Evaluation of Depression Storage Using Grid-Based GIS Model

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Abstract: *Depression Storage is a volume that must be filled former to runoff. It might be treated as a rectification parameter to adjust runoff volumes and peak discharges. A semi-distributed GIS model is constructed for watershed delineation on a pixel scale. Model simulates hydrological processes of precipitation, surface runoff and depression storage, where water balance is maintained for each pixel. The total Surface runoff is produced using (SCS – CN) method that accounts for land use, soil cover and soil type. Total precipitation is calculated based on a uniformly distributed storm over the study area. The model attempts to calculate the depression volume within the study area by using the Arc Hydro toolbox as well as the Spatial Analyst in the ArcGIS platform. Model purpose is to develop a more accurate estimation of initial abstractions due to the presence of depressions over the duration of the adopted storm event. The goal is to evaluate the effect of depressions on total surface runoff volumes and peak discharges using the model which could significantly reduce the sizing of the hydraulic structures.*

Keywords: Runoff, precipitation, Depression, ArcGIS

1. Introduction

The Digital Elevation Model (DEM) is a depiction of ground surface topography often represented via a Cartesian grid, a triangulated irregular network (TIN) or a contour-based flow net [1]. For hydrological applications, a DEM can also be used for catchment delineation and determination of its morphological parameters [2]. Most DEMs contain numerous topographic depressions, which are defined as areas without an outlet and often referred to as sinks [3]. In regular-grid DEMs, topographic depressions are recognized as an area composed of one or more adjacent cells lower than all of its surrounding cells. This creates difficulty in determining flow directions as the flow cannot continue downstream until the depressions are filled or removed [4].

The Fill Sink algorithm is used to produce a DEM with no depressions to proceed forth with catchment delineation. In order to ensure a continuous extraction of drainage network, the Fill Sink tool forces the flow direction to pass through each cell on a certain path [5]. However, if such depressions are considered, we can characterize their potential effect on the total surface runoff [6] classification model for a time series data, and then to compare the results of time series experiment to choose the best algorithm.

2. Model Assumptions

The following assumptions are considered through the model.
1) For each grid cell, properties are isometric and homogenous.
2) The total rainfall depth based on continuous rainfall event.
3) Precipitation is uniformly distributed over the study area.
4) Evaporation and Evapotranspiration are neglected during a rainfall event.
5) The model is not temporal. Therefore, the total cumulative precipitation depth is used as an input.
6) Surface water losses are estimated using the SCS-CN methodology.
7) The volume of the depression is equal to the volume is filled with different values up to highest elevation along outer perimeter of depression rather than getting drained starting from lowest cell elevation.

3. Data Collection and Assimilation

The following information are needed to carry out the assessment.
1) A projected DEM representing the land topography of the study area.
2) A projected CN map covering the extents of the study area.
3) Rainfall records from the hydrometric station.
4) A user specified threshold for the depression area in squared meters for identification purposes.

4. Methodology

A traditional approach in watershed delineation by using the Arc Hydro toolset. However, this systematic process fails to take into consideration the effect of depression storage. Since the Fill Sink tool removes all depressions to produce a hydrologically corrected DEM, the resulting stream network runs continuously until they reach the edges of the DEM used rather than getting disconnected at the location of depression, that is, all the runoff from the DEM will reach its edges.

By using this approach, the surface area of non-filled depressions and their corresponding catchments are considered in calculations of peak discharges and total runoff volumes. And these areas should be missed as the Precipitation volume (V_P) and Runoff volume (V_R) are not sufficient to fill the Depression volume (V_D).
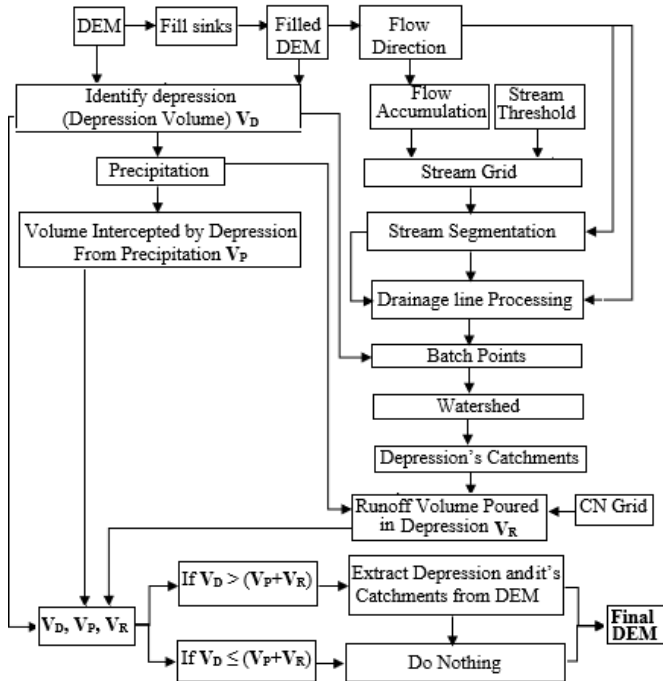
Figure 1: Revised Approach

A revised approach is proposed to avoid the inaccuracy caused by the former traditional approach. The entire model was created in the model Builder environment within an ArcGIS platform. The model automates the process of extraction and calculation of the geometric characteristics of depressions and their corresponding catchments. The workflow illustrated in Figure 1 shows that the total precipitation depth is used as defining parameter to indicate which depressions will be filled through the adopted rainfall event as it is used to compute the precipitation and runoff volumes. The output produced from the model is a rectified DEM where the unfilled depressions as well as the catchments to the upstream side are excluded. The Fill Sinks tool implements the eight directions pour point algorithm [7]. Depressions are located by using a filled DEM in combination with a Raw DEM (unprocessed Digital elevation model), Figure 2.
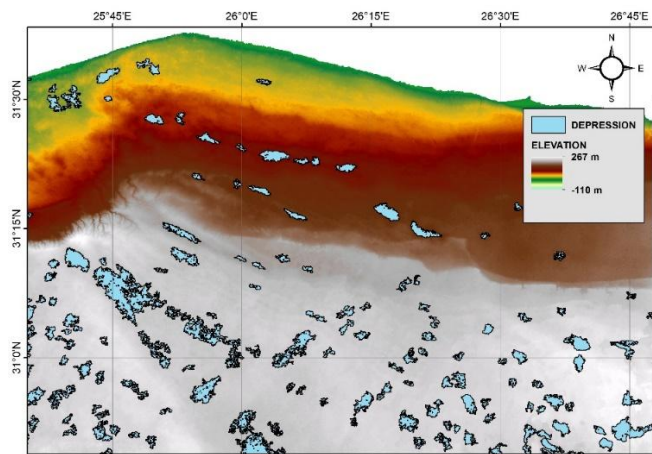

Figure 2: Depressions Allocation

Catchments contributing to depressions are delineated by Batch points generated from the intersection of the outer edge of the depressions with the drainage lines, Figure 3.
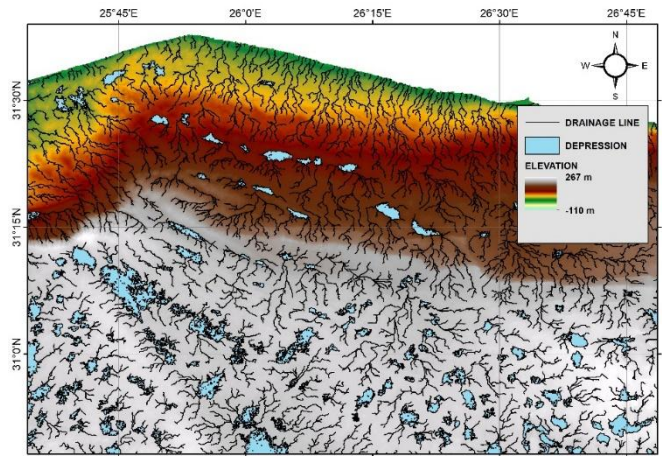

Figure 3: Depressions Drainage Lines Intersection

As a result, a delineation process illustrated in dashed box in Figure 1, takes place using Batch points to determine catchments contributing to depressions, Figure 4.
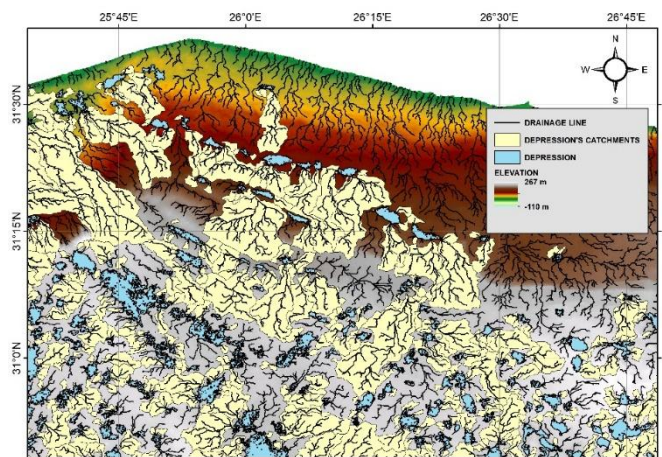

Figure 4: Catchments Contributing to Depressions

Hence, the amount of water filling the depression (V_D) is composed of two sources, the precipitation volume (V_P) and surface runoff volume (V_R). The precipitation volume is the amount of water intercepted by a depression and is calculated by multiplying the total precipitation depth with the top surface of the same depression. Similarly, the runoff volume is the amount of surface runoff generated by all catchments contributing to the depression for which, the SCS-CN methodology was adopted to calculate the runoff volume. The water balance equations can be expressed as below [8].

$$S = \left(\frac{1000}{CN} - 10 \right) * 25.4 \qquad \text{Eq. (1)}$$

$$R = \frac{(P - 0.2\,S)}{P + 0.8\,S} \qquad \text{Eq. (2)}$$

Where P is the total precipitation in mm, R is total runoff in mm, S is potential maximum retention calculated from a mapping equation expressed in terms of the curve number (CN) which is varying from dry condition (CN-I) passing through moderate condition (CN-II) to wet condition (CN-III), CN is dimensionless number ranging from (0 to 100) is determined from a table, based on land-cover, Hydrological Soil Group (HSG), and Antecedent Moisture Content (AMC). HSG is expressed in terms of four groups (A, B, C

and D), according to the soil's infiltration rate, which is obtained for a bare soil after prolonged wetting. AMC is expressed in three levels (I, II and III), according to rainfall limits for dormant and growing seasons. Finally, the summation of Precipitation (V_P) and Runoff (V_R) volumes are compared with the Depression volume (V_D) for any given depression. Two cases could result from such comparison, as follows:

1) ($V_P+V_R<V_D$) in which case, a new DEM will be produced without the unfilled depressions and their catchments, Figure 5.
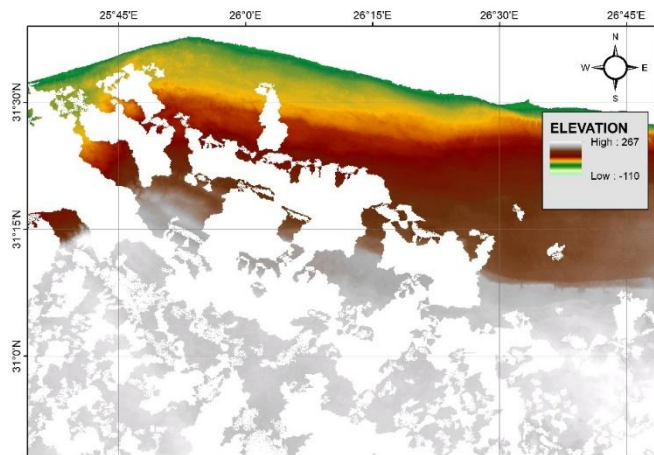2) ($V_P+V_R>V_D$) in which case, the stream net will continue uninterrupted to the specified outlet.

Figure 6: Study Area Layout

A SRTM digital elevation model (DEM) with a resolution of 90m cell size, Figure 7, which represents the cost line between Marsa Matruh and Sidi-Barrani and watershed area affecting the cost line.

Figure 5: DEM Free of Depressions and their Contributing Catchments

5. Model Application

The model is tested through its application on a study area in Egypt western desert which has an enormous number of depressions that could affect the runoff volume and peak discharge reaches specific outlets at northern coast.

Qattara Depression is one of the topographic land mark depression in this area where lies in the northern part of the Western Desert in Egypt. It is a natural depression covers about 2% of Egypt area with depth about 134 (m) below the sea level [9].

The selected area focuses on watersheds affecting the north western coastal zone of Egypt. which lies between Marsa-Matruh and Sidi-Barrani with coast length of 65 km east of Sidi-Barrani, Figure 6. Climatic conditions of the study area are characterized by a temperate Mediterranean climate. The study area is characterized by short rainy season (Nov.-Feb.). December is the rainiest month (32 mm). The maximum annual rainfall was recorded in 1989/1990-season (275mm) while the annual mean value reaches 100 mm [10].
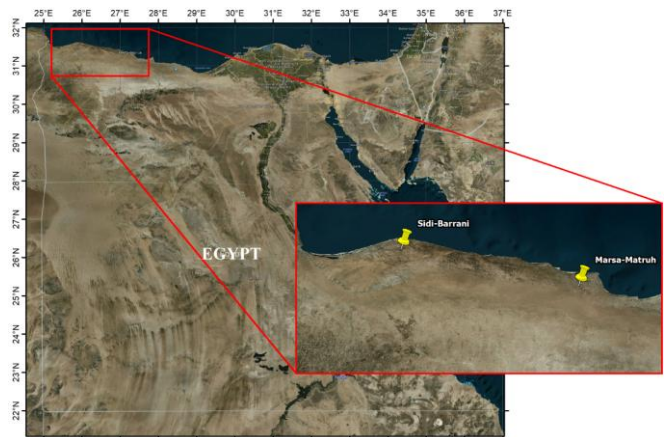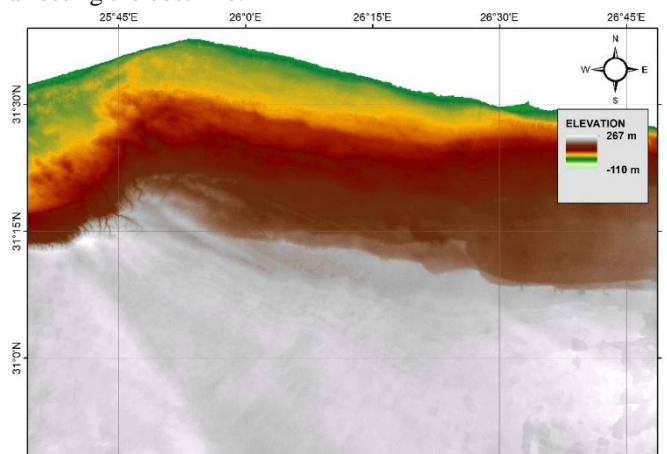

Figure 7: (DEM) of Study Area with Resolution of 90m

Also, a spatially variable (CN-II) grid of Egypt was estimated from satellite images for Egypt is used as input data for the study area which is categorized by the mountainous (reddish brown zone) of the Red Sea and South Sinai mountains, the beginning of the Great Sahara sandy soils (light blue zone) and the mixture of agriculture lands and urbanized centers in the Nile River narrow valley and Delta (green Zone) [11]. Figure 8
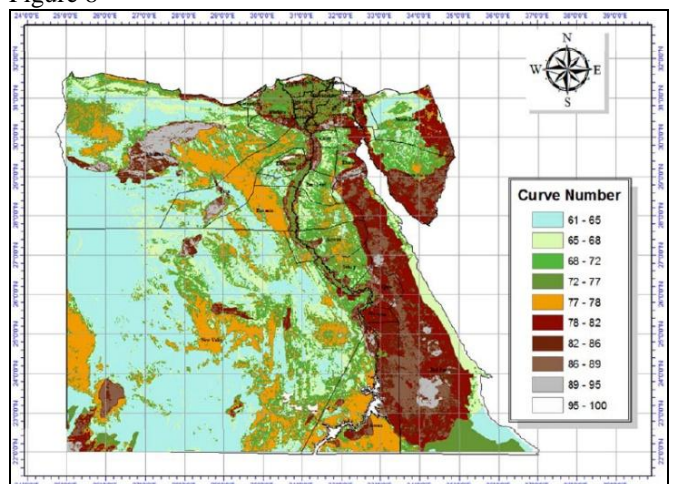

Figure 8: CN Grid Map. [11]

There is a number of rainfall gauge stations are located in north coast region. Data of Marsa-Matruh station is available in maximum daily rainfall depth (mm/day) in every year for the period (1976 – 2016). A value of 70.6 mm was taken as a rainfall depth which was the maximum rainfall depth occurred at 1989 as shown in
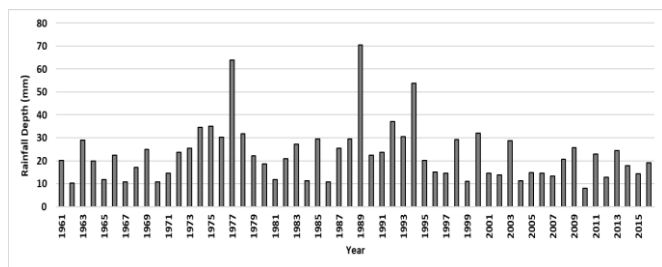
Figure 9.

Figure 9: Max. Daily Rainfall Depth (1961-2016) [12]

And 1 sq. Km is used as specified threshold for the depression area to identify the minimum depression area that will be taken into consideration through model application.

6. Discussion of Result

Peak discharges and Runoff volumes are calculated using the Hydrologic Modeling System (HEC-HMS) that simulates the precipitation – runoff processes of drainage catchments through applying SCS methodology equations. Using traditional delineation approach, about thirty catchments drain directly to the north coast line as shown in Figure 10. These catchments' areas are ranged from 20 sq. Km to 1230 sq. Km.
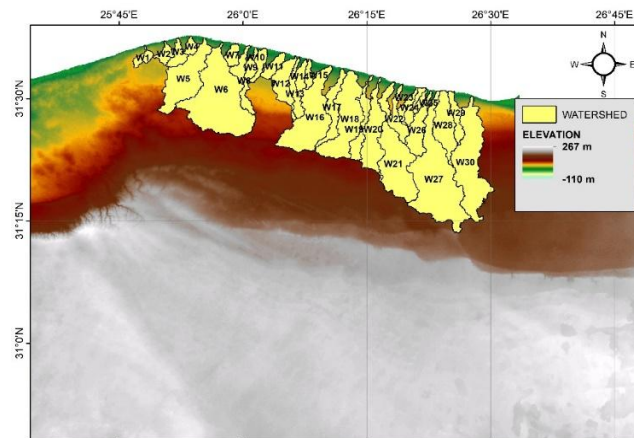

Figure 10: Catchments Generated using Traditional Approach

Revised approach is also applied on the same study area to evaluate the effectiveness of using DEM free of depressions and their corresponding catchments on determination of catchments' peak discharge and runoff volume. Figure 11. A big reduction in catchments' areas as a result of using revised approach ranged from 8 sq. Km to 157 sq. Km.

Figure 11: Catchments Generated Using Revised Approach

As shown in Figure 12, some of catchments areas are detracted by a significant portion such as W6, W12, and W27 which are the largest three watersheds in the study area. As W6 is reduced by 1053 sq. Km (87%), W12 by 550 sq. Km (95%) and W27 by 1070 sq. Km (87%).
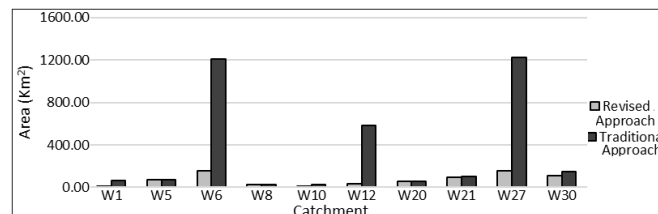

Figure 12: Catchments' Areas Using Two Different Approaches

Correspondingly, as a result of reduction in catchments' areas, peak discharges are also declined by different values such as W6 is reduced by 118 m3/sec (66%), W12 by 156 m3/sec (86%) and W27 by 88 m3/sec (73%), Figure 13.
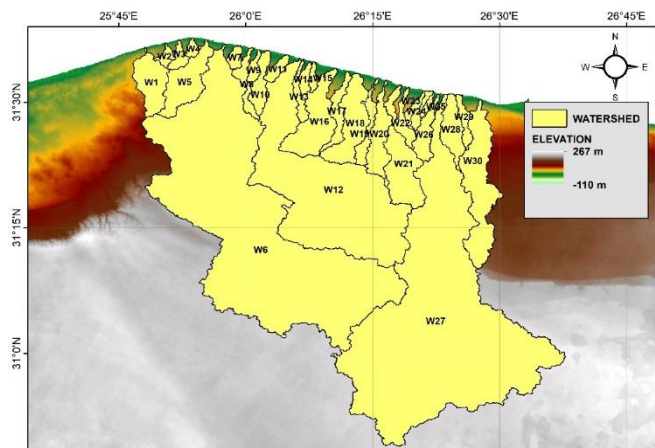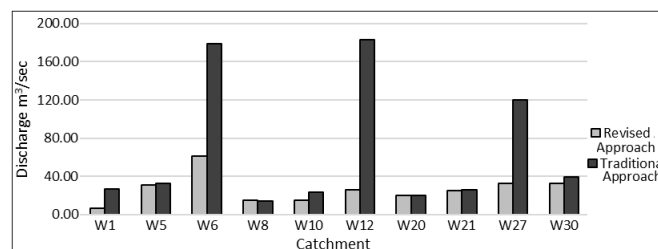

Figure 13: Catchments' Peak Discharges Using Two Different Approaches

Finally, as well as peak discharge, Runoff volume is also reduced by different amounts. as W6 is reduced by 16200 m^3 (87%), W12 by 13000 m^3 (95%) and W27 by 11300 m^3 (87%), Figure 14.
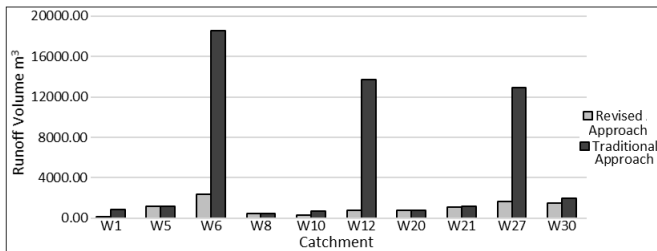
Figure 14: Catchments' Runoff Volumes Using Two Different Approaches

7. Conclusions

As presented in the previous section, the detailed results of applying the revised approach provide more accuracy in determining peak discharge and runoff volume showing better results than the traditional approach used to delineate drainage catchments. Providing DEM free of depressions and their corresponding catchments affect significantly on drainage catchments' geometrical features.

Hence it can be concluded that the proposed revised approach can be used as an engineering application on both small and large scale. In addition, it is a feasible and efficient tool for hydrologists seeking accurate drainage catchments' characteristics determination especially when depression storage is considered.

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