A window-based inquiry system for design discharge based on geomorphic runoff modeling

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Abstract

When hydraulic design decisions are made in a watershed, engineers rely on estimation of the design discharge. Historically, they have applied empirical methods to do this, but empirical methods can only describe the hydrologic characteristics of the watersheds from which they were derived. Although more advanced methods now exist, engineers find them challenging to use because of the abundant data needed and intensive data analyses. In this study, we make the more advanced hydrological analysis methods simpler to use by linking them with DEM terrain analyses in a GIS platform. The system provides hydrologic and geomorphic information needed to create a design discharge at any location in a watershed. Since the system allows users to test several locations of subwatershed outlets, it is convenient for them to examine different aspects for engineering alternatives.

Keywords: Design discharge; Inquiry system; Geomorphic runoff model; Geographic information system; Digital elevation model

1. Introduction

The design discharge is used to indicate the peak discharge that is adopted as the basis for water resources engineering design, after giving due consideration to storm frequency, flood damage potential, and economic factors. In a small watershed, the rainfall duration usually exceeds the time of concentration, $T_c$, which is the time required for runoff to travel from the hydraulic remote point to the watershed outlet. Consequently, rainfall can be assumed to be a temporal and spatial constant under these circumstances. The rational method (Kuichling, 1889) combined with empirical $T_c$ equations (for example, see Kirpich, 1940; Huggins and Burney, 1982) is most widely used for the design discharge from small watersheds. For a midsize watershed, although rainfall can be assumed to be uniformly distributed in space, the influence of intensity variation during a storm needs to be considered. The synthetic unit hydrograph methods (for examples, Snyder, 1938; SCS, 1964) are extensively applied to midsize watersheds for the purpose of hydrologic analysis. However, these empirical methods, for both small and midsize watersheds, can only describe the hydrologic characteristics of the watersheds from which they were derived.

During the past 20 years, theoretically based $T_c$ equations and distributed hydrologic models have been
developed by hydrologists, but it may not be a simple task to obtain the abundant geomorphic data needed to use these methods. Geographic information systems (GISs) have now significantly changed the way in which spatial data are acquired and used; hence, they have opened up the potential for expanded application of physical-based hydrologic models (Djokic and Maidment, 1991; Garrote and Bras, 1995; Levy and Baecher, 1999). However, due to the diverse training received by practicing engineers, we have found that a system with highly intuitive and easily performed functions is required. This paper presents an inquiry system that incorporates the spatial analysis capabilities of GIS techniques into watershed hydrologic modeling. The topography, land cover, and rainfall characteristics are coded into separate layers, and the attribute information for each layer is used to construct database attribute tables. In contrast to previous lumped empirical models, the coordinate values that define the locations of features in the database are used directly to include the spatial heterogeneity of watershed characteristics in the modeling process.

In this study, a watershed in northern Taiwan was used to demonstrate the feasibility of the proposed windows-based inquiry system. Rainfall records were collected for the purpose of frequency analysis. The geomorphic factors of the study watershed were obtained through digital elevation model (DEM) calculations, and the roughness coefficient for overland areas was determined through remote sensing image classification. For a watershed area smaller than 10 km², the rational formula combined with a kinematic-wave time of concentration equation (Lee and Yen, 1997), which can consider the effect of the stream network structure, was used to estimate the watershed peak discharge. For a watershed area larger than 10 km², the alternating block method (Chow et al., 1988) was used to obtain a synthetic hyetograph from intensity–duration–frequency curves, and then the synthetic hyetograph was routed through a topographic runoff model (Lee and Yen, 1997) to generate the design hydrograph. Note that although abundant terrain analyses and complicated hydrologic simulations can be conducted using this information inquiry system, engineers can easily use it to perform design discharge estimation as well.

2. Design discharge estimation in watersheds

2.1. Design discharge for small watersheds

For small watersheds, the storm duration usually exceeds the watershed time of concentration; i.e., the flow equilibrium state is usually reached. The magnitude of watershed peak discharge at equilibrium can be estimated by using rational formula as follows:

\[
Q = i_e A, \quad (1)
\]

in which \(Q\) is the peak discharge, \(i_e\) is the average rainfall excess intensity within a duration equal to the time of concentration, \(A\) is the watershed area. Once the time of concentration is determined, the rainfall intensity can be determined from an intensity–duration–frequency curve with the rainfall duration being equal to the time of concentration.

The time of concentration is the time required for runoff to travel from the hydraulic remote point to the watershed outlet, which can be expressed as (Lee and Yen, 1997)

\[
T_c = \frac{\max_{1 \leq i,j \leq \Omega} \left( T_{xoj} + \sum_{i=1}^{\Omega} T_{xj} \right)}{\max_{1 \leq i,j \leq \Omega} \left( \frac{n_i T_{xoj}}{S_{xoj}^{1/2}} \right)^{1/m}}
\]

\[
+ \sum_{i=1}^{\Omega} \frac{B_i}{2\ell_i L_{oj}} \left( \frac{h_{coi}}{\ell_i B_i} + \frac{2i_e T_{xoj} T_{xji}}{S_{xji}^{1/2} B_i} \right) - h_{coj} \right),
\]

in which \(T_c\) is time of concentration of the watershed, \(\Omega\) means the maximum value in parentheses, \(n_i\) and \(n_o\) are the roughness coefficients for overland planes and channels, respectively, \(S_{xoj}\) and \(S_{xji}\) are the mean \(i\)-th-order overland and channel slopes, respectively, \(L_{oj}\) and \(L_{xji}\) are the mean \(i\)-th-order overland and channel lengths, respectively, \(B_i\) is the width of the \(i\)-th-order channel, \(h_{coi}\) is the inflow depth of the \(i\)-th-order channel due to water transported from upstream reaches, \(i_e\) is the excess rainfall intensity, \(\Omega\) is the highest stream order of the watershed, and \(m\) is an exponent equal to \(5\) while comparing with Manning’s equation, which is usually used to estimate flow velocity.

2.2. Design discharge for midsize watersheds

For midsize watersheds, the influence of temporal rainfall variation on the runoff hydrograph is significant. The average rainfall excess intensity applied in Eq. (1) cannot well represent the hydrologic response of the watershed. A small watershed has been defined as being one with an area smaller than around 10 km², while the upper limit of a midsize watershed can range from 100 to 1000 km² (Ponce, 1989; Bedient and Huber, 2002). For design purposes, the result of intensity–duration–frequency analysis combined with the results obtained using the alternating block method (Chow et al., 1988) can be adopted to derive the design hyetograph. Then, hydrograph routing techniques can be applied to generate a runoff hydrograph that reflects
the effects of a time-varying hyetograph in a midsize watershed.

In this study, a geomorphologic instantaneous unit hydrograph model (GIUH) proposed by Rodriguez-Iturbe and Valdes (1979) was adopted for runoff simulation in both gauged and ungauged midsize watersheds. The GIUH of the watershed can be expressed as (Rodriguez-Iturbe and Valdes, 1979)

\[ u(t) = \sum_{w \in W} \left[ f_{x_j}(t) * f_{x_j}(t) \right]_w : P(w), \]

in which \( f_{x_j}(t) \) is the travel-time probability–density function in state \( x_j \) with a mean value of \( T_{x_j} \), \( * \) denotes a convolution integral, \( P(w) \) is the probability of a specified runoff path \( w \), and \( W \) is the runoff path space. The travel times for the overland areas and channels can be estimated by using kinematic wave approximation as shown in Eq. (2). The results obtained by applying the kinematic-wave-based GIUH model (KW-GIUH) have been shown to be in good agreement with records in Taiwan (Lee and Yen, 1997) and in the US (Yen and Lee, 1997).

3. Watershed geomorphic characteristics extraction

3.1. Geomorphic factors calculation

When the geomorphic-based runoff model is used, abundant geomorphic information is required to produce the unit hydrograph. It is a time-consuming task to obtain geomorphic factors by performing conventional measurements on a topographic map. The existing network extraction models (Band, 1986; Jenson and Domingue, 1988; Freeman, 1991; Turcotte et al., 2001) have been shown to be capable of performing watershed delineation and geomorphic parameter calculation, and can be used for hydrologic simulation. The algorithms are performed on a spatial grid system (raster data structure). These techniques are based on neighborhood operations, where calculations and decisions are made for a cell according to the elevations in the eight cells that are spatially adjacent in the raster. The analytical procedure consists of depression elimination, flow direction determination, flow accumulation counting, and then channel network extraction. Since the Horton–Strahler ordering system was adopted in this study to perform hydrologic calculations, the algorithms further include stream order determination and sub-watershed delineation.

We developed a series of FORTRAN programs called WAGIS (Watershed Geomorphic Information System). The algorithms are based on Jenson and Domingue (1988) and use a “threshold area” to extract stream networks from digital elevation data. Consequently, stream networks are delineated by estimating a threshold of flow accumulation, which is essentially the minimum drainage area that can support a stream element. All cells having a flow accumulation equal to or greater than the threshold area value are then assumed to contain a stream element. The length and slope for different orders of overland areas and streams as well as other geomorphic factors can be directly obtained from the data generated by a DEM, which are detailed listed in Table 1. Procedures for geomorphic factor calculation can be found in Lee (1998).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>( \mathcal{A} )</td>
<td>Watershed area</td>
</tr>
<tr>
<td>( A_i )</td>
<td>Mean of ( i )th-order drainage areas</td>
</tr>
<tr>
<td>( \mathcal{H} )</td>
<td>Mean elevation of the watershed</td>
</tr>
<tr>
<td>( L )</td>
<td>Length of the main stream</td>
</tr>
<tr>
<td>( T_{x_i} )</td>
<td>Mean of ( i )th-order stream length</td>
</tr>
<tr>
<td>( N_i )</td>
<td>Number of ( i )th-order channel</td>
</tr>
<tr>
<td>( P_{x_i,x_j} )</td>
<td>Transitional probability of raindrop moving from ( i )th-order channel to ( j )th-order channel</td>
</tr>
<tr>
<td>( P_{w,a} )</td>
<td>Ratio of ( i )th-order overland area to total watershed area</td>
</tr>
<tr>
<td>( \bar{S}_c )</td>
<td>Mean of ( i )th-order channel slope</td>
</tr>
<tr>
<td>( S_o )</td>
<td>Mean of ( i )th-order overland slope</td>
</tr>
<tr>
<td>( \mathcal{S} )</td>
<td>Mean watershed slope</td>
</tr>
<tr>
<td>( S_m )</td>
<td>Slope of the mainstream</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>Stream order of the watershed</td>
</tr>
</tbody>
</table>

3.2. Overland and channel roughness coefficient determination

When Eq. (2) is applied for the time of concentration estimation, the geomorphic factors listed in Table 1 could be calculated by using a DEM except the channel roughness coefficient \( n_c \) and overland roughness coefficient \( n_w \). In gauged watersheds, these two roughness coefficients can be calibrated by using hydrologic record data. For ungauged watersheds, field investigation is required to choose adequate channel roughness coefficients based on values suggested by Chow (1959). As proposed by HEC (1990), the overland roughness coefficient can be correlated to watershed land cover conditions. Previous researches have shown the possibility of applying remote sensing images to classify the land cover distribution of a watershed for runoff modeling (Ragan and Jackson, 1980; Rango et al., 1983; Still and Shih, 1985; Zevenbergen et al., 1988).

A supervised classification technique is usually adopted to categorize pixels into land cover classes. In
the training stage, numerical data from training areas on spectral response patterns of land cover categories are collected. In the classification stage, each pixel in the image data of the study watershed is categorized into the land cover class it most closely resembles. After the data set of the entire watershed has been categorized, the digital data file is included in the geographic information system. Consequently, once an outlet is specified for subwatershed boundary delineation, the percentages of different land covers within the subwatershed can be calculated based on the land cover database to obtain a corresponding overland roughness coefficient \( n_o \).

4. Inquiry system and user interface

From the user’s point of view, the inquiry system should provide a user-friendly graphical interface for design work. For the system to be useful as a decision-support tool, its implementation must be usable under various design considerations, for example, different choices of water work locations and design return periods. Through the interface, the user can easily access the watershed database and model output for a specified design condition. In this study, the interface code was written in Borland C++, based on an object-oriented design methodology (Cox, 1986). Following the analytical procedure mentioned previously, the core of the inquiry system is composed of data acquisition, a geomorphic factor calculation module, and a design discharge calculation module. Each module consists of several executable Fortran programs that operate in the same database environment.

The GIS functions were used to assign all the attributes to corresponding locations in the watershed. The strategy that the inquiry system uses to deal with abundant watershed information is to let the user select preferred thematic maps to be displayed on the screen, which are interactively managed by the user. The user interface module can extract geomorphic descriptions of watersheds from the database. The inquiry system is flexible enough to offer detailed information about any point within the study watershed to satisfy the users’ needs. Once the user has specified the location of the subwatershed outlet, subsequent calculations are performed to delineate the watershed boundary and then to generate geomorphic factors for the time of concentration calculation. Since the kinematic-wave time of concentration varies with the rainfall intensity, the user needs to further specify a design return period, which corresponds to a prepared intensity-duration regression equation. Consequently, the design discharge can be obtained by using Eq. (1) or (3), depending on the size of the specified watershed.

5. Application examples using the inquiry system

The inquiry system can be flexibly applied to any watershed if geomorphic and hydrologic information are available to satisfy the input requirements of the system. In this study, the Heng-Chi watershed located in northern Taiwan was used as an example to illustrate the capabilities of the system. The size of the entire watershed is 53 km\(^2\) with a mean elevation of 329 m. The annual rainfall of the watershed is 2934 mm in average. Recently, rapid development has occurred in the downstream area of the Heng-Chi watershed. To avoid serious inundation and sediment deposition in the downstream area, upland soil conservation and downstream channel regulation works are required. Consequently, it was considered useful to establish a convenient inquiry system that can provide detailed geomorphic and hydrologic information for use in design work at any desired location within the watershed. Fig. 1 shows the main window of the inquiry system, which displays a map of the watershed. When the cursor is moved to a specific location on the map, the corresponding coordinate and the runoff states are shown in the upper right corner of the window. The coordinate system is the two degrees transverse Mercator coordinated system (TM2), and the runoff state indicates that the specified location is an overland cell or a channel cell.

5.1. Watershed geomorphic characteristic extraction

The terrain analytical module of the system can provide geomorphic information not only for the watershed outlet but also for any location within the watershed. Currently, only one type of digital elevation data is available in Taiwan, and the resolution of the raster data is 40 m × 40 m as provided by the Space and Remote Sensing Research Center at National Central University, Taiwan. The stream network was extracted from this data set using a threshold-area value. The trial threshold-area value that we applied to extract stream networks in Taiwan was around 300 cells with respect to the 40 m resolution DEM data set. The stream network of the watershed is fourth order, as shown on the main window of the inquiry system (Fig. 1).

The Heng-Chi watershed is a forest watershed with heavy brush, and channels filled with large boulders and weeds with brush on the banks. To account for the spatial variation of runoff on overland areas, the land cover conditions of a study watershed need to be known. In this study, SPOT images were used to represent the spatial distribution of the land cover conditions. The commercial package IDRISI (Eastman, 1995) was adopted for image classification, and supervised classification using the maximum likelihood technique was applied. With supervised classification, we identified...
examples of the information classes of interest in the image. The software system was then used to develop a statistical characterization of the reflectances for each information class. Once a statistical characterization had been achieved for each information class, the image was classified by examining the reflectances for each pixel.

Fig. 1. Main window of inquiry system.

Fig. 2. Accessing land cover database.
and making a decision about which of the signatures it resembled most.

In this study, results from the October 1997 SPOT2 image classification showed that the land cover distribution for the entire Heng-Chi watershed was 89% forest, 9% grassed and agricultural land, 1% barren land, and 1% urban or built-up land. The error between the ground truth and the image classification result was 6.8%. The spatial distribution of the land cover from the image classification was then included in the GIS database system. As shown in Fig. 2, by the user-driven interface, the land cover database can be easily accessed and modified, which makes it easy for the user to adjust the system to account for the hydrologic impact of environmental changes in the watershed.

5.2. Runoff simulation and design discharge estimation

In the Heng-Chi watershed, only the Da-Pao rain gauging station and Heng-Chi water-stage gauging station provide hourly hydrologic records. Hydrologic records collected from storm events at the watershed outlet (i.e., the Heng-Chi water-stage gauging station) were used to verify the applicability of the model to this watershed. As shown in Fig. 3, two example storms that occurred on July 1996 and October 2000 show good agreement between the recorded and simulated hydrographs. This verifies the applicability of the network time of concentration equation (Eq. (2)) and the KW-GIUH model to the study watershed.

For design discharge estimation, a three-parameter regression equation, which was derived using the rainfall records of the Da-Pao station, was used to represent the rainfall excess intensity–duration relationship for different return periods. Once the return period was specified, the design rainfall intensity could be determined by using the intensity–duration equation and the \( T_c \) equation. The overland roughness coefficient in the \( T_c \) equation can be determined according to the land cover condition of the subwatersheds once the outlet of the subwatersheds is specified. Based on overland roughness coefficients suggested by HEC (1990) and the authors’ previous experiences with gauged watersheds in Taiwan, the recommended overland roughness \( n_o \) is 0.77 for forest, 0.3 for grassed and agricultural land, 0.2 for barren land, and 0.15 for urban and built-up land when applying the model. Field investigation showed that the channel roughness coefficient of the fourth order channel (downstream main channel) could reach nearly 0.04, and that for the other lower order channels, it could reach 0.06 in the kinematic-wave channel-flow simulation.

As mentioned previously, the system can provide hydrologic and geomorphic information needed to create a design discharge at any location in a watershed. When the user clicks on the desired location, the calculation module performs calculations, and then the interface automatically delineates the subwatershed boundary on the screen. Fig. 4 shows the estimated peak discharges of a small watershed for different return periods, where the size of watershed A is 1.8 km\(^2\), and the design discharge for the 25-yr return period is 29.27 m\(^3\)/s. For a subwatershed area larger than 10 km\(^2\), the synthetic hyetograph generated by the alternative block method can be routed through the KW-GIUH model to produce a runoff hydrograph. Fig. 5 shows the design hyetograph and hydrograph of a midsize watershed, where the size of watershed B is 17.4 km\(^2\), and the peak discharge of the 25-yr hydrograph is 301.78 m\(^3\)/s. The geomorphic factors derived by using the DEM for these two watersheds are listed in Table 2.

5.3. Hypothetical example for engineering alternatives

To demonstrate the capability of the inquiry system to choose among physically feasible engineering alternatives, a hypothetical example involving the selection of adequate locations for a detention basin is presented.

![Figure 3](image-url)  
**Fig. 3.** Storm events simulated by using KW-GIUH model.
The detention basin is designed to attenuate the increased peak discharge due to a new developed community located near Chu-Lun in the watershed area. It is well known that urban development in a watershed area will usually result in increased peak outflows and shorter response times as development proceeds, and that natural storage in the watershed will decrease as urbanization expands (Bedient and Huber, 1982).
Therefore, a detention basin is proposed to attenuate the excess discharge of 10 m³/s, which is due to the development of the community under a 25-yr return period.

The shaded area in Fig. 6 shows the region occupied by the community, and two topographically feasible locations (points C and D) for establishing the detention basin are also shown in this figure. By clicking on these two points in the inquiry system, the user can obtain the geomorphic factors, the time of concentrations, and the design peak discharges for these two feasible locations. If the modified rational method is adopted to derive the triangular inflow hydrograph for the detention basin (Chow et al., 1988), and if the Runge–Kutta method (Carnahan et al., 1969) is used to simulate the flood attenuation effect in the detention basin, then the size of the detention basin can be determined. Fig. 7 shows inflow and outflow hydrographs for two possible detention basin sites.

where $Q$ is the discharge in m³/s and $H$ is in m. To attenuate the excess discharge of 10 m³/s, the detention basin requires 40,783 m³ for location C and 26,305 m³ for location D. If the initial cost of the detention basin construction is the only economic factor considered, then location D should be selected for this design case.

6. Conclusions

This paper has presented a user-friendly inquiry system for hydrologic design in small and midsize...
watersheds. The system integrates a geomorphic and hydrologic database within a graphical computer environment. Instead of using empirical methods for runoff estimation, we have developed a physical-based analytical procedure to incorporate watershed geomorphic and hydrologic characteristics on a GIS platform. This greatly simplifies the time-consuming work involved in geomorphic parameter measurement on topographic maps. In this paper, case studies have been presented to show the potential of the decision-support system for implementing design work for any location within a watershed. A hypothetical example for the selection of physically feasible alternatives based on economic factors has also been given. This system also has potential for further improvement by including channel routing techniques for not only small and midsize watersheds, but also for large watershed design work.

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