Application of GIS, Hydraulic and Hydrologic Modelling to Investigate the Changes of Flood Inundation Characteristics due to the Construction of Dams for different scenarios, case study of Wadi Elarish

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Abstract: The novelty of the research project reported in this paper is the coupling of hydrological and hydraulic modeling which are based on the first principal of fluid mechanics for the simulation of flash floods at Wadi Elarish watershed to optimize the new location of another dam rather than Elrawfa dam which already exist. Results show that, the optimum scenario is obtained by the construction of the west dam. As a direct result of this dam, the downstream inundated area can be reduced up to 15.7% as function of reservoir available storage behind the dam. Furthermore, calculations showed that the reduction rate of inundated area for 50-year floods is largely more than 100-year floods, implies the high ability of west dam on flood control especially for floods with shorter return period.

Keywords: HEC-1, HEC-RAS, GIS, Wadi Elarish, computational fluid mechanics, and Flood Inundation.

1. INTRODUCTION

The behavior of a "watershed" could be divided into two different phase. Each phase is completely different in its conditions of water flow, behaviors, parameters, and study method. The first phase, hydrological phase, within a natural unit of land which is known as watershed in which water from direct precipitation, snowmelt, and other storage collects in a (usually surface) channel and flows downward along the main stream from a point of high elevation to a point of lower elevation till it reaches the outlet station. At the second phase, hydraulic phase, the water flow is considered as channel flow from point to point, which is completely different in its characteristics, (Elhanafy, et al 2007)[1]. Some hydrological models have been applied recently to calculate the flood wave within the channel in terms of discharge verses time, hydrograph. HEC-1 as an example of these models, deals with the watershed as a lumped unit to estimate the hydrograph at the most downstream point, outlet station. It have been implement from small watersheds to a very large
scale basins such as studying the effect of renaissance dam on the Egyptian water budget (Elhanafy, et al 2015)[2].

At the end, when the water flow overcome the capacity of the mainstream of the watershed the flood occurs. The negative effects of floods are spread worldwide (Lee and Lee 2003 [3]; Hudson and Colditz 2003 [4]; Roy et al. 2003 [5]; john et al. 1992 [6]; Knebl et al. 2005 [7]; Dhital et al. 2005 [8]; WDR 2010 [9]). Many studies show that the damages of floods disasters have been increased through the last four decades (Parry et al. 2007 [10]; Alley et al. 2003 [11]; Changnon et al. 2000 [12]; Ashmore and Church 2001 [13]; Guhasapir et al. 2004 [14]; Luger et al. 2010 [15]).

Because of the negatives of floods, the governmental agencies, communities and researchers all over the world have paid more attention to this disaster. The human capabilities can not fully control the flash floods. But, flood delineation as a result of accurate calculations of flood prediction could help in the reduction of the damage resulting from flash flood event. Many studies have used hydrological models for floods prediction (Sadrolashrafi et al. 2008 [16]; Ahmad et al. 2010 [17]; Yang and Tsai 2000 [18]; Yang et al. 2006[19]; Natale et al. 2007 [20]; Salimi et al. 2008 [21]; Lastra et al. 2008 [22]; Sarhadi et al. 2012 [23]; Patro et al. 2009 [24]; Madadi et al. 2015 [25], Moawad, M.B, 2013 [26]). Many studies coupled ArcView GIS with the HEC-RAS hydraulic model to; delineate the flood plain for flood risk assessment (Abdalla et al. 2006 [27]), or to just estimate the flood plain (Earles et al. 2004 [28]).

Although, there are a lot of good studies in the area of flood modelling and calculation of Inundation, including those cited above, little investigations have been carried out to study the impact of a storage dam on the reduction of downstream inundated area as in the work done by Madadi et al. (2015) [25]. But none of the previous studies coupled the hydrologic simulation with the hydraulic routing as the research reported in this paper. This paper proposes utilizing of different models to investigate the effect of construction proposed dams on the reduction of flood characteristics at Elarish city and its borders. The final results are present on Google earth software to simplify the results in 3-d visualization.

2. Study area

Many studies consider Wadi Elarish as a real river (Hamdan 1980 [29], El Husseini 1987 [30]). Recently, a great attention from the government has been directed towards the establishment of agricultural and industrial projects in Wadi Elarish (EL-Bihery and Lachmar 1994 [31]). Unfortunately, the frequent flash floods inflicting huge economical damage and threaten any developments. Especially the main stream of Wadi Elarish divide Elarish city into two halves. To support building new communities and development in this area, Elrawfa dam was constructed in 1946 about 52 km to the south of Elarish City, to hold 3*10⁶ m³ of water (Botrous 1960 [32]). Many developments have been carried out for the dam till the storage capacity reached about 5.5 *10⁶ m³ at the end.

The destruction caused by the flash floods in January 2010 revealed the necessity to improve the system of flood protection for this area.

2.1 Location

Wadi Elarish is the largest watershed in Sinai Peninsula, Egypt, covering about 22000 km² that about one third of whole Sinai area and about 2% of Egypt. The main stream flows generally to the north for about 370 km from lat. 29° N to its outlet in the Mediterranean at lat. 31° 09' N. Most of its tributaries are mainly located in Sinai and a few others comes from the neighboring Negev Desert. Drainage network is organized in a dendritic-like pattern as shown in figure 1.
2.2 Geology
Many studies (Moawad B.M., 2013 [26], 2014, Elewa et al, 2013 [33], Abd-El Monsef 1991 [34]) summarize the geology of this Wadi based on topographic maps, Landsat ETM+ images and DEMs. They showed that Wadi Elarish gets most of its water from the gentle back slopes of El Tih and El Egma Plateaus in Central Sinai. El Egma Plateau is higher than El Tih Plateau since the highest point in El Egma is 1647 m a.s.l whereas the highest point in El Tih is 1400 m a.s.l. The plateaus are composed mainly of Eocene and Cretaceous. The strata go down in a northward direction at a very low slope and are locally dissected by minor faults and basaltic dykes. In the central part, the Wadi crosses over the Northern Sinai anticlines (e.g. Jabals Halal, Dalfa and Mitmitni) through some gorges of which gorge of El Daiyaga (the Narrow) is the most obvious. Elrawfa dam has been constructed on this main stream about 52 km south the outlet station. After the dam location towards the north three main streams from the east and one from the west pour their water into this main stream, El Daiyaga.

2.3 Meteorology
In this paper, two return periods of 50 and 100-year are taken into consideration using the available data from the Egyptian meteorological authority data for the stations that lies in the watershed. The storm of 2010 was taken into account not only because it was the worst in 100 year, but also for the calibration of the hydrological model. The analysis of the meteorological data of this storm has been studied deeply by Moawad, M.B, (2013) [26]. From the study carried out by [26], the actual rainfall of 2010 event has been taken into consideration while the rainfall is considered as 45 mm for 50 year return period, and 51 mm for 100 year return period.

3. Methodology
Providing spatial view of inundation due to flash floods is considered one of the important issues for hydrologists and watershed professionals. Therefore, the implementation of GIS in flood risk studies, flood management and floodplain mapping is becoming powerful tool for water resources applications. The research project reported in this paper starts with obtaining the DEM of the study area. Then, the hydrological simulation is carried out using HEC-WMS software to obtain the flood hydrograph at six locations.
At Elrawfa dam and downstream, outlet station on the Mediterranean Sea, which are used as boundary condition later in the hydraulic calibration in HEC-RAS model. The other four locations are Awlad Ali, Elazariq South, Elazariq North, and Hasana. These four locations are the proposed location of the dams and they actually the outlet stations of sub-watersheds as shown in figure 2 and figure 3.

Then inundation mapping for different return periods with different scenarios of dams locations are obtained and presented on Google Erath, the schematics steps are illustrated in figure 4.
3.1 Watershed modelling systems (WMS):

Watershed modelling systems (WMS) is implemented in this study to determine the flood water characteristics represented by the hydrographs in six locations. Two of these hydrographs are used for the calibration processes of HEC-RAS. The other four are used in the flood routing, and to analyze the effects of constructing additional dams at these locations.

The task of automatic extraction of drainage network was performed inside the WMS 9.1 (AQUAVEO, 2008 [35]) Software platform using the “Main Drainage Module” then through its sub-modules using the TOpographic PArameteriZation (TOPAZ) subroutine for the purpose of computing flow directions and flow accumulations for use in basin delineation with DEMs.

The watershed hydrographic criteria derived from the WMS 9.1 Software are used for the determination of flood water volume and the hydrographs which are used in the hydraulic routing in HEC-RAS.

Figure 5 represents the extracted tributaries of Wadi Elarish projected on the DEM of Sinai Peninsula using WMS.

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**Figure 4.** Methodology scheme for the visualization of floods under different scenarios.
3.2 Geographical information system (GIS)

GIS is defined as a computer system for assembling, collecting, storing, processing, integrating and analyzing the earth related information [25, 36]. Now, GIS is commonly used in different engineering disciplines especially in water quality, hydrology and hydraulics. Nowadays, advancement in the field of geographic information system has greatly facilitated the operation of flood risk and inundation mapping. Since natural hazards are spatially variables, the role of GIS is great in natural hazard management [43]. Generation a visualization of flooding and estimation probable damage due to flood are considered the most important advantages of GIS for flood studies management (Hausmann and Weber 1988 [37]; Clark 1998[38]).

In this paper, GIS is implemented to extract the necessary information from digital elevation model for input into a HEC-RAS i.e., hydraulic model and then used to map the flood inundation or current spatial extent of floodwaters due to construction of additional dams according to specified scenarios. The main software for carrying out of the hydraulic phase of this study is ArcView GIS and its extension, HEC-GeoRAS together with the HEC-RAS. The inundation maps are projected in the final step using Google Earth software. The extracted main stream of Wadi Elarish and the six locations of interest are project on DEM as shown in figure 6.
3.3 HEC-GeoRAS:

Madadi et al. (2015) [25] defined HEC-GeoRAS extension as a set of procedures, tools and utilities for the preparation of GIS data to be exported to HEC-RAS. Then, the results obtained are exported back again in a reverse direction from HEC-RAS output to be represented in GIS. It works directly with the HEC-RAS to create a geometric data file for the desired hydraulic simulation. This interface developed by the Hydrologic Engineering Center for ArcView GIS in the form of a dropdown menu in the toolbar of ArcView GIS (USACE) [39]. The computed water profiles exported from HEC-RAS are processed into HEC-GeorAS. Indeed, the HEC-GeoRAS establishes a connection between the HEC-RAS hydraulic model and ArcView GIS, allowing for excellent visualization and analysis in a form of flood plain extent, depth, and velocity. Figure 7 shows the main stream, the bank lines, flow paths, and cross sections cut lines that describe the study area which are created in HEC-GeoRAS.
3.4 HEC-RAS:

The River Analysis System (HEC-RAS) is a one-dimensional hydraulic model developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (Brunner 2010 [40]). To run HEC-RAS, all data about Cross-sectional geometry, Manning’s n values, hydraulic data, flow rates, and boundary conditions are required as input parameters. The model equations were described by Horritt and Bates (2002) [41]. The HEC-RAS model solves the Saint-Venant equations formulated for natural channels:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_i \tag{1}
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial \left( \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial H}{\partial x} + gAS = 0 \tag{2}
\]

Where: \(A\) = cross-sectional area perpendicular to the flow; \(Q\) = discharge; \(q_i\) = lateral inflow due to tributary; \(g\) = acceleration due to gravity; \(H\) = elevation of the water surface above a specified datum, also called stage; \(S_f\) = longitudinal boundary friction slope; \(t\) = temporal coordinate; and \(x\) = longitudinal coordinate. The equations are solved using the four-point implicit box finite difference scheme (Hicks and Peacock 2005 [42]).

Figure 8 shows the prospective view of the main stream of Wadi Elarish, banks boundaries, and cross sections along the main stream.
3.5 Google earth

Many studies summarized Google Earth. But as reported by [25] Google Earth is a virtual globe, map and geographical information program that was created by Keyhole Inc., a Central Intelligence Agency (CIA) funded company acquired by Google in 2004. It considers the earth as a 2-D and 3-D enhancement colored map by the superimposition of images obtained from satellite imagery, aerial photography and GIS 3D globe. Google Earth uses digital elevation model (DEM) data collected by NASA’s Shuttle Radar Topography Mission (SRTM). In this study, Google Earth is successfully used for visualization the inundated areas characteristics as shown in figure 9.

Figure 8. A prospective view of the main stream of Wadi Elarish.
4. RESULTS

Figure 10 illustrates the flood inundation area downstream Elrawfa dam under different conditions for the event flood of 2010. Panel (a) presents the flooded area with the current exist Elrawfa dam only, the other four panels from panel (b) to pane (e) represent the effect of constructing different dams in addition to the exist Elrawfa dam. So, Panel (b) presents the flooded area under the assumption of constructing a dam at Hasana, while Panel (c) presents the flooded area under the assumption of constructing a dam at Elazariq-N, while Panel (d) presents the flooded area under the assumption of constructing a dam at Elazariq-S, and Panel (e) presents the flooded area under the assumption of constructing a dam at Awlad-Ali.

While figure 11 and figure 12 represent flood inundation area downstream Elrawfa dam under different conditions for a 50 years and 100 years respectively return period storm.
Figure 10. Flood inundation area downstream Elrawfa dam under different assumptions of dam constructions for the flood event of 2010.
Figure 11. Flood inundation area downstream Elrawfa dam under different assumptions of dam constructions for a 50 years return period.
Figure 12. Flood inundation area downstream Elrawfa dam under different assumptions of dam constructions for a 50 years return period.

The downstream flood hydrographs and stages for 15 scenarios have been gathered in figure 13. The Numerical results of figures 10 - 13 are tabulated in table 1.
Table 1. The effect of different dams on the flood characteristics.

| Event    | Dam Situation | Total Flood Area (km²) | \( v_{max} \) (m³/s) | Total Flood Volume (m³) \( \times 10^6 \) | percentage (%) | Rank | \( Q_{max} \) (m³/s) downstream | \( v_{max} \) (m) downstream |
|----------|----------------|-------------------------|------------------------|---------------------------------------------|----------------|------|-------------------------------|----------------------------|
| 2010 Flood | Elrawfa       | 34.17                   | 4.46                   | 95.512347                                   | 76.20122311    | 1    | 836.15                        | 4.93                       |
|          | Elbasana      | 33.165                  | 4.46                   | 19.654353                                    | 15.48095687    | 1    | 764.99                        | 4.86                       |
|          | Elazari - N   | 34.165                  | 4.46                   | 0.59249295                                   | 0.47264939     | 4    | 835.15                        | 4.93                       |
|          | Elazari - S   | 33.876                  | 4.46                   | 8.4124125                                    | 6.7115524      | 2    | 801.02                        | 4.89                       |
|          | Awla Ali      | 34.156                  | 4.46                   | 1.1707335                                    | 0.934029237    | 3    | 834.66                        | 4.93                       |

| Event    | Dam Situation | Total Flood Area (km²) | \( v_{max} \) (m³/s) | Total Flood Volume (m³) \( \times 10^6 \) | percentage (%) | Rank | \( Q_{max} \) (m³/s) downstream | \( v_{max} \) (m) downstream |
|----------|----------------|-------------------------|------------------------|---------------------------------------------|----------------|------|-------------------------------|----------------------------|
| 100-Years | Elrawfa       | 40.546                  | 5.042                  | 145.173875                                   | 76.6563601     | 1    | 1403.59                       | 5.38                       |
|          | Elbasana      | 40.086                  | 5.042                  | 29.11322326                                   | 15.37455353    | 1    | 1269.44                       | 5.29                       |
|          | Elazari - N   | 40.541                  | 5.042                  | 0.817518792                                   | 0.46843184     | 4    | 1402.59                       | 5.38                       |
|          | Elazari - S   | 40.181                  | 5.042                  | 12.46083243                                   | 6.58059408     | 2    | 1336.77                       | 5.34                       |
|          | Awla Ali      | 40.531                  | 5.042                  | 1.734175872                                   | 0.915810066    | 3    | 1402.05                       | 5.38                       |

| Event    | Dam Situation | Total Flood Area (km²) | \( v_{max} \) (m³/s) | Total Flood Volume (m³) \( \times 10^6 \) | percentage (%) | Rank | \( Q_{max} \) (m³/s) downstream | \( v_{max} \) (m) downstream |
|----------|----------------|-------------------------|------------------------|---------------------------------------------|----------------|------|-------------------------------|----------------------------|
| 50-Years  | Elrawfa       | 34.765                  | 4.53                   | 103.8241452                                  | 79.9570158     | 3    | 886.81                        | 4.98                       |
|          | Elbasana      | 34.418                  | 4.53                   | 20.82366727                                   | 15.23453634    | 1    | 810.17                        | 4.9                       |
|          | Elazari - N   | 34.756                  | 4.53                   | 0.62764488                                    | 0.459221027    | 4    | 885.81                        | 4.98                       |
|          | Elazari - S   | 34.513                  | 4.53                   | 8.912857896                                   | 6.52643189     | 2    | 848.44                        | 4.93                       |
|          | Awla Ali      | 34.75                   | 4.53                   | 1.240397966                                   | 0.90743977     | 3    | 885.28                        | 4.98                       |

5. RESULTS AND DISCUSSION

The disaster of 2010 flood event that attacked Elarish city highlighted the inefficiency of the exiting Elrawfa dam in protecting the city against violent floods. So, there is a great need to
construct at least another dam. From the tabulated results shown in Table 1, the most appropriate dam from four suggested location is at Ehasana. The share of the total flood water volume that attacks the city is about 15% for the three events. If this dam was constructed before 2010 flood event, it was able to reduce the max flood discharge at the most downstream location from 836 m³/s to 765 m³/s. While for a 100 year return period to should reduce it from 1403 m³/s to 1269 m³/s and for a 50 year return period to should reduce it from 886 m³/s to 810 m³/s. The total flood volume estimated using HEC-WMS that implemented in this study is in a great agreement with the measured values during the flood event of 2010. This agreement gives a high confidence level for future studies for this Wadi. More future studies should be carried out to investigate the effect of increasing Elafwa dam on the reduction of the flood event. Also, due to the need of future development in Sinai, application of early warning system is needed. The research reported in this paper emphasis the importance of coupling the hydraulic and hydrologic coupling for the flood event simulations. Most of the hydrologic studies focus only on the flood characteristics calculation at the outlet station only. The novelty of coupling both models reported in this paper is of great importance since it provides the decision maker with a clear image about the flooded area before and after any suggestion of construction additional protection structures against floods. Also, presenting the overall view in Google earth interface facilitate the imagination of the effects of both the flood event and the effect of protection structures on the inundation areas.

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