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Identifying hydrograph parameters and their relationships to urbanization variables

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Abstract This study examines relationships between model parameters and urbanization variables for evaluating urbanization effects in a watershed. Rainfall–runoff simulation using the Nash model is the main basis of the study. Mean rainfall and excesses resulting from time-variant losses were completed using the kriging and nonlinear programming methods, respectively. Calibrated parameters of 47 events were related to urbanized variables, change of shape parameter responds more sensitively than that of scale parameter based on comparisons between annual average and optimal interval methods. Regression equations were used to obtain four continuous correlations for linking shape parameter with urbanization variables. Verification of 10 events demonstrates that shape parameter responds more strongly to imperviousness than to population, and a power relationship is suitable. Therefore, an imperviousness variable is a major reference for analysing urbanization changes to a watershed. This study found that time to peak of IUH was reduced from 11.76 to 3.97 h, whereas peak discharge increased from 44.79 to 74.92 m^3/s.

Key words hydrograph parameter; urbanization variables; hydrological modelling; urbanization change; time to peak; peak discharge

Identification des paramètres d'un hydrogramme et leurs relations aux variables d'urbanisation

Résumé Cette étude examine les relations entre les paramètres d'un modèle et des variables d'urbanisation afin d'évaluer les effets de l'urbanisation dans un bassin versant. La simulation pluie-débit utilisant le modèle de Nash est la principale base de l'étude. La pluviométrie moyenne et les surplus résultant de pertes variant au cours du temps ont été estimés en utilisant respectivement le krigeage et la programmation non linéaire. Les paramètres calés de 47 événements ont été reliés à des variables d'urbanisation, les changements du paramètre de forme étant plus sensibles que ceux du paramètre d'échelle sur la base des comparaisons entre les moyennes annuelles et des méthodes d'intervalle optimum. Des équations de régression ont été utilisées pour obtenir quatre corrélations continues reliant le paramètre de forme avec les variables d'urbanisation. La vérification sur 10 événements démontre que le paramètre de forme réagit plus fortement à l'imperméabilisation qu'à la population, et une relation en puissance est appropriée. Par conséquent, une variable d'imperméabilisation constitue une référence majeure pour l'analyse des changements dus à l'urbanisation d'un bassin versant. Cette étude a révélé que le temps de montée de l'hydrogramme unitaire instantané a été réduit de 11.76 à 3.97 h, alors que le débit de pointe a augmenté de 44.79 à 74.92 m^3/s.

Mots clefs paramètre de l'hydrogramme; variables d'urbanisation; modélisation hydrologique; changements d''urbanisation; temps de montée; débit de pointe

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INTRODUCTION

In Taiwan, the development of an urban area usually results from populations becoming increasingly concentrated in downstream areas of a basin where human societies or cities have gradually developed. The development of urban areas within watersheds typically involves a significant change of land use, for example to parking lots, streets and roofs. Such change, involving an increase in impervious surfaces, affects the mechanism of infiltration in the hydrological cycle because rainwater infiltration into the soil layer near the surface is diminished and, simultaneously, it causes changes in rainwater loss. In other words, the hydrological characteristics of a developed watershed vary with different degrees of urbanization. These changes include response function, runoff volume, peak discharge and time to peak (Bonta *et al.* 1997, Kang *et al.* 1998, Singh 1998, Junil *et al.* 1999, Gremillion *et al.* 2000, Cheng and Wang 2002, Rodriguez *et al.* 2003). The component of a watershed contributing to surface runoff has been shown to be proportional to the impervious area (Brown 1988, Boyd *et al.* 1994, Arnold and Gibbons, 1996, Matheussen *et al.* 2000, Cheng *et al.* 2008b).

The unit hydrograph (UH)-based models, derived from unit hydrograph theory, are used to solve these urbanization problems. These models have generally treated a watershed as input–output transformations of an independent system (or multiple linked systems). Systems analysis is now being increasingly applied to facilitate understanding and to develop solutions to complex urban problems. Numerous derivations based on the instantaneous unit hydrograph (IUH) have been applied to: Clarke mathematical models (Clarke 1973, Ahmad *et al.* 2009); nonlinear programming (NLP) (Mays and Taur 1982); geomorphologic IUH (Jin 1992, Franchini and O'Connell 1996, Nourani *et al.* 2009); distributed parallel models (Hsieh and Wang 1999); sub-watershed division (Agirre *et al.* 2005); the linear cascade reservoir model (Yue and Hashino 2000); and a model of three serial linear reservoirs (Cheng 2010a, 2010b, 2010c). Further applications sought to model rainfall–runoff processes (O'Connell and Todini 1996, Melone *et al.* 1998, Bhadra *et al.* 2010) and contend with the hydrological effects of urbanization (Hundecha and Bardossy 2004, Cheng *et al.* 2008b, Huang *et al.* 2008a, 2008b, Cuo *et al.* 2008). However, hydrological modelling is not the only option for analysis of urbanization change (Olivera and DeFee 2007).

Changes of runoff characteristics, such as decreased flow time, increases of runoff volume, and peak discharges, are familiar problems in urban stormwater management. The problems encountered in urban systems should be analysed to account for both spatial and temporal variations. Because of the unique topography of the bowl-shaped study watershed, when a larger storm occurs, enormous amounts of overland runoff on the upstream mountain area flow rapidly into the downstream level ground, which is frequently inundated. The imperviousness of the downstream watershed is still being developed, resulting in significantly larger and swifter runoff than in the past. As a result, preventing flood disasters has become an essential and immediate concern. For flood prevention, changes to runoff hydrographs, such as volume, peak discharge, and time to peak, in areas undergoing urbanization must be identified. To date, lumped modelling approaches remain valuable tools for studying change to an outlet hydrograph on an entire watershed system over time; however, such approaches ignore certain spatial variations. Hence, this study used a lumped model to generate hydrographs of surface runoff based on urban hydrology.

The urbanization variables, imperviousness and population, are easily observed changes in the development of a watershed. The specific parameters resulting from hydrological modelling are conveniently used to connect with urbanization variables. The goal of this study was to observe the changes in hydrological parameters that reflect the growth of impervious areas and populations. We then sought to determine useful relationships between significant model parameters and given urbanization variables during complex processes of urbanization. Figure 1 shows the research processes for the development of the main goals of this study. Urbanization growth derives from urbanization variables, including imperviousness, population percentage and population density. Popular approaches were applied, such as: block kriging, nonlinear programming, simple lumped modelling, the annual average method, a computation of optimal interval and regression analysis. The processes of rainfall translating into runoff were given by parameters n and k of the Nash model. These parameters vary with different degrees of imperviousness and population, and have been confirmed by calibration and verification using three criteria. The results of analysis can facilitate the evaluation of hydrological impacts for an urbanized watershed and management of water resources by

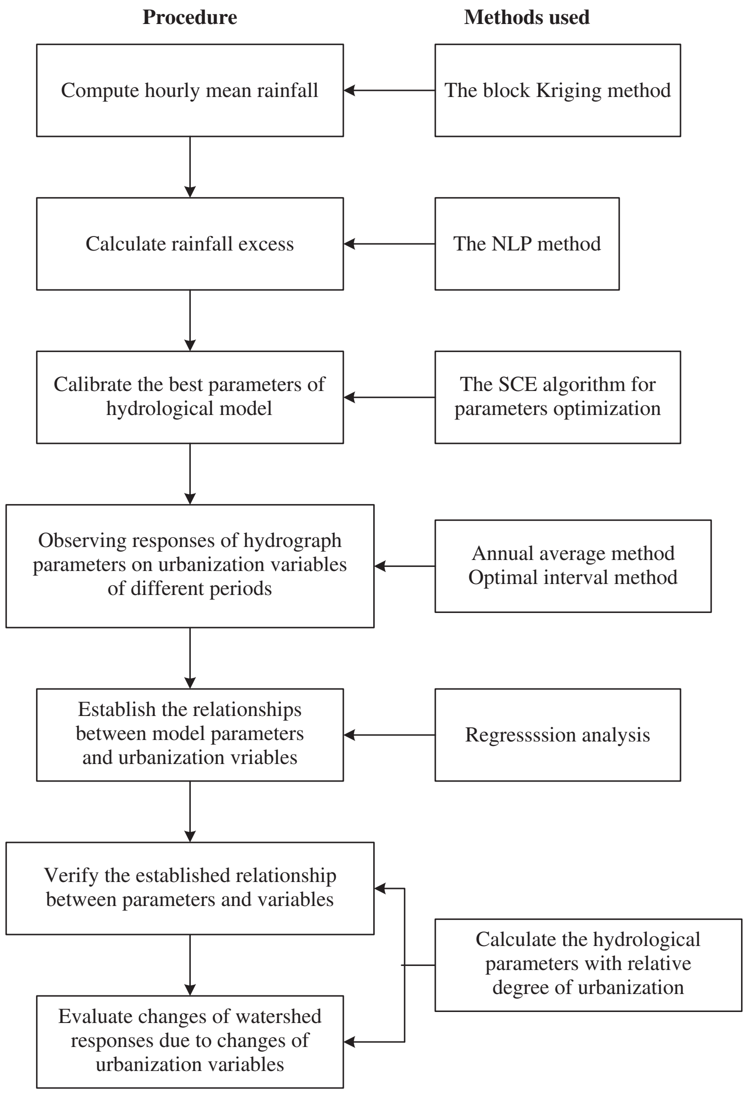

Fig. 1 Flowchart of the research procedure of this study.

referring to the established relationships between hydrograph parameters and urbanization variables.

WATERSHED DESCRIPTION

Geographical features

The Kee-Lung River is one of the chief tributaries of the Tamshui River, which is the third longest river in Taiwan (Fig. 2). The Wu-Tu watershed is located upstream of the Kee-Lung River and covers nearly 204 km^2. This watershed was chosen to study the available relationships between hydrograph parameters and urbanization variables in an area undergoing urbanization. The selected watershed surrounds Taipei City, in northern Taiwan (Fig. 2). Mean annual precipitation and runoff depth in the watershed are 2865 and 2177 mm, respectively. This watershed consists of a large pervious area (high mountains) and a smaller impervious area (watershed downstream), i.e. the greater part of runoff-contributing area is in the pervious area. Owing to the rugged topography of the watershed, the runoff path lines are short and steep. The rainfall is not uniform in terms of both time and space. Large floods occur rapidly in the middle-to-downstream reaches of the watershed, causing serious damage during summer. The land use in the Wu-Tu watershed may be classified into four main areas: construction, direct production, communication and conservancy, and others uses. These four land uses are further divided into several sub-classifications, as shown in Table 1.

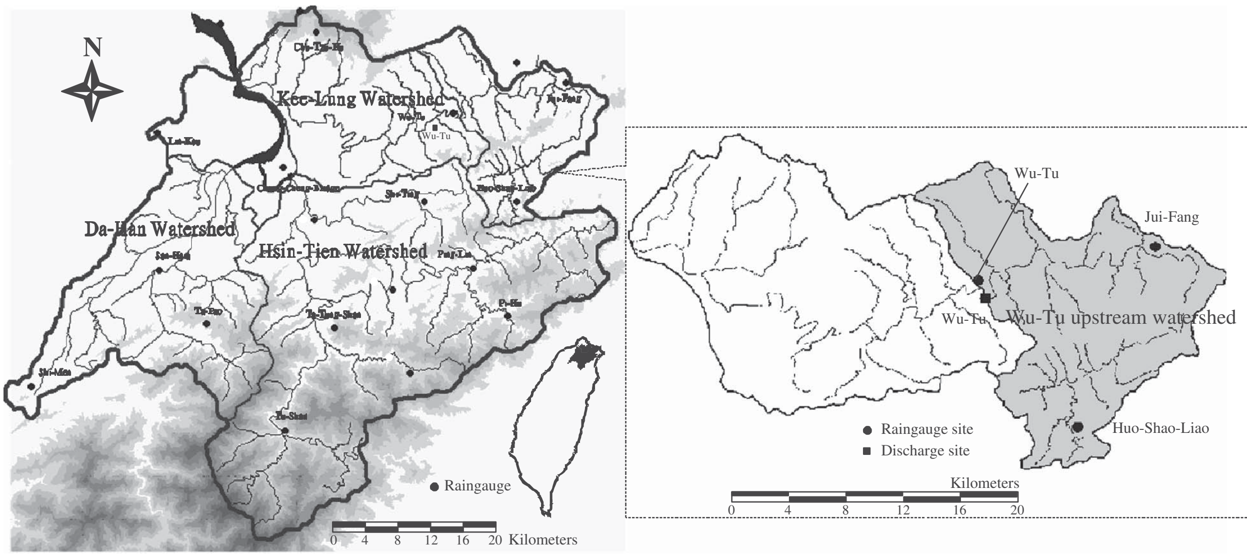

Fig. 2 Location maps of the Tamshui River basin and the Wu-Tu watershed, Taiwan.

Table 1 Classification of land use in the Wu-Tu watershed, Taiwan.

Classification of land use	Sub-classification
Construction	Building site
	Misc. land
	Land for temples and shrines
	Land for rail-way land
	Park land
	Graveyard
Direct production	Paddy filed
	Dry field
	Forest
	Piscicultural pond
	Farm
	Mineral spring
	Reservoir
Communication and conservancy	Railway lines
	Road and highway
	Irrigation water ways
	Pond
	Drainage
Other uses	Dike land
	Wild land

Table 2 Essential background of the selected telemetered raingauges (raingauge type: automatic; acquisition time interval: 1 h).

Raingauge name	Location		Data continuity
	Longitude	Latitude	
Lin-Kou	121°22′E	25°04′N	1974–2008
San-Hsia	121°22′E	24°56′N	1980–2008
Shi-Men	121°14′E	23°49′N	1978–2008
Ta-Pao	121°25′E	24°53′N	1975–2008
Ta-Tung-Shan	121°33′E	24°52′N	1979–2008
Ping-Lin	121°42′E	24°56′N	1978–2008
Huo-Shao-Liao	121°45′E	25°00′N	1957–2008
Jui-Fang	121°48′E	25°07′N	1972–2008
Wu-Tu	121°42′E	25°05′N	1965–2008
Shi-Ting	121°39′E	25°00′N	1971–2008
Chung-Cheng-Bridge	121°31′E	25°01′N	1978–2008
Pi-Hu	121°44′E	24°53′N	1971–2008
Fu-Shan	121°30′E	24°47′N	1971–2008
Chu-Tzu-Hu	121°32′E	25°10′N	1978–2008

Hydrological data

Fourteen raingauges are located along the Tamshui River (Table 2), of which three raingauges (Jui-Fang, Wu-Tu and Huo-Shao-Liao) and one discharge site (Wu-Tu) are within the Wu-Tu watershed. Available records for 57 rainfall–runoff events during 1966–2008 were used as the study sample. The annual data for population density and imperviousness percentage served as the degree of urbanization in the research area.

In this study the impervious portion and population density in an area were treated as major variables of urbanization. An impervious portion is defined as one in which all rainfall falling onto it generates surface runoff. The annual imperviousness percentage was obtained from the above definition, and was applied to streets, roads, railway lines, highways, roofs, buildings, parking lots, ponds, lakes and waterways for each year. The growth of population density and percentages of impervious areas over the Wu-Tu watershed for 1966–2008 are plotted in Fig. 3. These two urbanization variables are convenient for approximating the extent of urbanization.

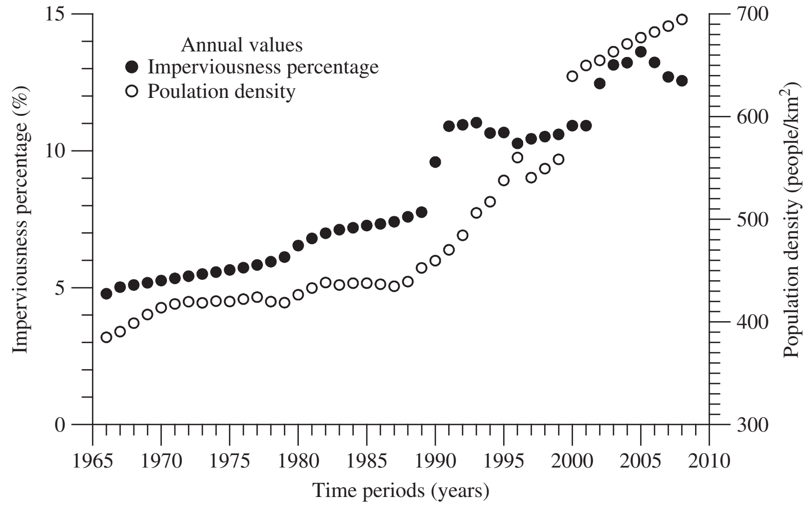

Fig. 3 Growths of imperviousness and population with time in the Wu-Tu watershed.

METHODS

The block kriging method

Rainstorms vary greatly in space and time. Some essential raingauges can be considered spatially representative for rainfall variation; thus, relative weights can be assigned to these raingauges for calculating an areal average. Areal rainfall computed from these representative sites is usually used to represent rainfall characteristics of a particular region. Traditional methods, such as the Thiessen polygon method, have been used to compute mean rainfall. For the block kriging method, a semivariogram with a spatial relationship has also been used to describe variation of rainfall processes in space and determine the point or areal rainfall via the block kriging system. The kriging approach has many applications in various research fields, especially for the design of raingauge networks (Bastin *et al.* 1984, Cheng *et al.* 2008a), variogram identification (Lebel and Bastin 1985), spatial interpolation of rainfall (Goovaerts 2000, Syed *et al.* 2003), and space–time rainfall interpolation (Cheng *et al.* 2007).

Climatological mean semivariogram

The set of time sequences of discontinuous point-rainfall depths located on $\boldsymbol{x}$ with time period $p(t, \boldsymbol{x})$ can be considered as a realization of two-dimensional random fields. Considering n raingauges in a river basin, for each time period t, a realization $\pi(t)$ of the random $\boldsymbol{n}$ vectors can be expressed as:

$$\pi(t) = \{p(t, \boldsymbol{x}_1), p(t, \boldsymbol{x}_2), \ldots, p(t, \boldsymbol{x}_n)\} \quad (1)$$

A basic semivariogram, called the scaled climatological mean semivariogram, was proposed (Bastin *et al.* 1984) and established through dimensionless rainfall data on a project basin (Cheng *et al.* 2007). The relationship between the hourly semivariogram, $\gamma(t, h_{ij})$, and the scaled climatological mean semivariogram, $\gamma^*{}_{\mathrm{d}}(h_{ij}, a)$, is:

$$\gamma(t, h_{ij}) = \omega(t)\gamma_d^*(h_{ij}, a) = s^2(t)\gamma_d^*\left(h_{ij}, a\right) \quad (2)$$

where h_{ij} represents the distance between arbitrary raingauges $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ (m); $\omega(t)$ denotes the sill of the semivariogram for time period t (mm^2) and is time-variant; a represents the range of the scaled climatological mean semivariogram (m) and is time-invariant; and $s(t)$ denotes the standard deviation of rainfall of all raingauges for time period t (mm). The basic semivariogram is expressed as:

$$\gamma_d^*\left(h_{ij}, a\right) = \frac{1}{2T}\sum_{t=1}^{T}\left\{\left[\frac{p(t, \boldsymbol{x}_i) - p\left(t, \boldsymbol{x}_j\right)}{s\left(t\right)}\right]^2\right\} \quad (3)$$

The basic experimental semivariogram can be calculated using equation (3). Because this semivariogram is derived from discontinuous point observations, it is not spatially continuous. A realistic application for a block kriging method is to use a semivariogram model to obtain spatial continuity of rainfall variations.

Block kriging system

The block kriging method obtains optimal weights that are obtained from the kriging system by assuming a given spatial structure of rainfall. The system (equation (4)) is derived by applying Lagrange's multipliers and the estimated area V must be divided into M grids before calculating the hourly mean rainfall of storm events over the watershed:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j \gamma(\boldsymbol{x}_i, \boldsymbol{x}_j) + \mu = \frac{1}{M} \sum_{m=1}^{M} \gamma\,(V_m, \boldsymbol{x}_i), \\ \quad i = 1, 2, \ldots, n \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \tag{4}$$

where $\gamma(\boldsymbol{x}_i, \boldsymbol{x}_j)$ is the semivariogram of raingauge x_i and raingauge $\boldsymbol{x}_j$ (mm^2); V_m is the mth grid in the estimated area; $\gamma(V_m, \boldsymbol{x}_i)$ represents the semivariogram of the mth grid V_m and raingauge $\boldsymbol{x}_i$ (mm^2); and λ_i is the weighting of each raingauge. Figure 4 shows the computation procedure of the mean semivariogram, $\sum_{m=1}^{M} \gamma(V_m, x_i)/M$, between the estimated area and raingauges.

Nonlinear programming

Cheng and Wang (2002) demonstrated that time-variant estimations of rainfall losses that result from nonlinear programming (NLP) predict flood hydrographs more precisely than those based on the traditional Φ-index method. Interestingly, the NLP method is useful for obtaining suitable hydrological parameters to illustrate urbanization characteristics of specific watersheds. The NLP method is unlike the Φ-index method, which only obtains a time-invariant value of rainfall loss. Thus, NLP was used to calculate excess amounts of hourly mean rainfall. The objective function and the constraints of the NLP are as follows:

$$\text{Minimize } F = \sum_{t_Q=1}^{T_Q} \left(Z_{t_Q} + V_{t_Q}\right) \tag{5}$$

subject to the constraints

$$\sum_{t_R=1}^{T_Q \le T_R} \left(R_{t_R} - H_{t_R}\right) U_{t_U} + Z_{t_Q} - V_{t_Q} = Q_{t_Q} \tag{6}$$

$$\sum_{t_R=1}^{T_R} \left(R_{t_R} - H_{t_R}\right) = \sum_{t_Q=1}^{T_Q} Q_{t_Q} \tag{7}$$

$$\sum_{t_U}^{T_U} U_{t_U} = 1 \tag{8}$$

$$0 \le H_{t_R} \le R_{t_R},\ Z_{t_Q}, V_{t_Q} \text{ and } U_{t_U} \ge 0 \tag{9}$$

The input and output are the total hourly rainfall R_{tR} and the direct runoff Q_{tQ} of an event, respectively. The rainfall losses H_{tR}, unit hydrograph U_{tU}, estimated errors Z_{tQ} and V_{tQ} for each time period are all decision variables. The objective function, F (equation (5)) comprises the minimized summation of estimated errors Z_{tQ} and V_{tQ}, where Z_{tQ} represents the deviation of the tth time period for the simulated direct runoff below the observed direct runoff, and V_{tQ} is the simulation above the observation at the tth period. The constraints consist of: the computation of a discrete convolution integral with estimated errors (equation (6)); the effective rainfall volume equaling

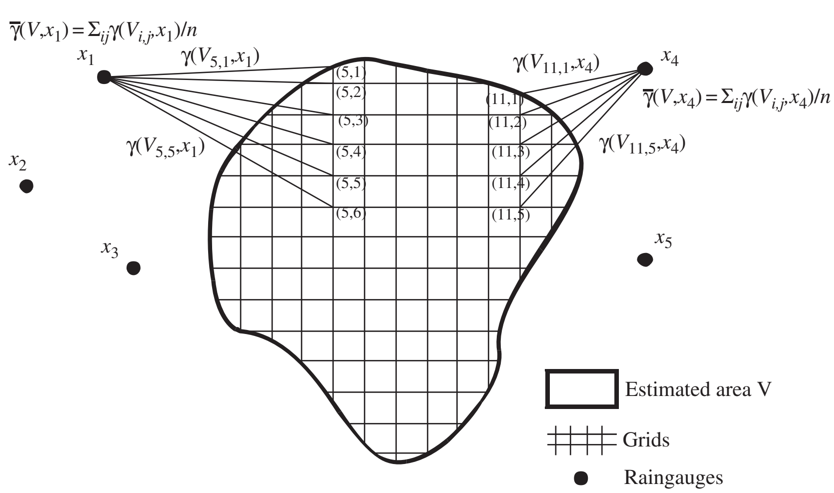

Fig. 4 Computation of the mean semivariogram between the estimated area and raingauges.

the direct runoff volume (equation (7)); the volume of the unit hydrograph being set to unity (equation (8)); and other non-negative constraints (equation (9)). The term t_Q denotes the ordinate index of each observed hydrograph, T_Q represents the total number of ordinates of the observed hydrograph, t_U is the unit hydrograph ordinate, T_U denotes the total number of unit hydrograph ordinates, t_R is ordinate index of each rainfall observation, and T_R represents the number of periods of precipitation excess, $t_U = t_Q - t_R + 1$.

The simple lumped model

The conceptual models derived from an IUH normally possess special definitions for parameters. These parameters with physical significance are conveniently used to represent the hydrological status of urbanized watersheds at various periods. The general form of the IUH, U_n from the nth linear cascaded reservoir with different storage constants k_n and time period t can be written as (Hsieh and Wang 1999):

$$U_n(t) = \int_0^t U_{n-1}(\tau)\frac{1}{k_n}e^{-\frac{t-\tau}{k_n}}d\tau = \begin{cases} \frac{1}{k_1}e^{-\frac{t}{k_1}} & n = 1 \\ \sum_{i=1}^{n} \frac{k_i^{n-2}}{\prod_{j=1, j\neq i}^{n}(k_i - k_j)} e^{-\frac{t}{k_i}} & n \geq 2 \end{cases} \quad (10)$$

A common case of the above expression assumes that the storage coefficients of all of the linear cascaded reservoirs have the same value. The instantaneous unit hydrograph of n linear cascaded reservoirs for one SI unit of effective rainfall (Nash 1957) is given by:

$$U(t) = \frac{1}{k\Gamma(n)}e^{-\frac{t}{k}}\left(\frac{t}{k}\right)^{n-1} \quad (11)$$

where $\Gamma(\cdot)$ denotes the gamma function, $\Gamma(n) = (n-1)!$; n denotes the shape parameter and k is the scale parameter.

Hydrograph simulation

The IUH parameters with physical significance are conveniently linked to urbanization variables to represent the hydrological status of urbanized watersheds at different periods. Generally, these significant parameters can be obtained through an optimization approach in calibrations. Before optimization calibration, the hourly data of mean rainfall excess and direct runoff must be determined using the block kriging, NLP, and baseflow separation methods.

Optimization processes In this study, baseflow was assumed to be a constant to obtain the direct runoff hydrograph of a rainfall–runoff event. The hourly mean rainfall was estimated using the block kriging method and the digital values of rainfall losses, and the IUH of a case could be obtained through the NLP method. The NLP method has an objective function and several constraints based on equation of continuity and the convolution integral. Hence, the hourly rainfall losses were used to compute the time-variant distribution of rainfall excesses. Then, the rainfall excesses and direct runoffs were input to the simple lumped model for optimization calibration to observe Nash parameter changes relating to urbanization variables at different levels of urbanization. The shuffled complex evolution (SCE) optimal algorithm (Duan *et al.* 1993) was used in this study.

Objective function of parameter optimization When optimizing the parameters, an objective function must be assigned. This objective function is used to minimize error between simulations and observations of the runoff hydrographs. This study used the following expression for parameter optimization:

$$F_{obj} = \left\{\frac{1}{T}\sum_{t=1}^{T}[Q_{obs}(t) - Q_{est}(t)]^2 \cdot W(t)\right\}^{\frac{1}{2}} + \Delta Q_p \quad (12)$$

where F_{obj} is the value of the objective function; T is the total duration of the observed hydrograph; $Q_{obs}(t)$ is the observed value of the runoff hydrograph at time period t; $Q_{est}(t)$ is the estimated value at time period t; and $W(t)$ is the weighting value of time period t and is expressed as follows:

$$W(t) = \frac{Q_{obs}(t) + \overline{Q}_{obs}}{2\overline{Q}_{obs}} \quad (13)$$

where $\overline{Q}_{obs}$ represents the average value of observations. The definition of ΔQ_p is as follows:

$$\Delta Q_p = \begin{cases} \frac{Q_{obs,p} - Q_{est,p}}{D^2}, & Q_{est,p} < Q_{obs,p} \\ 0, & Q_{est,p} \geq Q_{obs,p} \end{cases} \quad (14)$$

where $Q_{\text{est},p}$ and $Q_{\text{obs},p}$ are the peaks of the estimated hydrograph and observed hydrograph, respectively; $Q_{\text{obs},p}$ is the number of observations; and D is the total duration of observations. In equation (13), the first term on the right side of the equal sign is the mean squared error and the second term is the error between the observed and simulated peak discharges.

Model evaluation To measure the suitability of the model parameters for the basin of interest, three criteria were chosen to analyse the degree of goodness of fit. These criteria are as follows:

(a) Coefficient of efficiency, CE, is defined as:

$$\text{CE} = 1 - \frac{\sum_{t=1}^{T} [Q_{\text{est}}(t) - Q_{\text{obs}}(t)]^2}{\sum_{t=1}^{T} \left[Q_{\text{obs}}(t) - \bar{Q}_{\text{obs}}\right]^2} \tag{15}$$

where $Q_{\text{est}}(t)$ denotes the discharge of the simulated hydrograph for time period t (m^3/s), $Q_{\text{obs}}(t)$ is the discharge of the observed hydrograph for time period t (m^3/s), and $\bar{Q}_{obs}$ represents the average discharge of the observed hydrograph (m^3/s). A CE value closer to 1 indicates a better fit.

(b) The error of peak discharge, EQ_p (%), is defined as:

$$\text{EQ}_p(\%) = \frac{Q_{p,\text{est}} - Q_{p,\text{obs}}}{Q_{p,\text{obs}}} \times 100\% \tag{16}$$

where $Q_{p,\text{est}}$ is the peak discharge of the simulated hydrograph (m^3/s), and $Q_{p,\text{obs}}$ is the peak discharge of the observed hydrograph (m^3/s).

(c) The error of the time for peak to arrive, ET_p, is given by:

$$\text{ET}_p = T_{p,\text{est}} - T_{p,\text{obs}} \tag{17}$$

where $T_{p,\text{est}}$ denotes the time for the peak arrival (h) of simulated hydrographs, and $T_{p,\text{obs}}$ represents the time required for the peak arrival (h) of observed hydrographs.

RESULTS AND DISCUSSION

Investigating variations of hydrograph parameters in response to changes of urbanization variables (imperviousness percentage and population density) is convenient for understanding the different hydrological statuses of watershed development. Performing rainfall–runoff simulations using a conceptual model can obtain representative parameters from different event observations in different time periods. In calibration processes, the block kriging and nonlinear programming were used to produce precisely time-variant estimations of rainfall losses and corresponding rainfall excesses. The estimations of excess rainfall, which were input to the model, are beneficial for simulations and are close to observations. The available relationships were derived from regression results by linking model parameters and urbanization variables. These regression equations efficiently provide model parameters varying with urbanization variables for understanding urbanization processes of watershed developments. The most appropriate correlation of regression results based on model verification can facilitate obtaining parameter values corresponding to urbanization variables. Finally, changes of IUH shapes can be further evaluated to understand changes of outlet-runoff characteristics of a developing watershed.

Calibration of lumped parameters

The hourly semivariogram for rainfall is a function of time period t, isotropy and a time average form with nonzero and T time intervals. The results of the scaled climatological mean semivariogram from the 57 selected rainfall events and the power form applied for fitting is shown below:

$$\begin{aligned} &\gamma_d^*\left(h_{ij}, a\right) = \omega_0 h^a = 0.093h^{0.243} \\ &R^2 = 0.906 \end{aligned} \tag{18}$$

where ω_0 denotes the scaled parameter of the scaled climatological mean semivariogram (mm^2). Variance $s^2(t)$ of a realization $\pi(t)$ for each time period t can be easily obtained from hourly measurements of rainfall, and then hourly semivariograms of rainfall events can be directly calculated using equations (2) and (18). The inputs of the model, rainfall excesses and direct runoff, were calculated by using the NLP and baseflow separation methods. The lumped parameters were obtained from the 47 rainfall–runoff events in 1966–2001 and the shuffled complex evolution (SCE) optimal algorithm in the optimal calibration.

Table 3 Calibrated results with three evaluation criteria of the selected events (typhoon names are upper case).

Event name (date)	Evaluation criteria			Event name (date)	Evaluation criteria		
	CE	EQ_p (%)	ET_p (h)		CE	EQ_p (%)	ET_p (h)
Storm (20 June 1966)	0.95	−1.15	0	SARAH (10 September 1989)	0.98	−3.02	2
ALICE (2 September 1966)	0.91	−2.14	0	Storm (1 September 1990)	0.95	−6.89	1
CORA (6 September 1966)	0.99	−0.94	0	Storm (2 September 1990)	0.90	−8.27	1
ELSIE (13 September 1966)	0.97	−12.35	1	Storm (22 September 1991)	0.95	−10.19	−2
GILDA (16 November 1967)	0.98	−4.92	0	NAT (29 September 1991)	0.99	−2.79	0
BETTY (7 August 1969)	0.93	−11.67	0	RUTH (28 October 1991)	0.99	−4.96	0
Storm (9 August 1969)	0.88	−8.20	1	Storm (29 August 1992)	0.97	−8.00	1
BESS (22 September 1971)	0.97	−2.44	0	Storm (18 June 1994)	0.91	−9.68	1
BETTY (16 August 1972)	0.95	−20.34	1	DOUG (7 August 1994)	0.97	−4.95	1
Storm (20 August 1973)	0.99	1.95	1	FRED (20 August 1994)	0.95	−7.45	1
JEAN (19 July 1974)	0.97	−12.08	1	GLADYS (1 September 1994)	0.91	−21.76	1
BESS (11 October 1974)	0.91	−1.61	0	SETH (9 October 1994)	0.98	−4.05	1
Storm (4 August 1975)	0.92	−14.98	0	ZANE (27 September 1996)	0.97	−12.87	0
BILLIE (9 August 1976)	0.93	−4.94	1	AMBER (29 August 1997)	0.96	−6.10	0
Storm (11 August 1976)	0.87	−16.49	1	Storm (4 October 1998)	0.96	5.82	−1
Storm (16 September 1976)	0.94	−7.58	0	ZEB (15 October 1998)	0.97	−0.79	−2
VERA (31 July 1977)	0.94	−14.61	0	Storm (13 December 1999)	0.98	−4.42	1
Storm (15 November 1977)	0.98	−3.30	1	Storm (24 April 2000)	0.99	−6.84	1
ANDY (29 July 1982)	0.96	−12.74	0	BILIS (22 August 2000)	0.92	−15.72	0
FREDA (6 August 1984)	0.89	−12.51	1	BEBINCA (8 November 2000)	0.98	1.82	0
Storm (14 August 1984)	0.95	−8.84	0	Storm (13 December 2000)	0.99	−6.36	0
Storm (18 November 1984)	0.99	−0.94	1	Storm (19 December 2000)	0.97	−8.44	1
ALEX (27 July 1987)	0.87	−4.81	−1	NARI (16 September 2001)	0.99	0.29	−1
Storm (29 September 1988)	0.99	−5.41	2				

Comparisons of simulated and observed runoff hydrographs from the three criteria (CE, EQ_p, ET_p) are listed in Table 3.

The CE for model calibration exceeded 0.80 for all calibrated events, as revealed in Table 3. The EQ_p values of 47 cases were smaller than 25%. The ET_p values were all below two hours. Based on the satisfactory calibration results, the calibrated parameters can be used to represent the urbanization indexes of the research watershed.

Behaviours of hydrograph parameters in time periods

Accordingly, outlet-hydrograph simulations were completed to examine changes of these parameter estimations in complex urbanization processes of the researched watershed. These calibrated parameters varying with the time periods in 1966–2001 are plotted in Fig. 5. The large differences of representative parameters in the same year or in neighbouring years can be found in Fig. 5, which seemingly presents disorder and unsystematic variations for the parameter estimations of selected cases in calibration. In a complex rainfall–runoff process, some hydrological uncertainties, such as weather factors, antecedent moisture condition and others, often caused those calibrated parameters to appear irregularly with no obvious tendency. Thus, parameter changes relating to urbanization variables (imperviousness and population) in various degrees of urbanization must be re-analysed using other valid methods for further applications.

We used the methods of annual average and optimal interval to smooth behaviours of parameters n and k with different degrees of urbanization. The annual average method was easily used to obtain annual parameters n and k of different levels of urbanization. In that method, an annual parameter was computed by averaging the different calibrated parameters in the same year. The averaged results of model parameters resulting from the annual average method are plotted in Fig. 6. The changes of parameters n and k in Fig. 6 are more obvious than those in Fig. 5. However, change tendencies of model parameters in Fig. 6 are still somewhat disordered. The optimal interval method was also used to smooth the behaviour of parameter changes and the computational results are plotted in Fig. 7. The optimal interval method can attempt a suitable interval according to variations between model parameters and time periods; clear tendencies of model parameters can then be obtained. These hydrological parameters in the same

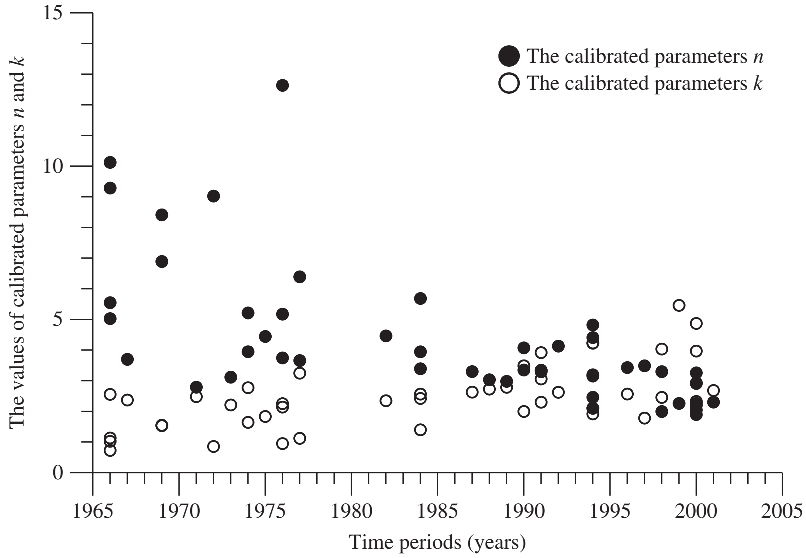

Fig. 5 Variation of the calibrated parameters with time in the period 1966–2001.

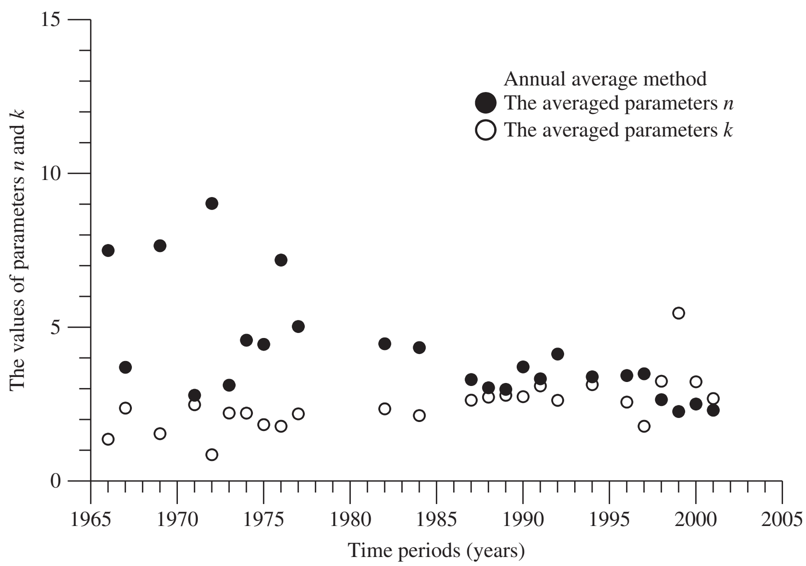

Fig. 6 Computed results of model parameters using annual average method.

determined time intervals were considered to have identical average values. By comparing Figs 5–7, we concluded that the optimal interval method is more advantageous than the annual average method for observing changes of model parameters in urbanization processes.

Responses of hydrograph parameters under urbanization of different periods

Changes of averaged parameters with time periods are shown in Fig. 7, in which the changed scope of parameter n is obviously larger than that of parameter k. We individually calculated the simple statistics for value variations of parameters n and k in Figs 5–7 and listed the calculation results in Table 4: the values of mean and standard deviation for parameters n and k are based on results of parameter calibration (Fig. 5), the annual average method (Fig. 6) and the optimal interval method (Fig. 7). The statistical results of three figures for parameter variations reveal that standard deviations of parameter n are larger than those of parameter k. The comparison shows that the change of parameter n is more sensitive than that of parameter k in urbanization processes. Based on the comparisons of Figs 5–7 and Table 4, parameter k, representing the storage effects of the linear reservoir, seems to be assumed a constant because of low sensitivity. That

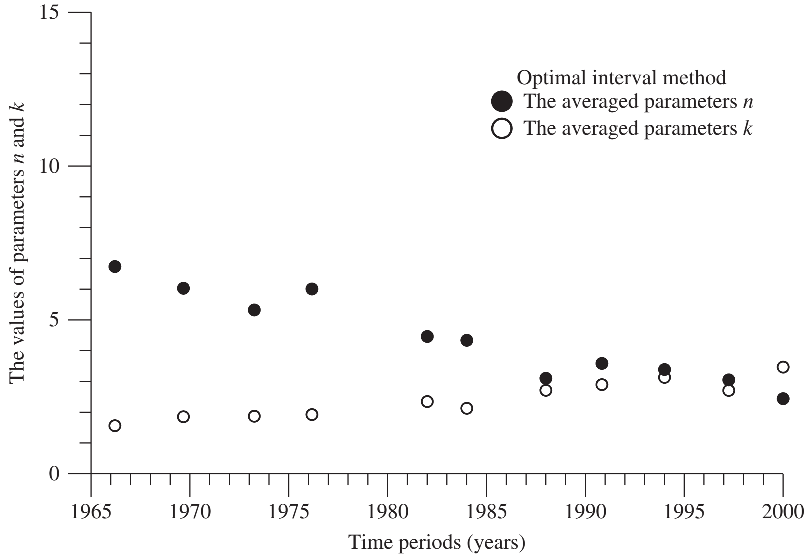

Fig. 7 Computed results of model parameters using optimal interval method.

Table 4 Statistics of parameter changes resulting from the calibration, annual average method and optimal interval method.

Method	Figure	Mean		Standard deviation	
		n	*k*	*n*	*k*
Calibration	Fig. 5	4.334	2.500	2.121	1.008
Annual average	Fig. 6	3.713	2.695	1.165	0.815
Optimal interval	Fig. 7	4.175	2.506	1.274	0.567

constant is a value of 2.506, which was computed from analytical results of the optimal interval method, listed in Table 4.

To identify this assumption, we used the fixed value (2.506) of parameter k to recalibrate 47 rainfall–runoff events for evaluating simulation results. Table 5 lists the recalibrated results and satisfactory results found when comparing them with previous calibration results (Table 3). The CE for model calibration exceeded 0.80 for all calibrated events, but those of five events (a storm on 20 June 1996, a storm on 11 August 1976, Typhoon Gladys on 1 September 1994, Typhoon Bilis on 22 August 2000, and a storm on 19 December 2000), spanned an interval of 0.7–0.79, as revealed in Table 5. The EQ_p values of 47 cases were smaller than 25%, aside from those of three events (a storm on 20 June 1996, Typhoon Betty on 7 August 1969 and Typhoon Billie on 9 August 1976) that were between 25 and 32%. The ET_p values were all below two hours, except for a storm (29 August 1992), Typhoon Fred (20 August 1994), Typhoon Gladys (1 September 1994), Typhoon Seth (9 October 1994), and another storm (19 December 2000). The advantages of this assumption involve reducing the number of parameters required to analyse the urbanization behaviours, and avoiding a dependent relationship between parameters n and k when deriving them from the direct unit hydrograph, especially for the time to peak.

The relationships between the parameter *n* and urbanization variables

Urbanization in a basin brings growth of impervious paving and prevents rainwater from accessing the land surface. The imperviousness was developed because of population concentration. As previously described, urbanization change of a watershed is relative to the urbanization variables of imperviousness and population. Relationships should exist between model parameters and urbanization variables. Furthermore, the analytic result of parameter sensitivity shows that the response of parameter n is more sensitive than that of parameter k, which slightly changes in urbanization processes. Additionally, the optimal interval method

Table 5 Recalibrated results with three evaluation criteria of the selected events (typhoon names are upper case).

Event name (date)	Evaluation criteria			Event name (date)	Evaluation criteria		
	CE	EQ_p (%)	ET_p (h)		CE	EQ_p (%)	ET_p (h)
Storm (20 June 1966)	0.75	−31.34	−1	SARAH (10 September 1989)	0.97	5.89	2
ALICE (2 September 1966)	0.91	5.70	0	Storm (1 September 1990)	0.85	17.07	2
CORA (6 September 1966)	0.96	−13.42	−1	Storm (2 September 1990)	0.90	−8.31	1
ELSIE (13 September 1966)	0.94	−15.64	0	Storm (22 September 1991)	0.82	9.99	0
GILDA (16 November 1967)	0.98	−0.73	0	NAT (29 September 1991)	0.99	−2.03	1
BETTY (7 August 1969)	0.90	−26.74	1	RUTH (28 October 1991)	0.96	5.78	1
Storm (9 August 1969)	0.88	−22.11	2	Storm (29 August 1992)	0.95	−7.60	3
BESS (22 September 1971)	0.95	−2.45	2	Storm (18 June 1994)	0.91	−11.84	1
BETTY (16 August 1972)	0.94	−24.81	0	DOUG (7 August 1994)	0.96	−6.92	2
Storm (20 August 1973)	0.99	4.77	1	FRED (20 August 1994)	0.81	12.81	3
JEAN (19 July 1974)	0.91	2.43	2	GLADYS (1 September 1994)	0.79	−1.09	3
BESS (11 October 1974)	0.94	0.67	−2	SETH (9 October 1994)	0.94	3.48	3
Storm (4 August 1975)	0.92	−16.95	0	ZANE (27 September 1996)	0.98	0.34	1
BILLIE (9 August 1976)	0.88	−28.38	1	AMBER (29 August 1997)	0.96	−7.19	0
Storm (11 August 1976)	0.79	−23.25	2	Storm (4 October 1998)	0.96	6.78	0
Storm (16 September 1976)	0.94	−6.58	0	ZEB (15 October 1998)	0.96	12.73	−1
VERA (31 July 1977)	0.93	−19.22	0	Storm (13 December 1999)	0.95	13.91	2
Storm (15 November 1977)	0.98	4.82	2	Storm (24 April 2000)	0.98	1.04	1
ANDY (29 July 1982)	0.97	2.70	0	BILIS (22 August 2000)	0.73	6.05	2
FREDA (6 August 1984)	0.89	−6.48	1	BEBINCA (8 November 2000)	0.98	2.82	0
Storm (14 August 1984)	0.94	−4.65	0	Storm (13 December 2000)	0.88	−8.34	2
Storm (18 November 1984)	0.96	−10.16	2	Storm (19 December 2000)	0.76	18.62	3
ALEX (27 July 1987)	0.94	−1.62	1	NARI (16 September 2001)	0.98	3.06	0
Storm (29 September 1988)	0.99	−3.35	2				

is more advantageous than the annual average method for observing changes of model parameters in urbanization processes. This study first used the optimal interval method to compute individually the responding tendencies of Nash parameter n to imperviousness percentage and that of population density; the computations are plotted in Figs 8 and 9, respectively. The best interval of parameter n to imperviousness percentage is 0.5% in Fig. 8 and 25 people per km^2 for parameter n to population density in Fig. 9.

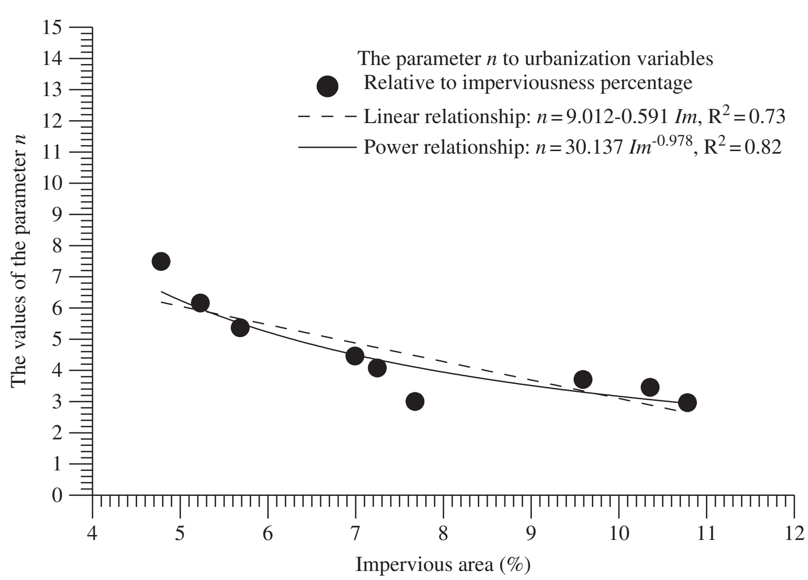

Fig. 8 Regression relationships of the averaged parameters n to imperviousness.

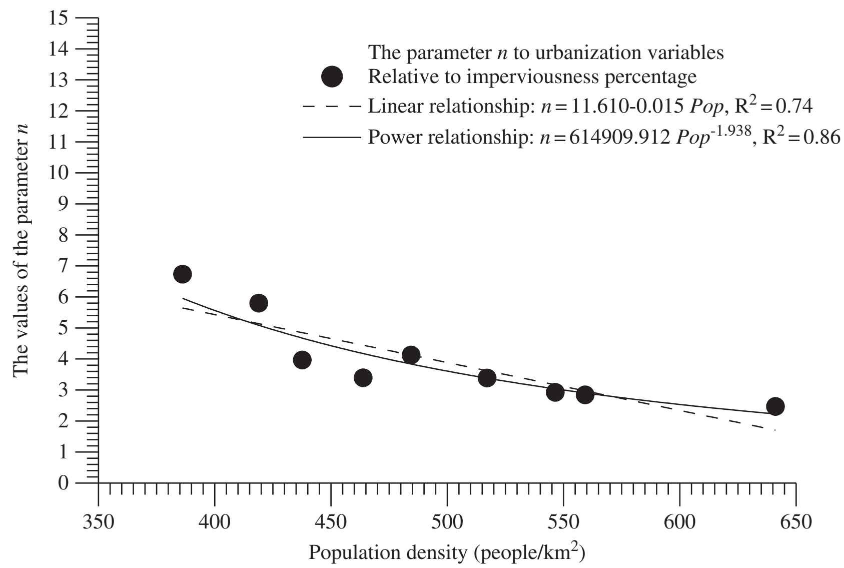

Fig. 9 Regression relationships of the averaged parameters *n* to population.

A limitation exists for using the optimal interval method to smooth changes of the model parameters, that is, a selection of the best interval value should not be overly large, because stationary assumption of these averages may not be valid. This study examined the separated interval of imperviousness percentage as 0.5% and 25 people/km^2 for population; these interval values are small. Additionally, the imperviousness percentages vary between 4.78 and 10.92%, and between 385.01 and 649.84 people/km^2. For both urbanization variables on the study area in 1966–2001, 26 intervals for imperviousness and population were separated from the optimal interval method involving a 36-year span. One interval is averagely equivalent to 1.38 years. Thus, the selected interval for averaging values of parameter *n* is acceptable.

This study considered that the changes of Nash parameter *n* responding to both urbanization variables, which were results of the optimal interval method, may be linear or nonlinear. The linear and power equations (linear form of natural logarithm) of the regression analysis were adopted to determine a suitable relationship for further applications. The four possible forms were attempted for obtaining the available relationships based on the coefficient of determination (R^2). The regression results are presented in Figs 8 and 9, and are given below:

– Linear relationship between parameter *n* and imperviousness:

$$n = 9.012 - 0.591\text{Im}, R^2 = 0.73 \qquad (19)$$

– Power relationship between parameter *n* and imperviousness:

$$n = 30.137\text{Im}^{-0.978}, R^2 = 0.82 \qquad (20)$$

– Linear relationship between parameter *n* and population:

$$n = 11.610 - 0.015\ \text{Pop}, R^2 = 0.74 \qquad (21)$$

– Power relationship between parameter *n* and population:

$$n = 614909.912\ \text{Pop}^{-1.938}, R^2 = 0.86 \qquad (22)$$

where both Im and Pop are urbanization variables: Im denotes percentage of impervious area, while Pop represents population density.

The coefficient of determination (R^2) for imperviousness was 0.73 for linear regression, and 0.82 for power correlation, according to regression analyses from equations (19) and (20). The R^2 values resulting from the linear correlation (0.74) and power from (0.86) are the regression results between parameter *n* and population density, according to equations (21) and (22). Based on these analytical results, this study tentatively confirmed that use of power relationship is more favourable than that of linear correlation.

Urbanization of a region begins with population concentration and is accompanied by an increase of impervious areas. Urbanization variables, imperviousness percentage and population density can be theoretically classified as indexes of urbanization change. Imperviousness is directly related to changes in outlet-hydrograph characteristics; therefore, imperviousness should be more significant than population for an evaluation of hydrological impacts. From previous results, decreasing parameter *n* caused the selected samples to vary more widely than slightly varied parameter *k*. Parameter *k* was assumed to be independent of urbanization variables and, therefore, a fixed constant. The coefficients of determination (R^2) resulting in equations (20) and (22) show that power relationships are closer than the linear correlations. However, linear relationships in equations (19) and (21), which exceed the R^2 value of 0.7, still exist such that these relationships may not be neglected. Hydrological uncertainties often form complete relationships that illustrate the fact that parameter rules reflect different levels of urbanization in specific watersheds. Thus, the most favourable correlation between parameter *n* and urbanization variables needs to be further verified for an evaluation of changes of watershed response due to urbanization effect.

Verification of the correlations between parameter *n* and urbanization variables

Ten rainfall–runoff events in 2002–2008 were examined to test further and verify the usability of four previously established equations between parameter *n* and urbanization variables in urban areas. The baseflow was still assumed to be a constant derived from the flow discharge before the rainfall began. The excesses of mean rainfall for 10 events were estimated using the block kriging and NLP methods. The value of Nash *k* was fixed ($k = 2.506$) for the hydrological model applied. The values of Nash parameter *n* were determined through four urbanization relationships presented in equations (19)–(22); that is, *n* linearly/nonlinearly varies with changes of imperviousness percentage or population density. The annual impervious percentage with equation (19) was used to determine the values of parameter *n* linearly derived from the first relationship and those nonlinearly derived from equation (20) for the second relationship. The annual population density was applied to obtain estimations of Nash *n* for the linear relationship in equation (21) of the third relationship and those for nonlinear correlations in equation (22) of the fourth relationship. The effective rainfall, fixed parameter *k* and Nash parameter *n* (varying with the imperviousness variable or corresponding to the population factor) were then used to calculate direct runoff estimations, which were evaluated with runoff observations using three evaluation criteria.

Table 6 presents the verification results of using rainfall–runoff routings for four urbanization relationships. The coefficient of efficiency, CE of model verification, exceeded 0.70 in all but nine events for the first relationship, one event for the second relationship, eight and four events for the third and fourth. The error of peak discharge, EQ_p was under 25% in all but seven events for the first relationship, and one case for the second relationship, seven and four cases for the third and fourth. The error in the arrival time of the peak of all examined events was three hours or less for the second relationship, but other relationships had several events exceed four hours.

The results for coefficient of determination (R^2) in regression analyses previously showed that nonlinear correlations between Nash *n* and urbanization variables are more favourable than linear correlations of parameter *n* and urbanization variables. Herein, verifications of 10 rainfall–runoff events for change of Nash *n* related to urbanization changes also clearly indicate agreement. Furthermore, the nonlinear relationship for equation (20) is more effectively verified with 10 cases than other relationships for equations (19), (21) and (22), based on three evaluation criteria. These verification results confirm that equation (20) clearly reflects the hydrological impacts of urbanization, and the impervious area is consequently a major variable of the Wu-Tu watershed with ongoing urbanization. Furthermore, this analysis can be applied further to relevant applications.

Changes of watershed responses due to changes of impervious area

The watershed response, which is denoted as the transformation relationship of rainfall excess transformed to direct runoff, can be obtained from the above-established relationships between the model parameters and urbanized variables. After determining the most effective relationship between hydrograph parameters and urbanization variables in the Wu-Tu watershed, Nash parameter *n* can be obtained using equation (20) with corresponding imperviousness percentages for different urbanization degrees, whereas Nash *k* is a constant with a value of 2.506.

Table 6 Verification of the selected events for four possible urbanization relationships.

Event name (date)	Evaluation criteria											
	CE				EQ_p (%)				ET_p (h)			
	I[a]	II[b]	III[c]	IV[d]	I	II	III	IV	I	II	III	IV
Storm (4 May 2004)	−1.23	0.63	−0.54	0.30	58.58	−4.71	37.56	8.03	−2	0	−2	−1
NANMADOL (2 December 2004)	0.59	0.93	0.72	0.88	41.05	−0.04	27.32	10.01	−2	0	−2	−1
Storm (20 January 2006)	0.65	0.79	0.68	0.74	−2.85	3.90	1.24	5.33	−3	−3	−3	−3
Storm (6 March 2007)	0.55	0.70	0.54	0.62	24.06	16.12	24.97	22.72	−5	−3	−5	−4
Storm (21 September 2007)	0.37	0.90	0.20	0.69	59.20	11.64	66.63	31.16	−1	1	−1	0
KROSA (6 October 2007)	0.65	0.83	0.60	0.75	26.44	16.13	23.52	23.57	0	1	0	0
Storm (29 January 2008)	0.63	0.80	0.57	0.69	33.56	28.57	28.45	33.12	−4	−2	−4	−3
JANGMI (28 September 2008)	0.74	0.84	0.70	0.79	32.27	24.39	26.49	31.92	0	1	−2	0
Storm (6 October 2008)	0.56	0.91	0.37	0.72	39.65	12.81	48.12	26.32	−2	0	−2	−1
Storm (10 October 2008)	0.66	0.96	0.41	0.83	24.51	0.30	28.81	15.02	−1	1	−1	0

[a] I denotes first relationship for regression form $n = 8.826 - 0.520\mathrm{Im}$

[b] II denotes second relationship for regression form $n = 22.689\mathrm{Im}^{-0.789}$

[c] III denotes third relationship for regression form $n = 12.174 - 0.016\mathrm{Pop}$

[d] IV denotes fourth relationship for regression form $n = 65847.355\mathrm{Pop}^{-1.561}$

Table 7 Changes of IUH characteristics owing to increase of impervious area.

Imperviousness (%)	Characteristics of IUH:			
	Time to peak		Peak	
	Decrease (h)	Percentage decrease (%)	Increase (m^3/s)	Percentage increase (%)
4.78	11.76	100.00	44.79	100.00
5.02	11.23	95.53	45.80	102.24
5.10	11.07	94.13	46.13	102.98
5.18	10.90	92.76	46.45	103.71
5.26	10.75	91.43	46.78	104.44
5.34	10.60	90.14	47.10	105.16
5.42	10.45	88.88	47.42	105.88
5.50	10.30	87.65	47.74	106.59
5.57	10.18	86.60	48.02	107.21
5.65	10.04	85.43	48.34	107.92
5.73	9.91	84.30	48.65	108.62
5.83	9.75	82.91	49.04	109.49
5.95	9.56	81.30	49.51	110.53
6.12	9.30	79.12	50.16	111.98
6.54	8.72	74.18	51.74	115.51
6.80	8.39	71.39	52.70	117.66
6.99	8.17	69.47	53.39	119.20
7.12	8.02	68.21	53.86	120.25
7.19	7.94	67.55	54.11	120.81
7.27	7.85	66.81	54.40	121.45
7.33	7.79	66.26	54.61	121.93
7.41	7.70	65.54	54.90	122.57
7.59	7.52	63.98	55.54	123.99
7.76	7.35	62.56	56.13	125.32
9.59	5.90	50.19	62.31	139.10
10.27	5.48	46.61	64.51	144.02
10.44	5.38	45.78	65.05	145.24
10.52	5.34	45.40	65.31	145.81
10.60	5.29	45.02	65.57	146.38
10.65	5.27	44.79	65.72	146.73
10.67	5.25	44.69	65.79	146.88
10.90	5.13	43.65	66.52	148.51
10.92	5.12	43.56	66.58	148.65
10.92	5.12	43.56	66.58	148.65
10.95	5.11	43.43	66.68	148.86
11.03	5.06	43.08	66.93	149.42
12.18	4.53	38.49	70.52	157.43
12.46	4.41	37.49	71.38	159.36
12.56	4.37	37.14	71.69	160.05
12.70	4.31	36.66	72.12	161.01
13.14	4.14	35.22	73.46	164.01
13.22	4.11	34.97	73.71	164.56
13.23	4.11	34.93	73.74	164.62
13.62	3.97	33.74	74.92	167.27

Various values of parameter n and fixed parameter k can determine different shapes of IUHs for representing hydrological responses of a watershed undergoing urbanization changes. Comparing differences among various IUH shapes responding to urbanization changes can illustrate hydrological effects of a researched watershed due to urbanization. Table 7 lists changes of hydrograph characteristics of IUH due to imperviousness changes. Reduced time to peak and increased peak of IUH can be found in Table 7. The analytical results show that the IUH shape would become more sharp-pointed and shifted forward at the peak due to an increased impervious cover. Table 7 also lists IUH variations of the Wu-Tu watershed; time to peak was reduced from 11.76 to 3.97 h, is approximately 33.74% of the original value, and peak flow increased from 44.79 to 74.92 m^3/s, is an approximate increase of 67.27%, from pre-urbanization in 1966 to post-urbanization in 2008. The integral approaches this study proposed

(Fig. 1) are easily used by determining the parameters in successive periods. The runoff characteristics, such as time to peak and peak flow, can be obtained through equation (11) with the corresponding parameters and impervious areas.

CONCLUSIONS

The four correlations between Nash parameter *n* and urbanization variables are successfully compared based on applications of the integrated methods. These methods were easily used to establish the most favourable correlation of hydrograph parameters relating to urbanization variables. The base correlation was conveniently used to evaluate changes of watershed responses due to urbanization changes. Uses of the approaches this study proposed do not need detailed hydrological data, because data requirements are not high.

The methods of the block kriging and NLP methods effectively facilitate acquiring representative parameters for reflecting various degrees of an urbanized watershed based on model calibration. The optimal interval method more smoothly presents changes of calibrated parameters relating to urbanization variables than does the annual average method. This study confirms that parameter *n* varies more significantly than parameter *k* when relating model parameters to impervious area and population density. According to the analytical results of regression analyses, a nonlinear linkage (power form) is an available selection of linking continuous relationships between hydrograph parameters and urbanization variables. The verification results with three evaluation criteria further confirm that the power relationship between Nash *n* and imperviousness can appropriately respond to watershed changes. Finally, the power equation was applied to identify different characteristics of IUH shapes for representing various urbanization degrees of a watershed.

The advantage of hydrological modelling lies in realizing variations of urbanized watershed responses in the process of rainfall transforming into runoff. Regarding the runoff characteristics of the IUH in the Wu-Tu watershed, time to peak was reduced from 11.76 to 3.97 h, approximately 33.74% of the original value, and peak flow increased from 44.79 to 74.92 m^3/s, an increase of 67.27%, from pre-urbanization in 1966 to post-urbanization in 2008. These analytical results demonstrate that a watershed function inevitably varies with urbanization, thus possibly causing a greater occurrence of disasters. The evaluation of the flood changes is easily accomplished by the integrated methods.

REFERENCES

Agirre, U., Goñi, M., López, J.J. and Gimena, F.N., 2005. Application of a unit hydrograph based on subwatershed division and comparison with Nash's instantaneous unit hydrograph. *Catena*, 64, 321–332.

Ahmad, M.M., Ghumman, A.R. and Ahmad, S., 2009. Estimation of Clark's instantaneous unit hydrograph parameters and development of direct surface runoff hydrograph. *Water Resources Management*, 23, 2417–2435.

Arnold, C.L.J. and Gibbons, C.J., 1996. Impervious surface coverage-the emergence of a key environmental indicator. *Journal of the American Planning Association*, 62, 243–256.

Bastin, G., Lorent, B., Duque, C. and Gevers, M., 1984. Optimal estimation of the average rainfall and optimal selection of raingauge locations. *Water Resources Research*, 20, 463–470.

Bhadra, A., Bandyopadhyay, A., Singh, R. and Raghuwanshi, N.S., 2010. Rainfall–runoff modelling: comparison of two approaches with different data requirements. *Water Resources Management*, 24, 37–62.

Bonta, J.V., Amerman, C.R., Harlukowicz, T.J. and Dick, W.A., 1997. Impact of coal surface mining on three Ohio Watersheds—surface-water hydrology. *Journal of the American Water Resources Association*, 33, 907–917.

Boyd, M.J., Bufill, M.C. and Knee, R.M., 1994. Predicting pervious and impervious storm runoff from urban basins. *Hydrological Science Journal*, 39, 321–332.

Brown, R.G., 1988. Effects of precipitation and land use on storm runoff. *Water Resources Bulletin*, 24, 421–426.

Cheng, K.S., Lin, Y.C. and Liou, J.J., 2008a, Rain-gauge network evaluation and augmentation using geostatistics. *Hydrological Processes*, 22, 2554–2564.

Cheng, S.J., 2010a. Generation of runoff components based on serial exponential reservoirs. *Water Resources Management*, 24, 3561–3590.

Cheng, S.J., 2010b. Hydrograph characteristics of quick and slow runoffs of a watershed outlet, Taiwan. *Hydrological Processes*, 24, 2851–2870.

Cheng, S. J., 2010c. Inferring hydrograph components from rainfall and streamflow records using a kriging method-based linear cascade reservoir model. *Journal of the American Water Resources Association*, 46, 1171–1191.

Cheng, S.J., Hsieh, H.H. and Wang, Y.M., 2007. Geostatistical interpolation of space–time rainfall on Tamshui River Basin, Taiwan. *Hydrological Processes*, 21, 3136–3145.

Cheng, S.J., Hsieh, H.H., Lee, C.F. and Wang, Y.M., 2008b. The storage potential of different surface coverings for various scale storms on Wu-Tu watershed, Taiwan. *Natural Hazards*, 44, 129–146.

Cheng, S.J. and Wang, R.Y., 2002. An approach for evaluating the hydrological effects of urbanization and its application. *Hydrological Processes*, 16, 1403–1418.

Clarke, R.T., 1973. A review of some mathematical models used in hydrology, with observations on their calibration and use. *Journal of Hydrology*, 19, 1–20.

Cuo, L., Lettenmaier, D.P., Mattheussen, B.V., Storck, P. and Wiley, M., 2008. Hydrologic prediction for urban watersheds with the distributed hydrology–soil–vegetation model. *Hydrological Processes*, 22, 4205–4213.

Duan, Q., Gupta, V.K. and Sorooshian, S., 1993. Shuffled complex evolution approach for effective and efficient global minimization. *Journal of Optimization Theory Application*, 76, 501–521.

Franchini, M. and O'Connell, P.E., 1996. An analysis of the dynamic component of the geomorphologic instantaneous unit hydrograph. *Journal of Hydrology*, 175, 407–428.

Goovaerts, P., 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Journal of Hydrology*, 228, 113–129.

Gremillion, P., Gonyeau, A. and Wanielista, M., 2000. Application of alternative hydrograph separation models to detect changes in flow paths in a watershed undergoing urban development. *Hydrological Processes*, 14, 1485–1501.

Hsieh, L.S. and Wang, R.Y., 1999. A semi-distributed parallel-type linear reservoir rainfall–runoff model and its application in Taiwan. *Hydrological Processes*, 13, 1247–1268.

Huang, H.J., Cheng, S.J., Wen, J.C. and Lee, J.H., 2008a. Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. *Hydrological Processes* 22, 2075–2085.

Huang, S.Y., Cheng, S.J., Wen, J.C. and Lee, J.H., 2008b. Identifying peak–imperviousness–recurrence relationships on a growing-impervious watershed, Taiwan. *Journal of Hydrology*, 362, 320–336.

Hundecha, Y. and Bardossy, A., 2004. Modelling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model. *Journal of Hydrology*, 292, 281–295.

Jin, C.X., 1992. A deterministic gamma-type geomorphologic instantaneous unit hydrograph based on path types. *Water Resources Research*, 28, 479–486.

Junil, P., Kang, I.S. and Singh, V.P., 1999. Comparison of simple runoff models used in Korea for small watersheds. *Hydrological Processes*, 13, 1527–1540.

Kang, I.S., Park, J.I. and Singh, V.P., 1998. Effect of urbanization on runoff characteristics of the On-Cheon Stream Watershed in Pusan, Korea. *Hydrological Processes*, 12, 351–363.

Lebel, T. and Bastin, G., 1985. Variogram identification by the mean squared interpolation error method with application to hydrologic field. *Journal of Hydrology*, 77, 31–56.

Matheussen, B., Kirschbaum, R.L., Goodman, I.A. and O'Donnell, G.M., 2000. Effects of land cover changes on streamflow in the Interior Columbia River Basin (USA and Canada). *Hydrological Processes*, 14, 867–885.

Mays, L.W. and Taur, C.K., 1982. Unit hydrographs via nonlinear programming. *Water Resources Research*, 18, 744–752.

Melone, F., Corradini, C. and Singh, V.P., 1998. Simulation of the direct runoff hydrograph at basin outlet. *Hydrological Processes*, 12, 769–779.

Nash, J.E., 1957. The form of the instantaneous unit hydrograph. *In*: *Surface water, prevision, evaporation*. Wallingford: IAHS Press, IAHS Publ. 45, 112–121 [Available at: http://iahs.info/redbooks/a045/045011.pdf].

Nourani, V., Singh, V.P. and Delafrouz, H., 2009. Three geomorphological rainfall–runoff models based on the linear reservoir concept. *Catena*, 76, 206–214.

O'Connell, P.E. and Todini, E., 1996. Modelling of rainfall, flow and mass transport in hydrological systems: an overview. *Journal of Hydrology*, 175, 3–16.

Olivera, F. and DeFee, B.B., 2007. Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas. *Journal of the American Water Resources Association*, 43, 170–182.

Rodriguez, F., Andrieu, H. and Creutin, J.D., 2003. Surface runoff in urban catchments: morphological identification of unit hydrographs from urban databanks. *Journal of Hydrology*, 283, 146–168.

Singh, R.B., 1998. Land use/cover changes, extreme events and ecohydrological response in the Himalayan Region. *Hydrological Processes*, 12, 2043–2055.

Syed, K.H., Goodrich, D.C., Myers, D.E. and Sorooshian, S., 2003. Spatial characteristics of thunderstorm rainfall fields and their relation to runoff. *Journal of Hydrology*, 271, 1–21.

Yue, S. and Hashino, M., 2000. Unit hydrographs to model quick and slow runoff components of streamflow. *Journal of Hydrology*, 227, 195–206.