Environ Earth Sci (2014) 72:569–576
DOI 10.1007/s12665-013-2977-8

ORIGINAL ARTICLE

Optimized water surface ratio and pervious surface proportion in urbanized riverside areas

Cheng Gao · Jun Liu · Han Cui · Zhuowen Wang · Shuang He

Received: 26 December 2012 / Accepted: 24 November 2013 / Published online: 5 December 2013

Abstract An optimal group of water surface ratios and pervious surface proportions can reduce the risk of waterlogging in large urbanized riverside areas. In this study, the Storage Capacity Curve Method is proposed to calculate the drainage modulus, the essence of which is based on the assumption that the drainage area is a reservoir; and then draw the storage capacity curve after unsteady flow calculation. A series of drainage modulus is calculated with varying water surface ratio and pervious proportion using the Storage Capacity Curve Method. This is done in order to determine the quantitative relationship among these variables through regression analysis. The results indicate that the drainage modulus of a large urbanized riverside area has a good exponential function relative to the water surface ratio and has a linear relationship with the pervious surface proportion. By using an integrated impacts model and a cost function, the optimal group values of the water surface ratio (6.65 %) and the pervious surface proportion (26.4 %) are obtained by minimizing the cost function.

Keywords Urban drainage · Drainage modulus · Water surface ratio · Pervious surface proportion · Integrated impacts model

C. Gao (✉)
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
e-mail: gch830702@163.com

C. Gao · J. Liu (✉) · H. Cui · Z. Wang · S. He
College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
e-mail: ljfrom@163.com

Introduction

A riverside area, which is below the normal water level, is a closed system with no gravity outfall, thus draining local runoff through pump stations. These areas are economically developed urban locations in China, in which impervious areas expand constantly without regard to the suitability for urban growth and industrial development, although there have been some achievements (Bathrellos et al. 2012, 2013; Al-shalabi et al. 2013). Anthropogenic effects, such as the reduction of the infiltration capacity, the decrease in inner river storage capacity, and the disposal of sediment and solid wastes into rivers, decrease rivers' safe carrying capacity (Karamouz et al. 2011). Hydrologic responses are reflected by the increase in peak discharge and flood volumes, and decrease in the time it takes for flood flows to peak (Walsh et al. 2005; Shuster et al. 2005). Meanwhile, in terms of development and renewal, protected structures in the urbanized areas are of more importance, facing a greater risk of waterlogging brought about by urbanization.

In riverside areas, an integrated drainage system consists of pipe drainage and river drainage, which is reflected in the drainage modulus (the ratio of the pump stations' drainage capacity to the total drainage area). A number of models are used to describe runoff generation, overland flow concentration, and pipe drainage, such as the conceptual rainfall–runoff model (Burges et al. 1998), physically based distributed model (Jia et al. 2005; Cuo et al. 2008), geographical information system (GIS) based model (Moglen and Beighley 2002; Schmitta et al. 2004; Chen et al. 2009; Lhomme et al. 2004; Zhao et al. 2009; Quan et al. 2010), and storm water and sewer design models [e.g., SWMM5 (Huber and Dickinson 1988; Rossman 2007), MIKE URBAN (Mikkelsen et al. 2005), HydroWorks (HR Wallingford Ltd 1997), MOUSE (Danish Hydraulic Institute

1999)]. Moreover, some approaches were provided to deal with the complicated pump drainage boundary in large riverside areas (Gao et al. 2013a). However, the above-mentioned models need more sophisticated data inputs. The simple method was therefore derived for the calculation of drainage modulus (Gao et al. 2008, 2009), in which a graphical method and a tabular solution were proposed.

An appropriate water surface ratio, ratio of water surface area (including rivers, lakes, and other bodies of water) to the total drainage area, and pervious surface proportion serve important functions in a drainage system. These factors reduce the risk of waterlogging and avoid the excessive increase in the capacity of pump stations, especially in the rapidly urbanized areas (Walsh et al. 2005; Wang et al. 2008; Michael et al. 2010). The effect of the water surface area has been highlighted and discussed by many authors (Zhou et al. 2004; Ding et al. 2007; Xie and Huang 2007; Gao et al. 2008; Jiao et al. 2008); the water surface ratio drives the significantly decrease in drainage modulus. For the pervious surface, the literature focused on the influence of disaster reduction and infiltration (Guo and Baetz 2007; Elmore and Kaushal 2008; Hardison et al. 2009; Schueler et al. 2009; Fassman and Blackbourn 2010). The estimation and assessment of the effect of impervious surface on hydrologic responses has received considerable attention (Lee and Heaney 2003; Shuster et al. 2008; Beighley et al. 2009; Chabaeva et al. 2009; Glick 2009; Meierdiercks et al. 2010; Jacobson 2011). The effects of the spatial distribution of imperviousness were recently studied for the determination of spatial patterns of urban development (Mejia and Moglen 2009, 2010a). Based on low impact development, compensation mechanisms of water surface ratio and pervious surface proportion were derived for flood mitigation to restore the flood hydrographs (Gao et al. 2012, 2013b, c). Nevertheless, only a few studies have considered the water surface ratio and pervious surface proportion simultaneously, especially in the calculation of drainage modulus. The simple method does not consider the channel routing function of inner rivers. Channel routing is enhanced by the increase in drainage area according to the decreasing channel routing time (Mejia and Moglen 2010b).

The aim of this study is to determine the optimal group of water surface ratio and pervious surface proportion in large urbanized riverside areas, with the consideration of enhanced channel routing function. A new method, the storage capacity method, is proposed for the calculation of drainage modulus to obtain a series of corresponding drainage modulus by varying the water surface ratio and pervious surface proportion. Based on the results, the quantitative relationship between these variables is determined. In terms of the development and renewal of urban areas, cost is the important factor to select a policy or strategy with a fixed standard. The objective of this study is achieved after conducting a cost analysis.

Methodology

Storage capacity curve method

Local runoff drainage comprises runoff generation, overland flow concentration, pipe drainage, unsteady flow calculation, and pump drainage. Drainage modulus is the end-result of drainage calculation, which reflects all influencing factors. Under the design conditions, the first task is the design storm calculation. In China, the recurrence interval of one year for pipe drainage is equal to that of 20 years for river drainage because of the storage capacity of inner rivers. The general standard for drainage is to drain the local runoff generated by a 24-hour storm immediately with a recurrence interval of 20 years.

Currently, the calculation formula used is Eq. (1), in which the channel routing function is reflected by the storage capacity (ΔV). Therefore, storage capacity is crucial for calculating the drainage modulus (Gao et al. 2008). However, the derived value is not the real value for the riverside area owing to the different storage routing functions of different river networks.

$$M = \frac{\sum_{i=1}^{m} Q_i \Delta t - \Delta V}{3,600 \text{ mA}} \quad (1)$$

where M is the drainage modulus and m is the number of time intervals, when the local runoff is drained as the designed capacity of pump stations, surpassed water starts existing in rivers at the beginning and subsequently reaches the maximum. In a definite riverside area, ΔV, A, and Q_i can be easily determined.

The storage capacity curve method can be used to obtain a more accurate storage capacity for inner rivers, with the assumption that the drainage area serves as a reservoir. The steps are shown in Fig. 1.

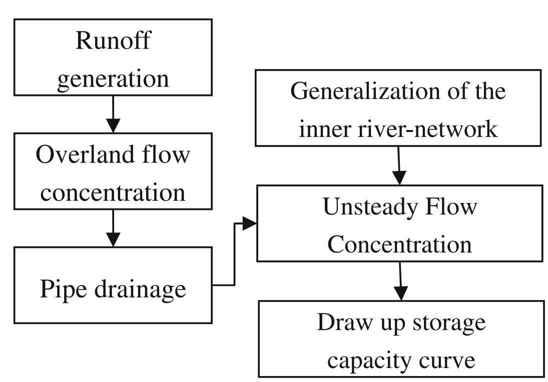

Fig. 1 Flow chart of the storage capacity curve method

1. *Generalization of the inner river network* The generalization of the inner river network is the basis of the unsteady flow calculation. In this process, the main inner rivers with high capacity of transportation are fully considered, whereas the subordinate ones are neglected. Nevertheless, the subordinate rivers' storage capacity is reflected by the water surface ratio in the generalized river network.
2. *Unsteady flow concentration* The basic equations describing one-dimensional flood wave are the Saint-Venant equations. Given that the drainage area is considered as a reservoir, the inflow of unsteady flow is caused by the pipe drainage, and the waterlogging is stored in the river network.
3. *Construction of the storage capacity curve* According to the result of step (2), the water level and accumulated inflows of the corresponding time are plotted (Fig. 2). Owing to the flat topography and the not too large drainage area, the water level exhibits small differences. The storage capacity curve is mostly influenced by the rivers' scale and controlled water levels.

In Fig. 2, the corresponding storage capacity (ΔV) of the drainage area is easily determined, with the highest water level (Z_m) of the inner rivers. Based on the curve, the drainage modulus is calculated using Eq. (1) with ΔV.

Channel routing is considered mainly in storage capacity curve method by means of the unsteady flow calculation, and the storage capacity obtained is just closer to the actual one. Compared with the Node's Water-level Control Method (NWCM) (Gao et al. 2013c), the former is much easier and needs less data inputs. In other words, it can be regarded as the improvement of the simple method (Gao et al. 2008) and used in not too large urbanized areas. The NWCM reflects all the aspects in drainage calculation with more accuracy, and it can be used in much larger areas.

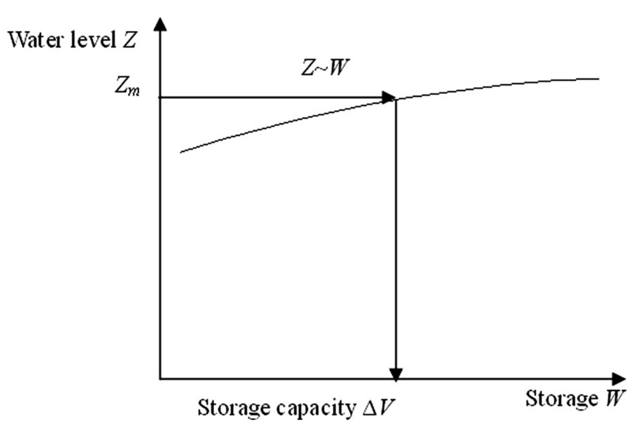

Fig. 2 Storage capacity curve of the drainage area

Relationships among drainage modulus, water surface ratio, and pervious surface proportion

In $\Delta V = kA\Delta h$, the water surface ratio is the most important determinant of the storage capacity when the routing depth of the inner rivers is fixed. The relationship between the two variables has been studied by some researchers (Zhou et al. 2004; Ding et al. 2007; Xie and Huang 2007; Jiao et al. 2008). However, previous studies revealed some limitations, such as the inapplicable calculation method of the drainage modulus, lack of attention given to urbanized riverside areas, and inefficient series.

The storage capacity curve of inner rivers is significantly related to the water surface ratio (Fig. 3). A group of drainage modulus can be calculated using the storage capacity curve method, with the changing variable being the water surface ratio and the others as the constants. Then the relationship between drainage modulus and water surface ratio can be obtained.

Urbanization causes increasingly more rapid local runoff. Pervious surface, such as public green space, is important to reduce the risk of waterlogging. Nevertheless, attention has not been directed toward the relationship between the drainage modulus and the pervious surface proportion. Pervious surface affects the drainage modulus by reducing the runoff generation and waterlogging, which are irrelevant to the storage capacity curve. The initial pervious surface proportion continually changes with other unchanged variables to calculate the corresponding drainage modulus using the storage capacity curve method. The storage capacity curve is identical, whereas the pervious surface proportion changes. Then the relationship between drainage modulus and pervious surface proportion can be fitted.

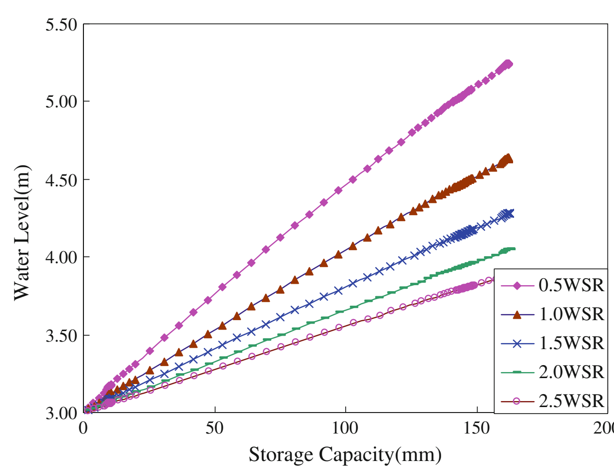

Fig. 3 Storage capacity curve with different water surface ratios; *WSR* represents water surface ratio and the constants represent the times of the current WSR

Optimized group of water surface ratio and pervious surface proportion

In urbanized riverside areas, three engineering measures are usually taken to prevent waterlogging: (1) increasing the capacity of pump stations; (2) enlarging the water surface ratio; and (3) expanding the pervious surface proportion. One or a group of several measures may be chosen in actual construction.

In order to obtain an optimized group of water surface ratio and pervious surface proportion, an integrated impacts model have to be founded. In urbanized riverside areas, a quantitative relationship exists among the drainage modulus, water surface ratio, and pervious surface proportion. For the performance of the integrated effect, an integrated impacts model is established as follows:

$$M = M_1(\mathrm{Wr}) \times M_2(P) \quad (2)$$

where $M_1(\mathrm{Wr})$ is the function of the relationship between the drainage modulus and the water surface ratio, and $M_2(P)$ is the function of the relationship between the drainage modulus and the pervious surface proportion.

Under the designed conditions, the measures are generally chosen through cost comparison. A cost function is established to determine the optimized group of measures.

$$C = b_1(q - q_0) + b_2(\mathrm{Wr} - \mathrm{Wr}_0)A + b_3(P - P_0)A \quad (3)$$

$$q = MA \quad (4)$$

where C is the total cost; b_1 is the unit price of increasing the capacity of pump stations; b_2 is the unit price of the enlarging water surface ratio; b_3 is the unit price of the expanding pervious surface proportion; q_0 is the current capacity of the pump stations; Wr_0 is the current water surface ratio; P_0 is the current pervious surface proportion; A is drainage area; and q is the capacity designed. Using Eqs. (2), (3), and (4), the total cost function can be derived.

According to the integrated relationship and cost analysis, the optimal group values of water surface ratio and pervious surface proportion are obtained by minimizing the cost, providing a scientific basis for the chosen measures.

Results and discussion

Storage capacity curve in a case study

Hexi New Town in Nanjing City (Fig. 4), which has an area of 54.7 km^2, is a priority area for development. Hexi New Town is characterized as an emerging modern new town, people-oriented new town, green new town, and riverside new town. It is expected to be the new center and symbol of the modern city of Nanjing. After urbanization and with the tributaries buried, Hexi New Town's impervious proportion reaches 78.5 %, and the water surface ratio decreases from 18 % before urbanization to 6.5 %. Consequently, the risk of waterlogging increases. The Storage Capacity Curve Method is used in this study to calculate a more accurate drainage modulus.

According to the available data series of measured rainfalls for 1, 3, 6, and 24 h, covering a period of 40 years in Nanjing City, the typical rainfall process is selected to generate a design of the 20-year recurrence period for Hexi New Town. In the runoff generation model, runoff generation is considered as the saturation-excess manner, and the

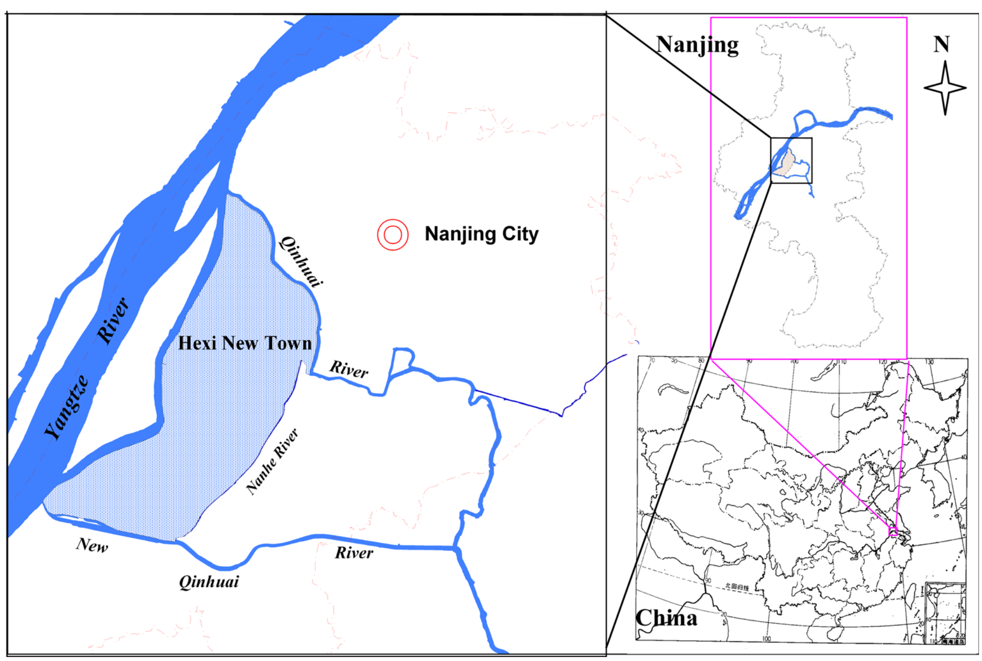

Fig. 4 Location of Hexi New Town

Table 1 A 24-h designed storm and runoff in Hexi New Town

Time interval (h)	Designed storm (mm)	Runoff (mm)	Time interval (h)	Designed storm (mm)	Runoff (mm)
1	12.4	7.88	13	8.7	7.74
2	1.2	1.56	14	10.6	9.7
3	0	0.17	15	5.6	5.74
4	0.8	0.44	16	1.2	1.61
5	1	0.7	17	1.2	1.08
6	0	0.07	18	1.2	0.98
7	0	0.01	19	1.2	0.96
8	12	8.94	20	1.8	1.45
9	73	61.6	21	1.4	1.18
10	21.3	25.07	22	12.6	10.48
11	4.6	7.16	23	1.2	2.1
12	4.1	4.41	24	1.2	1.15
			Total	178.3	162.17

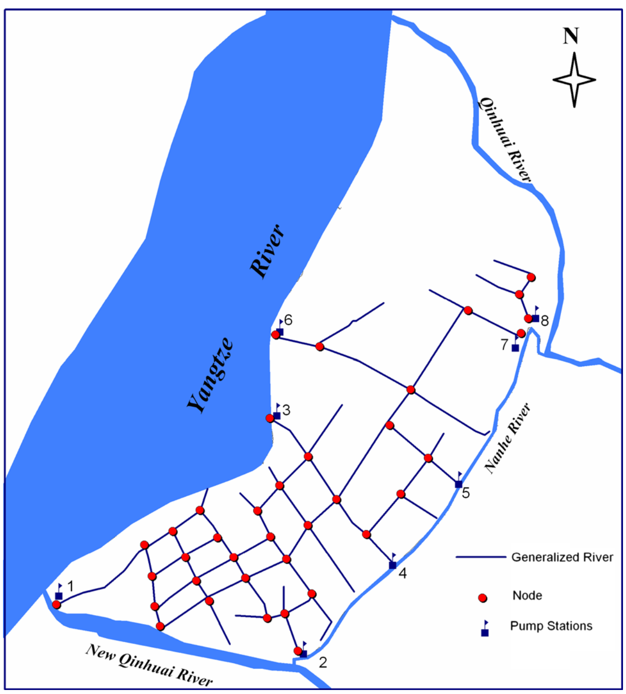

Fig. 5 Generalized river network of Hexi New Town

surface flow concentration is measured using the linear reservoir method. The result of runoff generation is listed in Table 1.

After calculating the overland flow concentration and pipe drainage, the outflow is generated as the inflow of unsteady flow calculation. Based on Fig. 1, the final generalized river network of Hexi New Town is displayed in Fig. 5 and Table 2.

Rivers' scale, roughness, sluice, pump stations, and other parameters for unsteady flow calculation are collected using

Table 2 Result of the generalized river network

Outer rivers	Outer rivers' sections	Inner rivers	Inner rivers' sections	Nodes
24	85	46	180	37

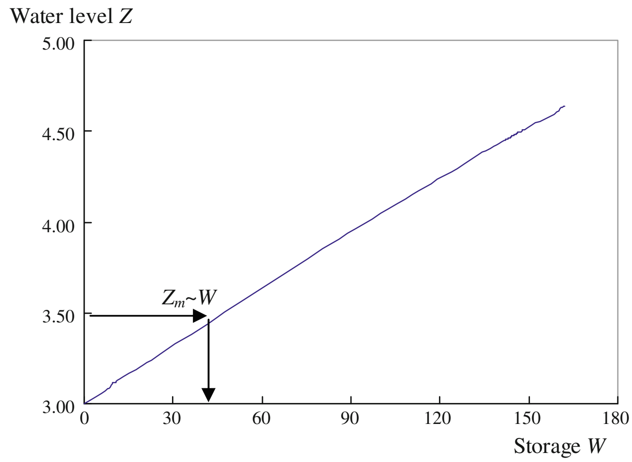

Fig. 6 Storage capacity curve of Hexi New Town, multiplied by *A* for conversion to volume (m^3)

on-site measurements and other statistical data provided by the administration. According to the actual operation, the initial water level is fixed at 3 m, which is the water level when pumping is started. Through unsteady flow calculation, the water level of inner rivers is determined, and the storage capacity curve is plotted with the water level and the corresponding inflow of inner rivers (Fig. 6).

If the maximum water level is controlled at 3.5 m, the highest permissible water level, the actual storage capacity can be read as 47.3 mm, as shown in Fig. 6. This observation indicates that the inner rivers can store local runoff of 47.3 mm under the condition of the current water surface ratio (6.5 %). Converting this value to volume, the storage capacity ΔV is 2.59 million m^3. Currently, the storage capacity (ΔV) is calculated as 1.78 million m^3 by $\Delta V = kA\Delta h$, where k is the water surface ratio, A is the drainage area, and Δh is the routing depth of the inner rivers (Gao et al. 2008). The two values of ΔV show that the inner rivers' storage routing function has significant influence on storage capacity.

Using the above storage capacity, the drainage modulus is easily obtained using Eq. (1), with a value of 3.13 $m^3/s/km^2$.

Relationship between drainage modulus and water surface ratio

In Hexi New Town, a group of drainage modulus can be calculated using the storage capacity curve method (Table 3).

Table 3 Drainage modulus under the different water surface ratio

Water surface ratio	Drainage modulus ($m^3/s/km^2$)	Water surface ratio	Drainage modulus ($m^3/s/km^2$)	Water surface ratio	Drainage modulus ($m^3/s/km^2$)
0.0065	4.41126	0.04875	3.46829	0.091	2.63053
0.00975	4.33599	0.052	3.39874	0.09425	2.57588
0.013	4.2598	0.05525	3.33076	0.0975	2.52132
0.01625	4.18723	0.0585	3.26373	0.10075	2.46954
0.0195	4.1161	0.06175	3.19729	0.104	2.45015
0.02275	4.04414	0.065	3.13132	0.10725	2.42897
0.026	3.97234	0.06825	3.0663	0.1105	2.38098
0.02925	3.90042	0.0715	3.00171	0.11375	2.33305
0.0325	3.82729	0.07475	2.93748	0.117	2.2852
0.03575	3.75417	0.078	2.87355	0.12025	2.23667
0.039	3.68139	0.08125	2.80963	0.1235	2.18819
0.04225	3.60931	0.0845	2.74592	0.13	2.09118
0.0455	3.53846	0.08775	2.68472	0.195	1.38212

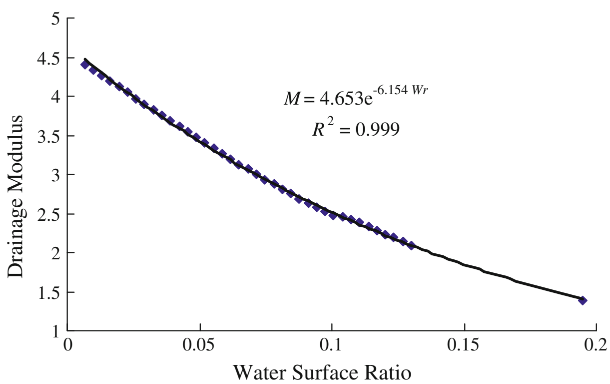

Fig. 7 Fitted with exponential function; *M* is the drainage modulus and Wr is the water surface ratio

As shown in Fig. 7, for the same storage capacity, the water level decreases rapidly with increasing water surface ratio. Meanwhile, the drainage modulus follows the rule stated in Table 3 and Fig. 7. The relationship demonstrates that the appropriate water surface ratio can help avoid an excessive increase in the capacity of pump stations.

Relationship between drainage modulus and pervious surface proportion

The initial pervious surface proportion is 15 % in Hexi New Town, and this keeps changing with other unchanged variables to calculate the corresponding drainage modulus using the storage capacity curve method (Table 4).

In Table 4, along with the greater pervious proportion, the drainage modulus seems to decrease linearly. The influence of the pervious surface ratio is significantly less than that of the water surface ratio, as shown in Tables 3 and 4. The fitted function indicates a linear relationship (Fig. 8), with a coefficient of determination of 1.

Integrated impacts model

According to the relationships above, the integrated impacts model of Hexi New Town can be shown as follows:

$$M=(\alpha_1 P+\alpha_2)\times e^{\alpha_3 Wr} \tag{5}$$

where α_1, α_2, and α_3 are the coefficients, calibrated by a nonlinear regression analysis with the series of data in Tables 3 and 4. The expression function of the relationship among the drainage modulus, water surface ratio, and pervious proportion is obtained, with the coefficient of determination being 0.998.

Table 4 Drainage modulus under the different pervious surface proportion

Pervious surface proportion	Drainage modulus ($m^3/s/km^2$)	Pervious surface proportion	Drainage modulus ($m^3/s/km^2$)	Pervious surface proportion	Drainage modulus ($m^3/s/km^2$)
0.015	3.18292	0.1125	3.14571	0.21	3.10872
0.0225	3.18007	0.12	3.14281	0.2175	3.10589
0.03	3.17723	0.1275	3.13995	0.225	3.10306
0.0375	3.17436	0.135	3.13708	0.2325	3.10027
0.045	3.1715	0.1425	3.13422	0.24	3.09744
0.0525	3.16862	0.15	3.13132	0.2475	3.09462
0.06	3.16576	0.1575	3.12936	0.255	3.09183
0.0675	3.16289	0.165	3.12565	0.2625	3.08901
0.075	3.16003	0.1725	3.12281	0.27	3.0862
0.0825	3.15717	0.18	3.11999	0.285	3.08057
0.09	3.15429	0.1875	3.11715	0.2925	3.07778
0.0975	3.15144	0.195	3.11435	0.3	3.07497
0.105	3.14857	0.2025	3.11152	0.45	3.01896

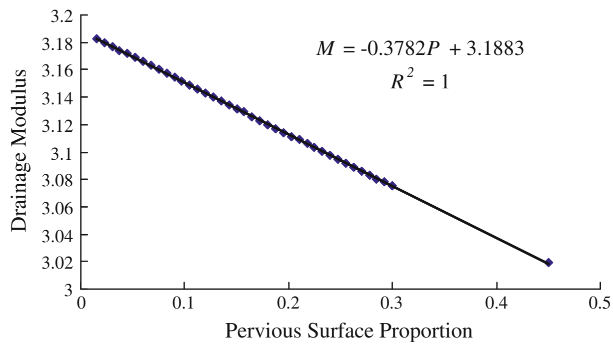

Fig. 8 Fitted with linear function; M is the drainage modulus and P is the pervious surface proportion

$$M = (-0.571P + 4.731)e^{-6.127\mathrm{Wr}}. \quad (6)$$

Using the above integrated model, the drainage modulus is tested by the corresponding group of water surface ratio and pervious proportion. All the errors are less than 5 %, indicating that the model is available for cost analysis.

Optimized group values

In Hexi New Town, the values of coefficients can be given as following, b_1 is RMB 1.5 million/(m^3/s); b_2 is RMB 28 million/(km^2); b_3 is RMB 0.57 million/(km^2); q_0 is 118 m^3/s; Wr_0 is 0.065; P_0 is 0.15; A is 54.7 km^2.

To minimize the cost, the partial derivative of Wr and P is fixed to zero.

$$\begin{cases} \frac{\partial C}{\partial Wr} = (287.11P - 2378.32)e^{-6.127Wr} + 1531.6 = 0 \\ \frac{\partial C}{\partial P} = -46.86e^{-6.127Wr} + 31.18 = 0 \end{cases} \quad (7)$$

From Eq. (7), the optimized group of water surface ratio and pervious surface proportion is obtained; the value of the former is 0.0665, whereas and the latter 0.264, with the total cost being RMB 78.9 million. Meanwhile, the designed capacity of the pump stations can also be determined as 166.7 m^3/s. Considering the cost, the value of the water surface ratio is 6.65 %, whereas that of pervious surface proportion is 26.4 %, with the minimum cost. The group values can be taken for the optimized ones.

Conclusions

For urbanized riverside areas, the storage capacity curve method is developed to obtain the optimal water surface ratio and pervious surface proportion. The main feature is reflected in the calculation of storage capacity (ΔV), which is obtained by considering the storage routing functions of inner rivers. The results of the case study show that the value of the storage capacity is significantly influenced by the channel routing function in large urbanized riverside areas, where such function should not be neglected.

In Hexi New Town, the results of the regression analysis indicate that the drainage modulus has a good exponential function with the water surface ratio and a linear relationship with the pervious surface proportion. Thus, an integrated impacts model is established to perform the integrated effects.

According to the integrated relationship and cost analysis, the optimal group values of water surface ratio (6.65 %) and pervious surface proportion (26.4 %) are obtained by minimizing the cost, providing a scientific basis for the selected measures. Meanwhile, this study provides other cities with a method to determine the suitable water surface ratio and pervious surface proportion through construction planning.

Acknowledgments This work was supported by the National Natural Science Foundation of China (Grant No. 41301016), the China Postdoctoral Science Foundation (No. 2012M520988), and the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research), Grant No. IWHR-SKL-201210. These supports are gratefully acknowledged.

References

Al-shalabi M, Billa L, Pradhan B, Mansor S, Al-Sharif AA (2013) Modelling urban growth evolution and land-use changes using GIS based Cellular Automata and SLEUTH models: the case of Sana'a metropolitan city, Yemen. Environ Earth Sci 70:425–437

Bathrellos GD, Gaki-Papanastassiou K, Skilodimou HD, Papanastassiou D, Chousianitis KG (2012) Potential suitability for urban planning and industry development by using natural hazard maps and geological–geomorphological parameters. Environ Earth Sci 66(2):537–548

Bathrellos GD, Gaki-Papanastassiou K, Skilodimou HD, Skianis GA, Chousianitis KG (2013) Assessment of rural community and agricultural development using geomorphological–geological factors and GIS in the Trikala Prefecture (Central Greece). Stoch Environ Res Risk Assess 27(2):573–588

Beighley RE, Kargar M, He Y (2009) Effects of impervious area estimation methods on simulated peak discharges. J Hydrol Eng 14(4SI):388–398

Burges SJ, Wigmosta MS, Meena JM (1998) Hydrological effects of land-use change in a zero-order catchment. J Hydrol Eng 3(2):86–97

Chabaeva A, Civco DL, Hurd JD (2009) Assessment of impervious surface estimation techniques. J Hydrol Eng 14(4SI):377–387

Chen J, Hill AA, Urbano LD (2009) A GIS-based model for urban flood inundation. J Hydrol 373(3):184–192

Cuo L, Lettenmaier DP, Mattheussen BV, Storck P, Wiley M (2008) Hydrologic prediction for urban watersheds with the distributed hydrology–soil–vegetation model. Hydrol Process 22(21): 4205–4213

Danish Hydraulic Institute (1999) MOUSE Ver. 1999 User Manual and Tutorial. Horsholm, Denmark

Ding GH, Yan W, Cheng JL (2007) Study on the correlation of the drainage criteria of polder on the course of urbanization in southern Jiangsu Province. J Irrig Drain (Chinese) 26(1):30–32

Elmore AJ, Kaushal SS (2008) Disappearing headwaters: patterns of stream burial due to urbanization. Front Ecol Environ 6:308–312
Fassman EA, Blackbourn S (2010) Urban runoff mitigation by a permeable pavement system over impermeable soils. J Hydrol Eng 15(6SI):475–485
Gao C, Liu J, Cui H, Xu HJ (2008) Study on drainage-modulus-calculation method and its correlation with the regulation storage in urban diked area. J Catastr 23(3):7–9
Gao C, Liu J, Cui H, Yudianto D (2009) An applicable method to calculate drainage modulus in urbanized lowlying area. In: Proc Int Conf on Education Technology and Training and Int on Geoscience and Remote Sensing 1:456-459
Gao C, Liu J, Liu XY, Zhang HY (2012) Compensation mechanism of water surface ratio and pervious surface proportion for flood mitigation in urban areas. Disaster Adv 5(4):1294–1297
Gao C, Liu J, Cui H, Hu J (2013a) Treatment of pump drainage boundary in Riverside City. Environ Earth Sci 68(5):1435–1442
Gao C, Liu J, Zhu J, Wang ZW (2013b) Review of current research on urban low-impact development practices. Res J Chem Environ 17(S1):209–214
Gao C, Liu J, Wang ZW (2013c) An ecological flood control system in Phoenix Island of Huzhou, China: a case study. Water 5(4):1457–1471
Glick RH (2009) Impacts of impervious cover and other factors on storm-water quality in Austin, Tex. J Hydrol Eng 14(4):316–323
Guo Y, Baetz BW (2007) Sizing of rainwater storage units for green building applications. J Hydrol Eng 12(2):197–205
Hardison EC, O'Driscoll MA, Brinson MM, DeLoatch JP, Howard RJ (2009) Urban land use, channel incision, and riparian water table decline along Inner Coastal Plain streams, VA. J Am Water Resour Assoc 45:1032–1046
Huber WC, Dickinson RE (1988) Storm water management model. User's manual Ver. IV, Us Environmental Protection Agency
Jacobson CR (2011) Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. J Environ Manag 92(6):1438–1448
Jia YW, Kinouchi T, Yoshitani J (2005) Distributed hydrologic modeling in a partially urbanized agricultural watershed using water and energy transfer process model. J Hydrol Eng 10(4):253–263
Jiao YY, Xu XY, Xu HJ (2008) Analysis on relation between modulus of surface drainage and main influencing factors in urbanized polder area. China Water Wastewater 24(2):40–43
Karamouz M, Hosseinpour A, Nazif S (2011) Improvement of urban drainage system performance under climate change impact: case study. J Hydrol Eng 16(5):395–412
Lee JG, Heaney JP (2003) Estimation of urban imperviousness and its impacts on storm water systems. J Water Resour Plan Manag 129(5):419–426
Lhomme J, Bouvier C, Perrin J (2004) Applying a GIS-based geomorphological routing model in urban catchments. J Hydrol 299(2):203–216
HR Wallingford Ltd (1997) HydroWorks: On-Line Manual. Oxon, UK
Meierdiercks KL, Smith JA, Baeck ML, Miller AJ (2010) Analyses of urban drainage network structure and its impact on hydrologic response. J Am Water Resour Assoc 46(5):932–943
Mejia AI, Moglen GE (2009) Spatial patterns of urban development from optimization of flood peaks and imperviousness-based measures. J Hydrol Eng 14(4SI):416–424
Mejia AI, Moglen GE (2010a) Impact of the spatial distribution of imperviousness on the hydrologic response of an urbanizing basin. Hydrol Process 24(23):3359–3373
Mejia AI, Moglen GE (2010b) Spatial distribution of imperviousness and the space-time variability of rainfall, runoff generation, and routing. Water Resour Res 46:W07509
Michael O, Sandra C, Anne J (2010) Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water 2:605–648
Mikkelsen PS, Madsen H, Arnbjerg-Nielsen K, Rosbjerg D, Harrmoes P (2005) Selection of regional historical rainfall time series as input to urban drainage simulation at ungauged locations. Atmos Res 77(1–4):4–17
Moglen GE, Beighley RE (2002) Spatially explicit hydrologic modeling of land use change. J Am Water Resour Assoc 38(1):241–253
Quan R, Liu M, Lu M, Zhang LJ, Wang JJ, Xu SY (2010) Waterlogging risk assessment based on land use/cover change: a case study in Pudong New Area, Shanghai. Environ Earth Sci 61:1113–1121
Rossman LA (2007) Storm water management model user's manual version 5-0, EPA/600/R-05/040. United States Environmental Protection Agency, Cincinnati
Schmitta TG, Thomasa M, Ettrich N (2004) Analysis and modeling of flooding in urban drainage systems. J Hydrol 299(4):300–311
Schueler TR, Fraley-McNeal L, Cappiella K (2009) Is impervious cover still important? Review of recent research. J Hydrol Eng 14:309–315
Shuster WD, Bonta J, Thurston H, Warnemuendes E, Smith DR (2005) Impacts of impervious surface on watershed hydrology: a review. Urban Water J 2(4):263–275
Shuster WD, Pappas E, Zhang Y (2008) Laboratory-scale simulation of runoff response from pervious-impervious systems. J Hydrol Eng 13(9):886–893
Walsh C, Roy A, Feminella J, Cottingham P, Groffman P, Morgan R (2005) The urban stream syndrome: current knowledge and the search for a cure. J N Am Benthol Soc 24:706–723
Wang J, Endreny TA, Nowak DJ (2008) Mechanistic simulation of tree effects in an urban water balance model. J Am Water Resour Assoc 44:75–80
Xie H, Huang JS (2007) Study on the relationship of municipal drainage and hydrological for urban area. J Irrig Drain (Chinese) 26(5):10–13
Zhao DQ, Chen JN, Wang HZ, Tong QY, Cao SB, Shen Z (2009) GIS-based urban rainfall-runoff modeling using an automatic catchment-discretization approach: a case study in Macau. Environ Earth Sci 59:465–472
Zhou JK, Zhu CL, Luo GP (2004) Calculation for the designed flood drainage modulus in small lowlying region of Taihu Lake Basin. China Water Wastewater 20(12):64–66