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STREAM NETWORK AND BASIN BOUNDARY EXTRACTION USING GRASS GIS: EL-BARUD BASIN, SAFAGA AREA, RED SEA COAST, EGYPT *

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Abstract: The objective of this research is to explore the merits of the geographic information system (GIS) technology in a watershed characterization exercise in Safaga area on the Red Sea coast of Egypt, focusing on El-Barud watershed, the characteristics of which are among the significant factors contributing to the flash flood vulnerability resulting in extensive losses of life and properties. These characteristics are being quantified based on digital elevation model (DEM) tailored by exploiting the inter-contour areas information extracted from scanned topographic maps. Horizon, a FORTRAN program is used to extract the height information and to build the DEM at a grid spacing of 28.5 m. GRASS GIS system functionality for hydrological terrain analysis is then applied to the DEM and the most significant parameters that control the flow paths and other water borne compounds to the watershed outlet were extracted (i.e. basin boundary, stream-network, basin area, average slope, and wetness index). These watershed characteristics are then analyzed with the landuse map and the flash flood risk-prone areas are then identified. Finally, DEM and its derived hydrological products are evaluated.

The study concludes that flash flood risk-prone populated area of about 7 km² with its infrastructure and road networks as well as 45 km of the vital highway within the flood plain are frequently affected by flood hazards and mitigation practices to reduce flash flood risks need to be undertaken. The resulted watershed maps and hydrologic parameters can quickly and cost effectively help in such mitigation as well as to optimally utilize the flash flood water in a spatially explicit manner previously not available.

Key words: DEM, Watershed Analysis, Safaga Area, Red Sea Coast, Egypt

1. INTRODUCTION

Hydrological modeling is a well-developed technology and has been widely applied with the use of GIS in various research and application fields such as geomorphology, soil science, hydrology, and land use planning studies. With the ability to compute the hydrologic parameters required for modeling, a GIS helps in solving problems that are time consuming, repetitive and error prone.

The first step towards hydrological modeling is the concept of a watershed-a topographically closed area where all surface water passes through a specific outlet point. The specific physical characteristics of watersheds control the flow paths and other water borne compounds to the outlet of the watershed. Location in the stream network influences the hydrologic and therefore physiographic characteristics of any watershed. Stream network and watershed delineation from DEM is one of the essential capabilities of most GIS systems today. Watersheds and their topographic properties can be delineated in a highly accurate and faster way, giving more reliable results. GIS has been used for determining the drainage pattern in a watershed for non-point source modeling (Kao, 1992), and for simulating surface runoff from flash floods (Julien et al., 1995). DEMs are also used for computing curvature, aspect, and slope of the terrain, and are used to model, characterize, and analyse the landscape.

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and to prepare shaded relief maps and to assist in many of the
geomorphological studies (Masoud et al., 2002).

Extreme rainfall and the watershed characteristics are
among the significant factors contributing to the flash flood vul-
nerability in El-Barud watershed located in Safaga area on the
Red Sea Coast of Egypt. Unfortunately, there is a lack of appro-
priate and accurate data to serve as a basic input to GIS, except
for 1:50,000 topographic maps. Data extracted from these maps
using efficient algorithms can serve to a great extent as a base
source input upon which much GIS functionality could be
applied.

The prime objective of this research is to explore the merits
of the GIS applicability as a tool for watershed characterization
in El-Barud watershed based on DEM data extracted from topo-
graphic maps to identify the flash flood risks in the study area.
To achieve this aim some objectives have been formulated
including DEM generation exploiting the inter-contour informa-
tion derived from scanned topographic maps, watershed and
stream channel network delineation, some physical characteris-
tics derivation of the watershed under consideration. Analyzing
such hydrologic features with the landuse map digitized from
the JERS-1 OPS natural color composite to accurately identify
the flood risk-prone areas.

In the next sections, the study area is introduced and the
DEM generation algorithm from scanned topographic maps is
briefly described. Further, the procedure for delineating the
watershed and extracting its hydrological parameters is
explained. The results obtained using these computational pro-
cedures are presented and the characteristics of extracted water-
sheds contributing to the flood vulnerability are evaluated and
the flash flood risk-prone areas are characterized. Finally, the
quality of the DEM and its products are investigated and conclu-
sions are drawn.

2. STUDY AREA

The study area covers about 1152 km² and is situated in the
northern part of the Central Eastern Desert of Egypt (Fig. 1).
Figure 2 shows the location of the study area on a natural color
composite of JERS-1 OPS image obtained through processing
the raw three blue, green, and red bands of the Japanese Earth
Resources Satellite Optical Sensor (JERS-1 OPS) data covering
the study area. The area represents the strip of the Red Sea
Coastal Plain of Egypt extending from Ras Abu Soma bay in the
north to Wadi Nuqara in the south as well as the mountainous
area till Nile River-Red Sea waterdivide to the west.

The coastal plain forms a low land running parallel to the
general trend of the Red Sea and is covered by gravel and sand
deposits with a small low lying hills and hummocks ranging in
age from Mesozoic, Tertiary to Quaternary. The basement rocks
forms the mountainous areas and consist mainly of Older
Granites together with a vast array of rock units comprising
metagabbro complex, metavolcanics, Dokhan Volcanics, Young
Gabbros, Younger Granites and post granite dyke suites
(Masoud, 1997). The climate in the study area is arid, but some
torrential floods frequently occur and reach its maximum
between November and January that result in serious problems
and excessive loss of life and property. El-Barud basin of 493
km² area, named after Wadi El-Barud flowing through that basin
upon its outlet Safaga city on the Red Sea coast is located, repre-
sents the highly destructive flash flood causative basin in the
study area. This watershed basin extends from the Red Sea
shoreline till the Red Sea hills watershed divide with a topogra-
phy varying from flat in the coastal plain to highly rugged
mountains of about 1446 m height. This basin was analysed in
details and the resulted products are highlighted.
3. DEM GENERATION FROM SCANNED TOPOGRAPHIC MAPS

DEM generation in this work is based on the algorithm proposed by Noumi et al. (1999). Terrain elevation observations are derived from four scanned topographic sheet maps of scale 1:50,000 (Egyptian Military Survey, 1989) designated Safaga, Ras Abu Suma, Gabal Umm Inab and Gabal Wairah. Each scanned image is subsequently edited into a map consisting of continuous contour lines and spaces between contour lines, and pixels within spaces between contour lines are tagged with inequality constraints such that elevation must fall within the interval defined by the contour lines. The algorithm implemented in the Horizon program (Shiono et al., 2001), a FORTRAN program revised from BASIC program (Shiono et al., 1987), generate an optimized interpolated surface consistent with a large amount of the inequality constraints extracted from the scanned image is subsequently edited into a map consisting of contour lines of 28.5 m. The final DEM is good enough to simulate the original topographic maps through iteration works based on an exterior penalty function method (Zangwill, 1967). The resultant DEM preserves a local variation in the terrain as well as smoothness without abnormalities.

A topographic map illustrates a dense distribution of inequality elevation information (Fig. 3) that enables the use of the algorithm to generate a DEM consistent with the topographic map.

The basic principals of the interpolation algorithm are summarized in the following simple notations:

\[
\begin{align*}
0 & \leq f(x_h, y_h), \text{ for } P \text{ above the surface} \quad \text{...(2)} \\
0 & > f(x_h, y_h), \text{ for } P \text{ below the surface} \quad \text{...(2)} \\
\end{align*}
\]

where \( f(x_h, y_h) \) is the spot height within the closure of a contour line.

A surface satisfying the constraints will generate a DEM consistent with the topographic map.

(1) A surface \( f(x, y) \) is approximated by a set of values \( f_k (j=1,..., N_j; i=1,..., N_i) \) at each grid point.

(2) Location of outcrop \( P(x_h, y_h), z_h(k) \) provides equality and inequality constraints to the surface:

\[
\begin{align*}
f(x_h, y_h) - z_h(k) = 0 & \quad \text{for } P \text{ on the surface} \quad \text{...(1)} \\
f(x_h, y_h) - z_h(k) > 0 & \quad \text{for } P \text{ below the surface} \quad \text{...(1)} \\
\end{align*}
\]

(3) Surface determination is equivalent to a constrained optimization problem, i.e., to find the optimal solution \( f(x, y) \) such that objective function \( J(\text{smoothness of the surface}) \)

\[
J(\epsilon) = \int (\frac{\partial^2 f}{\partial x^2})^2 + 2(\frac{\partial^2 f}{\partial x \partial y})^2 + (\frac{\partial^2 f}{\partial y^2})^2 \, dx \, dy \quad \text{...(3)}
\]

becomes minimum subject to the proposed constraints.

(4) The optimization problem is solved based on the exterior penalty method (Zangwill, 1967), in which

\[
Q(f; \alpha) = J(f) + \alpha \phi(f) \quad \text{...(4)}
\]

becomes minimum, where \( \phi(f) \) is the sum of the penalty.

\[
\begin{align*}
\sum_{i} [f(x_{h_i}, y_{h_i}) - z_h(k)]^2 / N' & \quad \text{for } f(x_{h_i}, y_{h_i}) - z_h(k) = 0, \\
\sum_{j} [\max(0, f(x_{h_j}, y_{h_j}) - z_h(k))]^2 / N' & \quad \text{for } f(x_{h_j}, y_{h_j}) - z_h(k) < 0, \text{ and} \\
\sum_{k} [\min(0, f(x_{h_k}, y_{h_k}) - z_h(k))]^2 / N' & \quad \text{for } f(x_{h_k}, y_{h_k}) - z_h(k) > 0 \\
\end{align*}
\]

(5) The smoothness, \( \alpha \) is a constant called a penalty and \( \phi(f) \) is the mean of squared residuals and \( N' \) is the number of data that does not satisfy the constraints. The optimal surface is a solution of linear simultaneous equation:

\[
\begin{align*}
\mathbf{A}u &= \mathbf{b} \quad \text{...(6)}
\end{align*}
\]

(6) defined by

\[
\begin{align*}
\frac{\partial Q}{\partial f_k} &= 0 (i=1,..., N_i; j=1,..., N_j) \\
\end{align*}
\]

where \( \mathbf{u} = (f_1, f_2, ..., f_{N'k}) \).

The penalty \( \alpha \) starts from \( \alpha_{\text{max}} \) and increases exponentially to \( \alpha_{\text{max}} \). The initial data values for the first \( \alpha \) are calculated by summing the squared residuals of all of the data points that don't satisfy the optimization conditions based on the information of the inter-contour area with its surrounding contour heights, then the iteration works on a least squared residuals at successively increasing penalty until the maximum \( \alpha \) is reached and a final estimation of the surface is acquired.

(5) The simultaneous equations are solved by Choleski’s method.

The resultant DEMs are subsequently edited and filtered to remove the errors resulted from the patching process within GRASS GIS and to produce the final DEM with a grid spacing of 28.5 m. The final DEM is good enough to simulate the original topographic map.

4. WATERSHED AND STREAM MODELING

Based on DEM as distributed spatial elevation information, many common GIS algorithms were developed to address hydrologic applications for automatic delineation of drainage
pathways and runoff contributing areas, and for a vast array of hydrological applications. The most widespread and more practically used approach consists of specifying a constant critical support area, which is the minimum area required to drain to a point for a channel to form (Band, 1986; Morris and Heerdegen, 1988, Jenson and Domingue, 1988; Gardner et al., 1991; Tarbton et al., 1991; Tribe, 1992).

In order that water can "flow" across the landscape, any depressions or sinks have to be filled in as these pose problems in creating an accurate representation of flow direction and therefore accumulated flow. DEM depressions have been treated utilizing r.fill.dir module in GRASS GIS. Once the sinks in a DEM are removed by breaching and filling, watershed basin analysis including basin delineation and extraction of channel streams and the basin topographic features can be conducted.

r.watershed, a watershed basin analysis program implemented within the GRASS GIS was used and a multiple step process was enacted to define the drainage pattern and boundary of the watershed. The r.watershed module depends on the A² search algorithm reported in Ehlschlaeger, 1989, that will find the shortest path between a start location and a goal location. Every cell in the map is a goal location and represents potentially an intermediate location for other cells in the map. The edge of the map is the start location and if there were any actual pits (sink holes and lakes without outlets), those pits would be added to the start location list. Noise in elevation data does not cause any algorithmic difficulties in the A² search because the drainage of a cell is not determined until its down stream location is determined, false pits will not cause drainage flow pointers to go askew (Ehlschlaeger, 1989).

Essentially three steps were carried out to delineate the drainage network and the watershed boundary using the elevation data: assigning flow direction per cell, assigning flow accumulation values per cell, and determining the threshold flow accumulation value that best represented the drainage pattern. Applying this program to the DEM, watershed and its topographic properties were delineated and many key products such as flow accumulation, flow direction, slope length, and slope steepness maps were generated. The r.watershed module execution time doesn’t exceed 10 minutes for the study area on a 800-MHz Pentium III PC with 1GB RAM running Linux.

4.1. Stream network extraction

The fundamental concepts that deal with channel initiation can readily be found in the scientific literature (Montgomery and Dietrich, 1988, 1989 and 1992). A stream network can be extracted from a DEM with an arbitrary drainage density (Tarboton et al., 1991). The characteristics of the extracted network depend on the definition of the constant threshold area used to represent the channel sources that is the minimum.

Fig. 4: Stream network and basin boundary extraction of El-Barud basin, a) Digital elevation Model of the study area, b) Stream network, c) Shaded relief watershed map, d) Shaded relief watershed map overlain by stream network.
Fig. 5: El-Barud basin products and quality investigations, a) Wetness index, b) Flash flood risk-prone areas, and c) Watershed boundary and its stream channel networks overlaying natural color composite of JERS-1 OPS image.
drainage area upstream necessary to define a stream. High thresholds produce major streams with no fine tributaries, for this reason, we tried to extract the network directly from the flow accumulation map by using r.mapcalc module by calculating the logarithm of the flow accumulation area and taking the logarithm that is greater than a threshold value. A threshold value of 4 is found to be the best depicting the stream network distribution. Fig.4b shows the extracted stream channel networks.

4.2. Watershed delineation

All grid cells flowing towards a specific stream link constitute its watershed or drainage area. The threshold value of the accumulation grid determines the smallest watershed that may contribute to that hydrographic basin. The higher the threshold values the lower number of watershed to be extracted. Figure 4c&d show the shaded relief map of the extracted watershed and its stream channel networks.

4.3. Physical characteristics derived from DEM

Additional analysis steps were carried out to derive physical characteristics of the watershed from the elevation data, including area, elevation parameters, perimeter of the watershed, and main-channel length and slope and the wetness index. The estimated watershed area was found to be 493.36 Km² with a perimeter of 180.57 km. The watershed showed elevation variation from 0 m to 1440 m with a mean elevation of 491.17 m. Slope values for the watershed were computed and their percentage of distributions were calculated for El-Barud watershed as follows:

- 0-10 degrees - 59.32%
- 11-20 degrees - 26.55%
- 21-30 degrees - 11.10%
- 31-40 degrees - 2.74%
- > 40 degrees - 0.28%

Main-channel length of 54.568 km was calculated that is the total length of the main channel from the basin outlet to a point on the basin divide representing the watercourse that drains the longest route through the watershed area. Main-channel slope of 12° was encountered representing the average slope of the watercourse between the points at 15 and at 85 percent of the distance along the main channel from the basin outlet to the drainage divide.

Wetness index has proven to be very useful in calculating runoff hydrographs for upland catchments (Beven and Kirkby 1979; O’Loughlin 1981; Moore et al., 1991; Wolok 1993a). Wetness Index sets catchment area in relation to the slope gradient. This is basically the famous \( W = \ln (A / \tan(\beta)) \), where \( A \) is the area drained per unit contour or the specific area, and \( \tan(\beta) \) is the slope. Regions of the landscape that drain large upstream areas or that are very flat give rise to high values of the index; thus areas with the highest values are most likely to become saturated during a rain event and thus are most likely to be areas that contribute surface runoff to the stream. The watershed wetness index is derived and sites with the highest index value (18-24) are identified and located (Fig.5a). Such sites can help identifying where wells can be recharged in arid terrains that would make resources available as sustainable water management at the watershed level.

5. FLASH FLOOD RISK-PRONE AREAS CHARACTERIZATION

A landuse map with the residential areas and roads located within the watershed under investigations is digitized in a raster format from the JERS-1 OPS natural color composite. Analyzing such map with the derived hydrological products as well as field investigations in the flood plain under concern, it was found that about 7 Km² residential areas located at the watershed outlet and about 45 km of the vital highway linking Safaga City to the Nile valley are annually affected by the flash flood hazards (Fig.5b). Numerous physical injuries are possible, and public infrastructure and private property may be damaged with inundation.

The principal watershed characteristics triggering flash floods are: a) large watershed (493 km²), and so the volume of runoff would be relatively large in relation to the extreme rainfall, b) the watershed comprises mainly of hard basement rocks (more than 80%) and shallow depth soils (15%) with generally low permeability, and therefore there is no significant reduction in the amount of rainfall available for runoff, and c) dense drainage networks that permit rapid flow within the channel banks and rapid concentration of runoff onto the floodplain. Further, field investigations indicated that expanding urbanization at the watershed outlet with impervious surfaces such as roofs and roadways that compacts soils and reduces infiltration rates as well as gentle slope ground floors that are poorly drained, not elevated more than about 1 meter above ground level, and the buildings are not properly anchored to their foundation that can be swept away during flooding, are among the major contributing factors to the flood vulnerability. Furthermore, major disruptions of the road network are activated by the absence of suitable bridges and culverts where the main streams meet these roads. The properties therefore provide little attenuation of the rainfall amount or little retardation of the travel of the flood volume toward the low-lying areas.

6. QUALITY INVESTIGATIONS

The drainage pattern derived from the DEM data provided a generally representative depiction of the watershed. For the sake of DEM quality investigations, there was no accurate refer-
ence height data to compare with and the DEM quality was assessed qualitatively by comparisons to drainage patterns of a JERS-1 OPS image acquired on 15 July 1994. JERS-1 OPS natural color composite obtained from the raw three blue (0.52-0.60 microns), green (0.63-0.69 microns) and red (0.76-0.86 microns) bands, and then rectified based on ground control points extracted from the topographic maps. An overlay of the extracted drainage pattern on the natural color composite image (Fig. 5c), revealed consistency, matching and correspondence of the location of the extracted drainage patterns particularly for the major stream channels, providing confidence in the DEM generation algorithm and the watershed analysis approaches applied to the DEM.

7. CONCLUSIONS

Starting from 1:50,000 topographic maps, a 28.5 m DEM is successfully generated. Based on this DEM, a watershed analysis algorithm is applied and the watershed characteristics are derived. The resulted products are then analysed to locate sites of high probability to recharge wells and to identify the flash flood risk-prone areas. Results indicated that flood risks are confined to the residential areas with its road networks as well as the vital highway linking Safaga City to the Nile valley. Many of the problems are owed to the physical characteristics of the watershed and its floodplain. Poor infrastructure design and uncontrolled human activities ongoing at the watershed outlet have a major role in the rising cost of floods, as well as other factors such as meteorological and the hydrological magnitudes of the flood occurrence.

Based on this study, watershed and its stream network maps as well as the watershed physical characteristics can be a starting point and act as a base information that can allow watershed managers in Safaga area to quickly and cost effectively address watershed problems in a spatially explicit manner previously not available. For example, based upon these maps, the best location for building dams and culverts and recharging wells can more easily be identified in order to mitigate and optimally utilize floodwater on a scientifically realistic term.

Overall, DEM generated from scanned topographic maps is well suited for automated watershed characterization utilizing GRASS GIS. This GIS system seems to be promising tool for analyzing such high resolution terrain data, since this technique increased the capability to extract highly accurate, faster, less subjective and more reliable reproducible information that hold the promise of making hydrological research and management tasks easier and provide capabilities previously unknown.

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