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Runoff hydrograph simulation based on time variable isochrone technique

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Abstract

A new method based on an extension to time–area (TA) concept is proposed for rainfall–runoff transformation in watersheds. The method uses time variable isochrones, such that the runoff hydrograph responds well to temporal changes in excess rainfall intensity. The method employs a kinematic-based travel time scheme, which improves existing isochrone extraction techniques. A raster-based approach deals with spatial domain discretization and supports rainfall–runoff simulations in a modular distributed model. The model uses digital elevation model (DEM) data, ground slope, flow direction, and flow accumulation maps to characterize the watershed terrain. The time series of travel time (or isochrones) maps constitute the basis for incremental and total runoff hydrograph computations. The model was calibrated and validated on a small catchment. The methods and modeling algorithms extend the original TA routing method to a distributed terrain-driven, hydraulic-based, and GIS-compatible technique where isochrones vary as the storm intensity and infiltration rate develop. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Runoff simulation; Non-stationarity; Variable isochrones; Spatial terrain data; Distributed rainfall–runoff modeling; Time of concentration; GIS

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1. Introduction

Time–area (TA) rainfall–runoff analysis is widely known as a hydrologic watershed routing technique to derive the discharge hydrograph due to a given excess rainfall hyetograph. In this technique, by ignoring storage effects, the watershed is divided into a number of subareas separated by isochrones; i.e. the isolines of equal travel time to the outlet (Fig. 1(a)). The Clark unit hydrograph (Clark, 1945) is based on the TA concept in which watershed storage effects are also taken into account. TA technique is believed to be applicable up to midsize watersheds (Ponce, 1989).

Similar to many other rainfall–runoff transformation techniques, the TA method shares the assumption of 'stationarity' with the unit hydrograph theory. This means that a unique time-invariant transfer function is applied for watershed runoff hydrograph calculations regardless of the excess rainfall input. Considering dynamics of the runoff system, however, the transfer function must respond to temporal changes in excess rainfall intensity. Rodriguez-Iturbe and Valdes (1979) recognized that instantaneous unit hydrographs (IUH) vary both from storm to storm and during a storm.

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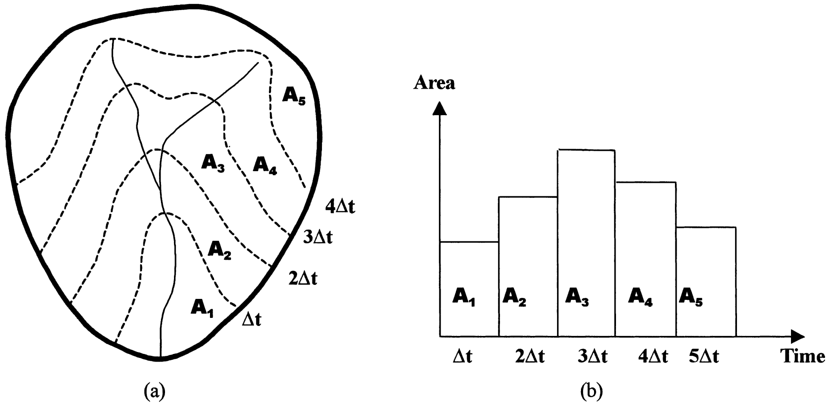

Fig. 1. (a) and (b). Isochrones and TA histogram for a watershed.

They added that such variability may account for the variability in the mean streamflow velocity. Rodriguez-Iturbe et al. (1979) suggested that the use of constant velocity at the peak discharge is justifiable for estimating peak and time to peak discharge. However, errors in estimating flow velocity may lead to large errors in discharge estimation when the flow velocity is smaller than 2 m/s.

Although ‘stationarity’ is a major constraint in the original TA, the method has several advantages and potential. The temporal distribution of excess rainfall may be accounted for in the runoff discharge calculations. As will be demonstrated in this paper, the influence of the shape and detailed drainage pattern of the watershed may be seen, provided that isochrones are based on distributed watershed hydro-geomorphologic characteristics. Many hydrologists consider TA a lumped-parameter model (e.g. Ponce, 1989). We will show, however, that TA has the potential to perform as a distributed model by including non-uniform excess rainfall and spatially variable watershed characteristics. Accordingly, use of suitable Geographic information systems (GIS) functions can facilitate preparation and analysis of model spatial input data. The algorithms outlined in this paper exploit the implicit spatio-temporal characteristics and potential of TA and advances it to a distributed, terrain-driven, Hortonian runoff, routing technique.

Topographic characteristics exert a strong influence on runoff direction, concentration and velocity. No conceptual or physically based rainfall–runoff model, be it distributed or lumped, may operate effectively without one or more quantitative topographic indices; slope and watershed area are probably the most widely used. Topographic maps have been the traditional source of extracting terrain information for watershed modeling. Yet, manual extraction of data from such maps is time-consuming and error-prone. With progress in digital systems, digital elevation models (DEM), representing a digital matrix of ground surface elevations, are becoming the dominant source of topographic data for distributed hydrologic modeling. Several quantitative hydro-geomorphic characteristics may be derived from a DEM. GIS are spatial software tools for preparing and managing DEMs and other digital maps.

Out of few available TA rainfall–runoff models, some rely on watershed DEM where runoff routing is performed on a grid cell basis. Maidment (1993) proposed one of the pioneering models of this type. He developed a distributed DEM-driven unit hydrograph based on the original TA method and a GIS toolbox. While Maidment’s work is considered a major contribution in watershed modeling, his model was limited in some aspects; e.g. the overland routing was based on constant velocity or subjectively predetermined velocity map. A similar approach was adopted by Muzik (1995).

In a conceptual framework following Maidment (1993), Kull and Feldman (1998) assumed that travel time for each cell in a watershed was simply proportional to the time of concentration scaled by the ratio of travel length of the cell over the maximum travel length. That is, average velocity of runoff traveling from any point to the outlet is assumed uniform and constant. Each cell's excess rainfall is then lagged to the outlet based on the cell's travel length. Travel time in overland and channel follows similar proportionality with travel length and the watershed time of concentration must be determined a priori. This approach has been implemented in the HMS model (HEC, 2000), which is a new version replacing HEC-1 model. In a more recent work, Olivera and Maidment (1999) proposed a raster-based, spatially distributed, runoff routing technique, where routing from one cell to the next was accomplished using the first-passage-time response function. Although the routing function was similar to those proposed by other researchers, the authors highlighted better linkages with spatially distributed databases and analysis functions provided by a GIS.

The objectives of this paper are as follows:

1. To advance the original TA method by introducing the idea of using 'time variable isochrones' in runoff hydrograph calculations. In the proposed scheme, the isochrones of travel times are not stationary in time, rather they vary in accordance with temporal change in excess rainfall intensity. Therefore, the 'stationarity' constraint embedded in the TA method may be resolved.
2. To upgrade known isochrone derivation techniques to a hydraulic-based approach by building upon the method by Saghafian and Julien (1995). While available techniques (e.g. Laurenson, 1964; Kull and Feldman, 1998) do not take the hydraulics of the flow system into account, we suggest using kinematic wave theory for the analysis of the travel time. Application of the proposed technique explicitly yields the value of time to equilibrium and, interchangeably, the time of concentration (T_c). The relationship for flow travel time over the watershed can account for spatial distribution of topographic characteristics such as slope, flow direction, and flow accumulation.
3. To propose a simple numerical framework whereby the travel time relationship can be discretized in space and time. The spatial domain discretization follows a raster-based data structure so that compatibility with most modern GISs is assured. The model has a terrain data processing module, which extracts various topographic characteristics from readily available topographic data. A major feature of the model is the dynamic changes in rainfall–runoff transfer function in response to the changes in infiltration rate and rainfall intensity.

In summary, the methods outlined in this paper relax some of the limitations and assumptions of original TA methods and introduces the application of temporally variable isochrones in hydrograph estimation.

2. Theoretical background

The histogram of consecutive contributing watershed subareas (Fig. 1(b)), from the outlet in upstream direction, is known as the TA histogram (TAH). This histogram constitutes the basis for the excess rainfall–runoff transformation, i.e. TAH acts as a transfer function in input–output relationship. To construct the TAH, the watershed time to equilibrium, loosely substituted by the time of concentration in hydrologic literature, must be divided into a number of equal time intervals. This time interval is the travel time difference between adjacent isochrones. After plotting the TAH, the runoff hydrograph may be determined through convolution

$$Q_j = \sum_{k=1}^{j} E_k A_{j-k+1} \tag{1}$$

where j is the time step number; Q is the runoff discharge; E is the excess rainfall intensity; and A is the area bounded by isochrones.

The concept of time to equilibrium (T_e) is fundamental to the derivation of isochrones and application of the TA method. Time to equilibrium is the time associated with the (maximum) steady state runoff discharge from a given watershed under constant excess rainfall intensity. This time is a function of rainfall intensity, as well as watershed characteristics, and may be defined as the time for the most hydraulically remote point in the watershed to contribute to the surface runoff at the outlet for infinitely long rainfall duration. Saghafian and Julien (1995) derived the general formula for the time to equilibrium, or total travel time, at any location in the watershed at a travel distance $x = L$ using Manning resistance equation as follows

$$T_w(x = L) = \int_0^L (1 - \gamma)\left[\frac{a_1}{Q_e}\right]^{\gamma}\left[\frac{n}{a_2^{2/3} S_0^{1/2}}\right]^{1-\gamma} dx \quad (2)$$

where L is the total length along the hydraulically longest flow path; x is the distance measured along the flow path; Q_e is the equilibrium discharge; a_1, a_2, and γ are flow cross sectional parameters; S_0 is the bed slope corresponding to the so-called *kinematic time to equilibrium*; and n is the Manning roughness coefficient.

The equilibrium discharge Q_e passing through a given cross section at location x, would be the spatially integrated excess rainfall rate over the drainage area associated with that cross section. This can be mathematically expressed by

$$Q_e(x) = \int_0^{A(x)} E \, dA \quad (3)$$

where $A(x)$ is the drainage area or flow accumulation at distance x and E is excess rainfall intensity at any point draining to x. The substitution for Q_e in Eq. (2) requires knowledge of spatial variability of excess rainfall and of the drainage area along the hydraulically longest flow path.

The total travel time (T_w) can be separated into the travel time for overland flow, T_{wo}, and for channel flow, T_{wc}, such that $T_w = T_{wo} + T_{wc}$. The travel time may be computed for all locations in the watershed using Eq. (2) and isochrones can be derived. Note that Eqs. (2) and (3) hold for spatially variable excess rainfall.

Certain relationships for flow cross section area $A_x(h, x)$, hydraulic radius $R(h, x)$, bed slope $S_0(x)$, and equilibrium discharge $Q_e(x)$, or alternatively E and $A(x)$, must be obtained to allow the calculation of the travel time integral for channel flow. A_x and R may both be expressed as functions of flow depth h, either precisely through geometrical relationships or approximately through regression curves. In a general form: $A_x = a_1 h^{b_1}$ and $R = a_2 h^{b_2}$, where a_1, a_2, b_1, and b_2 are constants for a given cross section. Also in Eq. (2), $\gamma = 2b_2/(2b_2 + 3b_1)$ when using Manning's equation. For overland flow and flow in wide channels, however, a_2, b_1, and b_2 equal unity and $\gamma = 2/5$ (Saghafian and Julien, 1995). If the excess rainfall intensity E is uniformly distributed in space, then $Q_e(x) = EA(x)$ and the term $1/E$ can be taken out of the integral. In such a case, the travel time is inversely proportional to E and for a special case of watersheds with wide channels we have

$$T_w = CE^{(-2/5)} \quad (4)$$

where C is a watershed hydro-geomorphologic index conglomerating spatially distributed characteristics such as surface roughness, slope, flow length and flow accumulation, drainage pattern, and channel geometry. By comparing Eq. (4) with time of concentration formulas, such as Kirpich, one observes that such formulas ignore the effect of rainfall intensity and only include lumped geomorphic parameters.

Since rainfall intensity generally varies over time following a hyetograph, travel time values will inevitably change as well and time variability in isochrone maps and TAHs must be considered accordingly. Procedural details of such considerations are outlined in the following sections and the algorithm for rainfall–runoff simulation is described.

3. Simulation algorithm

In the context of numerical formulation, the watershed domain is discretized by a raster grid and proper tools are developed whereby spatial variations inside the integral in Eq. (2) can be accounted for. The proposed algorithm consists of four modules. These modules were developed using a GIS toolbox and specially developed software. The first module derives terrain-based features. It takes digital topographic data, usually in vector format, as input and generates raster terrain maps such as depressionless DEM, flow direction and flow accumulation (i.e. upslope drainage area). Temporal and spatial distribution of excess rainfall are determined by the second module, which requires soil infiltration parameters as well as the spatio-temporal variation of rainfall intensity. The third module uses derived maps in conjunction with the map of roughness coefficient to determine differential and total cumulative travel-time-to-outlet maps as well as time series of isochrone maps corresponding to excess rainfall intensities. The fourth module performs TA convolution technique to calculate the total runoff hydrograph.

The following steps describe procedures executed by the first module for deriving terrain-based maps.

1. The DEM is generated from the digitized elevation contours of the watershed using a standard GIS equipped with interpolation functions in a raster spatial data model. A pixel size is selected according to the scale of the original contour map and spatial variability of other input data.
2. The generated DEM usually contains depressions and flat areas where flow direction is not defined. Tribe (1992) attributed such artifacts to mistakes in the input data, unsuitable interpolation techniques or the interaction of grid spacing with contour spacing and valley orientation. The algorithm of Nelson and Jones (1995) is adopted here to remove artificial depressions and flat areas, whereby a gridded smoothing filter is applied to the DEM. Elevation adjustments are kept within the tolerance of roundoff error so that the DEM is not over smoothed. Various other techniques, described in GIS related literature, may also be adopted.
3. A flow direction program based on the eight directional D8 approach (O'Callaghan and Mark, 1984) has been developed, which produces steepest slope direction by operating on the DEM. A map of the distance from any pixel to the outlet is obtained as well.
4. Flow accumulation map, as a direct measure of drainage or flow concentration at each pixel, is then derived. This map shows the number of pixels draining through any given pixel in the catchment. The program preparing this map records the addresses of all pixels contained in the drainage area of any given pixel. Such capability is essential if excess rainfall varies over the watershed.

The second module leads to the preparation of time series of excess rainfall intensity maps in the watershed and operates as follows. The temporal and spatial patterns of rainfall, or otherwise uniform intensity, must be provided. The instantaneous pixel-averaged excess rainfall intensity may be estimated based on the application of Green–Ampt infiltration equation, or alternatively user-specified excess rainfall hyetograph is accepted in case of uniform excess intensity over the watershed.

The third module prepares differential and cumulative maps of travel time corresponding to a given map of excess rainfall intensity in the following manner.

1. The map of equilibrium discharge (Q_e in Eq. (2)) is first prepared. This is done, for any pixel, by accumulating the excess intensity multiplied by the pixel area over the flow drainage area of that pixel known from the accumulation map (Eq. (3)).
2. Differential kinematic wave travel time over any pixel is calculated based on the piece-wise form of Eq. (2). The input maps for this part include flow direction, bed slope, equilibrium discharge, and roughness coefficient. The roughness map may be prepared by reclassifying vegetation and land use maps according to suggested tables in the literature (e.g. Woolhiser, 1975 and Engman, 1986). For a pixel with a channel overlaid, the travel time is determined based on channel geometric and hydraulic properties as noted in Section 2.
3. Accumulating the above differential map along flow paths to the outlet produces cumulative travel time map. This map indicates the spatial distribution of the time required for a kinematic wave to travel from any pixels to the outlet.
4. For a cumulative travel time map, isochrones of equal travel times are derived and the areas bounded by adjacent isochrones are determined. While aggregate time-area histograms may be sufficient for uniform excess rainfall, the spatial extent of the areas in a given travel time range is quite important in runoff computation when dealing with spatially variable excess rainfall. In the latter case, the 'time–discharge' histogram (TDH) replaces the TAH for hydrograph derivation. TDH in itself represents the runoff hydrograph for any period of constant excess intensity.

All steps in the third module must be repeated N times, where N is the number of excess rainfall intensity maps. This is equal to the number of excess rainfall intervals with constant intensity. The final output will be N isochrone maps. However, note that in watersheds with wide channels subject to uniform excess rainfall, we need to execute the third module once. After derivation of TAH associated with any value of excess intensity (say E_1), the TAH of say E_2 may be easily produced by scaling the time axis with the ratio

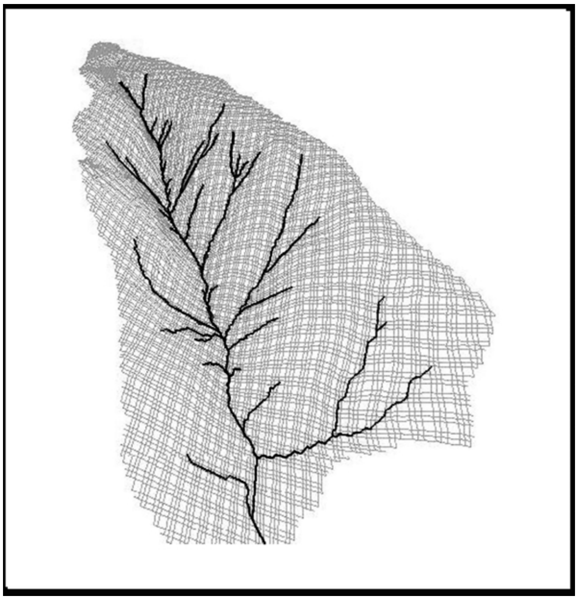

Fig. 2. 3D view of digital elevation model and stream network of W3 catchment.

of $(E_2/E_1)^{-0.4}$. A resampling of time axis of all TAHs may be necessary to achieve a common time interval.

In the fourth step, N incremental hydrographs corresponding to N isochrone maps are determined by convolution, where discharge is computed based on the integrated excess intensity over the areas bounded by appropriate isochrones. These incremental hydrographs, delayed by their corresponding excess intensity time, are then superimposed to yield the total hydrograph. Further details are illustrated in testing the model below.

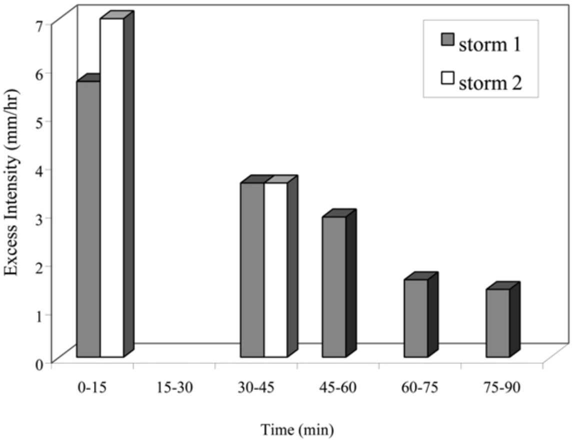

Fig. 3. Excess rainfall intensity hyetographs for two storms.

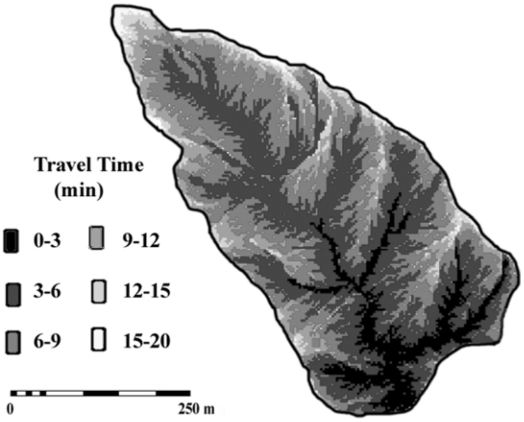

Fig. 4. Travel time map for 5.7 mm/hr excess rainfall intensity (Storm #1).

4. Model testing

The model was tested on a small 15.6 ha pilot catchment named W3 in the Cape Verde Islands located off West Africa. W3 catchment has been studied extensively by Mannaerts (1992). Elevation in the catchment ranges from 295 to 395 m. A 1:10000 topographic map has been prepared with 5-meter contour interval. The length of the main stream is 666 m. This small catchment has relatively uniform vegetation conditions and soil texture. To prepare input data for the simulation, a DEM with a pixel size of 3 m was generated using ILWIS GIS (ITC, 1997) from the digitized contour map. A 3D view of the DEM and stream network of W3 are shown in Fig. 2. Removal of pits and flat areas was performed by the first module to produce a depressionless DEM. Then slope, flow direction, and flow accumulation maps were produced.

Two dry-season, recorded, rainfall–runoff events were available for this study. A calibration run was conducted on Storm #1 and a validation run on Storm #2. Based on the available data and field observation made by Mannaerts (1992), rainfall and infiltration

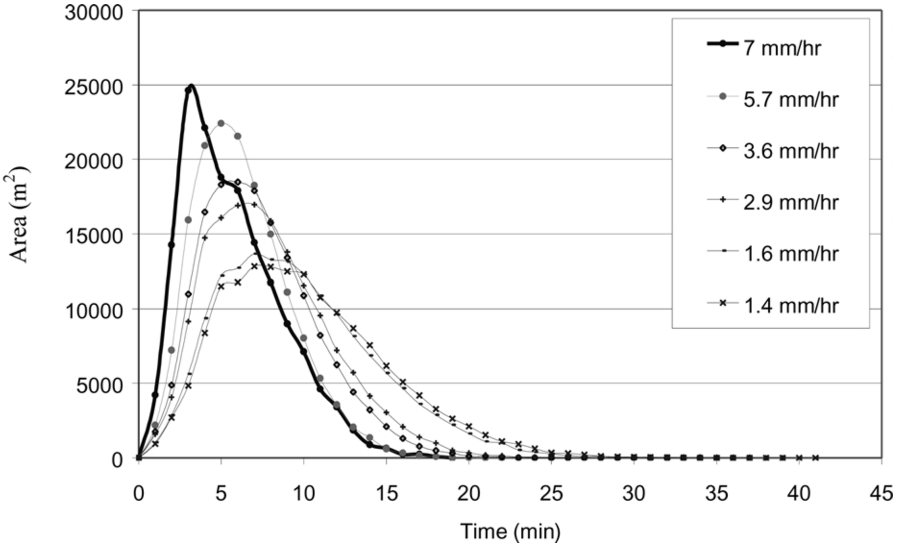

Fig. 5. TA curves for all excess rainfall intensities of two storms.

were assumed uniform over this small catchment. An empirical relationship derived from field measurements determined infiltration variation with time (Mannaerts, 1992). The total rainfall durations of the two storms were, respectively, 135 and 105 min; their excess rainfall hyetographs are shown in Fig. 3.

Differential- and total-travel-time-to-outlet maps were generated for each time interval with constant excess rainfall intensity. The computational time step, i.e. the time difference between adjacent isochrones, was taken as 1 min. Fig. 4 depicts travel time map for excess intensity of 5.7 mm/h occurring over the (0–15) min time interval in Storm #1. Note the dendritic pattern of the isochrones, where shorter travel times are generally experienced within the drainage network. The TAH derived from this isochrone map was used for calculating incremental discharge hydrograph over (0–15) min time interval based on the

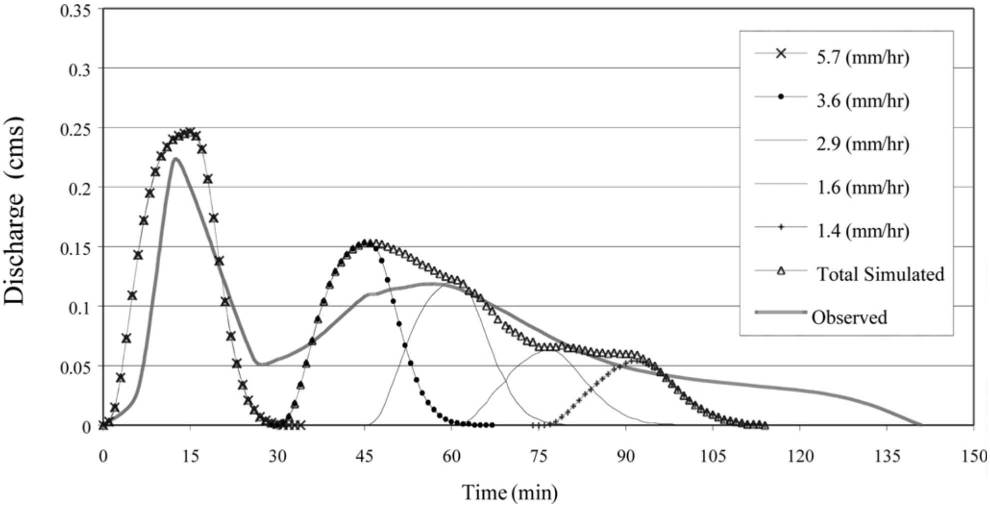

Fig. 6. Incremental and total simulated hydrographs compared with observed hydrograph (Storm #1).

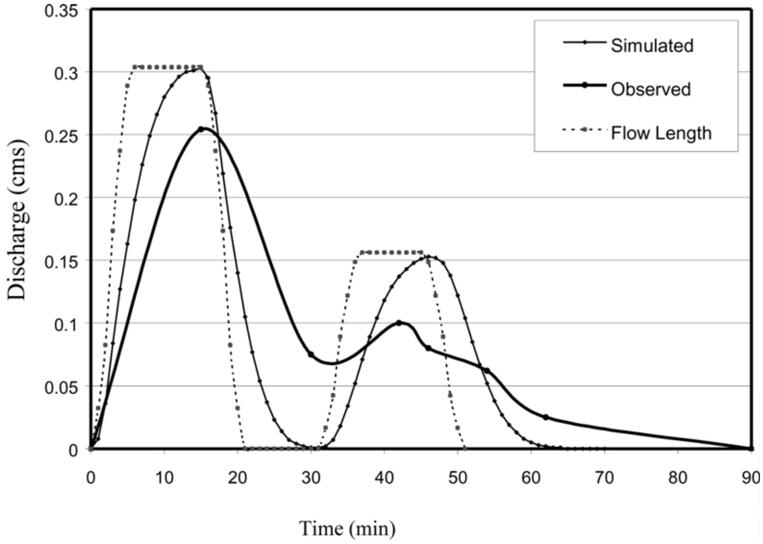

Fig. 7. Comparison of observed and simulated hydrographs (Storm #2).

convolution operation. Similar procedures were performed for other values of excess rainfall intensity occurring over subsequent time intervals, incremental discharge hydrographs lagged by 15 min were computed, and the total runoff hydrograph was constructed following the superposition rule. All TA curves corresponding to excess intensities in both storms are compared in Fig. 5. Inevitably, higher intensities cause the time base of the TAH to shorten as larger watershed sub-areas contribute to the runoff earlier.

The incremental and the total hydrographs are shown in Fig. 6 for the calibration run. A value of Manning roughness of 0.05 was estimated in this run with both peaks of the observed hydrograph being closely simulated. Fig. 7 shows the result of

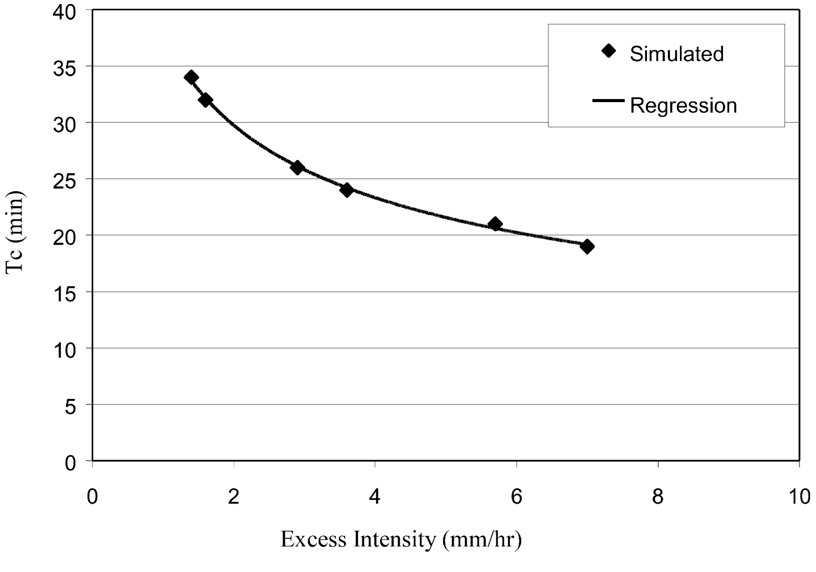

Fig. 8. Variation of time of concentration with excess rainfall intensity.

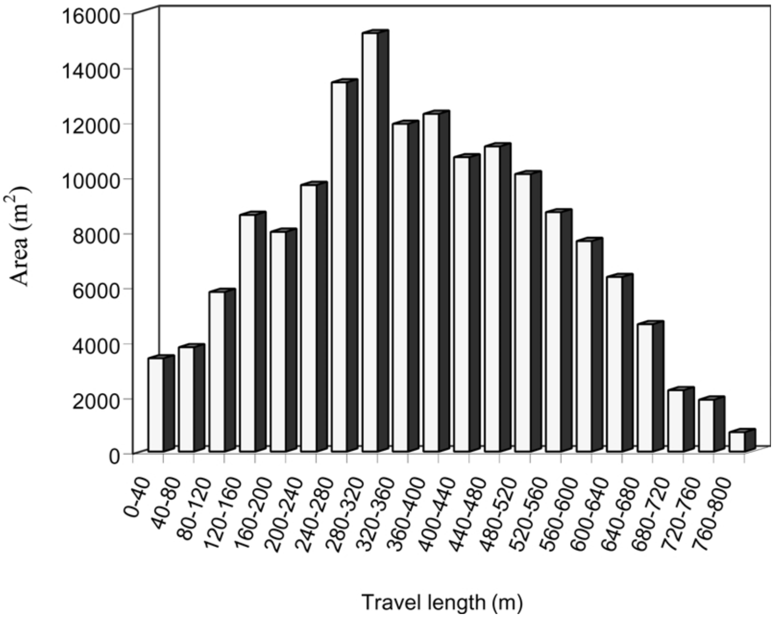

Fig. 9. TA histogram of W3 based on travel length to the outlet.

the validation run on Storm #2 with performance similar to the calibration run.

One may wish to study the relationship for the time of concentration for W3 catchment. Based on the maximum travel time values corresponding to different excess intensities, the following regression equation was fitted to the data (Fig. 8)

$$T_c = 37.9\, E^{-0.35} \tag{5}$$

with $R^2 = 0.99$. T_c is in minutes and E is in mm/hr. The absolute value of the exponent for E is smaller than 0.4 due to the effect of non-wide channel network in W3.

At this stage, we opted to evaluate the performance of another TA method in simulating rainfall–runoff in Storm #2. Specifically, we chose to look at the flow-length-based isochrone derivation method. Fig. 9 displays the 40-m travel-length-to-outlet histogram of W3, which the Modclark option in HMS assumes to be representative of TAH after its x-axis is rescaled into travel time. For this purpose, the time of concentration, or more accurately the time to equilibrium, must be estimated. We used the well-known Kirpich formula for W3 and calculated the runoff hydrograph for Storm #2. The result is shown in Fig. 7 which indicates a poor performance in both the rising and falling limbs of the hydrograph.

The model testing reported here represents a preliminary attempt limited to one watershed. A full testing, including spatially variable excess rainfall, will require a study of other watersheds which have more comprehensive data set and more recorded storms. The mathematical framework and overall modeling approach are believed however to be technically reliable and valid. We suggest that the hydrologic approach presented here is applicable up to midsize catchments, which have been characterized by Ponce (1989) as follows: (1) rainfall intensity varies within the storm duration; (2) rainfall may be assumed uniform over the catchment; (3) runoff travels as overland flow and channel flow; and (4) channel storage processes are negligible.

One limitation of the model is that depressions and flat areas cannot exist in the DEM and must be removed prior to model application. The model presently has no provision to deal with such terrain characteristics in the DEM. However, model application is possible when parts of the watershed, which do not contribute to the runoff at the main outlet, are located and masked out.

Although the sensitivity of the discharge calculations to DEM generation method and selection of pixel size for spatial discretization are broadly acknowledged, it is not the aim of this article to explore the fundamentals of DEM generation techniques or to conduct detailed study of the effect of pixel size on the results of raster-based simulations. It is expected that the role of pixel size diminishes as the excess intensity and/or duration of the storm increases (Molnar and Julien, 2000); this is equivalent to incremental hydrographs approaching equilibrium. Molnar and Julien (2000) reported that while studying effects of grid size on surface runoff modeling using a distributed hydrologic model, flow on overland cells was more sensitive to changes in cell size than was channel flow. Pixel size considerations on the portrayal of land surface and hydrologic simulations have been discussed by Zhang and Montgomery (1994). They suggested that a 10-m grid pixel size offers a rational compromise between increasing resolution and data volume for simulating hydro-geomorphic processes, but this clearly depends on many other factors as well.

In our experience with W3, a pixel size of 9 m produced negligible difference in peak discharge for $E = 5.7$ mm/hr in 15 min duration compared to the case of 3-m pixel size. We, therefore, believe that the 3-m pixel size provided sufficient accuracy in simulation of W3 catchment.

5. Conclusions

A distributed TA method has been proposed whereby maps of travel time and temporally varying isochrones throughout the storm duration can be determined. The procedure is modularized in a raster-based runoff simulation model, which relies heavily on terrain characteristics, such as slope, flow direction and flow accumulation. Spatio-temporal distribution of rainfall intensity and infiltration rate may be accounted for in the model. For any excess rainfall intensity, the travel time over the watershed is computed based on kinematic wave theory. Incremental discharge hydrographs corresponding to sequential excess rainfall intensities are computed. Then a total storm hydrograph is obtained by superposition.

The model algorithm elevates the original TA rainfall–runoff technique to a distributed terrain- and hydraulic-based methodology. It builds on isochrones that vary in time as the storm excess intensity develops. Thus, the 'stationarity' constraint is relaxed. The proposed algorithm offers flexibility in terms of GIS linkage and does not impose limits on storm duration and intensity. A major simplification in the algorithm can be made for cases of spatially uniform yet temporally variable excess rainfall intensity in watersheds with wide channels. This is rooted in the fact that the travel time in such cases is inversely proportional to the rainfall intensity raised to 0.4 power.

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References

Clark, C.O., 1945. Storage and the unit hydrograph. Trans. Am. Soc. Civil Engng 110, 1419–1446.

Engman, E.T., 1986. Roughness coefficients for routing surface runoff. J. Irrig. Drainage Engng, ASCE 112 (1), 39–59.

Hydrologic Engineering Center, 2000. Hydrologic Modeling System HEC-HMS. Technical Reference Manual. HEC 149p.

ITC (International Institute for Aerospace Survey and Earth Sciences), 1997. ILWIS 2.1 for Windows, Enschede, The Netherlands.

Kull, D.W., Feldman, A.D., 1998. Evolution of Clark's unit graph method to spatially distributed runoff. J. Hydrol. Engng, ASCE 3 (1), 9–19.

Laurenson, E.M., 1964. A catchment storage model for runoff routing. J. Hydrol. 2, 141–163.

Maidment, D.R., 1993. Developing a spatially distributed unit hydrograph by using GIS. Proceedings of HydroGIS'93. IAHS Publ. no. 211.

Mannaerts, C., 1992. Assessment of the transferability of laboratory rainfall–runoff and rainfall–soil loss relationships to field and catchment scales. PhD Dissertation, State University of Gent, Belgium.

Molnar, D.K., Julien, P.Y., 2000. Grid-size effects on surface runoff modeling. J. Hydrol. Engng, ASCE 5 (1), 8–16.

Muzik, I., 1996. Lumped modeling and GIS in flood predictions. In: Singh, V.P. (Ed.). Geographical Information Systems in Hydrology. Kluwer Academic Publishers, The Netherlands.

Nelson, J.E., Jones, N.L., 1995. Reducing elevation roundoff error in digital elevation models. J. Hydrol. 169, 37–49.

O'Callaghan, J.F., Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Comput. Vision, Graphics, and Image Process., 28, 323–344.

Olivera, F., Maidment, D., 1999. Geographic information systems (GIS)-based spatially distributed model for runoff routing. Water Resour. Res. 35 (4), 1135–1164.

Ponce, V.M., 1989. Engineering Hydrology. Prentice-Hall, New Jersey 640p.

Rodriguez-Iturbe, I., Valdes, J.B., 1979. The geomorphic structure of hydrologic response. Water Resour. Res. 15 (6), 1409–1420.

Rodriguez-Iturbe, I., Devoto, G., Valdes, J.B., 1979. Discharge response analysis and hydrologic similarity: the interrelation between the geomorphologic IUH and the storm characteristics. Water Resour. Res. 15 (6), 1435–1444.

Saghafian, B., Julien, P.Y., 1995. Time to equilibrium for spatially variable watersheds. J. Hydrol. 172, 231–245.

Tribe, A., 1992. Automated recognition of valley lines and drainage networks from grid digital elevation models: a review and a new method. J. Hydrol. 139, 263–293.

Woolhiser, D.A., 1975. Simulation of unsteady overland flow. In: Mahmood, K., Yevjevich, V. (Eds.). Unsteady Flow in Open Channels, vol. II. Water Resources Publication, Ft. Collins, CO, USA Chapter 12.

Zhang, W., Montgomery, D.R., 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. Water Resour. Res. 30 (4), 1019–1028.