Acta Sci. Pol.
Formatio Circumiectus 23 (2) 2024, 83–96
ENVIRONMENTAL PROCESSES

www.acta.urk.edu.pl ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/189809

ORIGINAL PAPER Accepted: 8.06.2024

ESTIMATION OF SUBSURFACE FLOW HYDROGRAPH OF CATCHMENTS USING TIME-AREA HYDROGRAPH METHOD

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ABSTRACT

Aim of the study

In this study, a novel approach was undertaken, employing the concept of SSF isochrones in tandem with the time-area histogram (TAH) method as a fresh model for SSF estimation within catchments.

Material and methods

Leveraging the subsurface travel time equation of hillslopes and GIS software, the spatial delineation of isochrones within the soil was accomplished. Furthermore, a methodology was introduced to compute the TAH of SSF. Subsequently, the subsurface hydrograph of the catchment was derived, by convoluting the TAH of SSF with the infiltration hyetograph. To validate the findings, the subsurface hydrographs calculated using the geomorphologic instantaneous unit hydrograph (GIUH) model were juxtaposed with those from two catchments in northern Taiwan – Heng-Chi and San-Hsia.

Results and conclusions

The mean error in comparison with the SSF time-area model stood at 10.5%, affirming the robustness of the proposed approach.

Keywords: subsurface time-area, subsurface flow, isochrones, GIS

INTRODUCTION

Part of the rain falling on the earth's surface percolates and causes subsurface flow (SSF), while another part leads to surface flow (SF). SF and SSF are the main constituents of the flood hydrograph of a catchment (Sabzevari, 2010; Sabzevari et al, 2013; Petroselli, 2020; Babaali et al, 2021; Ardekani et al, 2021). In the present work, SSF is understood as the fast and shallow subsurface flow produced near the soil surface, which is a central issue in the Dunne-Black mechanism in creating the saturation level of hillslopes and surface flow. This SSF finally enters the surface flow in the saturated zone and joins the stream. Deep subsurface flow (DSF) creates groundwater, which is not the subject of the present work. In the catchments with high soil permeability and suitable vegetation, the SSF will share a high role in the direct runoff therein. Therefore, an accurate estimation of this type of flow in such catchments would be very important (Sabzevari, 2017; Petroselli et al., 2020).

Many rainfall-runoff models such as the Time-Area Histogram (TAH) model, NASH, SCS, Clark, and

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Geomorphological Instantaneous Unit Hydrograph (GIUH) have been offered to predict surface runoff, and extensive research has been conducted on these models (e.g. Bai et al., 2019; Tarahi et al., 2022).

The TAH model is a method based on the time-area histogram of the catchment and on the excess rainfall hyetograph to estimate surface runoff without considering the effect of storage (Ponce, 1994). To calculate TAH, it is necessary to determine the position of surface flow isochrones (Saghafian et al., 2000). The position of the isochrones is governed by the surface runoff travel time, which depends, in turn, on parameters such as flow path length, Manning coefficient of the overland, path slope, hillslope shape, and excess rainfall intensity. The accuracy of the TAH method depends on the accuracy of the estimation of the isochrones or that of the travel time. The perfect travel time estimation, dependent on the infiltration, is practically impossible since infiltration changes spatially and temporally across the catchment. With the increasing use of Geographic Information Systems (GIS), and through the pixelization of the catchments and more accurate estimation of the parameters of the travel time formulas in a small-scale dimension, a more accurate estimation of TAH was possible and the results of runoff calculations were made more acceptable and simpler (Maidment, 1993; Muzik, 1996; Matei, 2012; Petroselli and Grimaldi, 2018).

TAH method was indeed applied in many hydrological models. For instance, Clark (1945) considered the effect of storage on the catchment's surface with TAH routing process and predicted the catchment's instantaneous unit hydrograph (IUH). The surface flow hydrograph can then be estimated by convolving the unit hydrograph calculated from the Clark method and the excess rainfall hyetograph.

The SCS model provided by the Soil Conservation Service of the United States is a well-known model to estimate surface runoff in ungauged catchments. The results of this model have been evaluated in many catchments globally (SCS, 1956, 1964, 1971, 1993; Mishra and Sink 2003; Sabzevari et al, 2009 Choi et al., 2016; Rawat and Sink, 2017).

Examining the subsurface hydrologic response of the hillslopes by numerical models has been very common in recent years and is still interesting to hydrologists. Solving the Richards and Bousinesq equations numerically is widely used to estimate surface runoff, the amount of storage, and soil moisture (Paniconi et al., 2003; Troch et al., 2003; Sahoo et al., 2018; Fariborzi et al., 2019). Pikul et al. (1974) also presented a model coupling the Richard and Bousinesq equations to investigate the SSF in the saturated-unsaturated zones of the hillslopes. The numerical modeling of SSF by solving Boussinesq and Richards equations in HYDRUS software is another approach for estimating SSF in the hillslopes (Essig et al., 2009).

The IUH model is widely used in estimating SF of the catchments. It was developed to estimate the SSF hydrograph as presented by Lee and Chang (2005). They used the equation of subsurface travel time of the catchment's overlands and applied the IUH function of the linear reservoir of the hillslope's soil layer. Finally, using the convolution technique, they worked on the IUH of the SSF of the entire catchment. The SSF hydrograph was calculated by convolution of the subsurface IUH of the catchment and the infiltration hyetograph.

Fariborzi et al. (2019) concluded that the surface rainfall-runoff models can estimate the SSF of the catchment's hillslopes and that the basic difference is in the concept of surface and subsurface travel time, excess rainfall, and rate of recharge to the aquifer. Surface models indeed estimate surface runoff based on the amount of excess rainfall and the surface travel time. So, this capability can be used to estimate the SSF based on the amount of infiltration and the subsurface travel time. In their research, Fariborzi et al. (2019) defined the concept of isochrone curves inside the soil and calculated the subsurface time-area histogram of a hillslope based on the real subsurface travel time equations. The SSF hydrograph of the hillslopes evaluated by the results of a rainfall simulator laboratory model and simulations was compared with the results of the HYDRUS 2D-3D model.

The subsurface travel time is a function of hillslope geometry, including length, slope, changes in hillslope width along the hillslope, bottom curvature, porosity, and soil hydraulic conductivity. In previous research, Sabzevari et al. (2010) provided equations to calculate the subsurface travel time of hillslopes for two cases where the hillslope is saturated. The proposed equation was a function of the shape and geometry of the hillslopes.

Based on this, the main goal of this research is to develop a TAH model to estimate SSF at the scale of catchments. As mentioned, with the use of GIS and the pixelization of the catchment by calculating the subsurface travel time of the isochrone curves inside the soil and the area between two isochrones, the time-area histogram of the subsurface area is estimated here. Finally, by convolving the obtained histogram with the infiltration hyetograph, SSF is calculated.

One of the important assumptions of this research is that the bedrock is close to the earth's surface. The entire rainfall penetrated into the soil in the form of a fast subsurface flow that enters the stream, and the groundwater as a deep subsurface is practically not considered.

Hence, the objectives of this research are:

1. Delineation of subsurface isochrone curves and SSF histogram using GIS software.
2. Calculation of the subsurface unit hydrograph using the subsurface time-area method.
3. Prediction of the subsurface flow of catchments by GIS.

The present manuscript is organized as follows: in paragraph 2, materials and methods are provided. In paragraph 3, the results showing the application of both TAH and GIUH models are presented for two case studies located in northern Taiwan. Finally, in paragraph 4, conclusions are summarized.

MATERIALS AND METHODS

Time-Area Model

Clark (1945) first introduced the time-area method to estimate surface runoff to simulate the spatial variations in the catchment and the temporal changes of rainfall. This technique, as a rainfall-runoff model or a hydrological routing method, calculates the flood hydrograph based on the excess rainfall hyetograph. This model is one of the most effective methods for routing surface flow (Maidment, 1993; Singh, 1996). Ignoring the storage effects, this technique divides the catchment into several sub-areas with the help of travel time isochrone curves (i.e. is the curves connecting points with equal travel time to the catchment outlet) until the catchment's outlet. The histogram of the obtained subareas, as a function of time and area, is called the time-area histogram (TAH). This histogram is the basis of the time-area method for converting excess rainfall into runoff. To develop a TAH, the equilibrium time of the catchment, referred to as concentration time in the hydrological literature, must be divided into several equal parts. TAH is determined based on the isochrone curves of the catchment. The isochrone curves are a function of the time of water movement on the overland and stream networks of the catchment.

According to the established definition, an isochrone curve is the geometric locus of points whose travel time to the catchment's outlet is equal. A catchment map can also be prepared for these curves, which is called an isochronal map (Fig. 1a).

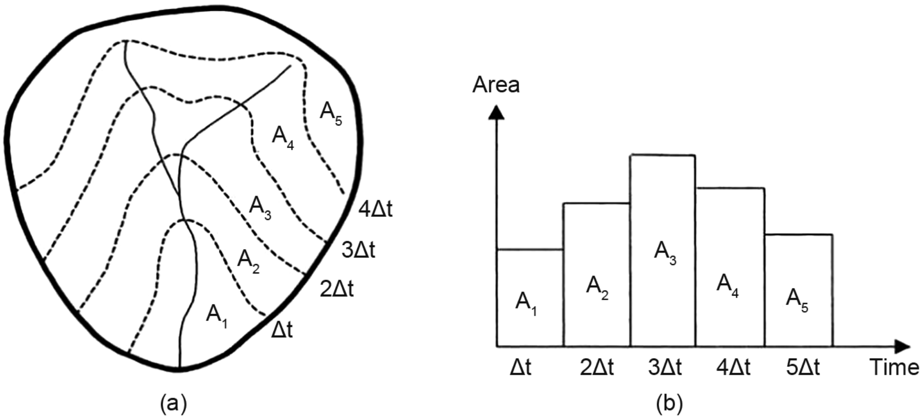

Fig. 1. (a) Isochrones of a basin; (b) time-area histogram (source: after Saghafian et al., 2002)

In the time-area model, the catchment is divided into several sub-areas with the help of isochrones. The histogram of the areas between the travel time curves (Fig. 1b) is the basis of the time-area model for converting excess rainfall into runoff. Time-area diagram is also the step response function of the catchment. If the TAH values are convoluted with the excess rainfall hyetograph, then the runoff hydrograph of the catchment is determined according to Equation 1 (Saghafian et al., 2016):

$$Qs_j = \sum_{m=1}^{j} I_m \; A_{j-m+1} \tag{1}$$

In Eq. 1, Q is the outlet discharge, A is the area limited to two isochrone curves, j is the time step, and I_m is the excess rainfall.

Of course, any factor affecting the flow speed and runoff travel time over the hillslopes and river network directly affects the TAH.

Application of the Time-Area Model to the Estimation of Subsurface Flow

Since the aim of this research is to develop the subsurface time-area model to estimate the SSF, we have applied the amount of infiltration rate in the time-area model instead of the excess rainfall to estimate SSF in catchments.

Also, a method was suggested in the present work for delineating isochrone curves in soil and for SSF.

Figure 2 shows a rectangular overland with a length L and the slope of S_0. If the soil hydraulic conductivity of the soil is K and porosity is denoted ε, the subsurface travel time (t_c) of this soil layer is obtained according to Equation (2) (Sabzevari et al., 2010):

$$t_c = \frac{\varepsilon L}{K S_0} \tag{2}$$

According to Figure 2, isochrone No. 1 has a subsurface travel time equal to Δt and is located at a distance of x_1 from the upstream. Isochrone No. 2 has a travel time of $2\Delta t$ and is located at position x_2. The value of Δt is arbitrary, and it is calculated from the relation $\Delta t = t_c / N$ (where N is the number of the isochrone curves).

Equation (3) is used to calculate the position of the subsurface isochrones. For example, the J^{th} isochrone has a travel time $J\Delta t$, so we have:

$$J\Delta t = \frac{\varepsilon(L - x_j)}{K S_0} \Rightarrow x_j = L - \frac{J \Delta t K S_0}{\varepsilon} \tag{3}$$

If W represents the width of the overland, the areas of the elements A_1 and A_2 are calculated as follows:

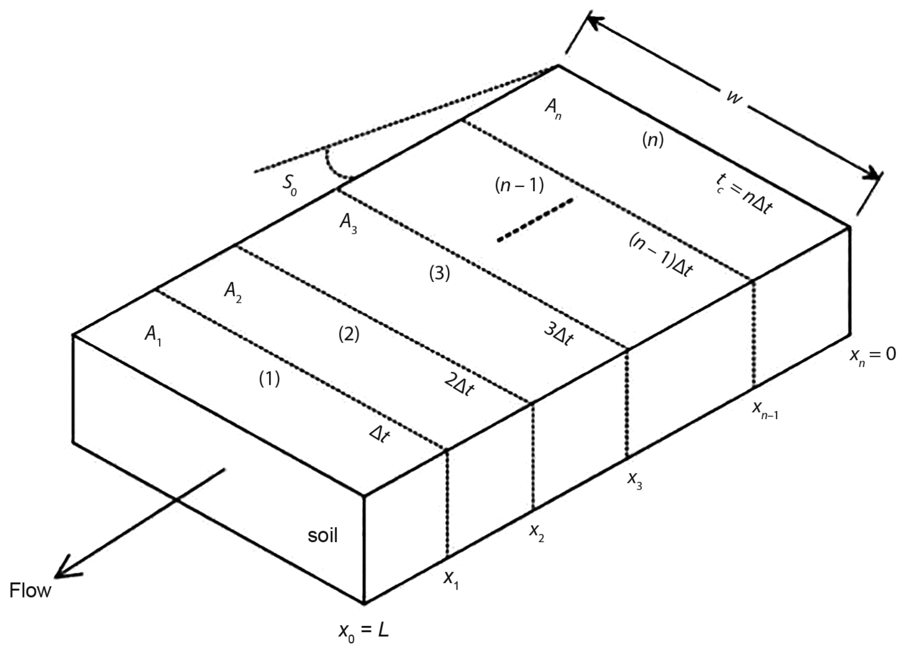

Fig. 2. Subsurface isochrone curve of a soil layer (source: after Fariborzi et al., 2019)

$$A_1 = (L - x_1)W \tag{4}$$

$$A_2 = (x_2 - x_1)W \tag{5}$$

The other elements are calculated as $A_j = (x_j - x_{j-1})$ W. According to Equations from 3 to 5, we obtain:

$$A_1 = A_2 = \ldots = Aj = \frac{K\Delta t S_0}{\varepsilon} \tag{6}$$

The area of all subsurface time-area elements is equal to $(KS_0\ \Delta t)/$ These values are constant because the relationship between length and travel time in equation (2) is assumed to be linear.

In the TAH method, the recharge rate to the soil layer (f) must be convoluted with the subsurface TAH values to calculate the subsurface runoff hydrograph according to the following equation:

$$Q_m = \sum_{m=1}^{j} f_m A_{j-m+1} \tag{7}$$

where m represents the time step, Q is the output flow rate, f is the infiltration value, and A stands for the area limited to two consecutive travel time curves.

Fariborzi et al. (2019) evaluated the STA model using the results of a subsurface laboratory model and HYDRUS numerical model. The laboratory model consisted of sandy loam soil comprising three rainfalls with different intensities and three slopes for nine rainfall events. The results of the hydrograph of the observed SSF were compared with those of the STA method in the present work. The average values of Nash-Sutcliffe coefficient of efficiency (CE), correlation coefficient (R), root mean square error (RMSE), and error of peak flow (EPF) of STA method for the nine events were, respectively, 0.81, 0.85, 0.98, and 0.017, which were regarded as good values. The results remained within the dimension of a hillslope. In this study, the intention is to determine the subsurface time-area model in the catchment scale. For this purpose, GIS was used to develop STA isochrones.

Histogram of Time-Area using GIS

To apply the time-area model to the SSF, it is necessary to calculate the subsurface isochrone curves of the catchment. Also, the area between the isochrones must be calculated and the time-area histogram should be drawn. The SSF hydrograph is calculated by convolving the obtained subsurface time-area histogram with the infiltration rate into the subsurface soil layer. When the time-area histogram is to be obtained in the catchment dimension, the subsurface isochrone calculation is not a simple task. Hence, utilizing a model or software capable of delineating the isochrones according to the specific geometry conditions of each catchment is necessary. In this work, we applied the widely used commercial software of ArcGIS. Figure 3 shows an example of subsurface isochrone curves in the Heng-Chi catchment in Taiwan.

The flowchart in Figure 4 illustrates the stages of estimating the subsurface histogram of the catchments using ArcGIS software.

Fig. 3. Area between the subsurface isochrone curves of Heng-Chi catchment (source: after Fariborzi, 2021)

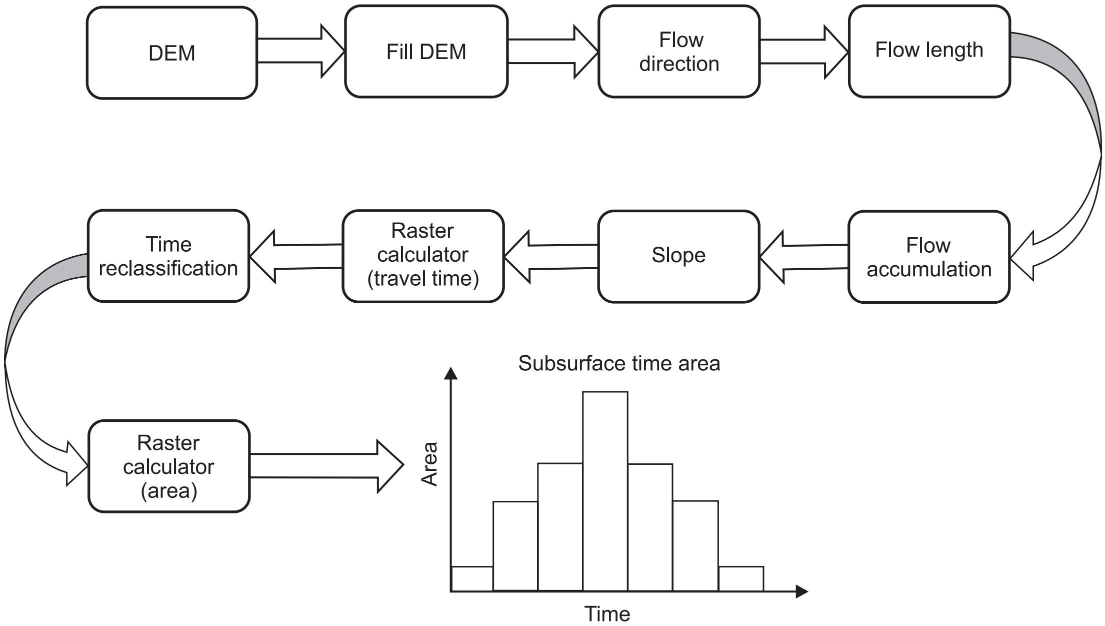

Fig. 4. Estimation of subsurface time-area histogram using ArcGIS (source: after Fariborzi, 2021)

A summary of the various stages of the flowchart in Figure 4 is as follows:

– **Digital Elevation Model (DEM)**

The desired catchment's Digital Elevation Model (DEM) represents the procedure's starting point. The DEM is a 3-dimensional representation of the earth's surface, which is usually organized to show the roughness of the earth using elevation data above sea level. DEM is a raster layer containing information, coordinates, and elevation (X, Y, Z) for each location with a specific cell size. Each cell (pixel) of the raster is identified with a numeric code that specifies the average elevation of the pixel. The accuracy varies depending on the source from which DEM is prepared. Accuracy can be named for each cell with height accuracy and spatial accuracy. Spatial accuracy is related to the size of the side of each cell. The smaller it is, the higher the accuracy. The height accuracy, however, detects the minimum height in each cell that can be measured and identified. Preparing the DEM of the catchment with proper accuracy is the basis of working with GIS software, whereas the remaining steps as well as other required data can be derived from the DEM. To prepare the DEM of catchments, websites such as Srtm.Csi.cgiar.org and earthexplorer.usgs.gov can be used. In this research, DEM 30 m*30 m from the USGS website was used.

– **Filling the DEM**

The Fill DEM tool was used to fix the errors in the existing DEM map. This tool treats spurious points (the so-called pits) in the DEM map. Indeed, if a pixel is surrounded by pixels with higher elevations (such points are called pits), the water will be trapped and will not flow downward. The Fill DEM tool fixes this problem by modifying the DEM map and increasing the pits' elevation until the lowest elevation among the neighboring ones is reached.

– **Assigning flow direction**

By executing this command, the direction of the runoff flow is drawn in different pixels of the catchment. This flow path is usually determined according to the maximum slope around each pixel. Particular lookup tables assign flow direction in flat areas.

– **Determining flow accumulation**

The flow accumulation is determined based on the flow network of the upstream pixels so that the numerical value of each pixel is calculated cumulatively from the source towards the outlet of the catchment. In fact, the highest number is related to the outlet of the catchment (Figure 5).

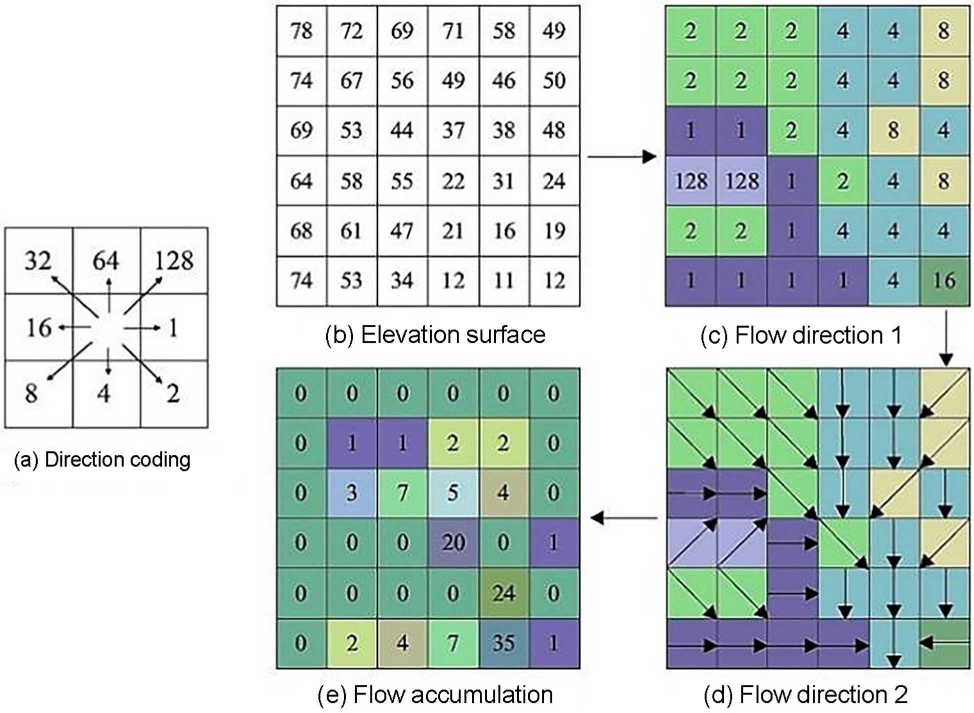

Fig. 5. Flow Direction and Flow Accumulation algorithm (source: after Huang and Jin, 2019)

– **Slope calculation**

The time of concentration of the catchment is highly dependent on the main river slope. First, using the "Longest Flow Path" command in the Arc Hydro tool, the longest path of the streamway is determined. Then, using the "Construct 3D Line" command, the longitudinal profile of the streamway is drawn, and finally, according to the length, and the minimum and maximum height of the stream way, the slope is calculated.

– **Calculation of Subserface travel time**

As stated in the introduction, the accuracy of the subsurface TAH method depends on isochrone estimation and the accuracy of the latter depends on the accuracy of subsurface travel time estimation. The subsurface travel time of the soil is generally a function of the catchment geometry, porosity, and hydraulic conductivity of the soil. In this research, according to the descriptions given before, Equation (2) was used to calculate the SSF travel time. To calculate and draw the position of the isochrones, one should first introduce Equation (2) to the software. The "Raster Calculator" command was employed to introduce Equation (2) to Arc GIS software.

– **Time reclassification**

After introducing the subsurface travel time equation of the catchment and calculating it in the software, the subsurface travel time was divided into *n* equal parts, and the isochrone curves were drawn on the catchment by the ArcGIS. This operation was carried out using the "Reclassify" command in ArcGIS. Finally, to estimate the subsurface time-area histogram via ArcGIS software, according to the obtained isochrones and also the DEM accuracy in the catchment, the area between each isochrone can be computed and the subsurface time-area histogram of the catchment can be drawn.

Geomorphological Instantaneous Unit Hydrograph Model

One of the models developed in the field of estimating surface and subsurface runoff in ungauged catchments is the Geomorphological Instant Unit Hydrograph (GIUH) model suggested by Rodriguez-Iturbe and Valdes (1979). IUH is the response of the catchment area to the arrival of a unit of instantaneous excess rainfall. Lee and Chang (2005) have given the following GIUH equation to predict the SSF of the catchments:

$$Q = \int_0^t u_{sub}(t - \tau)\, N(\tau)\, d\tau \qquad (8)$$

where u_{sub} *(t)* represents the subsurface GIUH and *N* denotes the intensity of rainfall in the subsurface layer.

To evaluate the results and to assess the accuracy of the simulations, we use several statistical methods simultaneously instead of applying just a specific statistical method (Willems, 2009). Accordingly, four statistical evaluation indicators, i.e. Nash-Sutcliffe coefficient of efficiency (CE), correlation coefficient (R), root mean square error (RMSE), and error of peak flow (EPF) were used in this research to evaluate the results of the models.

1. The Nash-Sutcliffe coefficient of efficiency (CE) is one of the most common indicators used to evaluate the efficiency of hydrological models and is calculated from Equation (9) (Nash and Sutcliffe, 1970).

$$CE = 1 - \frac{\sum_{i=1}^{n} \left| O_i - S_i \right|^2}{\sum_{i=1}^{n} \left| O_i - \bar{O}_i \right|^2} \qquad (9)$$

where O_i is the observed values, S_i is the calculated values, and O_i^- is the average of observed values. If $0.75 < CE \le 1$, we have good results, $0.36 < CE \le 0.75$ gives acceptable results, and $CE \le 0.36$ corresponds to unacceptable results (Motovilov et al., 1999).

2. The correlation coefficient (R) of the model is obtained from the following equation (Sugiyono, 2016):

$$R = \frac{N \sum S_i O_i - \sum S_i \sum O_i}{\left[\left\{ N \sum S_i^2 - \left(\sum S_i \right)^2 \right\} \left\{ N \sum O_i^2 - \left(\sum O_i \right)^2 \right\} \right]^{0.5}} \qquad (10)$$

The closer the R-value is to 1, the better the values would be. The values $0.8 < R \le 1$ correspond to very good correlations, $0.6 < R \le 0.799$ gives a good correlation, $0.4 < R \le 0.599$ represents a medium correlation, the range $0.2 < R \le 0.399$ is associated with a low correlation, and the correlation $R < 0.19$ is very low.

3. The error of peak flow (EPF) is calculated from the following equation:

$$REP = 100 \cdot \frac{\left[Q_{PS} - Q_{PO} \right]}{Q_{PO}} \qquad (11)$$

where Q_{PS} is the calculation peak discharge and Q_{PO} is the observation peak discharge.

RESULTS

In this part of the research, the geomorphological information and hydrological records of two catchments in northern Taiwan, i.e. Heng-Chi and San-Hsia catchments were used (Figure 6). The minimum and maximum heights of the Heng-Chi catchment are, respectively, 20 m at the outlet and 970 m at the entrance of the catchment with an area of 23.53 km^2. The majority (70%) of the area of the catchment consists of forest, 25% is agricultural land and 5% embodies buildings and roads. The minimum and maximum heights of the San-Hsia catchment are 30 m and 1770 m, respectively, spanning an area of 125.88 km^2. As for the former case study, the major-

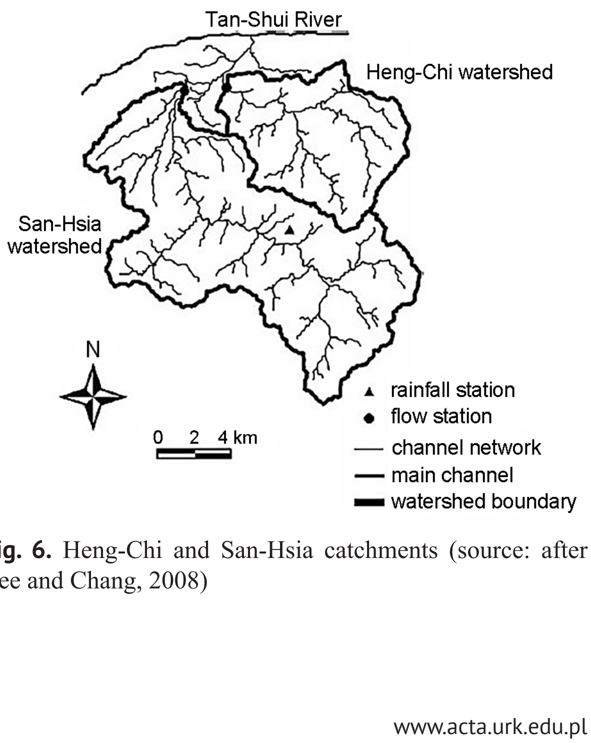

Fig. 6. Heng-Chi and San-Hsia catchments (source: after Lee and Chang, 2008)

ity (75%) of the area of this catchment is covered by forest, 20% is made up of agricultural land and 5% is composed of buildings and roads. In these catchments, records of hydrological data are over 30 years old. Also, a rainfall intensity of more than 50 mm/h can be observed every year.

The DEM maps, Flow Direction, Flow Accumulation, Flow length, and Slope map, as well as the subsurface isochrones by ArcGIS, are presented in Figure 7.

Figure 8 shows the subsurface time-area histogram (STAH) of the Heng-Chi and San-Hsia catchments.

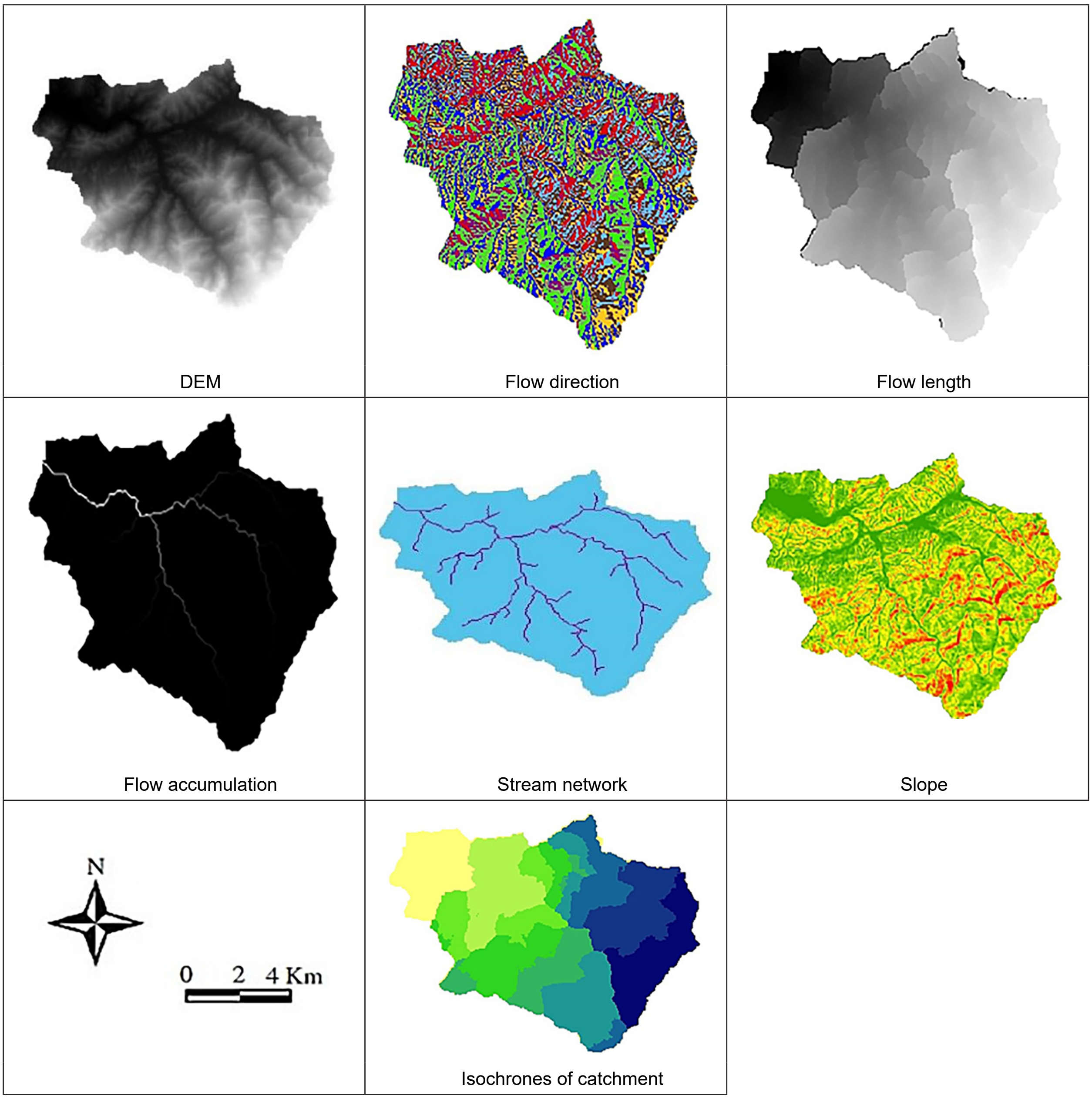

Fig. 7. DEM map of Heng-Chi catchment and maps prepared to estimate subsurface time-area histogram (source: after Fariborzi, 2021)

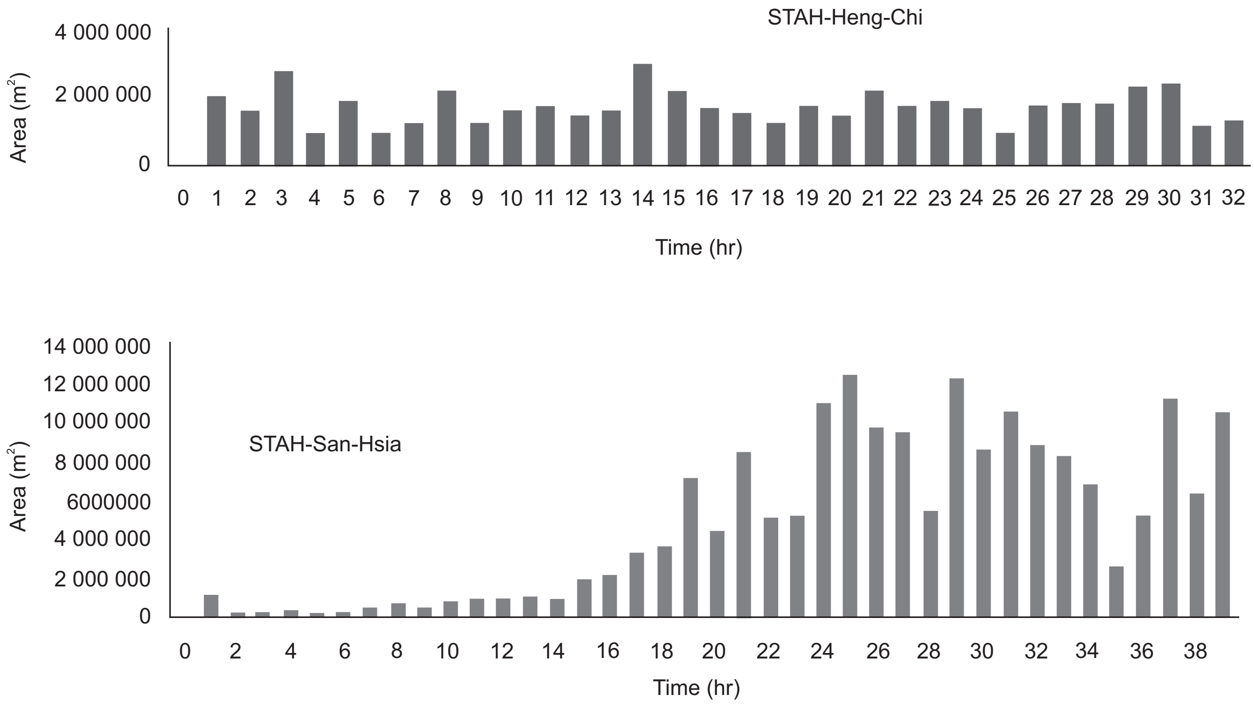

Fig. 8. STAH for Heng-Chi and San-Hsia catchments (source: Authors' own elaboration)

Based on Figure 8, the values of the STAH contributing areas in the Heng-Chi catchment are almost uniform at different times. In the San-Hsia STAH, in the early times, the contributing areas are low, and it increases from 15 hours onwards. This issue causes the subsurface flow to reach the maximum values in a longer time during the rainfall with almost constant infiltration intensity.

Figure 9 shows the excess rainfall histograms and the SSF hydrographs of the Heng-Chi and San-Hsia catchments for four different rainfall events by the proposed subsurface time-area method. The SSF hydrographs of the present work have been compared with the corresponding ones obtained employing the GIUH model of Chang and Lee (2008).

Table 1 contains the results of the time-area model in estimating the SSF of two catchments in northern Taiwan, i.e. Heng-Chi and San-Hsia, compared to the GIUH model of Chang and Lee (2008).

The average Nash-Sutcliffe efficiency coefficie nt (CE) for 4 events in two case study catchments was 0.72 and the average correlation coefficient (R) was 0.84. The average value of the subsurface flow peak error (REP) was 10.5%, which is an acceptable value for subsurface flow considering the complexities of subsurface flow in catchments. It is worth noting that the selection of DEM accuracy of the catchment (cell size) is effective in calculating the isochrones and, as a result, in developing the SSF hydrograph.

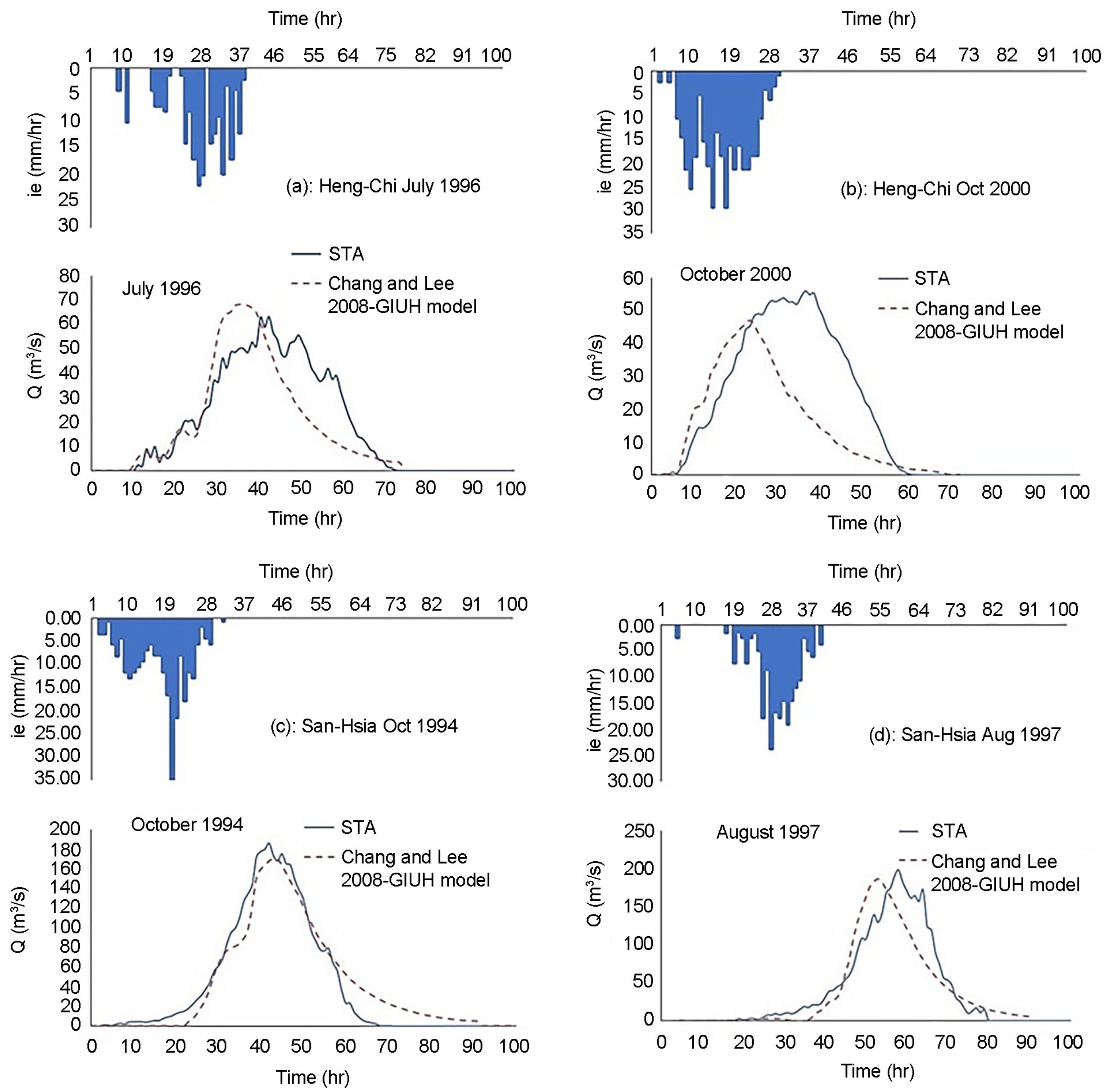

Fig. 9. Excess rainfall histogram and SSF hydrograph of Heng-Chi and San-Hsia catchments (source: Authors' own elaboration)

Table 1. Comparison of the peak subsurface flow results of the time-area model with the GIUH model (source: Authors' own elaboration)

Basin	Event	Subsurface flow (m^3/s)				
		Time-Area	Modeled with GIUH	CE	R	REP%
Heng-Chi	July 1996	63.3	68.1	0.63	0.82	7
	October 2000	56	47	0.51	0.68	19
San-Hsia	October 1994	186	170	0.92	0.96	9.4
	August 1997	198.5	186.2	0.8	0.9	6.6
Mean error				0.72	0.84	10.5

CONCLUSION

Assessing subsurface flow (SSF) within a catchment is crucial, particularly in areas where it constitutes a significant portion of total runoff. This study focuses on estimating SSF hydrographs using the subsurface time-area model. Subsurface isochrones, indicative of travel times, were derived to facilitate this estimation. Employing ArcGIS software and Arc Hydro, a method was developed to compute isochrones and construct time-area histograms for the catchment. This model was applied to two catchments in Taiwan, and the SSF hydrographs for four events were analyzed and compared with previous research. Key findings include:

1. The subsurface travel-time model proves to be both straightforward and effective, offering reliable estimates for SSF runoff across hillslopes and the entire catchment.
2. Utilizing ArcGIS software for isochrone positioning and evaluating the time-area model throughout the catchment, the average peak error of SSF hydrographs for Heng-Chi and San-Hsia catchments in northern Taiwan was found to be 10.5%, compared to the Chang and Lee (2008) results that were based on the GIUH model.

This research underscores the viability of the subsurface time-area model in estimating SSF hydrographs and highlights its practical applicability in catchment studies.

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OSZACOWANIE HYDROGRAMU PRZEPŁYWU PODPOWIERZCHNIOWEGO ZLEWNI METODĄ HYDROGRAMU PRZESTRZENNO-CZASOWEGO (TAH)

ABSTRAKT

Cel badania

W badaniu przyjęto nowatorskie podejście, wykorzystując koncepcję izochron SSF w połączeniu z metodą histogramu przestrzenno-czasowego (TAH) jako nowy model szacowania SSF w zlewniach.

Materiał i metody

Wykorzystując równanie czasu przepływu pod powierzchnią zbocza oraz oprogramowanie GIS, dokonano przestrzennego wyznaczenia izochron w glebie. Ponadto wprowadzono nową metodologię obliczania TAH SSF. W rezultacie uzyskano hydrogram podpowierzchniowy zlewni poprzez splot całkowy TAH SSF z hietografem infiltracji. Aby potwierdzić ustalenia badawcze, zestawiono hydrogramy podpowierzchniowe obliczone przy użyciu modelu geomorfologicznego hydrogramu jednostek chwilowych (GIUH) z hydrogramami z dwóch zlewni w północnym Tajwanie – Heng-Chi i San-Hsia.

Wyniki i wnioski

Średni błąd systematyczny w porównaniu z modelem hydrogramu przestrzenno-czasowego SSF wyniósł 10,5%, co potwierdza zasadność proponowanego podejścia.

Słowa kluczowe: podpowierzchniowy hydrogram przestrzenno-czasowy, przepływ podpowierzchniowy, izochrony, GIS