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Risk Assessment of Flash Floods in the Valley of the Kings, Egypt

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Synopsis

Flash floods unavoidably affect various archaeological sites in Egypt, through increased frequency and severity of extreme events. The Valley of the Kings (KV) is a UNESCO World Heritage site with more than thirty opened tombs. Recently, most of these tombs have been damaged and inundated after 1994 flood. Therefore, KV mitigation strategy has been proposed and implemented with low protection wall surrounding tombs. The present study focuses on the evaluation and risk assessment of the current mitigation measures especially under extreme flood events. Two dimensional hydrodynamic model combined with rainfall runoff modeling by using TELEMAC-2D to simulate the present situation without protection wall and determine the risk of 1994 flood. The results revealed that the current mitigation measures are not efficient. Based on the simulation scenarios, risk of flash floods is assessed, and the more efficient mitigation measurements are proposed.

Keywords: Flash floods, The Valley of the Kings, TELEMAC-2D, Mitigation measures

1. Introduction

Egypt is one of arid and semiarid Arabian countries that faces flash floods in the coastal and Nile wadi systems. Wadi is a dry riverbed that can discharge large water volumes after heavy rainfall. Recently, flash floods are extensively occurred in Egypt as shown in Table 1. There are many archeological heritages sites in Egypt, which have also been exposed to the risk of flash floods. The Valley of the Kings (KV) in Luxor is one of the most well-known and historical valuable heritages in the world. KV has more than 30 open tombs and is visited by many tourists as a tourist spot behind Giza with the pyramid after it was registered to a UNESCO World Heritage site in 1979. Since the first tombs were constructed, at least 24 historical flood events have been identified, each of which has contributed to the destruction and deterioration of the tombs. Recently, most of these tombs have been damaged and inundated after 1994 flood. In response to this flood event, the American Research Center in Egypt (ARCE) hired an interdisciplinary team of consultants to prepare a flood-protection plan. The consultants, known as the Valley of the Kings Research Group (VOKRG), conducted research and analysis of flood hazards and prepared a master plan for mitigating the impact of flash flooding. This mitigation strategy has been proposed and implemented with mainly low wall as a protection around each tomb. However, the current mitigation measurements were taken without enough hydrological studies. Therefore, risk of the current mitigation measures especially under extreme flood events should be assessed based on the enough hydrological study.

Based in the background, this paper shows the following research topics.

1) reproduce the 1994 flash flood inundation dynamics by using fully two-dimensional (2D) hydrodynamic model based on Saint-Venant equations TELEMAC-2D
2) assess the risk of flood in the Valley of the Kings with the existing protection strategy
3) propose efficient mitigation measures based on future scenarios for extreme rainfall

Table 1 Historical data of flash floods in Egypt

Date	Affected Area	Recorded Damages
2016	South Sinai, Red Sea, Sohag, Qena, and Assuit)	At least 17 dead, 50 injured and hundreds of houses destroyed
2015	Sinai, Red Sea region	Road damages
2014	Taba, Sohag, Aswan, Kom ombo	Dam failure at Sohag, road damages
2013	South Sanai	2 death, road damage
2012	W. Dahab, Catherine area	Dam failure, destroyed houses
2010	Along the Red Sea coast, Aswan, Sinai	12 death, Damaged houses and roads
2004	W. Watier	Road damage
1997	Safaga, El-Qusier	200 death, destroy roods demonstrated houses damaged vehicles
1996	Hurghada, Marsa Alam	
1994	Dhab, Sohage, Qena, Safaga, El-Qusier	

2. Study area

2.1 Outline

Thebes (known as city of Luxor) including the valley of Kings is one of the largest, richest, and best-known archeological sites in the world. It lies about 900 km south of Cairo on the banks of the River Nile. The Valley of the Kings (KV) consists of two sub-basins, the huge West Bank wadi, and in the desert west of the temples at Deir al-Bahari, called the East Valley and West Valley. The former is the better known because of the 60 tombs that have been found there. This study focuses on the East Valley (purple location in Fig. 1). The study area is located on the western side of Luxor in the Upper Egypt from 25°75’ N to 25°80’ N and longitudes 32°56’ E to 32°65’ E (Fig. 1). The area is ungagged wadi with limited data for rainfall and runoff. Post flood survey of 1994 events for the peak discharges and maximum inundation depths were reported specially at the downstream of the larger catchment. Therefore, a larger catchment area including KV basin has been considered at the beginning as a target study area, which is from 25°73’ N to 25°80’ N and longitudes 32°56’ E to 32°65’ E. The larger catchment area is 20.3 km^2 and the KV catchment area is 0.46 km^2.

2.2 The valley of the Kings

KV served as the burial place of Egypt’s pharaohs during the New Kingdom, from 1550 to 1070 BC. During its five centuries of use, 62 tombs were dug in KV. Each has been assigned a number; the first 22 were numbered by John Gardner Wilkinson in the mid-1800s. Wilkinson’s scheme assigned numbers geographically from the entrance of the Valley southward and from west to east. Since then, tombs have been numbered in order of their discovery, the most recent being KV 62 (King’s Valley tomb 62, the tomb of Tutankhamun, found by Howard Carter in 1922).

KV is a small wadi cut by torrential rains and erosion during several pluvial periods in the Pleistocene into a thick layer of limestone that lies about a discontinuous stratum of Esna shale. The Valley lies about 70 m above the level of the River Nile (140 m above mean sea level), and the immediately surrounding hills rise an average of 80 m above the valley floor. It was probably chosen as the burial place of royalty because of its geology, its relatively convenient access from the Nile floodplain, and the pyramid-shaped mountain, “the Qurn”. Fig. 3 is the picture of main road of KV. Tombs and protection walls like this picture. There are many historical valuable decorations and coffins in tombs.

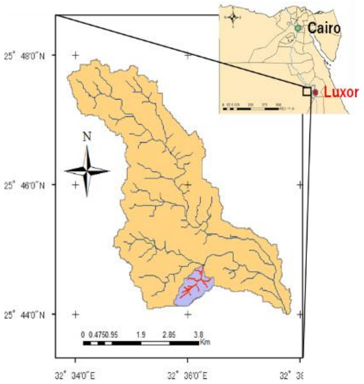

Fig. 1 Location of the Valley of the Kings (KV) study area and catchment basin

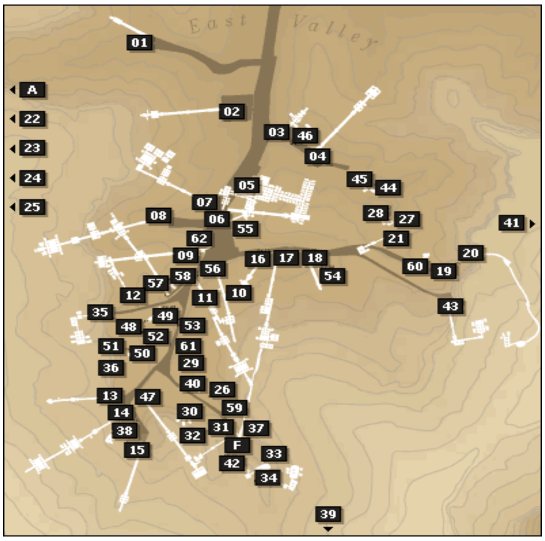

Fig. 2 Tombs code and locations of tombs

Fig. 3 The valley of the Kings

Fig. 4 The protective wall

2.3 Existing alleviation measures at the KV

The protection walls are set as the current measures to alleviate the flash floods and protect tombs to be inundated. The height of the walls is ranging from 0.75 to 1.0 m. Fig. 5 shows the location of walls and distribution of tombs. In this study, the number of tombs set to targets forty-nine.

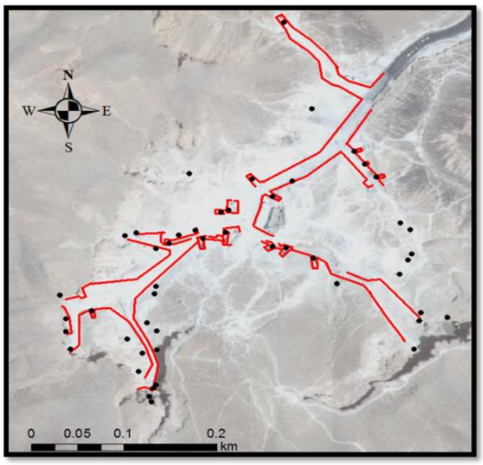

Fig. 5 Locations map of protection walls and the distribution of tomb

3 Methodology

3.1 Daily Rainfall Analysis in Luxor

The Valley of the Kings is located in the western desert with less rainfall intensity and frequencies in the basin of the Nile River in Egypt. The previous researches indicate the duration of the storm is about more than 1 to 2 hours. Fig. 6 shows a decreased tendency of the storms frequency, while the intensity of storms has an increasing tendency.

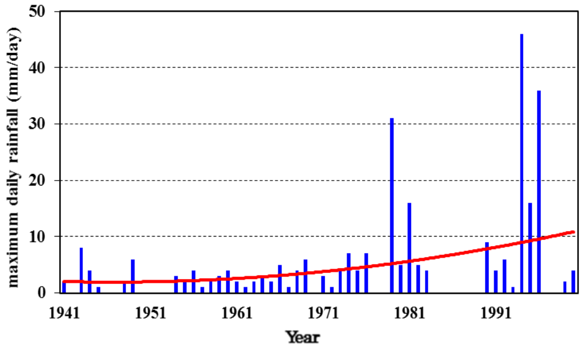

Fig. 6 Histogram of measured maximum daily rainfall at Luxor Airport (1941-2000)

Most of the storms are low intensity rainfall since 1994. However, intense rainfall storms are observed in the recent years due to the impacts of climate change. Currently there is a possibility that a storm as intense as or more intense than 1994 storm may come that may lead to catastrophic consequences especially in such touristic areas. Previous research indicates that the rainfall intensity of the 1994 storm was around 16 mm/h during two hours. Fig. 7 presents the Intensity-Duration-Frequency (IDF) curves for available rainfall data (4). This represents the rainfall intensity for the return period of 10, 50, 100, and 200 years, taking the duration of the storm on the x axis. We use these to simulate the 1994 storm event at return periods of 50 and 100 years with two hours of the duration.

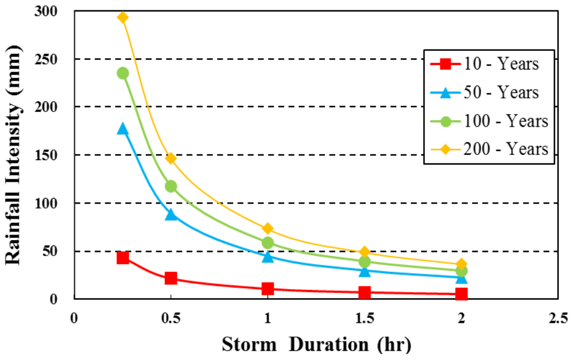

Fig. 7 IDF curves at different return period predicted by Ashraf H

Table 2: Available observed data and predicted storms

Return Periods	**1994 storm**	**50 year**	**100 year**
Rainfall intensity	16mm/h	22mm/h	30mm/h

3.2 Rainfall-Runoff analysis

TELEMAC-2D (developed by edf) is based on 2D model adopting a finite-element scheme based on triangular elements over the non-structured grids. The TELEMAC system is widely used to study environmental processes in free surface transient flows in two dimensions of horizontal space for various hydrodynamic modelling applications (dam-break, river flood etc.). The primary purpose is to simulate the dynamics of flow in a water-body via the solution of Shallow Water Equations .

The governing equations are:

Continuity

$$\frac{\partial h}{\partial t} + \vec{u}\vec{\nabla}(h) + h.div(\vec{u}) = S_h \qquad (1)$$

x-momentum

$$\frac{\partial h}{\partial t} + \vec{u}\vec{\nabla}(h) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}div(hv_t\vec{\nabla}u) \qquad (2)$$

y-momentum

$$\frac{\partial h}{\partial t} + \vec{u}\vec{\nabla}(h) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}div(hv_t\vec{\nabla}u) \qquad (3)$$

Where h is the depth of water (m); u, v are velocity components (m/s^2); Z is the free surface elevation (m); t is ti+me (s); x, y are horizontal space coordinates (m); S_h is the source of sink of fluid (m/s) and S_x, S_y are source or sink terms in dynamic equation (m/s^2) and $\vec{\nabla}$ is divergence

(1) Model development and topographic dataset

Topographical data used in this study is the Digital Elevation Model (DEM), each cell of which consists of information of the x- and y-coordinates and elevation z. The entire modeling domain was discretized using a system oh irregular triangular elements combining the mesh for the channel. The mesh for the channel was created with a default edge length of 3 m. The elevation z was assigned to nodes on the mesh using the nearest neighborhood method.

The simulation implemented by TELEMAC-2D was used to model the flood event from November 1994 in Luxor. The computational tome step was 36 seconds. Number of physical parameters are the bottom friction, turbulence model and diffusivity. Strickler’s friction coefficient was used to model the friction on the bed, which was assumed to be the same throughout the entire computation domain.

The extreme storm event with 16mm/hour rainfall intensity of duration of two hours was designed for the KV modelling. The Blue Kenue software (Canadian Hydraulics Centre) was used to create the mesh from DEM, define the boundary conditions and view the pose-processing data.

3.3 Model and Parameters Calibration

(1) Accuracy of digital elevation model

The topography data used in this study consists of the Digital Elevation Model (DEM). DEM is converted to triangular grid used in TELEMAC-2D as topographic data. Fig. 8 illustrates two different DEM accuracy, where the results are affected by such resolution differences. It will lead to some impacts on the wadi channel shitting, water movement and flood accumulation in the modelling computation.

1) The simulated flow using DEM of 30 m is a little away from the wadi channel where water will flow actually.
2) The longitudinal profile on the main channel was quite different.
3) The simulated flow using DEM of 30 m had many much discontinuous flow.

The simulated flow and depressions were different from the actual location because topographic data was roughly supplemented when DEM of 30 m was converted to Triangular grid of 5 m. Therefore, high resolution DEM is required when examining exact water distribution in small watershed like this study.

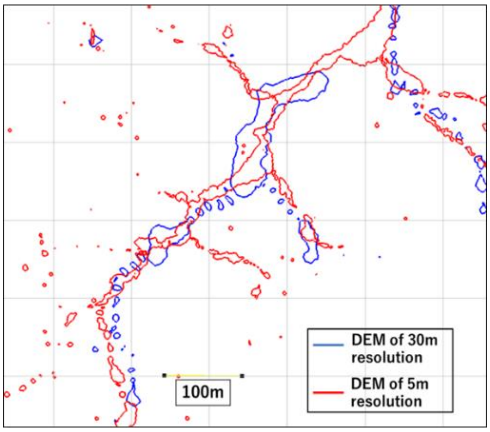

Fig. 8 Case study areas visualized on coarse and fine resolution data

(2) Setting parameters

In this area, there are few records of rainfall intensity and floods such as discharge and water depth, and topographic data such as high resolution DEM and cross sections. In 1994, there is no remote sensing data such as GSMap. According to the SCA that took mitigation measures in this area, the peak water depth in the 1994 flood event is known at two points, which is 45 cm at the entrance of KV 10 and 2 m around the Carter house downstream. Moreover, Table 3 shows KV10, KV13 KV16, KV17 KV 34, KV 35 and KV62 were flooded. Calibration is performed flooded based on this information. Parameters to be calibrated are the roughness coefficient, the porosity, the runoff coefficient and hydraulic conductivity coefficient.

Table 4 shows the fixed parameters. When the runoff coefficient was 28.5, the water depth at the entrance of KV10 was about 35 cm, which was almost same as actual water depth. Moreover, Fig. 10 shows that KV 10, KV13 KV16, KV 17, KV34 KV35 and KV62 were flooded, which matched the fact in 1994.

Table 3 The information about 1994 flood by Raphael A. J. Wüst

Name of Tomb	Inundation situation
KV10	Water depth was 45cm at the entrance
KV13	Water volume inside the tomb is more than 360 m^3
KV16	Water depth in the burial chamber is 42 cm
KV17	Water volume in the tomb is about 6 m^3
KV34	Water volume in the shaft is more than 90 m^3
KV35	Water volume in the shaft is more than 60 m^3
KV62	Water depth is unknown

Table 4: Setup the model parameters

Main Parameters	Model
Mesh size	3 m
Calculation elements	1128404
Boundary conditions	Open boundary at the DS
Strickler coefficient	70 $m^{1/3}s^{-1}$
Duration	10800 sec
Porosity	0.1
Runoff coefficient	90
Hydraulic conductivity coefficient	1.0×10^{-6}

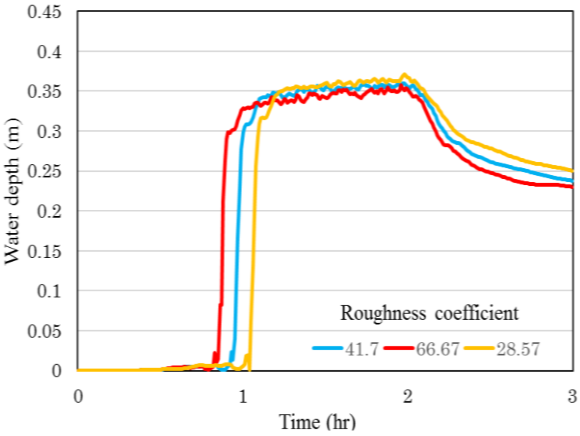

Fig. 9 Water depth at the entrance of KV10

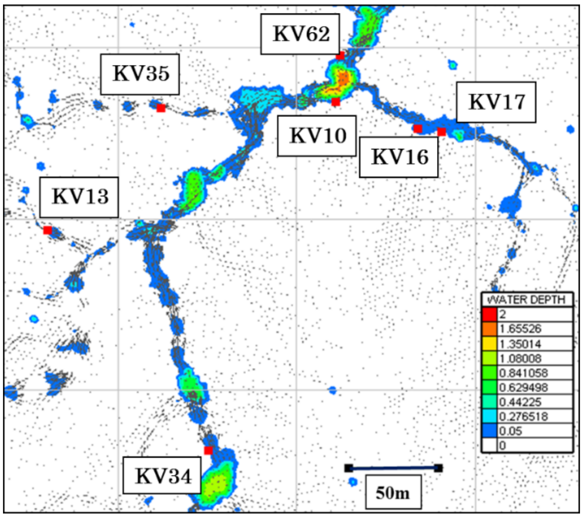

Fig. 10 The simulation result of the 1994 flood

3.4 Method of Risk Assessment

Based on the simulation results of TELEMAC-2D, it is judged whether tombs are flooded or not. The standard of whether to be flooded or not is 30 cm or more at the entrance to tombs. In addition to this, it is also judged tombs are flooded in case the water depth is not deep due to steep slope, but it is assumed that the water obviously enters tombs.

The tombs fifer in touristic value: i.e., some tombs such as Tutankhamun are famous worldwide, some have decoration and stone coffins with historical value, some are accessible to tourists with economic value, and others have less touristic value because of lacking information. Therefore, tombs should be preferentially protected considering such value when assessing the mitigation measurement.

Following four criteria were set as a method for ranking the importance of tombs.

1- **Number of publications about tombs**
2- **Number of visits by guides**
3- **Accessibility for tourists**
4- **Existence of decoration and stone coffin**

Number of publications about tombs indicates comprehensive value and name recognition. Number of visits by guides indicates popularity with tourists, that is, economic value. Table 3 shows results of the evaluation survey on the tombs.

Publication index (P_i^1) and visits index (P_i^2) are defined by the following formula using the original value of the index ($P_i^{original(1)}$ and $P_i^{original(2)}$) and the maximum in the original value ($P_i^{Max(1)}$ and $P_i^{Max(2)}$) (i : tomb code).

$$P_i^1 = \frac{P_i^{original(1)}}{P_i^{Max(1)}} \tag{4}$$

$$P_i^2 = \frac{P_i^{original(2)}}{P_i^{Max(2)}} \tag{5}$$

The importance index (δ_i) is defined by the following formula using publication index (P_i^1) and visits index (P_i^2).

$$\delta_i = P_i^1 + P_i^2 \tag{6}$$

Fig. 11 shows the rank of the important of tombs. From this, KV62, KV9, KV11 and KV17 should be preferentially protected and are called important tombs in this study from here.

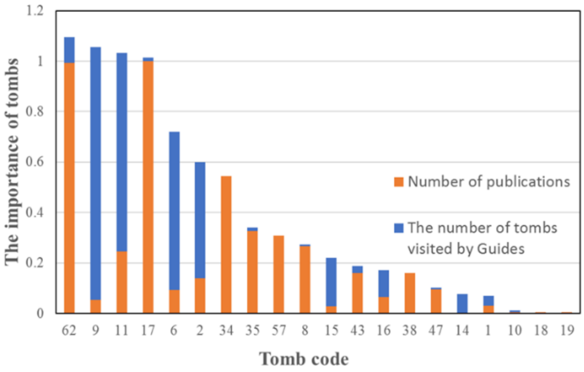

Fig. 11 Rank of the importance of tombs

4 Results and Discussions

The simulation was implemented in the area focused on the Valley of the Kings, and Fig. 12 shows the distribution of the water depth and flow patterns along with the location of tombs with the red dots. The lower left is upstream and the upper right is downstream. The characteristic of the flood event in this area is water running fast and reaching downstream in a short time. Therefore, it is difficult to take measurements to floods after it starts raining. This is a characteristic of general flash floods and this area is particularly remarkable because this area is steep and runoff coefficient is high.

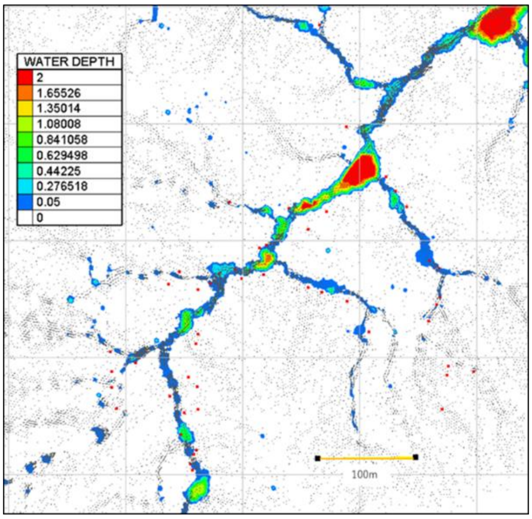

Fig. 12 Result of 1994 flood event on water depth and flow velocity

4.1 Scenarios with no Mitigation Measures

Fig. 22, 23 and 24 show the water depth distribution of 30 cm or more in the rainfall of the 1994 flood and the 100-year return period. There is a large difference in the distributions at one hour later, but the distributions are almost the same at two and three hours later although the rainfall in the 1994 flood is twice as intense as the rainfall of 100-year return period. It is assumed that this is because the topography of the valley is so steep that there is a limitation on the capacity where floodwater is stored and it goes downstream when the capacity is full. This indicates that even if the rainfall intensity is stronger, there is no big difference in the distribution of the water depth. Therefore, it is assumed that the safety to risk of floods can be secured when tombs are not damaged in the rainfall of 100-year return period. Fig. 13 shows the hydrograph at the outlet in the valley.

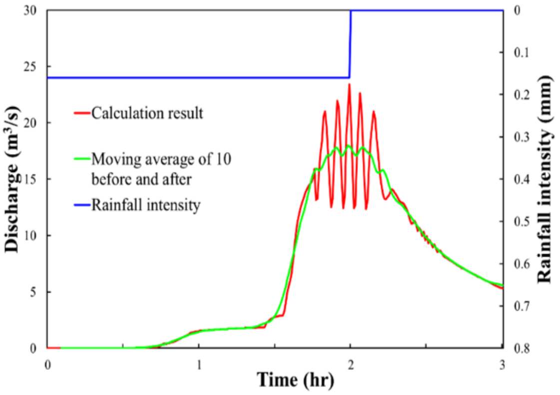

Fig. 13 The hydrograph at the outlet of the Valley

4.2 Simulation with current mitigation strategies

The simulation of the current KV was implemented by incorporating the walls into the mesh.

(1) Which important tombs are at protected from highest risk of damaging floods?

Table 5 shows whether the important tombs are flooded or not, and two of the four tombs were flooded with the rainfall of 100-year return period, and others were flooded.

KV62 is surrounded by walls and the entrance is not faced with flow and the shape of the wall is effective. However, KV62 was flooded in the rainfall of 100-year return period because water was stored in the depression in front of KV62 and overflowed the wall. KV9 don’t have the wall at the entrance and water easily flowed into KV9. KV11 and KV17 were protected by walls from floodwater because the direction of walls was proper. Therefore, the two tombs to be protected were flooded, which is the big problem. KV62 is the tomb of Tutankhamun, one of the most famous tombs in the world. KV9 has many decorations in the tomb.

Table 5 Whether important tombs were flooded

KV62	**KV9**	**KV11**	**KV17**
Flooded by 100yr R.P. flood	Flooded by 1994 flood	Not flooded	Not flooded
Problem in the height of wall	Problem in the shape of wall		Protected by wall

(2) Effects and problem of the current mitigation strategies

A detailed flow behavior and associated inundation depth are presented for some of important tombs as shown in Fig. 14 and 15. Fig.14 shows the flow from western side and southern side was blocked by the wall of KV57. The water spill over the wall because the water depth of the flow from southern side was higher than 1m. However, the tomb KV57 was not flooded as the flow diverted and did not reach to the tomb. KV58 was flooded heavily because the water was stored due to the wall with bad shape. This wall is a good example which shows walls gave bad influence. Fig. 15 shows the wall of KV62 prevented KV62 from being flooded. There were three problems about the current mitigation measures.

1) Some of important tombs which should be preferentially protected were flooded.

2) Water stored in a depression were increasing the risk of tombs flooded and can prevent workers from restoring damaged tombs after the flood event.

3) Tombs more than half of whole tombs were flooded, which is big damage.

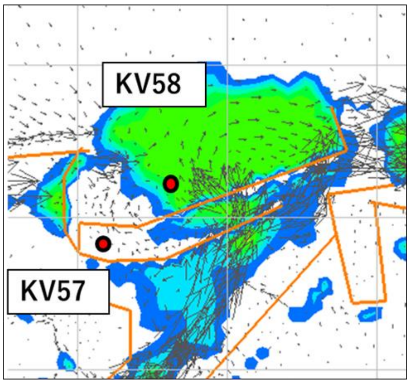

Fig. 14 Inundation around walls of KV57 and KV 58

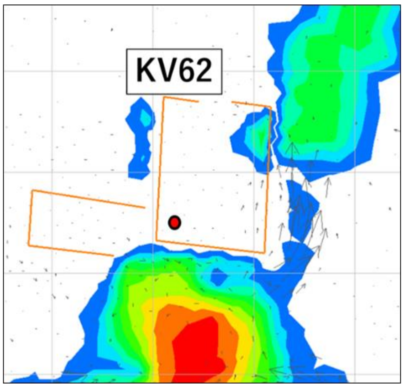

Fig. 15 Inundation around walls of KV62

4.3 Propose Efficient Mitigation Scenario

Based on the simulation result of the current mitigation measurement, the more efficient mitigation measurements are proposed.

(1) Measures for protecting important tombs (additional wall)

Flooded important tombs was KV62 and KV9. They should be protected preferentially because they have more historical and economic value than other tombs.

1) KV62

The peak water depth around the wall with the rainfall of 100-year return period is 1.4 m and the current height of the wall is 1m. Therefore, it is considered that water can’t overflow the wall when the height of the wall when the height of the wall is raised by 50 cm.

2) KV9

KV9 has no wall at the entrance, which faces the floodwater flow. The wall should have the function of blocking flow of floodwater in front of the entrance. Therefore, new wall was set like Fig. 16. Fig. 17 shows that KV62 and KV9 were protected with the rainfall of 100-year return period

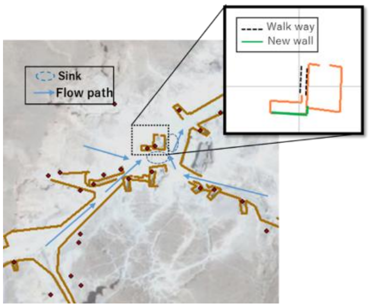

Fig. 16 New proposed measure (additional wall)

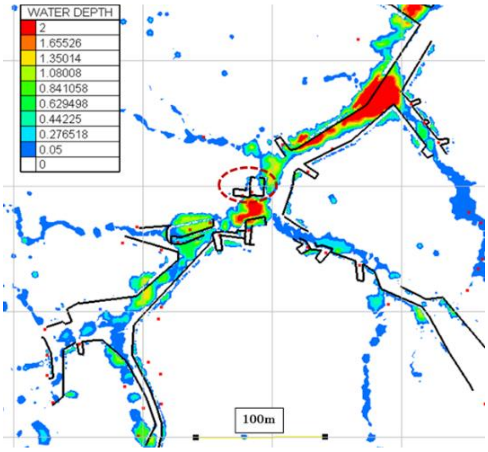

Fig. 17 The simulation result of proposed mitigation measure (additional wall) in the rainfall of 100 R.P.

(2) Measures for fundamental resolution (Reshaping wadi channel)

As mentioned before, it is problem that there are depressions causing a rise of water depth and overflow. Therefore, depressions should be eliminated so that the water can flow downstream smoothly. Using Arc GIS, depressions were eliminated. Fig. 18 shows the longitudinal profile of main channel. The simulation was conducted using this filled topography.

Fig. 20 shows the water depth degreased and water flowed downstream. As mentioned, rock forming tombs, Esna shale has the characteristic of swelling as it is exposed to moisture. It is assumed that this measure is effective because the amount of water infiltration will degrease. This simulation was conducted by filling depressions, however it was not realistic to fill depressions in the large area. Therefore, it is assumed that the combination of filling depressions removing high land and setting wall is needed.

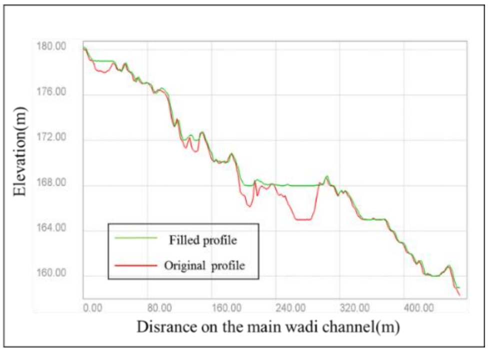

Fig. 18 Longitudinal profile of the main wadi channel

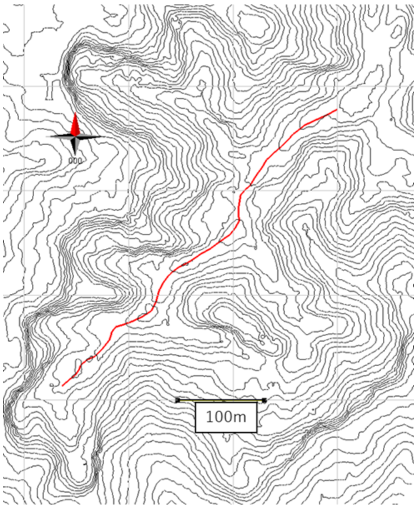

Fig. 19 Location of the main wadi channel

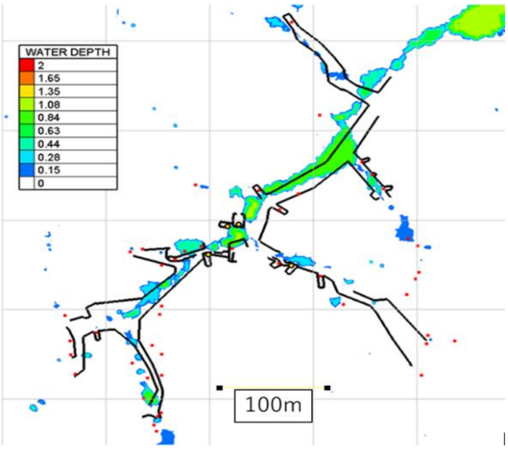

Fig. 20 The result of the scenarios of filled depression

Fig. 21 shows number of flooded tombs among different scenarios. From this, the number of flooded tombs in the scenario with current mitigation measure decreased a little compared with the scenario without measure, which indicates the current measure is effective to a certain extent. However, there are still many flooded tombs in the rainfall of 100-year return period. The number of flooded tombs in the scenario with proposed mitigation measure decreased much. It is assumed that this new measure is more effective.

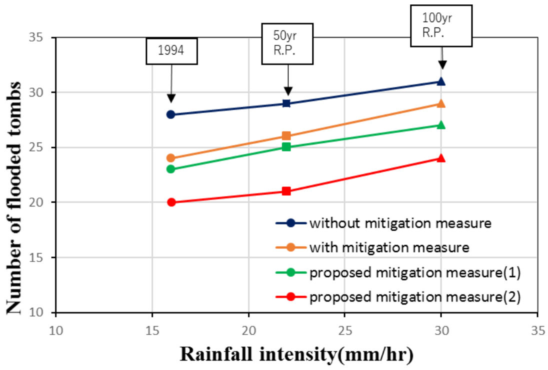

Fig. 21 Difference of the number of flooded tombs among scenarios simulated under different rainfall intensity

5 Conclusion and Outlook

Flash floods unavoidably affect various archaeological sites in Egypt, through increased frequency and severity of extreme events. In the present study, the current measures of floods in the Valley of the Kings, Egypt were assessed.

1) Tools and methods for flash floods simulation

In the present study, TELEMAC-2D model was used to capture the details of flow paths which are very complex in the real world situations. The dynamics of flow in a water-body via the solution of Shallow Water Equations are simulated using TELEMAC-2D. DEM data with 30 m and 5 m resolution were used as topographical data. Through the simulation using them, it was revealed that high resolution DEM data has the clear advantage of describing the ground surface in the Valley of the King's and fine mesh with 3 m has a better detailed results. When using Hydrological River Basin Environment Assessment Model (Hydro-BEAM), is one of the distributed models exact flow paths wasn't simulated because the depressions were filled. On the other hand, TELEMAC-2D was able to describe discontinuities of the flow in the real world situations. Moreover, since it can easily reshape bathymetry, mitigation measures can be proposed and assessed. From this, it can be concluded that TELEMAC-2D is suitable for simulating flash floods in such arid environment after calibration and validation phases.

2) Risk assessment of the Valley of the Kings

Through this study, the flood risk of each tomb in the Valley of the Kings was revealed. Moreover, it was confirmed whether important tombs with historical and economic value was flooded. Fifty-nine percent of the whole tomb was flooded and the KV62 (Tutankhamun) and KV9 (Rameses VI) which should be most protected were flooded in the simulation of the storm of 100-year return period. It can be concluded that the current measures are not enough. From this, two following measures were proposed.

1)- To rise the walls by 50cm.

2)- To fill the depressions by reshaping bathymetry.

The result of these simulations showed that the flood damage was reduced by about ten percent and important tombs were protected.

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Appendix

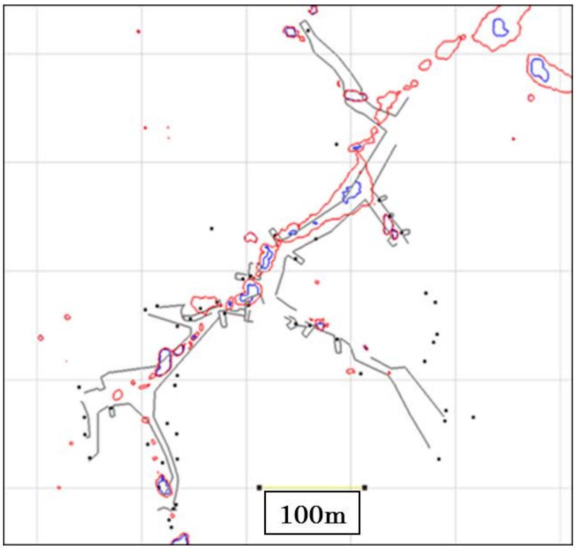

Fig. 22 Area of water depth exceeding 30 cm simulated for the flooded in 1994 (blue line) and for that of 100-year return period (red line) at one hour later from rain beginning

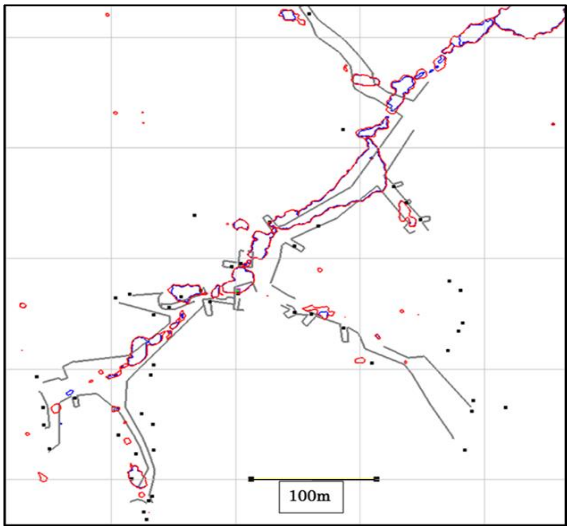

Fig. 23 Area of water depth exceeding 30 cm simulated for the flooded in 1994 (blue line) and for that of 100-year return period (red line) at two hour later from rain beginning

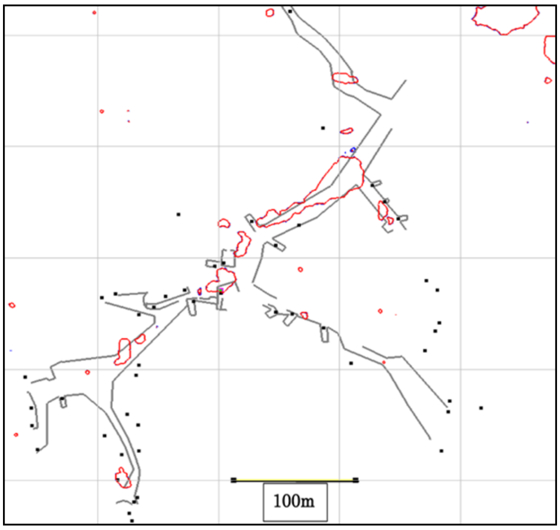

Fig. 24 Area of water depth exceeding 30 cm simulated for the flooded in 1994 (blue line) and for that of 100-year return period (red line) at three hour later from rain beginning

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