Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (40) No. (3) July, 2018

A GIS AUTOMATED HYDROLOGIC MODEL FOR ENGINEERING APPLICATIONS

Omar H. Zohny [1], Ashraf M. El Moustafa [2], Mohamed A. Gad [3],
1 B.Sc. Civil Engineering, Irrigation and Hydraulics Dept., Ain Shams University.
2 Professor of Environmental Hydrology, Irrigation and Hydraulics Dept., Ain Shams University.
3 Associate Professor of Environmental Hydrology, Irrigation and Hydraulics Dept., Ain Shams University.

الملخص

يطور هذا البحث نموذجا أتوماتيكيا داخل نظم المعلومات الجغرافية "**GIS**" يستهدف تطبيقات الهندسة الهيدرولوجية. وإستنادا إلى المفهوم التقني لتطوير النموذج، تم إعطائه مسمى "**STA-UH**" و هو إختصار لمسمى التوزيع المكاني للزمن- المساحة لهيدروجراف الوحدة.
يستخدم هذا النموذج في الأساس الخصائص الهيدرولوجية المتضمنة في نظم المعلومات الجغرافية تحت أدوات المحلل المكاني "**Spatial Analyst**" و التي تحتوي على العمليات الهيدرولوجية الرئيسية بداخله، وهذه الأدوات هي البوابة الرئيسية نحو تطوير هذا النموذج الذي لديه القدرة على تحديد مسارات الأودية و مستجمعات المياه المتعددة لأي خط يمثل حدود مصبات تلك المستجمعات وتحديد المعاملات الهيدرولوجية ذات الصلة (مساحة مستجمعات المياه وقيمة رقم المنحنى المتوسطة وزمن التركيز) من خلال عمليات تحليل الخلايا الشبكية واستخدام أدوات المحلل المكاني، والمعادلات الرياضية على أساس وحدة الخلية.
يتم حساب زمن التركيز للخلايا الشبكية باستخدام معادلة مانينغ التي تستند إلى تقنية تربط نصف القطر الهيدروليكي في كل خلية شبكية بخصائص منطقة مستجمعات المياه في المنبع وعمق الأمطار الفعلي.
يتم تطبيق و اختبار نموذج "**STA-UH**" في هذا البحث على حالة كبيرة هي شبه جزيرة سيناء وتظهر النتائج أن نموذج "**STA-UH**" قوي جدا ومفيد لأنه يقوم بتطبيق جميع العمليات و الحسابات أتوماتيكيا بالكامل ويتطلب الحد الأدنى من الوقت والجهد من المستخدم الذي هو ما يعتبر ملائم جدا للتطبيقات الهندسية. وتتمثل السمة الرئيسية لنموذج "**STA-UH**" في قدرته على تحديد أي عدد من مناطق مستجمعات المياه في وقت واحد بإستخدام نماذج الارتفاع الرقمية.

ABSTRACT

This research develops a GIS automated model that is intended for hydrologic engineering applications. Based on the technical concept of development of the model, it was entitled as Spatially-distributed Time Area Unit Hydrograph **"STA-UH"** model.
The model originally uses the built-in hydrological features in GIS under the spatial analyst tools which contain the main hydrological processes within it, and these tools were the main gate towards the development of this model which has the ability to delineate multiple watersheds and streams for any given downstream boundary line and determine their relevant hydrologic parameters (watershed area, weighted CN value & time of concentration) through raster analysis processes and using spatial analyst tools, map algebra and mathematical equations on cell by cell basis.
Time of concentration through the grid cells is estimated using spatially varied grid-based Manning's formula that is based on a technique that relates the hydraulic radius at each grid cell to the characteristics of its upstream watershed area and excess rainfall depth.
The STA-UH model is tested in this research on a major case study which is Sinai Peninsula and the results show that STA-UH model is very powerful and useful as it is fully automated and requires minimum time and effort from the user which is very favorable for engineering applications. The main attractive feature of STA-UH is its ability to automatically delineate any number of watershed areas simultaneously on digital elevation models.

1. INTRODUCTION

In the last decade, the problem of flash floods and its effect on infrastructure and urbanized communities has arisen severely specially in the arid and semi-arid regions where flash floods are characterized by its severity and high intensity. The main problem lies in the accurate estimation of resultant runoff discharges and flooding volumes as they are considered the base where flood mitigation/protection works are designed on and consequently the values of runoff discharges and flooding volumes affect significantly the types and sizes of mitigation/protection works against flash floods, this means that both of safety measures required for infrastructure facilities, urbanized communities, roads….etc. and economical perspectives are directly affected by accurate estimation of runoff discharges and flooding volumes affects. Runoff discharges and flooding volumes are the result of Rainfall/Runoff transformation process. This process can be estimated through rainfall and discharge measurements or be simulated through Rainfall/Runoff (Hydrologic) modeling. Rainfall/Runoff (Hydrologic) modeling is the most commonly used approach to simulate the process of rainfall/runoff transformation. The first and main step to develop a complete hydrologic model is the delineation of watersheds affecting the downstream boundary line of interest (i.e., road centerline, project boundary….etc.) and the determination of their relevant hydrologic parameters (watershed area, weighted curve number (CN) values and time of concentration). The time and efforts required to carry out this step by using the currently available models (i.e. GIS Arc Hydro Tools, WMS…etc.) become more significant especially when large and many watersheds are considered (e.g. a roadway drainage project) with spatial diversity in their hydrologic characteristics. Because of the above reasons, the need to develop an advanced hydrologic model for engineering applications has emerged. Automation, simplicity and accuracy are main requirements that should be available in the developed model. Also, it should be able to simulate any number of watersheds simultaneously to save the hydrologic design time.

The following sections present the development of the STA-UH model and application on test cases from semi-arid regions. Additionally, technical details including the ability to handle many watersheds simultaneously are briefly presented.

2. BACKGROUND

The STA-UH model is based on the time-area (TA) technique which is very similar to the concept of distributed modeling in the sense that it is able to consider the variation of sub-watersheds arrival times at the hydrologic system outlet. The time-area (TA) technique is based on using isochrones (contours of equal travel time to the outlet), this technique was implemented when Clark (1945) combined the TA diagram with a linear reservoir at the catchment outlet in order to find the unit hydrograph, however this technique was not applied practically when first demolished due to computer unavailability and the difficulty in constructing accurate isochrones since this process is very complex and time-consuming when carried out manually.

This technique can compute volumetric runoff hydrograph at the watershed outlet and it considers routing effect due to different arrival times at watershed outlet, as well as it can be used to determine unit hydrographs for watersheds due to the effect of one unit excess rainfall, but the main disadvantage of this technique is that it cannot consider the significant spatial variation in the hydrologic characteristics of each sub-watershed (area between isochrones) as it considers that each sub-area contributes to the runoff as one whole unit regardless of the runoff variation inside this sub-area.

Many efforts have been made to violate this disadvantage by introducing geographical information system (GIS) for spatial discretization of the watershed into an interlinked system of grid cells (Muzik, 1996; Maidment et al., 1996). Nowadays, it is the common practice to represent land surface elevations over the watershed by grid cell digital elevation models (DEM). Standard algorithms are available in GIS which can use the local terrain slope to connect each cell with one of the neighboring cells along the steepest path, and hence creating a 1D flow network over the entire terrain surface.

Maidment et al. (1996) showed that this terrain representation can be utilized for runoff estimation under spatially varying, but time/flow-invariant, velocity field. The linear system response at the watershed outlet can be decomposed spatially into a set of cell based linear systems where the sum of their individual response functions results in the actual response of the watershed. The work done by Maidment (1993) was one of the initial attempts to introduce GIS techniques to use travel length grid in determining a travel time grid for watersheds. Maidment (1993) used the velocity equations presented by Sircar et al. (1991) to estimate travel time. Ajward and Muzik (2000) tried to introduce a flow-dependent travel time calculations (hydraulics based) and a spatially weighted curve number (CN). Chiang et al. (2004) tried to take the rainfall intensity effect in travel time estimations based on spatially varied manning's relationship that relates the flow at a grid point to the flow accumulation value (i.e., the number of accumulating upstream cells). The intensity dependent travel times were used to construct the TA instantaneous unit hydrograph however channel geometry remains a main problem in Chiang et al. (2004) technique.

3. MODEL DEVELOPMENT THEORY

The model builder under GIS Arc Map software is used to develop an automated model that has the ability to delineate multiple watersheds through raster analysis and using spatial analyst, map algebra and mathematical equations on cell by cell basis. The developed model has the ability of using simple input data to produce the required outputs in very small time with high precision as it originally uses the built-in hydrological features in GIS under the spatial analyst tools which contain the main hydrological processes within it in an automated work frame and these tools were the main gate towards the development of this model.

The concept of carrying out cell by cell raster calculations and analysis in the developed model facilitates the application of spatially varied analysis on the terrain data and hence spatially distributed unit hydrographs is no longer a complicated issue to develop and apply in engineering applications.

STA-UH model consists of more than 50 main and secondary processes and the following subsections will present in details the development of the STA-UH model and its main processes and features.

3.1. INPUT DATA

The required input data for the STA-UH model are:

Digital Elevation Model (DEM): is the main input data in the model, as it holds the terrain elevation data, and it is used to determine watersheds based on terrain elevations and grid cell flow directions in addition to different morphological parameters and is used to carry out cell by cell based hydrological processes. It can be either based on SRTM or GDEM data with different resolutions (i.e., 30x30m & 90x90m) or developed based on Lidar or topographical data (i.e. digitized maps, topographical survey,…etc.).

Downstream Boundary: is a feature line data that represents the line of interest that requires flood protection (road center lines, infrastructure projects boundary….etc.) where all watershed outlets are determined on it based on the locations of intersection between streams and this boundary line, this feature data must be in shapefile format.

Curve Number (CN) Grid: is a raster data that represents the spatial variation of CN values (losses coefficient) for the terrain data (DEM) used in the model based on soil maps and land use maps (H.A. Hakeem et al, 2013).

Manning's Grid: is a raster data that is required in the model to represent spatial variation of manning's roughness coefficient values for the terrain data, and this data is used in grid-based velocity calculations using manning velocity equation (Manning, 1889).

Raster Cell Size: is a required value field to determine the cell size of all raster analysis processes and grids in the model.

Catchment Area Threshold: is a required value field to specify the value from which a watershed should be considered and delineated, which means that watershed area below the specified value will not be delineated and will be ignored, also this value determines the density of streams network inside the delineated watershed as it represents the value above which a stream is considered.

3.2. MAIN PROCESSES AND COMPONENTS

As previously mentioned, the model uses the built-in main hydrological processes provided by spatial analyst tools which are Fills sinks, Flow direction, Flow accumulation, Stream Link in addition to the following processes and components developed inside model builder using mathematical equations and conditioning map algebra:

3.2.1. Slope along flow directions

Based on the follow direction process, if the output drop raster option is chosen in the flow direction command, an output raster is created showing a ratio of the maximum change in elevation from each cell along the direction of flow to the path length between centers of cells and is expressed in percentages where this ratio represents the terrain slope between grid cells along flow directions.

3.2.2. Area Upstream Grid

The Area upstream function uses the flow accumulation grid and multiplies it by the grid cell area, to create a raster grid representing the accumulated watershed area contributing to each cell.

3.2.3. Watershed Outlets Grid

Watershed outlets grid is a raster grid which is created based on the intersection between the boundary layer and the stream link grid to create a grid containing unique values for the watershed outlets which are required to be delineated based on the selected watershed area threshold value, this raster grid is very important as it acts as the pour points data required for the delineation of watersheds, as these pour points are the outlet junctions for the streams network identified from the flow accumulation and stream link processes. The cell resolution of the watershed outlets grid is based on the raster cell value defined in the input data.

3.2.4. Watersheds Grid

Watersheds grid is a raster grid that represents the delineated watersheds at the outlet junctions determined by the watershed outlets grid, this grid is created using watershed process by using both the flow direction grid and watershed outlets grid which is used as the pour points data as previously mentioned.

Each watershed is given a unique ID value based on the unique values of the watershed outlets determined in the watershed outlets grid mentioned previously.

3.2.5. Spatially Varied Hydraulic Radius Grid

The Spatially varied hydraulic radius grid is a raster grid created within the model based on an approach which assumes that there is an intrinsic relationship between the hydraulic radius at any grid cell to the hydrologic parameters of the watershed area upstream of this cell (Gad, 2012). This relationship can be expressed in the following form:

$$R_i = 0.1\, A_{i-us}^{0.23} P_{i-e-us}^{0.45} S_{i-us}^{0.028}$$

Where:
R_i = hydraulic radius at point of interest, m.
$A_{i\text{-}us}$ = accumulated area upstream the point of interest, km^2.
$P_{i\text{-}e\text{-}us}$ = average excess rainfall depth upstream the point of interest, mm.
$S_{i\text{-}us}$ = average slope of the watershed upstream the point of interest, %.
0.1 = constant, S.I. units.

The spatially varied hydraulic radius grid is calculated using grid math, conditioning and other hydrologic operations within the model based on the area upstream grid, average slope upstream the grid cell and excess rainfall depth.

3.2.6. Velocity Grid

Velocity grid is a raster grid that is generated among the processing in the model using grid math and applying manning's velocity formula (Manning, 1889) and using the spatially varied hydraulic radius grid, slope along flow directions grid and manning's grid. The unit of the generated velocity grid is meter per second.

The manning's velocity formula to estimate the average velocity of flow for each cell is follows:

$$V_i = \frac{1}{n_i} \, x \, R_i^{(2/3)} \, x \, \sqrt{S_i}$$

Where:

V_i = average flow velocity, m/s.

n_i = average manning's roughness coefficient.

S_i = longitudinal slope (m/m).

The velocity grid will be used in the travel time calculations as each cell of the generated grid represents the average flow velocity at this cell based on the uniformly distributed excess rainfall depth.

3.2.7. Travel Time Grid

Travel time grid is a raster grid generated among the processing in the model using grid math and flow length process which calculates the distance covered by each cell to reach the outlet point and applying the following travel time equation:

$$\mathrm{T} = \frac{\mathrm{L}}{60\mathrm{V}_i}$$

Where:

T = travel time, min.

L = flow length, m.

V_i = average flow velocity, m/s.

60 = conversion factor.

Where a weighted flow length is calculated on the cell by cell basis following the downstream measurements towards the previously defined watershed outlets and the weight given to the flow length is the reciprocal of the velocity (velocity grid) in order to generate a travel time grid, where each cell distance along flow direction is multiplied by the reciprocal of the velocity value at the same grid and the total weighted flow length generated at the cell represents the travel time of this cell to the watershed outlet point.

Figure (1) shows a schematic diagram for the processes inside STA-UH model, whereas Figure (2) shows an example of the raster grids generated inside the model.

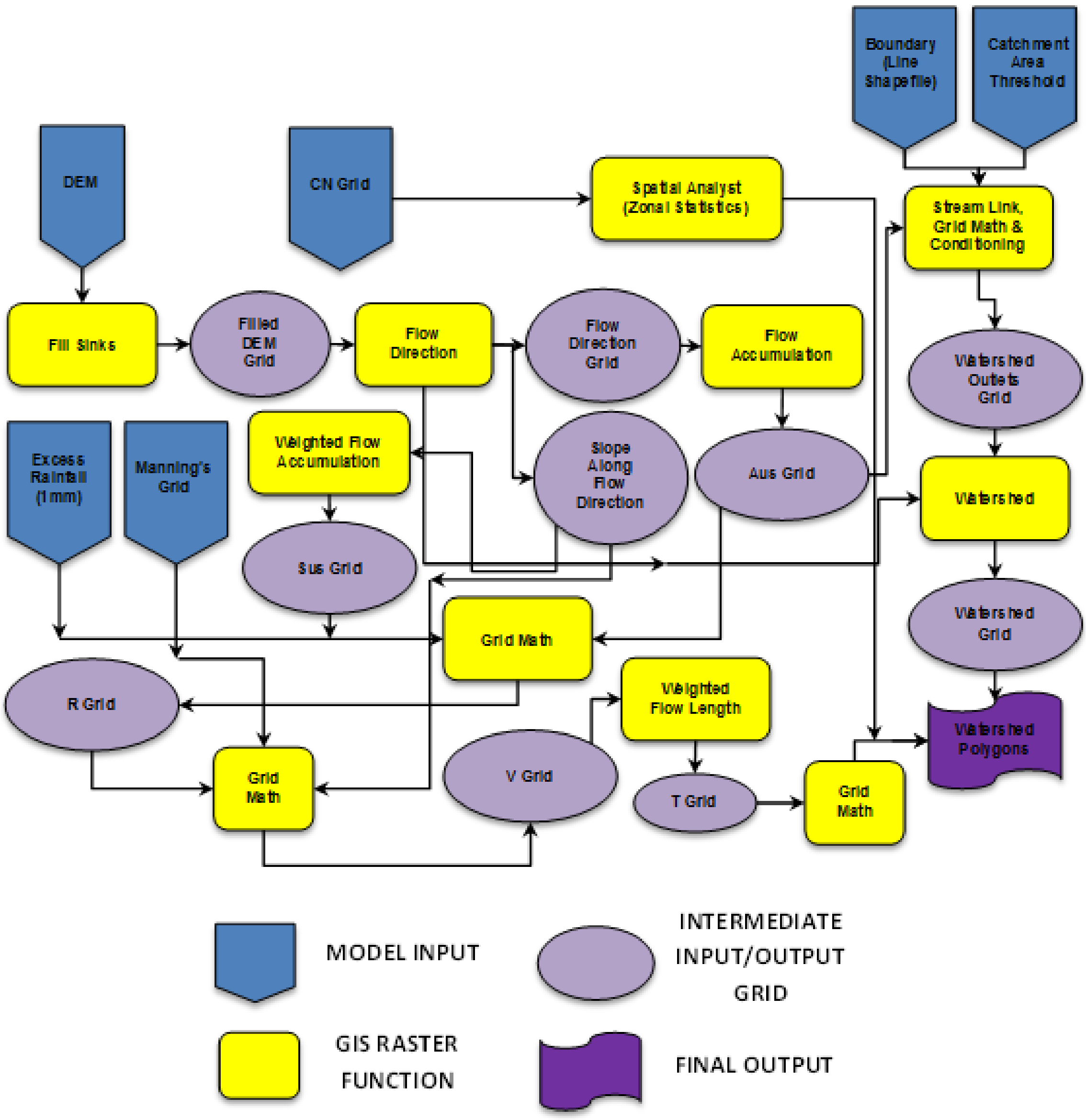

Figure (1): Schematic diagram for the processes inside STA-UH model

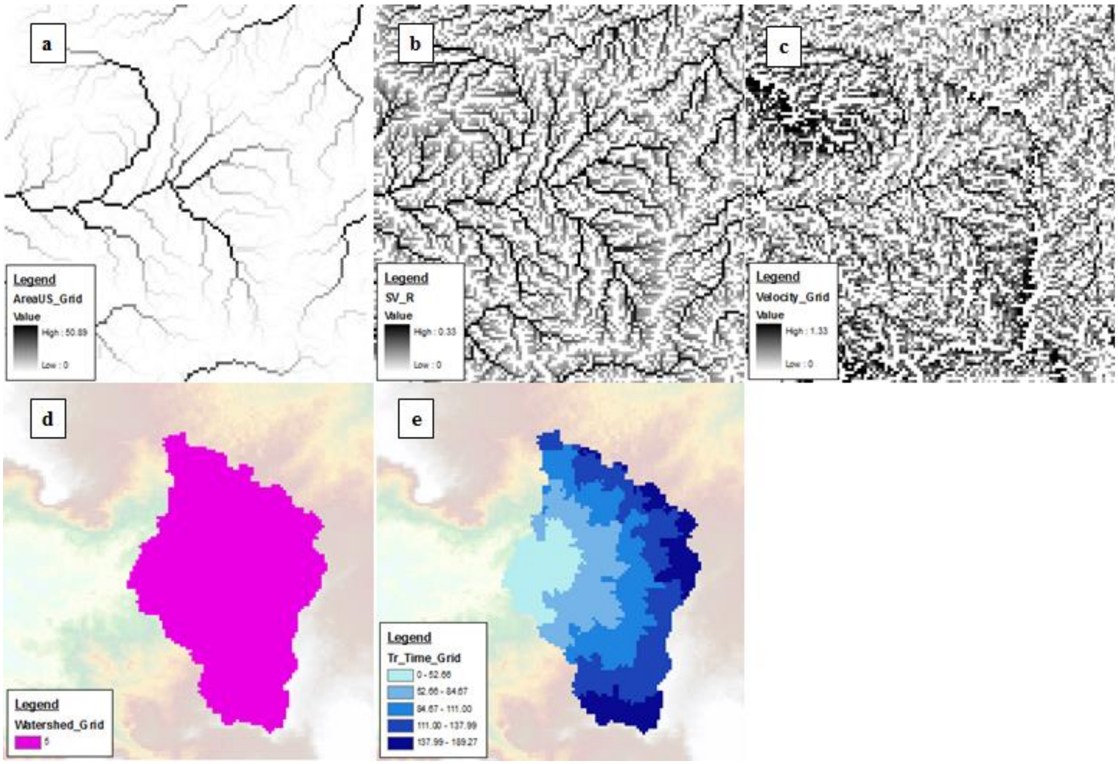

Figure (2): Example of the raster grids generated inside STA-UH model. a) Aus Grid (Km^2), b) RGrid (m), c) VGrid (m/s), d) Watershed Grid and e) TGrid (min.)

3.2. MODEL OUTPUT

The STA-UH model outputs can be summarized in the following:

- Watersheds shapefile with attributes table containing the estimated hydrological parameters from the model for each watershed which are:
    1. Watershed ID.
    2. Watershed Area (km^2).
    3. Watershed weighted CN value.
    4. Watershed time of concentration (min.) which is estimated as the largest travel time inside the watershed from the travel time grid.
- Streams network shapefile based on the catchment area threshold determined in the model.

Figure (3) shows sample of the model outputs.

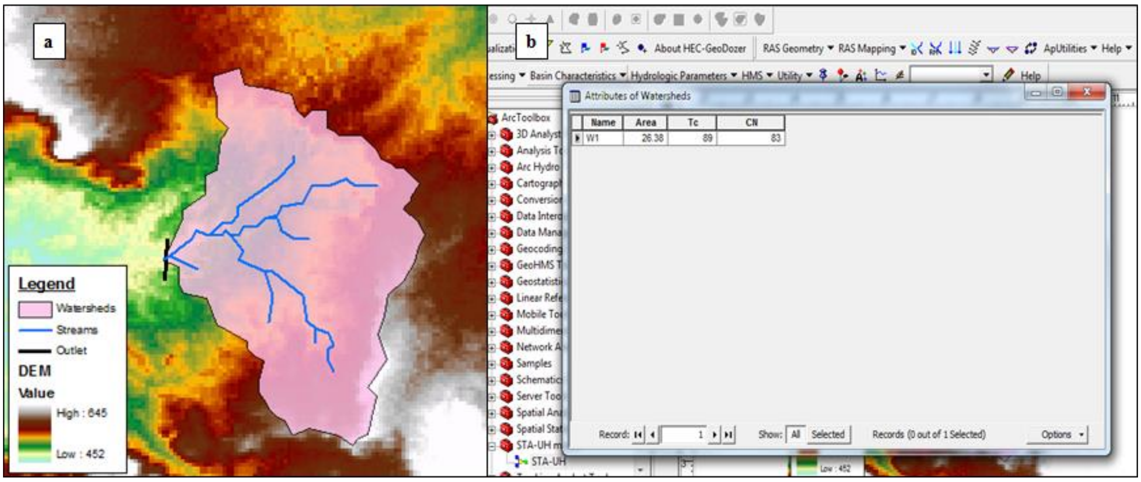

Figure (3): Sample of the STA-UH model outputs. a) Watersheds & Streams shapefile and b) Watersheds attributes table

4. MODEL APPLICATION

Model application is the final process to apply the developed STA-UH model to case studies to demonstrate the capability of the model to delineate any number of watersheds simultaneously and determine their different hydrologic parameters.

In order to fully evaluate the functionality, advantages and runtime of the STA-UH model, a major case study was chosen to be simulated using the developed model which is the Sinai Peninsula.

Sinai Peninsula is a huge area of about 57,250 km^2 that is characterized by mountainous areas and large number of watersheds that are disposing to the Mediterranean sea, Suez Gulf and Aqaba Gulf.

A SRTM digital elevation model (DEM) with resolution of 150m cell size and a spatially variable CN grid estimated from satellite images are used as input data in this case study as shown in Figure (4). In addition, a normalized value of 0.03 is used as manning’s roughness coefficient, a catchment threshold area of 25 km^2 and a boundary line shapefile is used surrounding the whole Sinai Peninsula adjacent to the sea and two gulfs side to ensure representing the downstream boundary of all watersheds in the Peninsula.

The results will be presented in the following section.

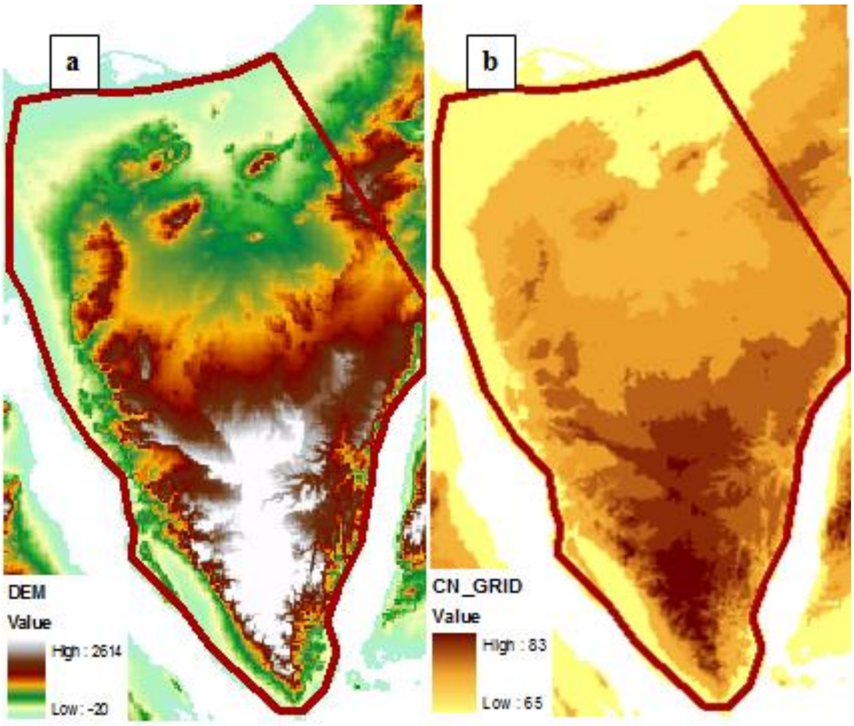

Figure (4): STA-UH input data used to simulate the whole Sinai Peninsula. a) DEM (m) and b) CN

5. MODEL RESULTS

The STA-UH model carried out all the analysis and processes (more than 50 processes) using the previously mentioned input data in a duration of 8 minutes and 15 seconds on an ordinary Core i5 Laptop @ 2.67GHz processor-6Gb RAM.

The results of simulating the whole of Sinai Peninsula for a total area of 57,250 km^2 are shown in Figure (5) which shows the simulated watersheds (128 watersheds) with their labels, whereas Figure (6) shows the attributes table containing the estimated hydrological parameters for each watershed.

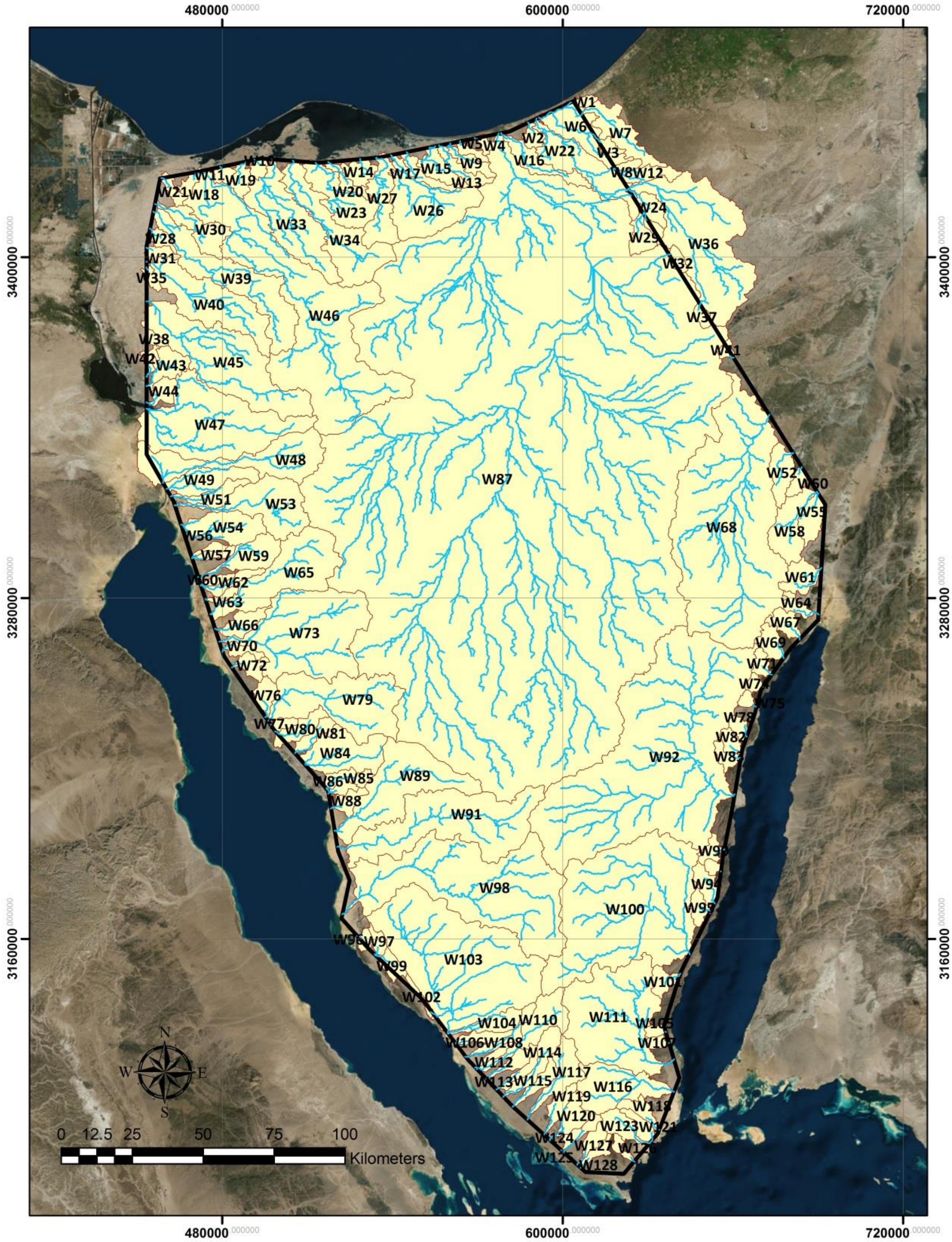

Figure (5): The 128 watersheds automatically simulated by STA-UH for Sinai Peninsula

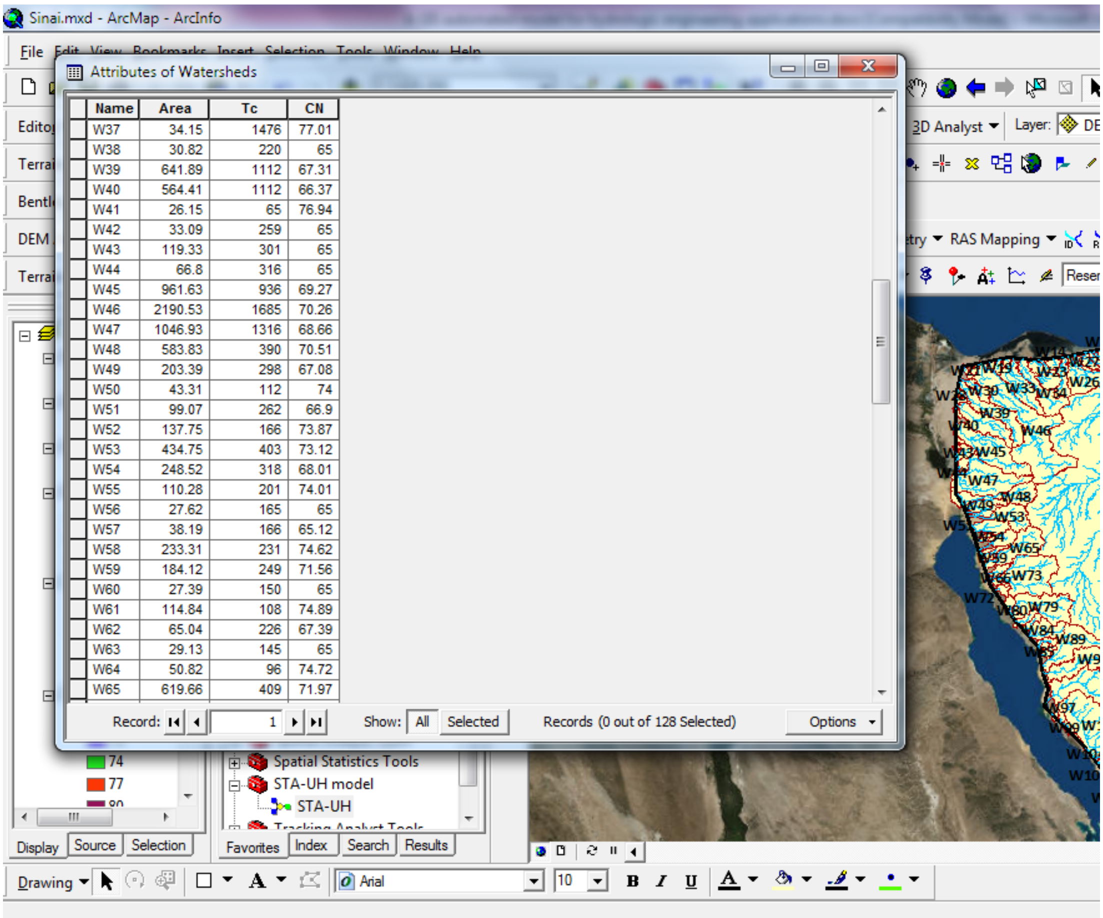

Figure (6): The attributes table containing the hydrological parameters for each delineated watershed in Sinai Peninsula

6. CONCLUSION

As presented in the previous section, the detailed results of applying the developed GIS model using the semi distributed time area technique proved its applicability in hydrologic modeling showing better results than the traditional hydrologic modeling techniques used to delineate watersheds affecting any boundary or line of interest and determine their relevant hydrological parameters, as the automated model proved its powerful capability to simulate an extremely large domain and determine all watersheds affecting the selected boundary line few minutes, hence it can be concluded that STA-UH model is a very useful model to be used in real time engineering applications on both small and large scale. In addition, it is a feasible and efficient tool for hydrologists seeking accurate and quick watershed determination especially when many watersheds are considered.

7. REFERENCES

1. Ajward, M.H. , Muzik, I., (2000), A Spatially Varied Unit Hydrograph Model. Journal of Environmental Hydrology (8), paper no. 7.
2. Chiang, S., Tachikawa, Y., Takara, K., (2004), Rainfall-runoff simulation by using distributed instantaneous unit hydrograph derived from applying flow accu-mulation. Annual Journal of Hydraulic Engineering, JSCE (48), 1–6.

3. Clark, C.O., (1945), Storage and unit hydrograph. Transactions of the American Society of Civil Engineers 110, 1419–1446.
4. Gad, M.A., (2012), Flow velocity and travel time determination on grid basis using spatially varied hydraulic radius. Journal of Environmental Informatics In preparation.
5. H.A. Hakeem et al, (2013), Uncertainty analysis of infiltration models in arid regions, 2: 1-12 & 4:35.
6. Maidment, D., (1993), Developing a spatially distributed unit hydrograph by using GIS. HydroGIS 93, edited by K. Kovar and H. P. Nachtnebel, publ. no 211, pp. 181–192, International Association of Scientific Hydrology, Wallingford, England, UK.
7. Maidment, D., (1993), Handbook of Hydrology. McGraw-Hill, Inc., New York.
8. Manning, R., (1889), "On the flow of water in open channels and pipes". Transactions of the Institution of Civil Engineers of Ireland. 20: 161–207.
9. Sircar, J.K., Ragan, R.M., Engman, E.T., Fink, R.A., (1991), A GIS based geomorphic approach for the digital computation of time-area curves, In: Proceedings of the ASCE Symposium on Remote Sensing Applications in Water Resources Engineering, May.