Journal of Hydrology (2008) **362**, 320–336

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Identifying peak-imperviousness-recurrence relationships on a growing-impervious watershed, Taiwan

Shao-yang Huang [a], Shin-jen Cheng [b,*], Jet-chau Wen [c], Ju-huang Lee [d]

[a] *Graduate School of Engineering Science and Technology, National Yunlin University of Science and Technology, Douliou, Yunlin 640, Taiwan*
[b] *Department of Environment and Resources Engineering, Diwan University, 87-1, Nan-shih Li, Madou 721, Tainan, Taiwan*
[c] *Department of Safety Health and Environmental Engineering, National Yunlin University of Science and Technology, Douliou, Yunlin 640, Taiwan*
[d] *Water Resources Agency, Ministry of Economic Affairs, Taipei 106, Taiwan*

Received 29 December 2007; received in revised form 21 September 2008; accepted 24 September 2008

KEYWORDS
Block Kriging;
Curve number;
Hydrological parameter;
Peak discharge;
Imperviousness;
Recurrence interval

Summary This study focuses mainly on increases in peak discharges with reductions in recurrence intervals for design hydrographs due to growing imperviousness. Rainfall–runoff simulation is a major basis for analyzing the hydrological effects of urbanization. Available recordings of 50 rainfall–runoff events during 1966–2002 were used as the study sample. Forty events were calibrated to determine the relationships between impervious areas and hydrological parameters in the Nash and SCS models. Block Kriging and non-linear programming methods were used to estimate the mean rainfall and its hourly excess value, respectively. The remaining 10 cases were used to test the established relationships. Calibration and verification results confirm that the methods used in this study effectively illustrate the hydrological and geomorphic conditions in complex urbanization processes. The rainfall–runoff routings, by using the design storm approach and the established relationships, demonstrated the following: (1) peak flows of the design flood hydrographs increased by about 127, 266, 375, 440, 515, 564, 593, and 629 m^3/s for eight return periods, respectively; (2) peak times were individually shortened from 9 to 6 h due to urbanization; (3) the recurrence intervals of 200, 100, 50, and 25 years before urbanization were reduced to about 88, 33, 16, and 8 years also due to urbanization if they would have occurred at the present time within the Wu–Tu watershed. Finally, these analytical results can be obtained easily from the designed diagram that shows the relationships

* Corresponding author. Tel.: +886 6 5718888x878; fax: +886 6 5718014.
E-mail address: sjcheng@dwu.edu.tw (S.-j. Cheng).

doi:10.1016/j.jhydrol.2008.09.002

among peak discharges, impervious areas and return periods. This research can be used to prevent disasters, loss of life and property damage.

Introduction

For several decades, populations have gradually occupied the downstream areas of basins, and tribal societies and cities have subsequently developed. The development of urban areas within a watershed is usually accompanied by drastic changes of land use, which generally alter the hydrological functions of that area (Simmons and Reynolds, 1982; Ferguson and Suckling, 1990; Leopold, 1991; Sala and Inbar, 1992; Singh, 1998; Gremillion et al., 2000). As hydrologists acknowledge, urbanization in a basin brings growth of impervious paving that prevents rainwater from accessing the land (Chow et al., 1988). The part of a watershed contributing to surface runoff is proportional to the amount of impervious areas (Brown, 1988; Boyd et al., 1994; Arnold and Gibbons, 1996; Matheussen et al., 2000; Cheng and Wang, 2002; Cheng et al., 2008; Huang et al., 2008).

Reduced flow time and volume increments and peak discharge for surface runoff are familiar problems in urban stormwater management. Surface runoff modeling derived from an instantaneous unit hydrograph (IUH) is a worthy technology used to solve these urbanization problems (Bonta et al., 1997; Kang et al., 1998; Junil et al., 1999; Wong and Li, 1999; White et al., 2002). These models generally have various kernel functions such as a geomorphologic IUH (Franchini and O'Connell, 1996), variable source area modeling from the TOP model (Valeo and Moin, 2000), tank model (Yue and Hashino, 2000; Lee and Singh, 2005), a conceptual linear reservoir (Hannah and Gurnell, 2001; Cheng and Wang, 2002), and morphological IUHs (Rodriguez et al., 2003). System analysis is increasingly used to understand and develop solutions to complex urban problems. It is also advantageous when applied to flood hydrographs characteristics such as runoff volume, flow rates, and urban storm runoff.

Problems encountered in urban systems should be analyzed to account for spatial and temporal variations. To date, lumped runoff modeling remains a useful tool for studying changes to an outlet hydrograph on a watershed. Lumped runoff modeling can be applied to explore changes from the past to the present by ignoring some spatial variations. Both simulation modeling and the design storm approach are frequently used to estimate the magnitude and frequency of flooding in urban areas. A design flood hydrograph is then typically used to evaluate hydrological effects of stormwater runoff on land with increased imperviousness. These combined effects include increased runoff volume, reduced flow time and, especially, an increase in peak discharges with a resulting shift in the flood frequency curve (Hollis, 1975; Moscrip and Montgomery, 1997; Moon et al., 2004). A combination question of urbanization results such as an increment in hydrograph peak, shortening of time to peak, and reduction of design criteria of flood, should be solved for water resources management in Taiwan.

Given the unique topography of the bowl-shaped study watershed, when a larger storm occurs, enormous overland runoff flows rapidly into the downstream is frequently inundated. The imperviousness of the downstream watershed still is developed, resulting in more massive and swifter runoff than that in the past. As a result, preventing flood disasters has become an essential and immediate concern. In flood prevention, changes to runoff hydrographs, such as volume, peak discharge, and time to peak undergoing urbanization must be identified. Hence, this study generates hydrographs of surface runoff based on urban hydrology.

This study has two important objectives. The first is to determine the tendencies of significant parameters that reflect the growth of impervious areas. The second is to draw and design an applicable diagram for relation among peak, imperviousness and recurrence. Fig. 1 shows the research processes. Fig. 1 also shows a simulated runoff hydrograph, the development of which is the main goal of this study. This study applied popular approaches such as block Kriging, non-linear programming, SCS, simple lumped modeling, and the design storm method. The design storm was used to unify rainfall—runoff events with specific durations and recurrence intervals. The process of rainfall translating runoff is given by parameters n and k in the Nash model and CN in the SCS model. These parameters vary with different degrees of imperviousness, and were confirmed by calibration and verification using three criteria. Finally, all changes to increased peak flows and reduced recurrence intervals were integrated into a designed diagram. This diagram is helpful when managing water resources by referring to the relationships among peak discharges, impervious areas and return periods.

Methods

The block Kriging method

Block Kriging, originally developed by Matheron (1971) and frequently applied in various research fields (Lebel and Bastin, 1985; Lebel et al., 1987; Goovaerts, 2000; Syed et al., 2003; Cheng et al., 2007), was used in this study to compute mean rainfall.

The estimator of hourly mean rainfall, Z_K^*, is a linear combination of n available point-rainfall recordings $Z(x_i)$ located at x_i and with weightings λ_i. The Kriging estimator can be expressed as

$$Z_K^* = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

Generally, the optimal weightings, λ_i, are computed from the block Kriging system based on Lagrange's multipliers method (Wackernagel, 1998; Chiles and Delfiner, 1999) and expressed as