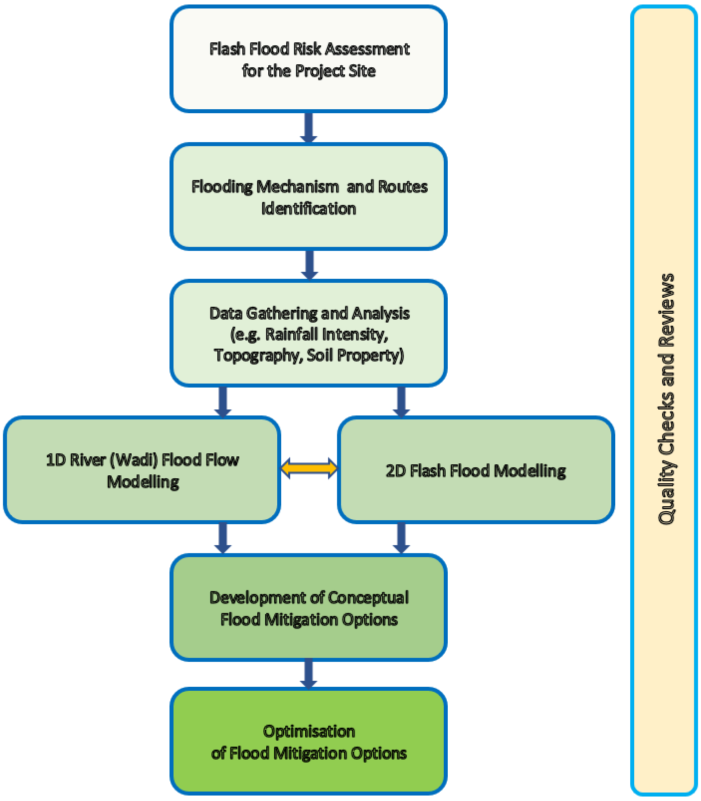

Fig. 1 Steps in a typical flash flood modelling study

3.2 Soil property

An infiltration rate of 7.5mm/hour was obtained from an infiltration rate of 0.15-0.30 inch/hour for soils having moderate infiltration rates when thoroughly wetted and consist mainly of moderately well drained soils. Infiltration rate of soils having low runoff potential and high infiltration rates even when thoroughly wetted have a high rate of infiltration (greater than 0.30 inch/hour). In the present study, an infiltration rate of 0.3 inch/hour (7.5 mm/hour) was used in absence of any measured soil property data.

3.3 Topography

Detailed topography data was available from survey for the study site. Topographic data are also available from various sources (such as satellite-derived) although coarse. Figure 2 shows the topography used in the modelling.

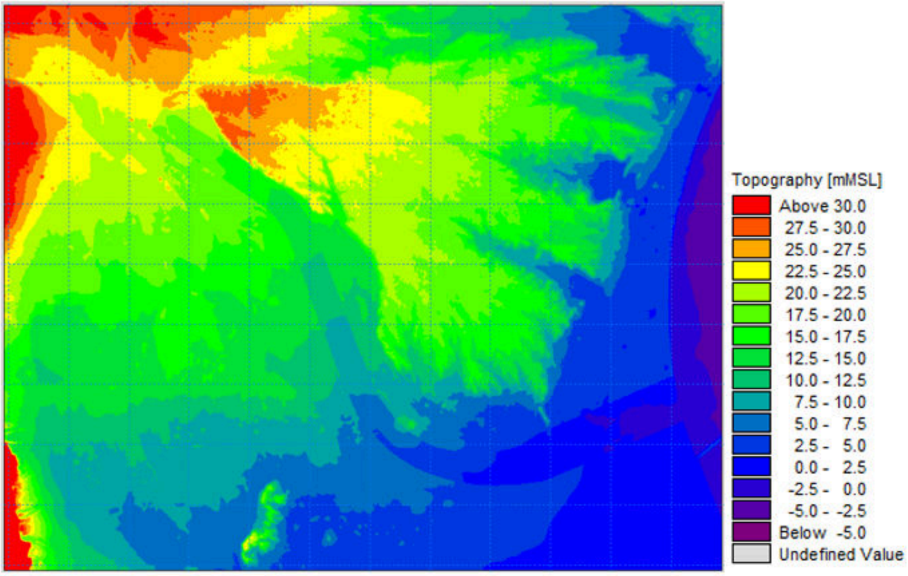

Fig. 2 Model domain and topography

4. WADI FLOOD FLOW MODELLING

4.1 Model selection

The one-dimensional (1D) wadi flood flow modelling was carried out to investigate the conveyance capacity of the newly constructed channel using the HEC-RAS modelling software [3]. HEC-RAS was designed to perform one or two-dimensional hydraulic calculations for a full network of natural and constructed channels. It was developed by US Army Corps of Engineers.

4.2 Model set up

Four channel cross-sections were used to set up the model. The length of the wadi channel was 12km, width 450m and depth 2-3m. The side slope of the wadi channel was 1:2. The longitudinal section of wadi bed levels was obtained from satellite-derived topography data. The model was run for flood flow of 1 in 100 year return period (2080m^3/s).

4.3 Model results

The model results are provided in Table 2. The results show that the wadi would be overtopped if the wadi depth is 2m. However, a wadi depth of 3m would provide sufficient flow capacity for conveying 1 in 100 year flood flow.

Table -2 Peak flood water levels

Cross-sections	Bed level (m MSL)	Bank level (m MSL) (if wadi depth: 2m)	Bank level (m MSL) (if wadi depth: 3m)	Modelled water level (m MSL)
1	20.7	22.7	23.7	22.9
2	13.9	15.9	16.9	15.8
3	3.6	5.6	6.6	6.2
4	-1.0	1.0	2.0	1.9

5. FLASH FLOOD MODELLING

5.1 Model selection

Numerical modelling of flash flood was carried out in two-dimension (2D) using the MIKE21 Flow Model FM developed by DHI [4] to determine the flooding extent and the maximum flood water depths within the development site. The model is based on the numerical solution of the shallow water equations - the depth-integrated incompressible Reynolds Averaged Navier-Stokes (RANS) equations. Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

The local continuity equation is written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

and the two horizontal momentum equations for the x- and y-component, respectively:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz-\frac{1}{\rho_0 h}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)+F_u+\frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right)+u_sS$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz-\frac{1}{\rho_0 h}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)+F_v+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+v_sS$$

where,
t = Time
x, y and z = Cartesian coordinates
ɳ = Surface elevation
d = Still water depth
h = Total depth (= ɳ + d)
u, v and w = Velocity components in the x, y and z directions
f = Coriolis parameter
g = Acceleration due to gravity
ρ = Density of water
ρ_0 = Reference density of water
v_t = Vertical turbulent (or eddy) viscosity
p_a = Atmospheric pressure
S = Magnitude of the discharge due to point sources
u_s and v_s = Velocity by which the water is discharged into the ambient water
F_u and F_v = Horizontal stress terms (described using a gradient-stress relation)
S_{xx}, S_{xy}, S_{yx} and S_{yy} = Components of the radiation stress tensor

5.2 Model set up

The model domain was 11,900m x 9,400m and the model grid resolution was 10m x 10m. the wadi was 2m deep and 450m wide. Figure 2 shows the model extent and topography.

5.3 Model parameters

Bed roughness is set to Manning's "n" of 0.036 which represents a surface covered by gravels. Time varying infiltration has been applied to the model. Infiltration was set to 7.5mm/hour during the first third duration of a storm. Infiltration was reduced from 7.5mm/hour to zero linearly in the second third duration of a storm. No infiltration was applied to the last third duration of a storm representing saturated soil.

5.4 Model results

The maximum flood water depths for 1 in 10 year condition with rainfall duration of 0.5, 1 and 9 hours are shown in Figures 3, 4 and 5 respectively. The maximum water depths for 1 in 100 year condition with rainfall duration of 0.5, 1 and 9 hours are shown in Figures 6, 7 and 8 respectively. Surface water volumes (in m^3) at various sub-areas of the study site was calculated from these plots and provided in Table 3.

Table -3 Surface water volume (m^3)

Sub-areas	Return periods	Rainfall duration		
		0.5 hour	**1 hour**	**9 hours**
A	1 in 10 year	21,400	21,900	15,300
	1 in 100 year	84,600	101,000	94,250
B	1 in 10 year	211,600	247,250	278,900
	1 in 100 year	962,300	1,206,450	1,709,150
C	1 in 10 year	260,000	300,100	346,000
	1 in 100 year	1,140,700	1,445,100	1,981,300

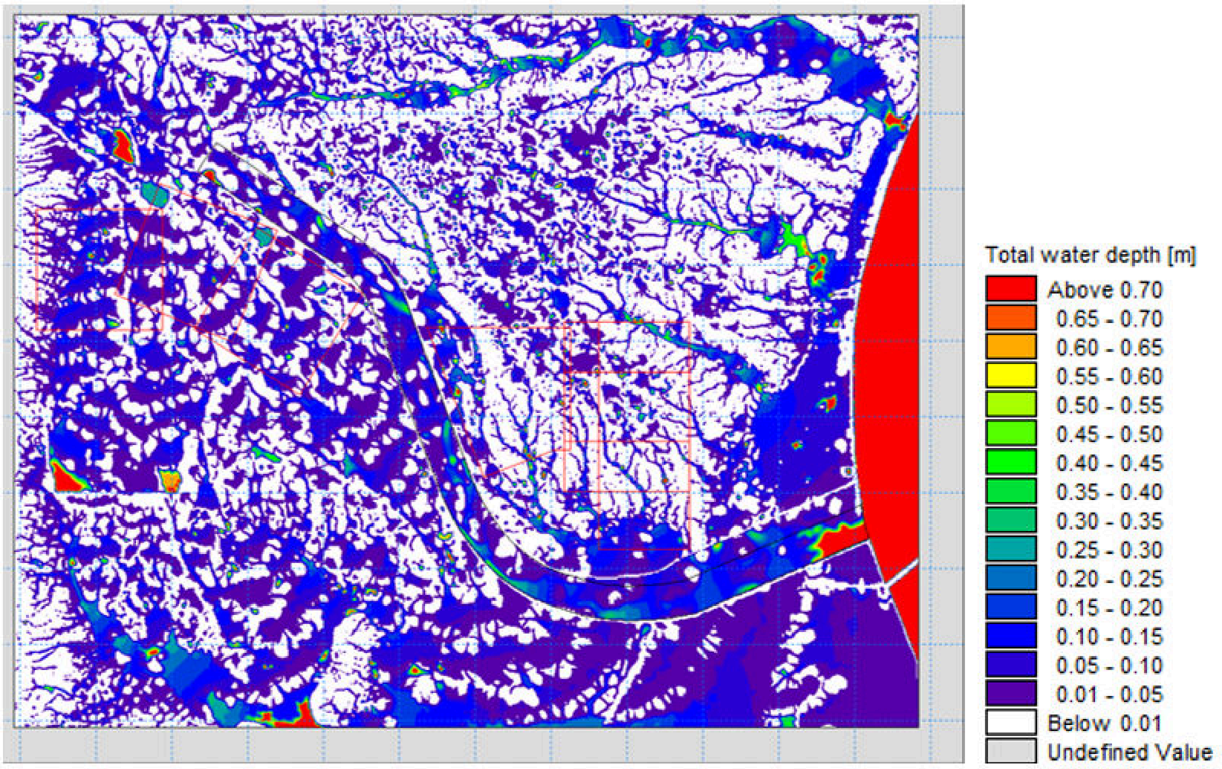

Fig. 3 Maximum flood water depth for rainfall duration of 0.5 hour (1 in 10 year)

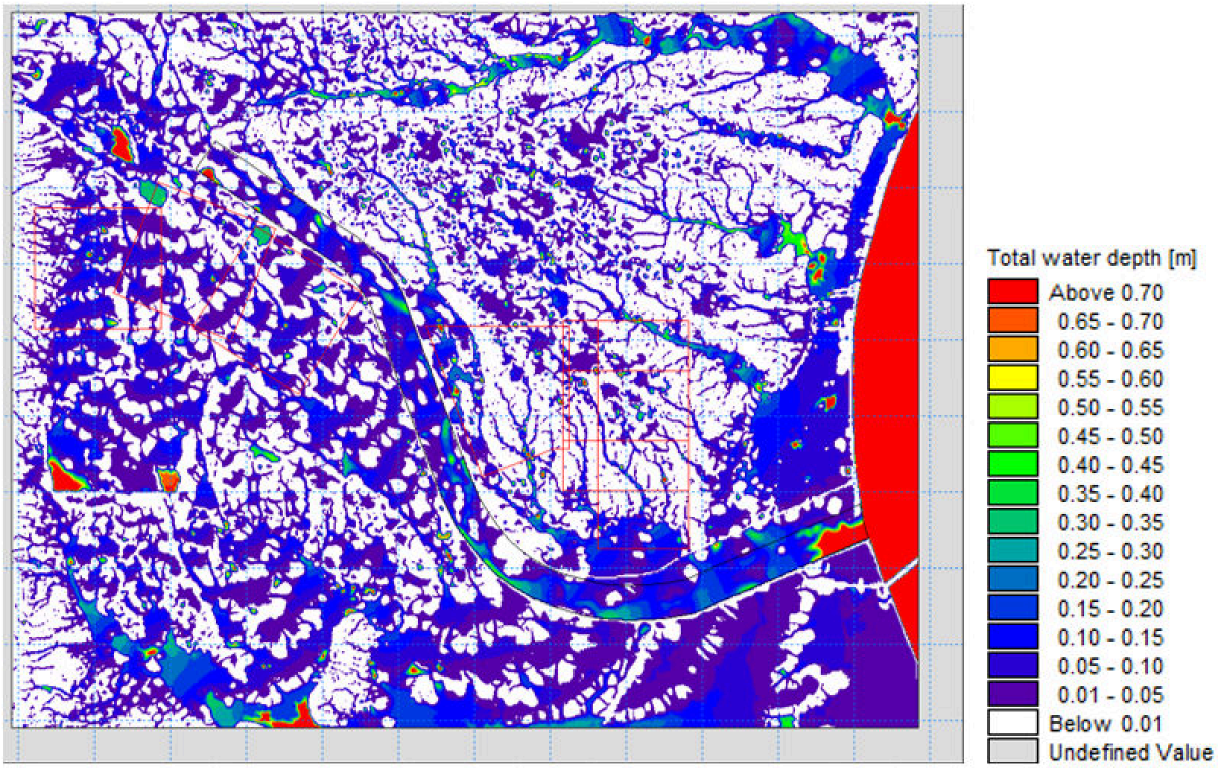

Fig. 4 Maximum flood water depth for rainfall duration of 1 hour (1 in 10 year)

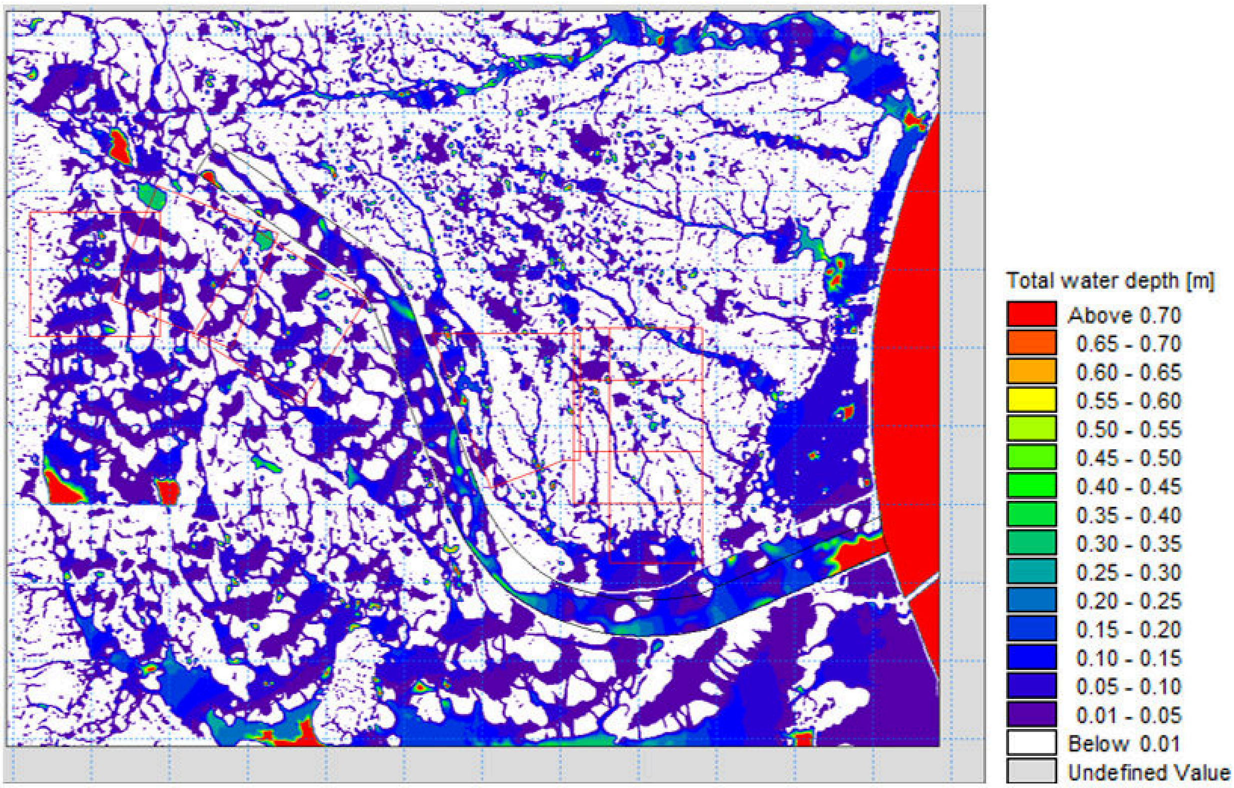

Fig. 5 Maximum flood water depth for rainfall duration of 9 hours (1 in 10 year)

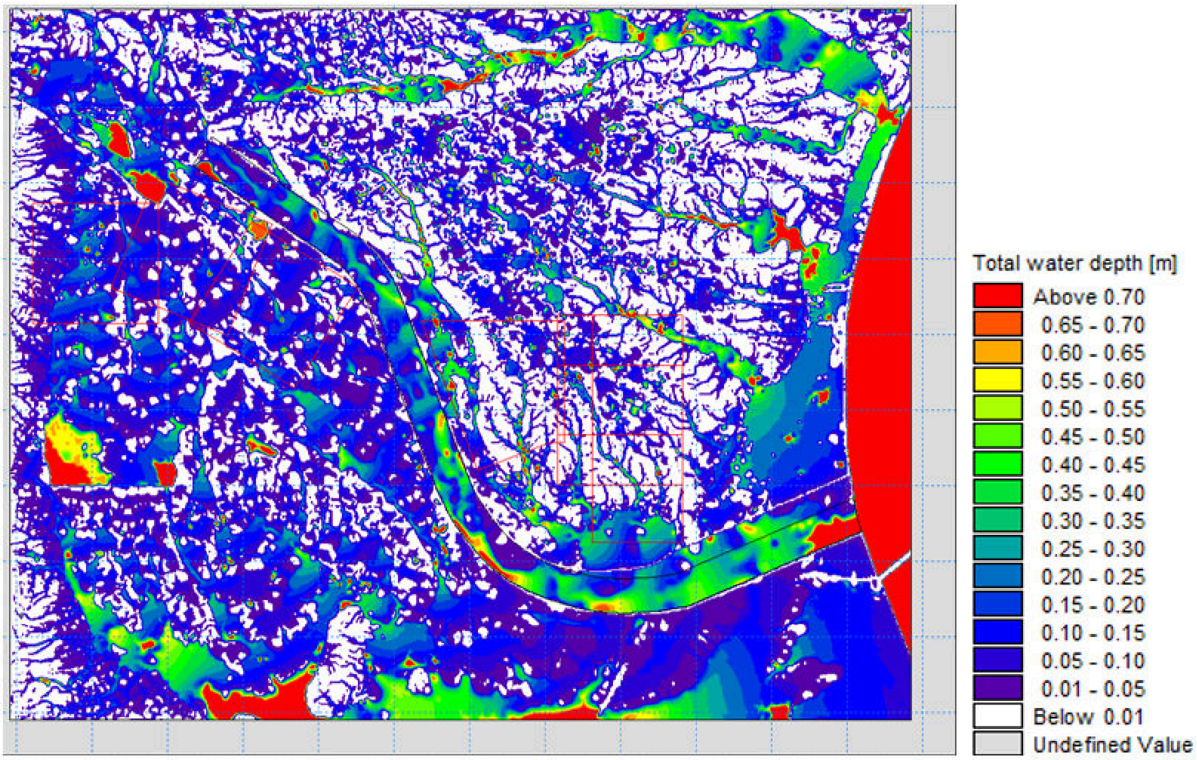

Fig. 6 Maximum flood water depth for rainfall duration of 0.5 hour (1 in 100 year)

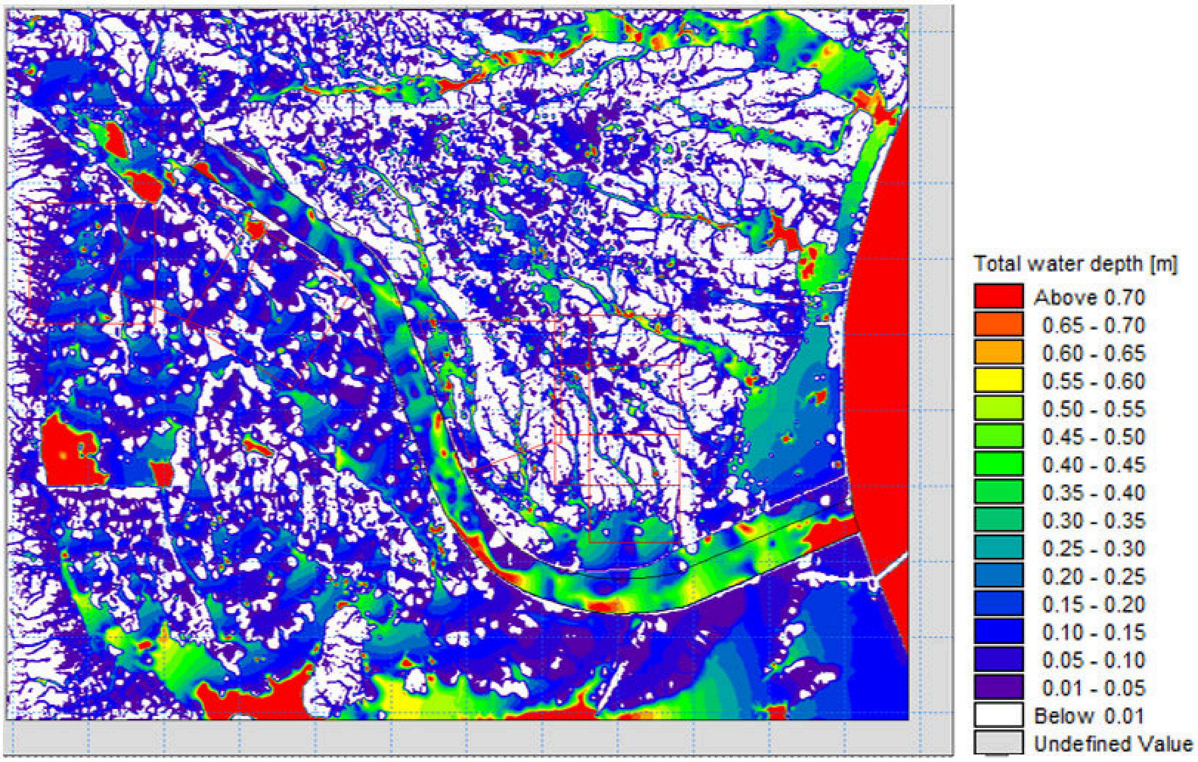

Fig. 7 Maximum flood water depth for rainfall duration of 1 hour (1 in 100 year)

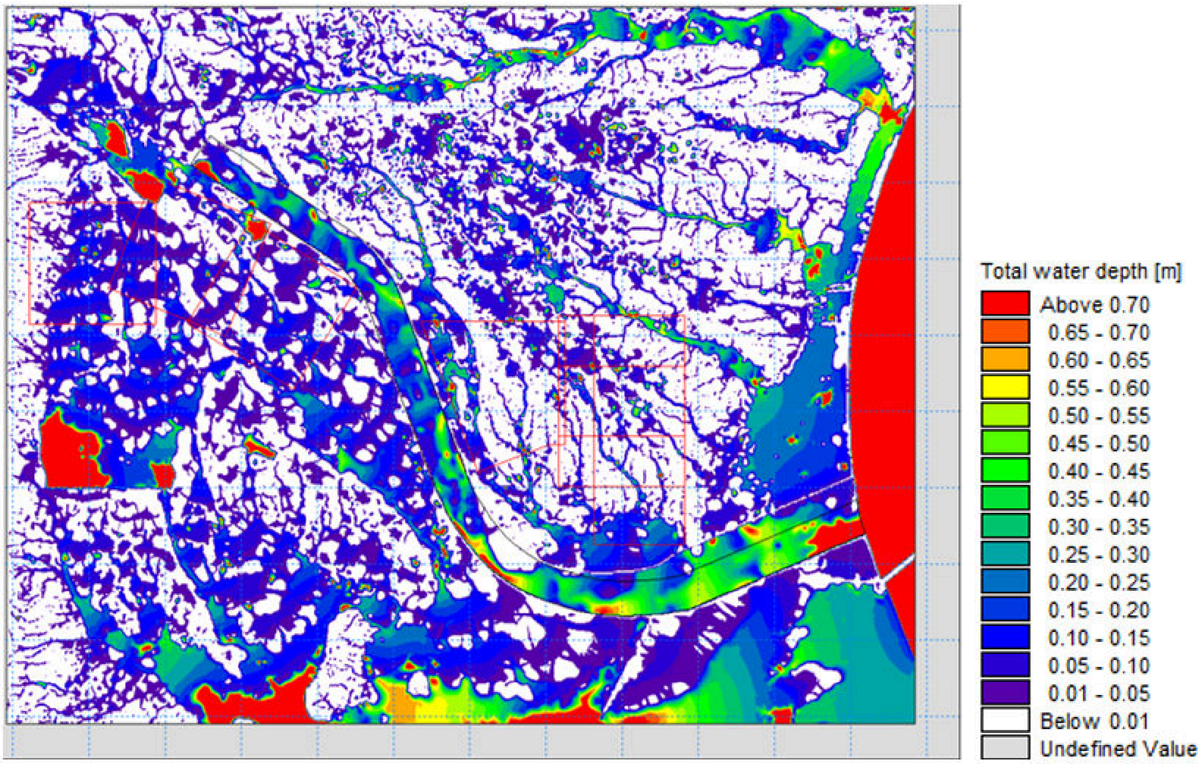

Fig. 8 Maximum flood water depth for rainfall duration of 9 hours (1 in 100 year)

6. DEVELOPMENT OF FLOOD MITIGATION OPTIONS

The numerical modelling results could be used to develop the conceptual flood mitigation options. The mitigation option along a coastal frontage might consist of raising and widening the beach crest in conjunction with the construction of a "back stop" wave wall and a buried revetment (to protect the wave wall from being undermined). The mitigation options along the other sides of the development site might include either constructing low bunds or sheet piling along the outer part of the boundary.

7. SUMMARY AND FINDINGS

This paper describes flood risk assessment, deriving of input conditions, wadi flood flow modelling in 1D, flash flood modelling in 2D and development of potential flood mitigation options. Rainfall duration of 0.5, 1 and 9 hours were considered for 1 in 10 year and 1 in 100 year return period conditions. Wadi flood flow modelling was carried out using the HEC-RAS model and the flash flood modelling was carried out using the MIKE21 Flow Model.

The findings from the modelling study can be summarised as below:

a) 1D wadi flood flow modelling
   The 1D wadi flood flow modelling suggests that the newly constructed wadi channel of 3m depth has the required flood flow capacity for 1 in 100 year flood flow.

b) 2D flash flood modelling for 1 in 100 year
   The model results for 0.5 hour rainfall duration show flooding at limited areas with maximum water depth above 0.3m but having depression areas with water depth above 0.6m. The overall flood extent and maximum water depth for 1 and 9 hours rainfall duration are less than those from the half-hour storm although flood depths in some depression areas are deeper.

c) 2D flash flood modelling for 1 in 10 year
   Flooding patterns are similar to the 1 in 100 year condition but at a lesser degree and extent.

The methodology described in this paper for flash flood modelling adopted by Royal HaskoningDHV could also be applied to similar sites around the world.

Acknowledgements

The author would like to thank Royal HaskoningDHV (an independent, international engineering and project management consultancy company, www.royalhaskoningdhv.com) for giving permission to publish this paper. The author would like to thank his colleague Debra Griffin for carrying out the proof reading of this manuscript. The author would also like to thank the external reviewers who provided valuable comments to improve this paper.

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