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A useful automated rainfall-runoff model for engineering applications in semi-arid regions

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ABSTRACT

This research develops a useful GIS-based automated Semi-Distributed Time–Area model (SDISTA) that is intended for engineering applications in semi-arid regions. SDISTA is a simple model that reconsiders the time–area technique using an improved approach that deals with each grid cell as a completely independent hydrologic unit. Travel times through the grid cells are estimated using a spatially varied grid-based Manning's formula that relates the hydraulic radius at each grid cell to the characteristics of its upstream catchment area and excess rainfall depth. SDISTA is tested in this research on cases from semi-arid regions including Sinai Peninsula. The results show that SDISTA can be as accurate as HEC-1/HEC-HMS using a very dense network. SDISTA is fully automated and requires minimum effort from the user which is very favorable for engineering applications. The most attractive feature of SDISTA is its ability to automatically delineate and simulate any number of catchment areas simultaneously on digital elevation models.

1. Introduction

Rainfall-runoff modelling (i.e., watershed modelling) tries to simulate the process of transforming rainfall hyetographs into runoff hydrographs. A number of hydrologic models are available with different degrees of complexity and accuracy. The available rainfall-runoff models can be divided into three main groups: the lumped models, the semi-distributed models, and the complicated distributed models. Starting from the simplest rational method to the most complicated distributed models, all models have limitations and advantages. The rational method, developed by Kuichling (1889), is a very simple method that has been subject to many modifications. The rational method determines the peak discharge and cannot determine the hydrograph. In addition, it suffers from inaccuracies when applied in larger catchment areas or areas of significant diversities in slopes or land cover. For example, considering a watershed that varies from steep slopes upstream to mild slopes downstream, the rational method may underestimate peak discharge if applied on the whole lumped watershed, while if applied on a part of the upper sub-catchments it provides a bigger value. This can be explained due to the high rainfall intensity obtained from the IDF (Intensity-Duration Frequency) curves using the quick travel time of the upper sub-catchment (although the area is much less). However, the main problem in the rational method is that it cannot simulate the transformation behavior of the catchment area (i.e., transformation of rainfall into runoff considering the differences in the arrival times of the system sub-catchments at the outlet). On the other side, distributed models break the catchment area into grids (array of cells) and treat grid cells as small hydrologic units where hydraulics is used to perform mass balance and energy/momentum in and between the grid cells (Kouwen, 1988; Jain et al., 2004; Liu, 2004; Moretti and Montanari, 2007; and others). Although distributed models seem attractive, they require computation time and data. For example, when the catchment area is large (order of more than 1000 km^2) and broken into high resolution grid (SRTM data for example), distributed models failed to satisfy engineering applications because of the unacceptable run time taken on personal computers especially if parameters optimization is involved. This requires significant downgrade of the resolution to satisfy run-time requirements. In addition, channel geometry, required as input to distributed models, are not available in semi-arid regions. Because of the above limitations of the simple and complicated groups, the semi-distributed rainfall-runoff models are still the most widely used for engineering applications. Examples of such models are HEC-1/HEC-HMS flood hydrograph packages (developed by the Center of the US Army Corps of Engineers). HEC-1 implements the unit hydrograph concept (i.e., the watershed response concept) where the watershed hydrologic system is broken down into components (i.e., network

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sub-divisions and reaches) of determinable responses that can be estimated using a few hydrologic parameters. The hydrologic parameters are calculated from the topographical and land cover characteristics. A significant limitation for this type of models is the time taken by a hydrologist to construct the network structure and to extract the hydrologic parameters of the system components. The time required to prepare HEC-1 input becomes more significant in larger catchment areas with significant spatial diversity in the hydrologic characteristics especially when many catchment areas are considered (e.g., a road drainage project). Because of the above reasons, the need to develop a rainfall-runoff model for engineering application in semi-arid regions (mostly ungauged) has emerged. Automation, accuracy, and simplicity are main requirements that should be available in the model. It should also be able to simulate any number of watersheds simultaneously to save the hydrologic design time. The following sections present the development of the Semi-Distributed Time Area (SDISTA) model including the implementation of a spatially varied hydraulic radius for travel time calculations, verification, and application on test cases from semi-arid regions. In addition, technical details including the ability to handle many catchment areas simultaneously are briefly presented.

2. Background

SDISTA is based on the old time–area (TA) method using isochrones (contours of equal travel time to the outlet). This idea goes back decades when Clark (1945) combined the time–area diagram with a linear reservoir at the watershed outlet in order to find the unit hydrograph. This concept was not implemented practically at this time because of computer unavailability and the difficulty in constructing accurate isochrones since the process is very time-consuming manually. The work done by Maidment (1993) was one of the first attempts that introduced GIS capabilities to determine a travel time grid (i.e., travel time to the outlet) from a travel length grid. Maidment (1993) used the velocity equations described by Sircar et al. (1991) to calculate travel time. Ajward and Muzik (2000) tried to include a discharge-dependant travel time calculations (based on hydraulics) and a spatially averaged curve number (CN). Chiang et al. (2004) tried to take the effect of rainfall intensity in travel time calculations based on a spatially varied Manning's formula that relates the discharge at a grid point to the flow accumulation value (i.e., the number of accumulating upstream cells). The intensity-dependent travel times were then used to construct the time–area instantaneous unit hydrograph. Channel geometry remains a problem in the technique of Chiang et al. (2004). In summary, the focus of the above studies was to determine a global unit/instantaneous hydrograph of the whole catchment area at its outlet, thus, assuming spatial uniformity of the excess rainfall when determining a convoluted hydrograph resulting from a real storm. Although loss parameters were taken spatially variable in some of the above studies but they were eventually spatially averaged over the catchment in the application stage to arrive at a single excess hyetograph to be convoluted with the TA unit/instantaneous hyetograph. The model presented in this paper differs from preceding trial in the way it deals with the problem. SDISTA does not develop a global time–area unit hydrograph at the outlet, but it deals with each grid cell as an independent hydrologic unit (i.e., has its own excess rainfall and unit hydrograph).

3. Model theory

The time–area (TA) technique is very close to distributed modelling in the sense that it is able to consider the differences in the arrival times of the sub-catchments at the system outlet. SDISTA implements the TA concept in a new approach which is to apply the unit hydrograph convolution on the cell level. This means that an excess rainfall hyetograph is obtained for each cell using a spatially variable soil loss method. The cell excess hyetograph is then applied on the cell mini-unit hydrograph to determine the mini-hydrograph resulting from this cell. Accordingly, the number of cells' mini-hydrographs are equal to the number of cells in the digital elevation model (DEM) that contribute at the watershed outlet. The determined mini-hydrographs are lagged according to their travel times to the outlet then, combined using timely superposition to produce the total hydrograph. In order to handle many watersheds, the digital elevation model (DEM) is swiped and each cell is assigned a number representing the watershed it belongs to. This way, a cell mini-hydrograph is combined with the corresponding hydrograph at its outlet. SDISTA uses Manning's formula to calculate travel time. Grid-based slope in Manning's formula is determined along flow directions while the hydraulic radius is determined in terms of the upstream catchment area, upstream excess rainfall depth, and upstream average slope. The following subsections present in detail the development of SDISTA model.

3.1. Spatially varied Hydraulic radius

There are many empirical formulas to calculate the time of concentration from topographic and/or rainfall characteristics (Wanielista et al., 1997). These formulae suffer from limitations either regional limits or limits of application in terms of the size of the catchment areas and slopes. In addition, other difficulties exist because of the nonlinearity associated with the discretization of the channel length in most of these formulae (i.e., subdividing a stream into more parts will not yield the same calculated time of concentration). Because of the above limitations and since the calculations are grid-based, it is necessary to use a travel time formula that can work on the cell level. Manning's formula requires both the slope and hydraulic radius which are the most sensitive parameters affecting the velocity of flow. The longitudinal slope can be calculated from a digital elevation model using different methods (slope is discussed in the following subsection). On the other side, the hydraulic radius has always been a difficult variable to be estimated using the typically available data for ungauged watersheds, especially if grid-based calculations are to be used. This difficulty arises as the available digital terrain data (usually the SRTM data) or topographic maps are of poor resolution to describe the cross-sectional details. For this reason, a new approach to estimate a spatially varied hydraulic radius has been implemented in this research. Development and technical details of this approach can be found in Gad (2012). The approach assumes that there is an intrinsic relationship between R at any cross-section and the hydrologic parameters of the catchment upstream. The relationship is in the following form:

$$R_i = 0.1\, A_{i-us}^{0.23}\, P_{i-e-us}^{0.45}\, S_{i-us}^{0.028} \tag{1}$$

where: R_i=Hydraulic radius at grid cell i (m); A_{i-us}=Accumulated area upstream grid cell i (km^2); P_{i-e-us}=Average excess rainfall depth upstream grid cell i (mm); S_{i-us}=Average slope of the catchment upstream cell i (%).

Fig. (1) presents a sensitivity analysis for the used hydraulic radius formula. SDISTA implements a procedure of grid math, conditioning, and hydrologic operations that are available in GIS to apply Eq. (1).

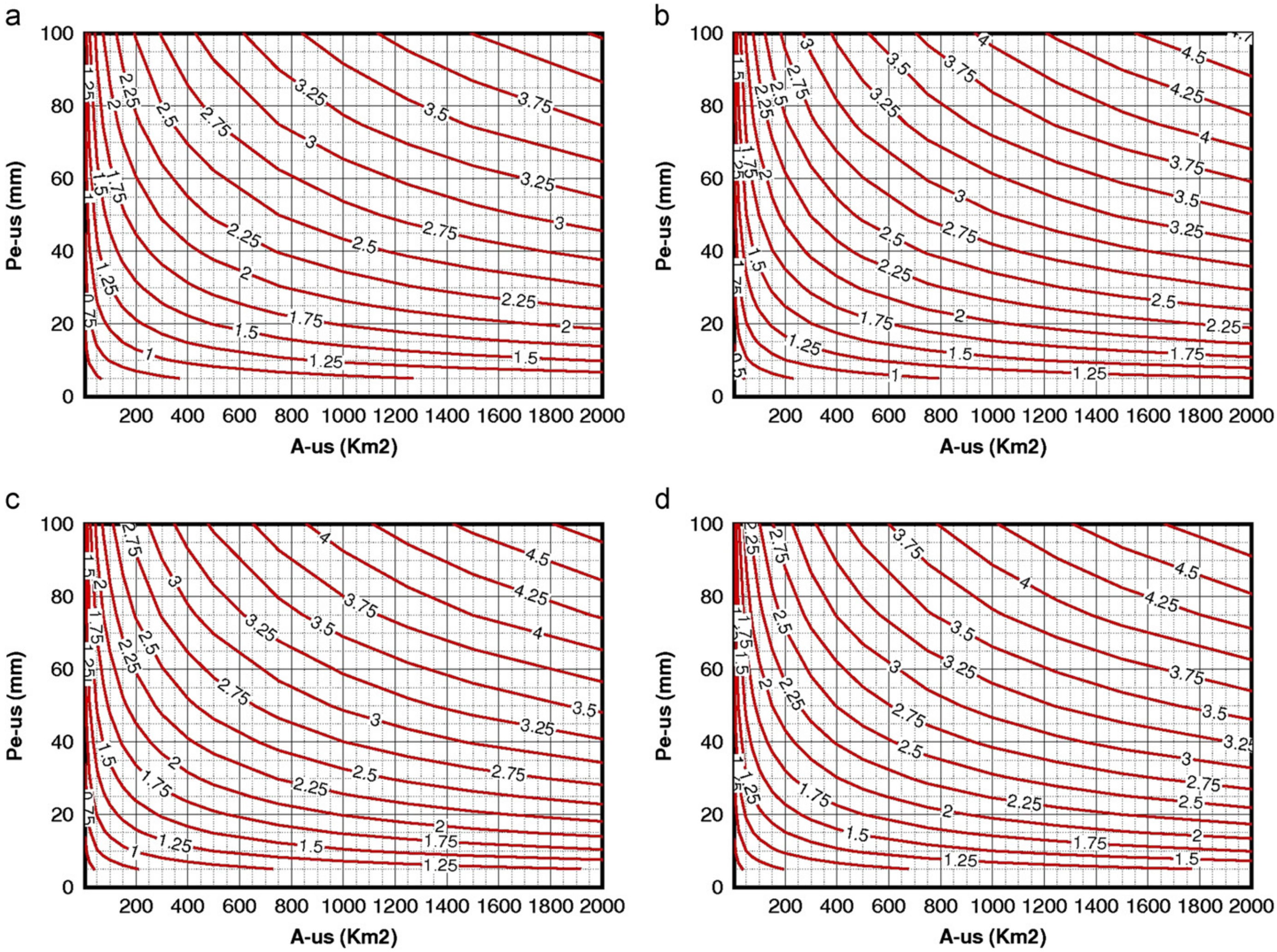

Fig. 1. Contours of hydraulic radius (m) at different levels of the upstream catchment area (km^2), upstream average excess rainfall (mm), and upstream average catchment slope (m/km). (a) S − us = 1 m/km, (b) S − us = 50 m/km, (c) S − us = 100 m/km and (d) S − us = 200 m/km.

3.2. Slopes along flow directions

There are different methods of grid-based slope estimation. The majority of methods depend on using a roving window approach to determine an average slope at the current cell from the elevation values of its neighbors in the roving window. This approach produces much higher slope than the actual slope along the flow direction path (Hickey et al., 1994; Hickey, 2000; Van Remortel et al., 2001; Van Remortel et al., 2004). For example, if the window is centered on a stream cell that is at the toe of a steep side slope, the window approach will be affected by the steep side slope and produce a much higher value than the actual longitudinal slope in the direction of the flow. Hence, the slope calculations in SDISTA are done along flow directions in which no roving windows or side neighborhoods are considered. SDISTA visits all grid cells and uses the flow direction value to specify the next cell downstream. A straightforward slope calculation is done by dividing the difference in elevation (between the current cell and the next downstream cell) by the length between the two cells (i.e., the cellsize for the orthogonal directions and 1.414 cellsize for the diagonal directions). If a zero slope is encountered, more cells are included downstream until a cell lower than the current cell is found. The current cell and the included cells downstream (i.e., cells of similar elevation as the current cell) are then assigned the same calculated slope. Boundary cells flowing outside the grid extents and cells flowing through equal elevation cells to the boundary are assigned Nodata.

3.3. Travel time

Travel time calculations are very important since the shape of the hydrograph and the value of the peak discharge of a watershed depend mainly on the arrival times of the mini-hydrographs. SDISTA uses grid-based Manning's formula to estimate flow velocity. Substituting from (1) into Manning's formula yields the velocity of flow as follows:

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

where: V_i=flow velocity at grid cell i (m/s); n_i=Manning's roughness at grid cell i; S_i=longitudinal slope at grid cell i (m/m); R_i is the hydraulic radius at grid cell i (refer to section 3.1).

Dividing the flow length through a grid cell by Eq. (2) and rearranging yields the following equation for travel time through the grid cell:

$$t_{ci} = \frac{1}{60 \times V_i} \times l_i = Weight_i \times l_i \tag{3}$$

where t_{ci} is the travel time through grid cell i in minutes and l_i is the travel length through the grid cell in meters. The linear relation between t_{ci} and l_i ensures that DEMs of different resolutions for the same area yield similar results. The travel time from a grid cell to the outlet Tc_i (time of concentration of this grid cell at the outlet) can be obtained by summing Eq. (3) along all downstream grid cells in the flow direction path until the outlet:

$$Tc_i = \sum_{i}^{outlet} t_{ci} = \sum_{i}^{outlet} Weight_i \times l_i \quad (4)$$

SDISTA applies Eq. (3) using grid math to calculate travel time inside grid cells (i.e., tGrid: a grid of incremental travel times). Eq. (4) is solved using the "FlowLength" function by using the spatially varied $Weight_i$ (defined in Eq. 3) to calculate a time of concentration grid (i.e., TcGrid). Fig. 2 presents examples from Wadi El-Meliha catchment area (Sinai, Egypt). The example shown in Fig. 2 is for a spatially uniform total rainfall depth of 23 mm, curve number (CN) of 83, and Manning's roughness of 0.025.

3.4. Hydrograph generation

A constant or spatially variable cumulative total rainfall hyetograph is required as input to the model. SDISTA encodes both the typical SCS (United States Soil Conservation Services) and Horton's infiltration methods for excess rainfall estimation. The implementation of the SCS module is presented here. Let S_i denotes the SCS storage value at cell i and dt denotes the simulation time step. $P_{i,\ t}$ and $Pe_{i,\ t}$ denote the cumulative total and excess rainfall depths at time t and cell i. The excess rainfall intensity $I_{i,t}$ during the simulation time step is calculated as follows:

$$S_i = \frac{25400-(254 \times CN_i)}{CN_i} \quad (5)$$

$$Pe_{i,t} = \begin{cases} \frac{(P_{i,t}-B_{ai})^2}{P_{i,t}+B_{ai}-S_i} & (P_{i,t} > B_{ai}) \\ 0 \text{ and } Continue & (P_{i,t} \le B_{ai}) \end{cases} \quad (6)$$

$$I_{i,j} = \frac{Pe_{i,t}-Pe_{i,t-1}}{dt} \quad (7)$$

where B_{ia} is the initial abstraction in mm (taken as $0.2S_i$ if not specified else by the user). The peak discharge of the cell mini-unit hydrograph u_{pi} (corresponding to 1 mm of excess rainfall of duration dt) depends on the relation between travel time through the grid cell t_{ci} and the length of the time step dt. The cell will reach the steady state condition if dt is larger than t_{ci} and the opposite is true (refer to Fig. 3). The steady state discharge (in m^3/s) resulting from 1 mm/hr unit excess rainfall intensity is given by:

$$us_i = 1 \times cell\ size^2 \times \frac{1}{36 \times 10^5} \quad (8)$$

where *cellsize* is in meters. The peak discharge of the cell mini-unit hydrograph u_{pi} is then calculated in terms of us_i as follows:

$$u_{pi} = \begin{cases} us_i \times \frac{dt}{t_{ci}} & (if\ t_{ci} > dt) \\ us_i & (if\ t_{ci} \le dt) \end{cases} \quad (9)$$

Note that the mini-unit hydrograph contains only one non-zero ordinate if $t_{ci} \le dt$ while a number of $(2t_{ci}/dt)-1$ non-zero ordinates are considered if $t_{ci} > dt$. The convolution can now be performed between the excess rainfall hyetograph (obtained from equation-7) and the mini-unit hydrograph (equation-9) to yield the cell mini-hydrograph. Following the typical unit hydrograph convolution concept, the cell mini-hydrograph ordinate leaving cell i at time t can be expressed as:

$$q_{(i,t)} = \sum_{k=1}^{k=t} I_{(i,k)} u_{(i,t-k+1)} \quad (10)$$

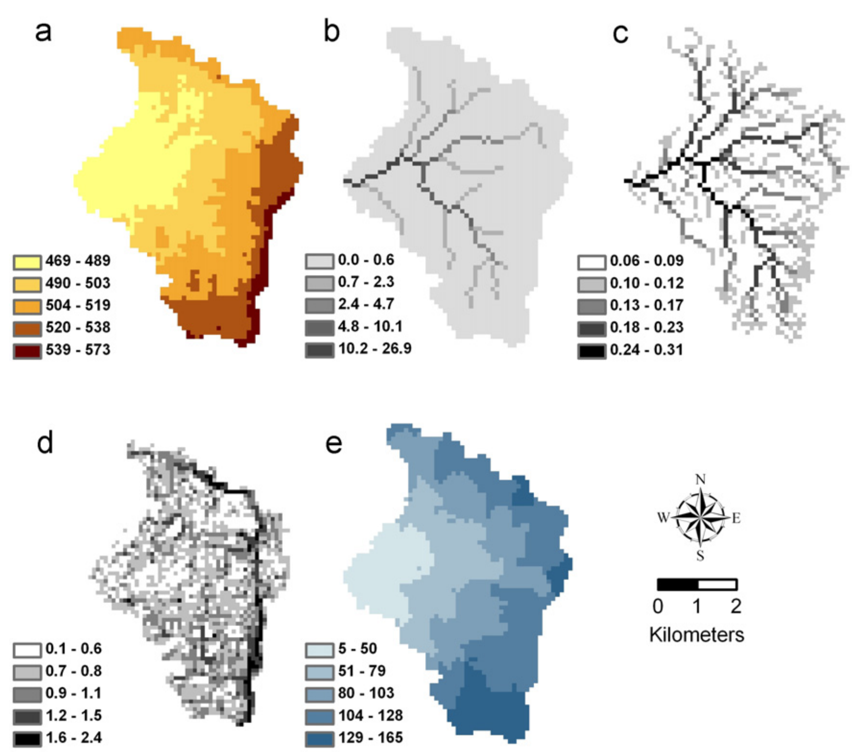

Fig. 2. Example of grid-based calculations of the time of concentration (i.e., TcGrid) for Wadi El-Meliha. (P=23 mm, CN=83, n=0.025). (a) DEM (m), (b) AusGrid (Km2), (c) RGrid (m), (d) VGrid (m/s) and (e) TcGrid (min.).

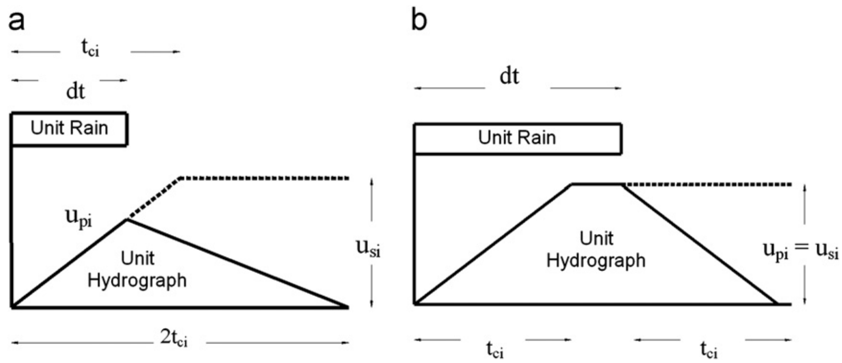

Fig. 3. Cell mini-unit hydrograph used to transform rainfall intensity to cell mini-hydrographs. Cell mini-hydrographs are routed and combined at the outlet according to the values of *TcGrid* to produce the total runoff hydrograph. t_{ci} is the travel time through a grid cell and u_{pi} is the cell UNIT hydrograph peak discharge. Note that u_{si} is the steady state UNIT peak discharge. (a) $t_{ci} > dt$ and (b) $t_{ci} \leq dt$.

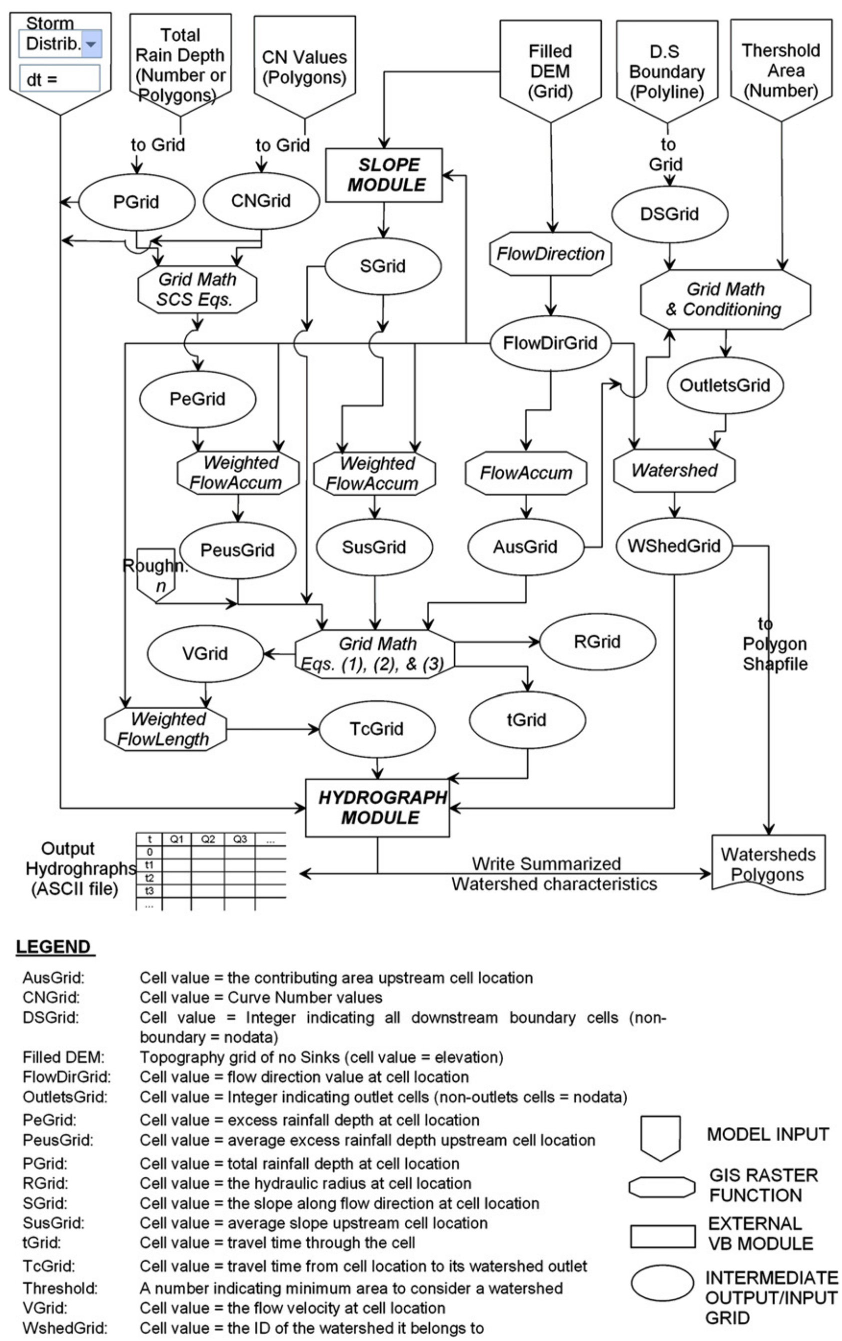

Fig. 4. Schematic diagram for the calculations in SDISTA model.

where $(t-k+1)$ moves across the mini-unit hydrograph ordinates. Note that Eq. (10) is reduced to $q_{(i,t)}=I_{(i,\ t)}\times u_{si}$ if condition b applies (i.e., $t_{ci}\leq dt$). The mini-hydrographs of all cells contributing at the watershed outlet are then lagged according to their travel times to the outlet and combined (i.e., super-positioned) with the hydrograph at the outlet. Hence, an ordinate of the total hydrograph at the watershed outlet at time t can be expressed in terms of the discharges from all cells that occurred exactly just before their travel times:

$$Q_t=\sum_{i=1}^{n} q_{(i,t-Tc_i)} \tag{11}$$

To account for fractions of the time step, a mini-hydrograph is placed on the time line at the outlet according to its arrival time then the mini-hydrograph ordinates are interpolated to the simulation time steps before doing the superposition. The interpolated ordinates ensure the same runoff volume. To explain this temporal adjustment, let us consider a mini-hydrograph from cell i where condition b applies (i.e., $t_{ci}<dt$). Tc_i places the start of the mini-hydrograph at a fraction of $(t-Tc_i)$ before the beginning of the time step at time t. The cell mini-hydrograph consists of only two ordinates that are distributed at the beginning and end of the time step starting at time t as follows:

$$q_{i,t}=\frac{t-Tc_i}{t_{ci}}\times q_{si}\ and\ q_{i,t+1}=q_{si}-q_{i,t}\ \left[if\ \ (t-Tc_i)<t_{ci}\right] \tag{12}$$

$$q_{i,t}=q_{si}\ and\ q_{i,t+1}=0\ \ [if(t-Tc_i)\geq t_{ci}] \tag{13}$$

where q_{si} is the cell steady state discharge (q_{si}=Rainfall intensity $\times\, u_{si}$).

4. Technical Details

SDISTA is written using VB6 and compiled as a dynamic link library (sdista.dll) that includes ESRICORE GIS library. This makes use of the broad built in GIS functions available in ESRICORE. SDISTA is computationally very efficient since it uses dynamic arrays (run time memory management) for storing grids in computer memory. After model installation, SDISTA library is made available to ArcMap interface as a button. Once SDISTA is invoked, the library is "hooked" to ArcMap and the main SDISTA window opens and starts listening to the event analysis. Model input consists of five main inputs: topographic, infiltration, roughness, storm, and the simulation time step in minutes. Topographic input includes a digital elevation layer (i.e., a raster layer), a downstream boundary polylines layer, and an area threshold value (i.e., number) above which a watershed is defined. The downstream polylines constitute the flow lower boundary. All watersheds "higher" than this boundary (and greater than the threshold area) are considered in the analysis and the hydrographs are calculated at the intersections with their main streams. This polylines boundary can represent the centerline of a road that requires flood protection, the sea coast on which all catchment areas need to be modeled, or even the national boundaries of a country. These examples show clearly the wide range of applications expected for SDISTA. The second input is a polygon layer containing the spatially varied infiltration parameters. Manning's roughness is similarly entered as a polygon layer. Both predefined storm distributions (e.g., SCS type-II) and user defined hyetograph are available for entering rainfall data. An optional polygon input is made available to provide rainfall spatial weights. This option is very useful when modelling very large areas with significant spatial variation in rainfall or areas experiencing spatial trends in rainfall distributions (i.e., orographic based rainfall). A schematic diagram of the model is presented in Fig. 4.

SDISTA produces two main outputs: a polygon shapefile and an ASCII text file. The polygon shapefile contains all delineated watersheds and its attribute table lists summarized hydrological characteristics (e.g., time of concentration, peak discharge, runoff volume). The ASCII file contains the hydrographs of all catchment areas considered. Additional (optional) outputs can be produced from the temporary grids calculated during the simulation (Fig. 4).

4.1. Treating multiple watersheds

SDISTA makes use of GIS grid math, conditional, and hydrological operations to produces a watershed grid in which each cell is assigned a number that represents the watershed it belongs to (refer to Fig. 4). The HYDROGRAPH module opens a two dimensional dynamic array for writing/retrieving discharge values in which the first array index denotes a watershed and the second index denotes the discharge at certain time. The calculations are very fast since the HYDROGRAPH module doesn't actually loop on the watersheds but it sweeps the grid cells and uses the watershed value to get and set the discharge array "on the fly".

5. Case studies

Two case studies are presented to demonstrate SDISTA and its comparison with HEC-1. In both cases, HEC-1 is applied using the subdivision approach to describe as close as possible the rainfall-runoff transformation behavior of the catchment areas. Each catchment area is sub-divided into smaller sub-catchments and a network diagram is constructed as usually done in engineering practice. The loss rate method used in HEC-1 is the SCS-loss rate method (CN method) and the transformation into runoff is done using the SCS-lag method. Reach routing is implemented using the lag method. The unit hydrograph lags and the routing lags are calculated using Kirpich's formula (Kirpich, 1940) that is recommended by different codes of practices in the region. It should be

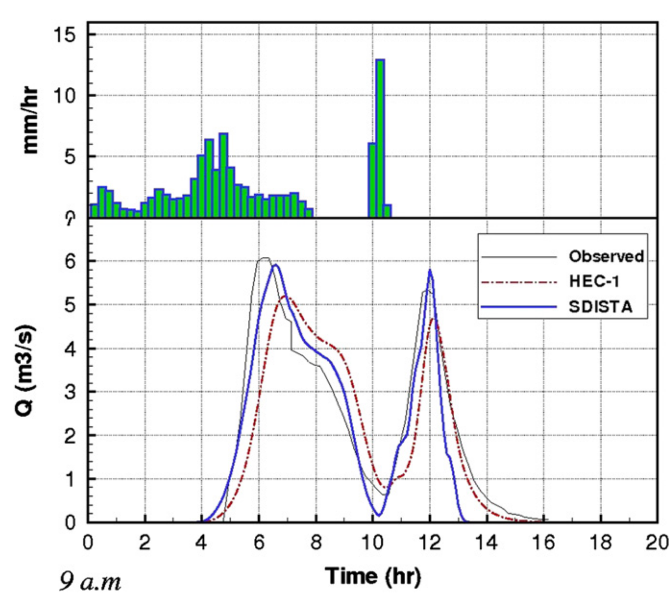

Fig. 5. Runoff hydrographs calculated using HEC-1 and SDISTA models for the storm of March 11, 1994 on Wadi El-Meliha experimental basin. Upper panel is the rainfall hyetograph and lower panel is the runoff hydrograph.

noted that this HEC-1 modelling procedure is the engineering procedure that is widely followed in the Middle East region.

5.1. Wadi El-Meliha

Wadi EL-Meliha is a small experimental catchment area ($A=26\ \text{km}^2$, Limeston) located at the upper of Wadi Sudr in Sinai, Egypt. The experimental basin is equipped with a number of automatic rain gauges and a Parshal flume at its outlet. Both HEC-1 and SDISTA are used here to simulate the event of March 11, 1994 that developed a total rainfall depth of 23 mm. Since the catchment area is small and homogeneous, the rainfall hyetograph and a CN value of 83 are assumed spatially uniform in both HEC-1 and SDISTA. A number of five sub-catchments and two routing reaches are used to build HEC-1 network. The Kirpich's formula gives a total time of concentration of 170 min while SDISTA time of concentration is 165 min (refer to Fig. 2e). Fig. 5 shows the comparison between the observed hydrograph and the calculated hydrographs using both models which are in good agreement.

5.2. Wadi Hassa

Wadi Hassa is located south east of the Dead Sea (Jordan). It is a major valley ($A=2308$ km2) that is generated from the Eastern

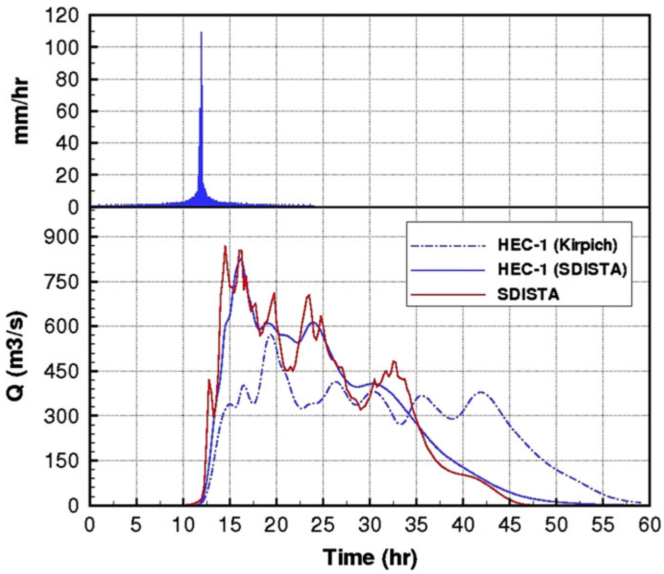

Fig. 7. Runoff hydrographs calculated using HEC-1 and SDISTA models for Wadi Hassa (Jordan). Rainfall input is 80 mm storm distributed using the SCS-II 24 h distribution. HEC-1 is run twice: using Kirpich's travel times and SDISTA travel times. Upper panel is the rainfall hyetograph and lower panel is the runoff hydrograph.

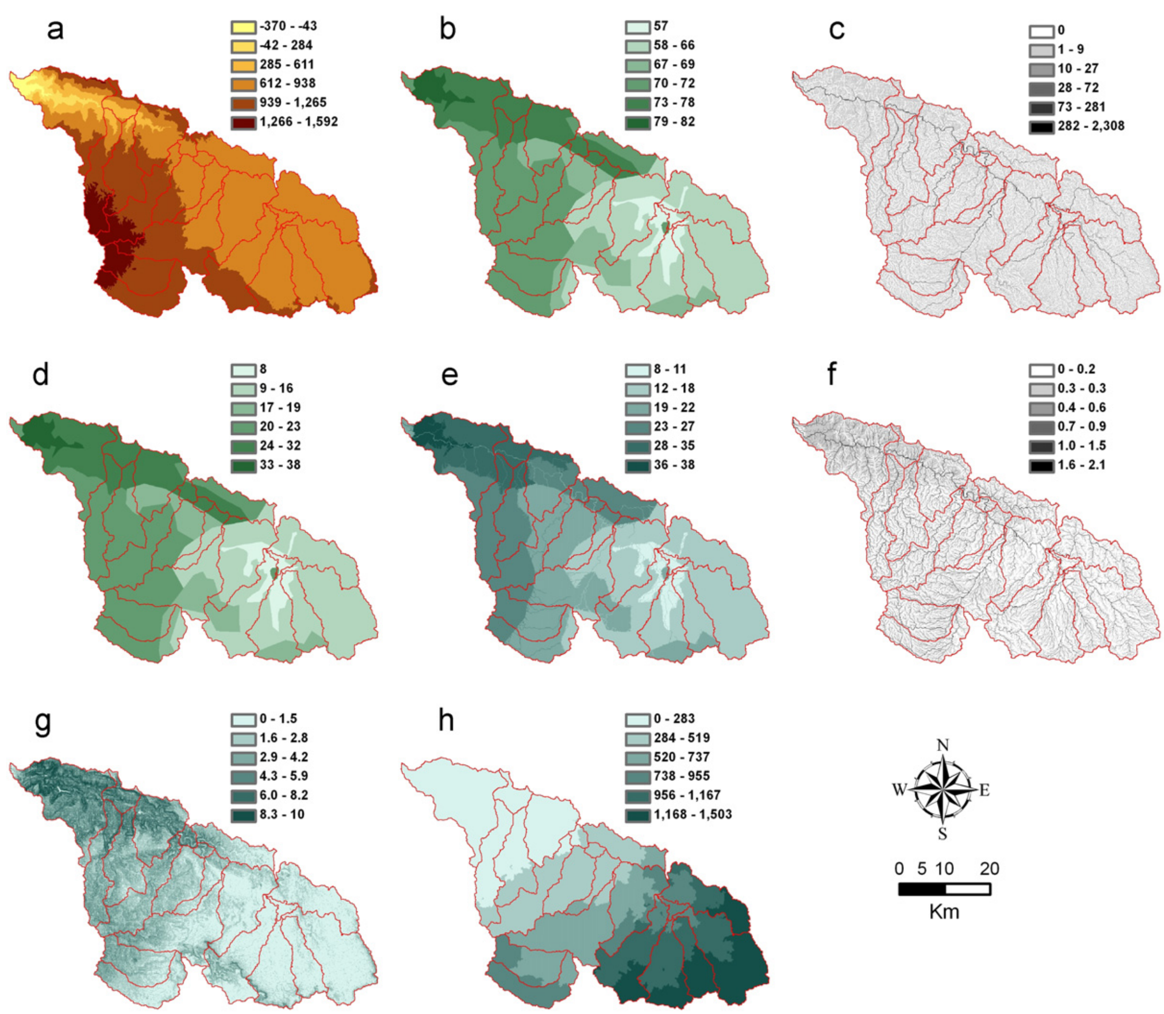

Fig. 6. SDISTA travel time calculations for Wadi Hassa. Note that (a) and (b) are inputs while (h) is the output. All intermediate grids are temporary grids unless specified else by the user. Note that the sub-catchments used in HEC-1 are shown on the figure. (a) DEM (m), (b) CNGrid, (c) AusGrid (km2), (d) PeGrid (mm), (e) PeUsGrid (mm), (f) Rgrid (m), (g) VGrid (m/s) and (h) TcGrid (min). PeGrid is the local excess depth at each cell while PeUsGrid is the average excess rainfall upstream each cell.

Jordan plateau. Wadi Hassa runs westwards until it eventually discharges into the southern tip of the Dead Sea. The digital elevation model of the study area and the CNGrid are shown in Fig. 6a and b respectively. A spatially uniform storm of average daily depth of 80 mm (distributed using the SCS type-II distribution) is used as input to both HEC-1 and SDISTA. Wadi Hassa is sub-divided into 21 sub-catchments and 10 routing reaches in HEC-1 application. Average CN values for the sub-catchments are extracted from the CNGrid (Fig. 6b) and Kirpich's lag parameters give a total time of concentration of 2086 min. On the other side, the digital elevation model and the CNGrid are used as input to SDISTA model (a spatially uniform Manning's $n=0.04$ is used since there is a large percentage of bed rocks). Fig. 6 presents the temporary grids produced by SDISTA to calculate a travel time grid (i.e., TCGrid). SDISTA calculated time of concentration (corresponding to 80 mm of rainfall) of Wadi Hassa is 1503 min (refer to Fig. 6h). Note that there is a difference of 583 min between the times of concentrations calculated by SIDSTA and Kirpich's equation. This is attributed to the fact that Kirpich's formula doesn't consider the level of rainfall as opposed to SDISA. To eliminate the effect of the time of concentration from the comparison, HEC-1 is run again using lag times extracted from the TcGrid calculated by SDISTA. Fig. 7 presents a comparison between the hydrograph calculated using SDISTA and those calculated using HEC-1 in the two lag scenarios. The visual comparison between the hydrographs indicates good agreement between the two models if the same times of concentrations are used. It should be noted that, corresponding to this level of average daily rainfall, historical peak discharges of Wadi Hassa above 1000 m^3/s were recorded at Safi gauge station (Gibb, 1994; DAR, 2006). In order to illustrate the effect of the rainfall level on the time of concentration calculated by SDISTA, the model is run on different levels of the storm rainfall depth and the calculated times of concentration are plotted (refer to Fig. 8) for the two case studies.

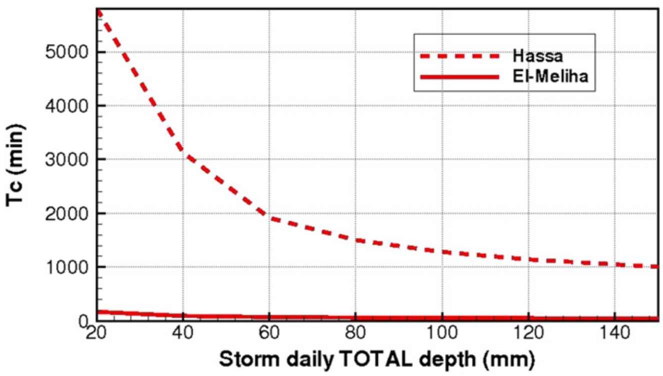

Fig. 8. The calculated times of concentration for Wadi Hassa ($n=0.04$) and Wadi El-Meliha ($n=0.025$) for different storm daily TOTAL rainfall depths. The curve of Wadi El-Meliha starts from 170 min at 20 mm and ends to 49 min at 150 mm.

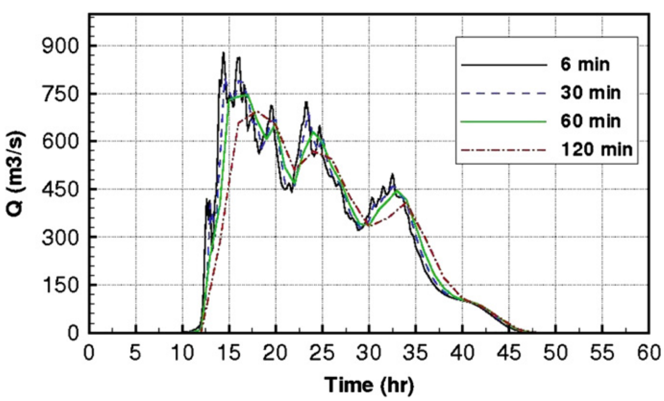

Fig. 9. SDISTA hydrographs for Wadi Hassa using different simulation time steps (*dt*).

6. The spatial and temporal resolutions

The temporal and spatial resolutions are independently used in the model. The model can be said to be almost insensitive to the spatial and temporal discretization. The effect of increased temporal resolution (*dt*) is merely the averaging of the input rainfall hyetograph and accordingly smoothed hydrograph result (local peaks and small variations are smoothed with increased time steps). Fig. (9) presents Wadi Hassa's hydrographs obtained using different time steps. Ideally, the optimum computations are achieved when the time step is equal to or slightly bigger than the travel time through a grid cell, yet the cell is still small enough to conform to the assumed mini-unit hydrograph shape.

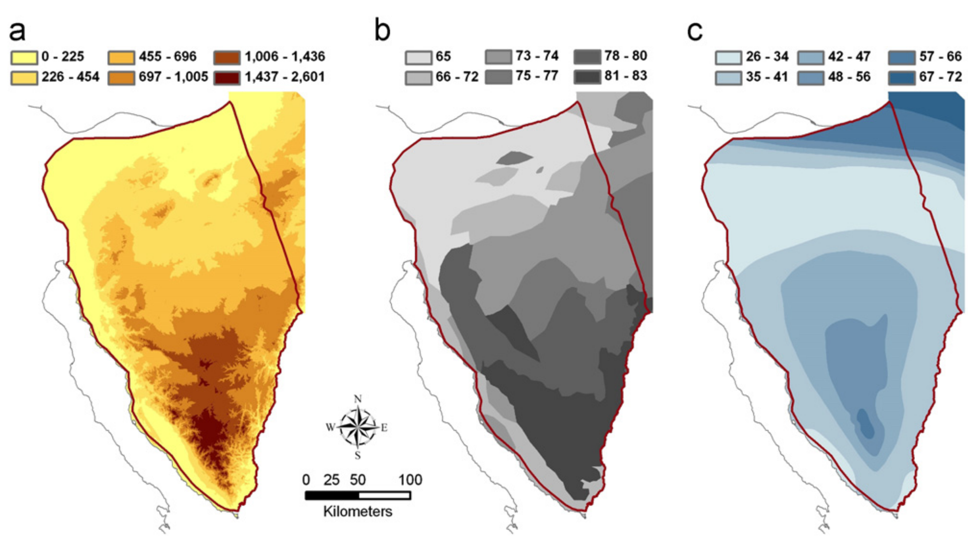

Fig. 10. SDISTA input used to simulate the whole peninsula of Sinai. Note the downstream polylines boundary that constitutes the lower catchment boundary. (a) Sinai DEM (m), (b) CN and (c) Daily Depth (mm).

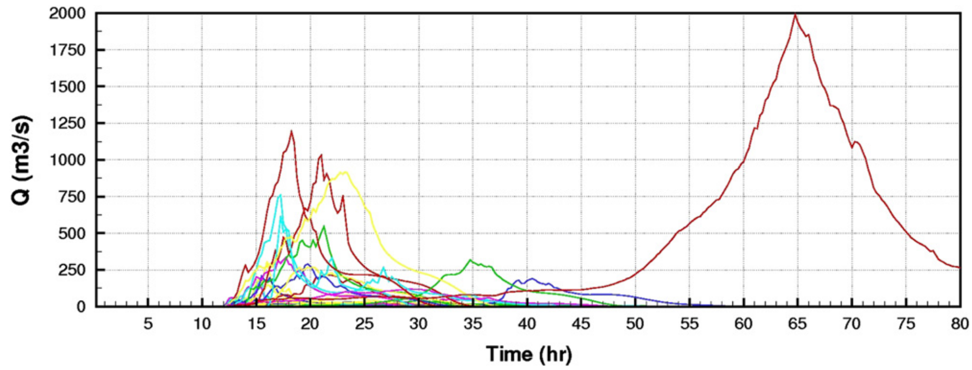

Fig. 11. The hydrographs of 217 Wadies in Sinai Peninsula calculated using the input shown in Fig. 10. The Wadies can be located on Fig. 12 using their peak values.

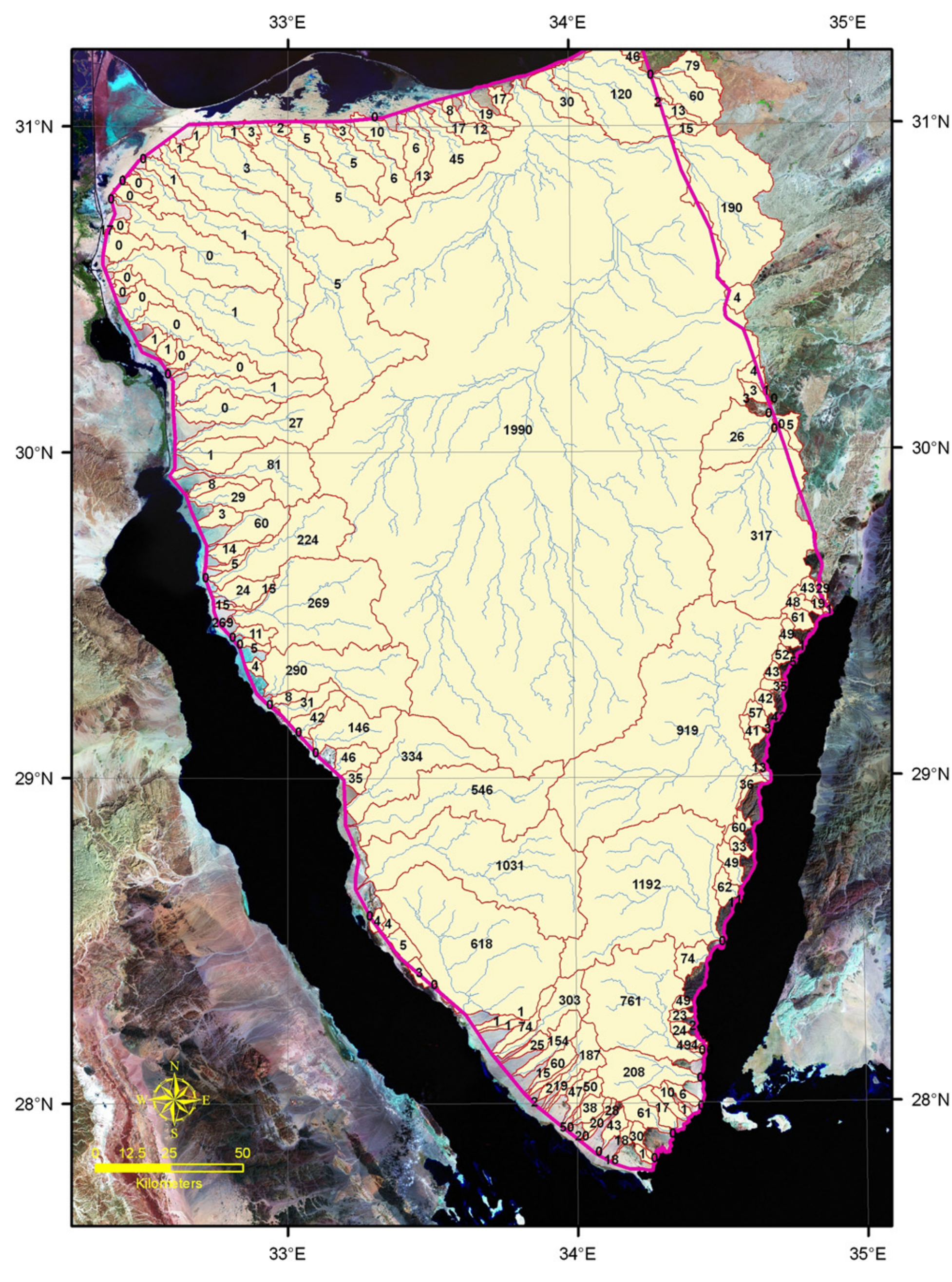

Fig. 12. The 217 Wadies automatically simulated by SDISTA. The polygons are labeled by the calculated peak discharges in m^3/s.

Accordingly, a minimum spatial resolution of roughly 1 km is recommended (i.e., cellsize <1000 m) while a corresponding time step (in minutes) of approximately 0.03–0.25 the cellsize (depending on the flow velocity) is also recommended, where the cellsize is in meters. Since SDISTA model is intended to use SRTM data (100 m resolution on average), the recommended time step is 3–12 min.

7. Functionality and run time

The run time of grid-based analysis depends mainly on the number of grid cells (i.e., grid dimensions: number of columns by number of rows). SDISTA run time is excellent for engineering applications. It takes seconds in small grids (areas up to 2000 km^2) using the typical SRTM resolution of 100 m (i.e., 2×10^5 cells). In order to fully evaluate the run time and to provide an example of the functionality and advantages of SDISTA, the model is applied on the whole DEM of Sinai Peninsula in Egypt. Sinai Peninsula is characterized with a large number of catchment areas that still have not been simulated yet. Fig. 10 presents the input used (DEM, CNgrid, and rainfall daily depth). The SCS-II distribution is used to distribute the daily depths (approximately representing the 100 year design depths). The SRTM is downgraded to a resolution of 220 m to produce the input DEM (1878 rows $\times$ 1166 columns) covering an area of 10,5983 km^2. The CN values are assigned roughly based on Landsat images. A time step of 10 min and an area threshold of 25 km^2 are used. Fig. 11 shows the hydrographs calculated for the 217 catchments delineated by SDISTA while Fig. 12 presents the output polygon shapefile labeled by the calculated peak discharges. The run time taken by SDISTA is 3.5 min on an ordinary Centrino-T1350 Laptop@ 1.86 Ghz processor-782 Mhz board-1 Gb RAM.

8. Conclusions

SDISTA proved to be as accurate as distributed HEC-1/HEC-HMS. On the other side, SDISTA requires minimum time and effort from the user as compared to HEC-1/HEC-HMS. SDISTA is able to take the effect of rainfall into consideration in calculating travel times with no channel geometry requirements. This option in addition to the fast run time and the ability to handle many catchment areas simultaneously make SDISTA very suitable to real time applications on both the small and large scales. In addition, it is a feasible and efficient tool for hydrologists seeking accurate and quick engineering hydrograph determination for ungauged catchment areas in semi-arid regions especially when many catchment areas are considered. It should be noted that Kirpich's formula (recommended by different codes of practices in the Middle East) seems to significantly underestimates travel times in areas subject to convective rainfall triggered either by thermal or orographic convection (the common flood producing types in semi-arid regions).

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