Environ Earth Sci (2013) 68:1435–1442
DOI 10.1007/s12665-012-1841-6

ORIGINAL ARTICLE

Treatment of pump drainage boundary in riverside city

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Received: 1 August 2011 / Accepted: 9 July 2012 / Published online: 22 July 2012

Abstract Waterlogging is drained by pump stations set on the inner river network in riverside cities. More importance is given to avoiding waterlog through an applicable design capacity of pump stations, confirmed by a reasonable method to deal with the complicated boundary of the pump drainage. Node's Water-level Control Method (NWCM) has been proposed in this paper. The core idea of NWCM was to transform the pump drainage boundary into the water level boundary, in accordance with the storage capacity curve and the characteristic of a less different water level in riverside cities. The design capacity of each pump station was obtained by unsteady flow calculation. In the case study, the design capacities of the eight pump stations of Hexi New Town in Nanjing City were confirmed conveniently by NWCM. The total design capacity was less than that obtained through regular methods due to the full consideration for storage capacity of inner river channels in the new method, which was designed in accordance with actual conditions.

Keywords Riverside city · Pump station · Pump drainage boundary · NWCM · Nanjing City

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Introduction

Riverside cities in low-lying areas prevent floods by embankments and draining waterlogging through pump stations. Along with climate change, cities face an increase in flood disaster risks, which have been hot topics in recent research. The current achievements are more focused on calculating the drainage modulus and determining the water surface ratio. Jiao et al. (2008) found out the regressive relationships among drainage modulus, water surface ratio and runoff coefficient by the multivariate linear regression analysis. Zhou et al. (2004) analyzed the nonlinear relationship between drainage capacity and water surface ratio. Xu (2009) and Qin (2010) calculated the drainage modulus using the water balance and the storage capacity. Cui et al. (2008) put forward the flat cut method (graphic method). Gao et al. (2008, 2009, 2010) gave the tabular solution and contrasted it with the graphic method. Zhang et al. (2007) found the objective function for the lowest cost and built an urban drainage system model through dynamic programming.

All the achievements above considered the entire city or urban area without considering the storage of the river channel and calculated the total drainage capacity by multiplying the drainage modulus and the area. Nevertheless, the river network in a riverside city has a higher density and larger storage of river channel as well as several pump stations set in the city. This situation needed an in-depth study on the drainage of the inner river network.

Inside the city, more researchers aimed at the inundation simulation of the pipe drainage (e.g., Schmitt et al. 2004; Lhomme et al. 2004; Chen et al. 2009; Quan et al. 2010) rather than the river drainage. Models such as Infoworks (2006), SWMM (2004) and Mike (2003) solve the problems of river drainage and capacity calculation of the pump station. However, other difficulties appear. The capacity of the pump station is designed by the unsteady flow calculation with Saint–Venant equations to deal with the boundary of the pump drainage. The boundary is closely related to the water level of the river network and the alternative for the drainage process, rather than the constant boundary of water level and flow. The above-mentioned models need the initial value input of each pump station's capacity to proceed with the river drainage calculation. The value's suitability determines the work load of the trial calculation, especially in the city with more pump stations. This approach is tedious and inconvenient for drainage calculation. Furthermore, the location needs to be confirmed by trial calculation as well if a new pump station is set up.

In this paper, a new method, Node's Water-level Control Method (NWCM), is proposed with the treatment of the pump drainage boundary to translate the urban drainage calculation into a general concentration calculation of the river network without pump stations, no matter how many pump stations are there.

Method

Core idea of NWCM

Under the design conditions, the operational principle of the pump station is as follows in the riverside city, which composes the boundary of the pump drainage (Fig. 1).

Stage 1: $Q_{in} < q$, then $Q_{out} = Q_{in}$, $Z = Z_0$, which is the water level boundary.
Stage 2: $Q_{in} \geq q$, then $Q_{out} = q$ surpasses water stay in the river network and makes Z rise to the maximum Z_m, which is the flow boundary.

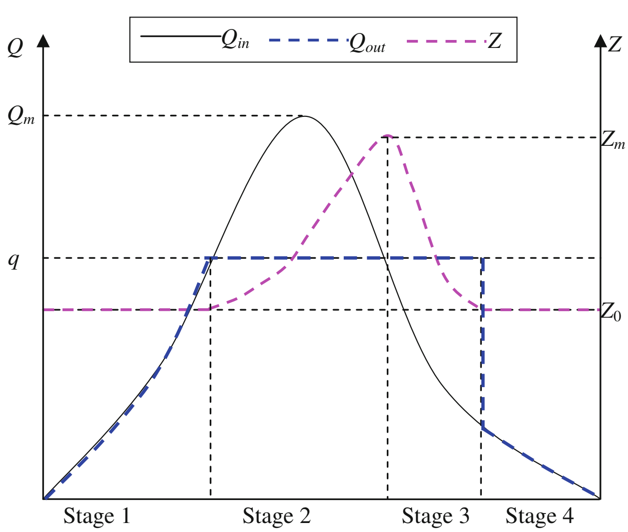

Fig. 1 Stages in the operation of a pump station

Stage 3: $Q_{in} < q$, but $Z > Z_0$, then $Q_{out} = q$, Z is low down to Z_0, which is still the flow boundary.
Stage 4: After Stage 3, $Q_{out} = Q_{in}$, $Z = Z_0$, which is back to the water level boundary.

In the stages above, Q_{in} is the inflow of the suction sump, Q_{out} is the actual discharge of the pump station, q is the total design capacity of the pump station, Z is the real-time water level, Z_0 is the starting level for drainage, and Z_m is the highest water level for flood control.

In the stages above, the real-time water level of the river network changes along with the drainage process, and the boundary of the pump drainage is the alternative. It is of utmost importance to deal with the boundary of the pump drainage for the capacity calculation of the pump station. In NWCM, the boundary of the pump drainage is transformed into the water level boundary, while the urban drainage calculation is transformed into a general concentration calculation of the river network. Through the given water level processes of nodes with the pump stations, the flow process is obtained by unsteady flow calculation and is regarded as the flow boundary for the next computation until the water level meets the stop condition.

Treatment of drainage boundary

Pre-conditions

In NWCM, the key step is to give the water level process as the water level boundary in the following conditions: (1) the maximum water level of the process is the highest permissible water level of the river network; and (2) the process of the water level is the concentration time behind runoff. Herewith, the key points in seeking the water level boundary of the nodes were to determine the concentration time and the process of the water level.

Calculation of concentration time

Concentration time was replaced by the time difference between the centroid of the runoff process and that of the flow process (Fig. 2) with the following equation:

$$\tau = M_1(Q) - M_1(R) \quad (1)$$

where $M_1(Q)$ is the first-order origin moment of flow process, $M_1(R)$ is the first-order origin moment of the runoff process, and τ is the concentration time.

In the riverside city, the inner rivers connect to the outer river by the pump stations, which differ from the natural river network. To get the flow process of the inner river network, the pump stations should be neglected and replaced by long suppositional rivers, making the flow of the nodes with pump stations freely influenced. Through

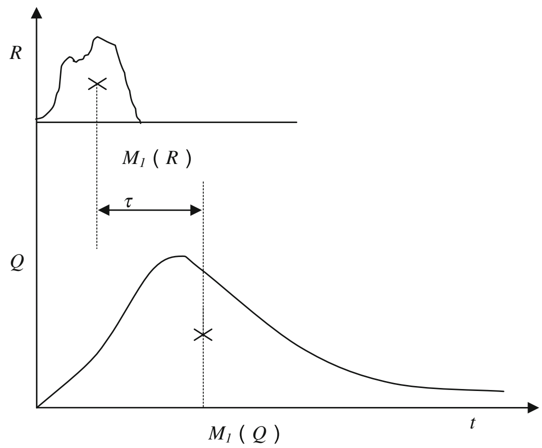

Fig. 2 Schematic plot of the concentration time

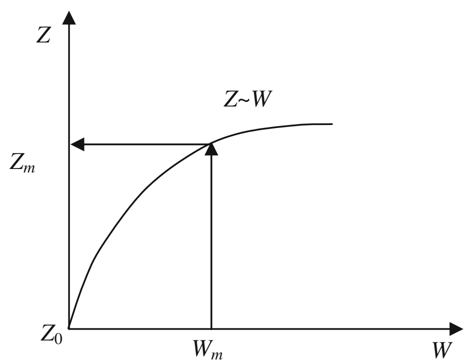

Fig. 3 Schematic plot of the stage capacity curve

the unsteady flow calculation, the flow process of the nodes is computed as well as the input process of the runoff. Then, the concentration time is obtained by Eq. (1).

Conversion to water level boundary

If the inner river network is regarded as a reservoir, the stage capacity curve (Fig. 3) is drawn up in the riverside city. Actually, the stage capacity curve reflected Stage 2 in the operation of the pump station, starting from Z_0. The following equation was derived by water balance:

$$W_{\mathrm{i}} = W_{i-1} + (Q_{\mathrm{in}}^{i} - q)\Delta t \tag{2}$$

where W_i is the storage of the inner rivers; i is the time interval, when $i = 1$, $W_{i-1} = 0$; and Δt is the duration. If $W_i < 0$, then $W_i = 0$. The initial capacity of the pump station (q) can be equal to the result of the tabular solution or graphic method.

According to Eq. (2) and the stage capacity curve, the water level of each time interval can be drawn from the process of the inner river network (Fig. 4). Obviously,

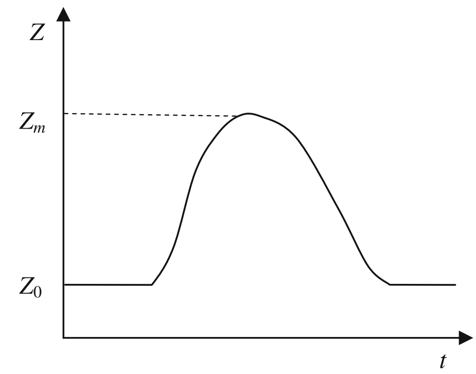

Fig. 4 Water level process derived from Fig. 3

the minimum water level is Z_0 and the maximum is Z_{m}, and the storage achieves the capacity of the inner river network. The water level boundary of the nodes with the pump station is created by moving the water level process behind for a certain time frame.

Design drainage capacity of the pump station

Basic equations describing one-dimensional flood wave include the Saint–Venant equations. Based on these equations, the hydrodynamic model was found to compute the design capacity of the pump station.

$$\begin{cases} B\dfrac{\partial Z}{\partial t} + \dfrac{\partial Q}{\partial x} = q_{\mathrm{s}}, \text{ continuity equation;} & (3) \\ \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\alpha\dfrac{Q^2}{A}\right) + gA\dfrac{\partial Z}{\partial x} + gAS_{\mathrm{f}} = 0, \text{ momentum equation} & (4) \end{cases}$$

where x is the longitudinal distance along the river, t is the time interval, A is the cross-sectional area of the flow, Z is the water level, B is the width of the river, Q is the discharge of cross section, g is the acceleration of gravity, S_{f} is the slope of energy grade line, and q_{s} is the inflow of riversides.

Through unsteady flow calculation with the water level boundary, the flow processes of the nodes with pump stations can be computed (Left one in Fig. 5). The discharges with higher water level than Z_0 are averaged as q_1 and are replaced by q_1 (Right one in Fig. 5). Next, the new flow process $Q(t)$ is taken and set as the flow boundary for the next unsteady flow calculation to get the new water level process $Z(t)$. To make good use of the storage capacity of the inner river network, the maximum of $Z(t)$ above should be equal to Z_{m}. Actually, if the $\max(Z(t))$ is of less difference from Z_{m}, the computation is stopped and q_1 of $Q(t)$ is the design drainage capacity

$$\begin{cases} q_1 = \left(1 + \frac{Z_{\max} - Z_m}{Z_m - Z_0}\right) q_1 & Z_{\max} > Z_m \quad \text{and} \quad |Z_{\max} - Z_m| > 0.05 \\ q_1 = \left(1 - \frac{Z_m - Z_{\max}}{Z_m - Z_0}\right) q_1 & Z_{\max} < Z_m \quad \text{and} \quad |Z_{\max} - Z_m| > 0.05 \end{cases} \tag{5}$$

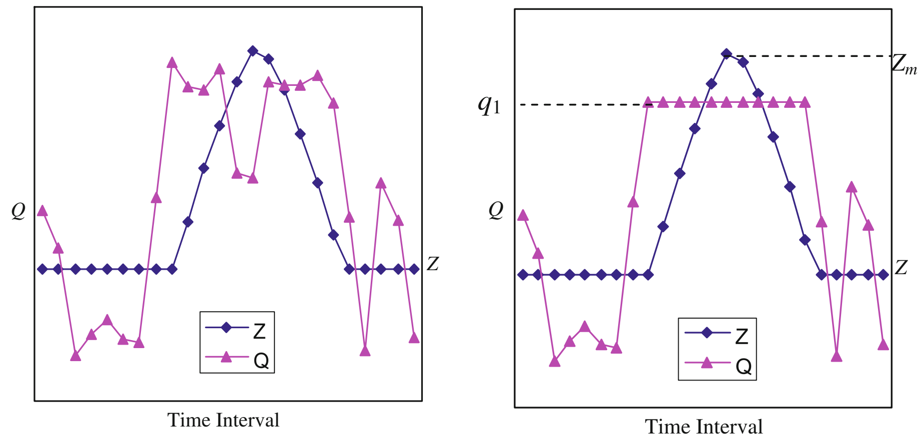

Fig. 5 Flow process changing into flow boundary for the next computation

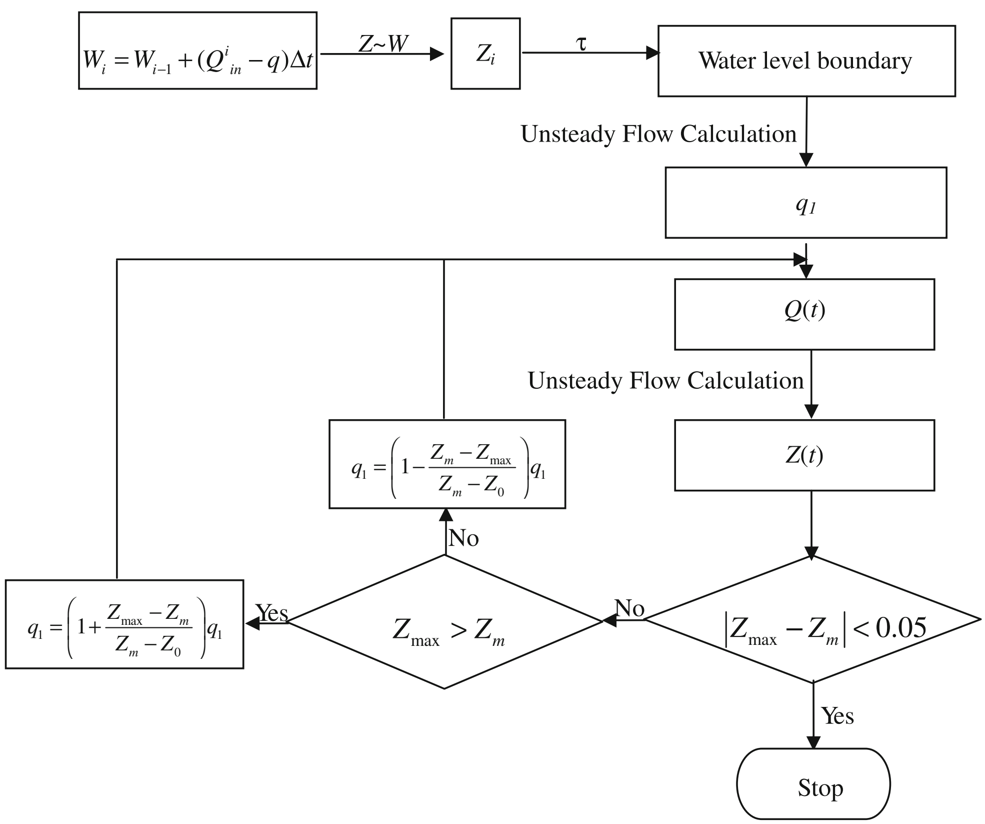

Fig. 6 NWCM's flowchart

of the pump stations located at the nodes. Otherwise, a new q_1 is confirmed by Eq. (5) for the next computation (Fig. 6).

In large riverside cities, several pump stations with different design capacities are always laid out. However, the water levels of the nodes with pump stations are closely

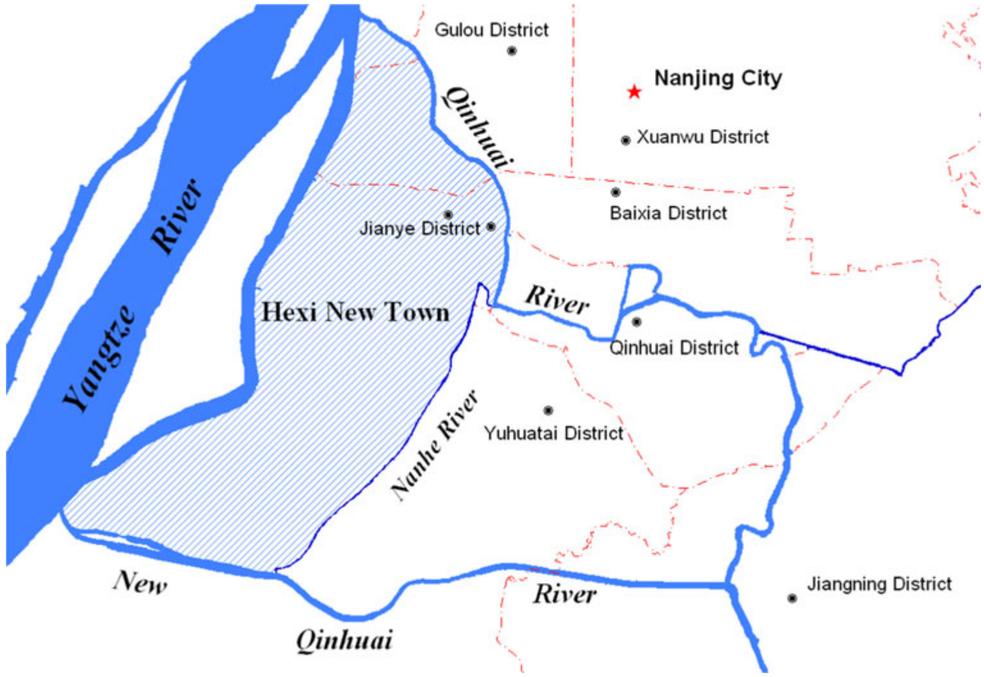

Fig. 7 Location of Hexi New Town

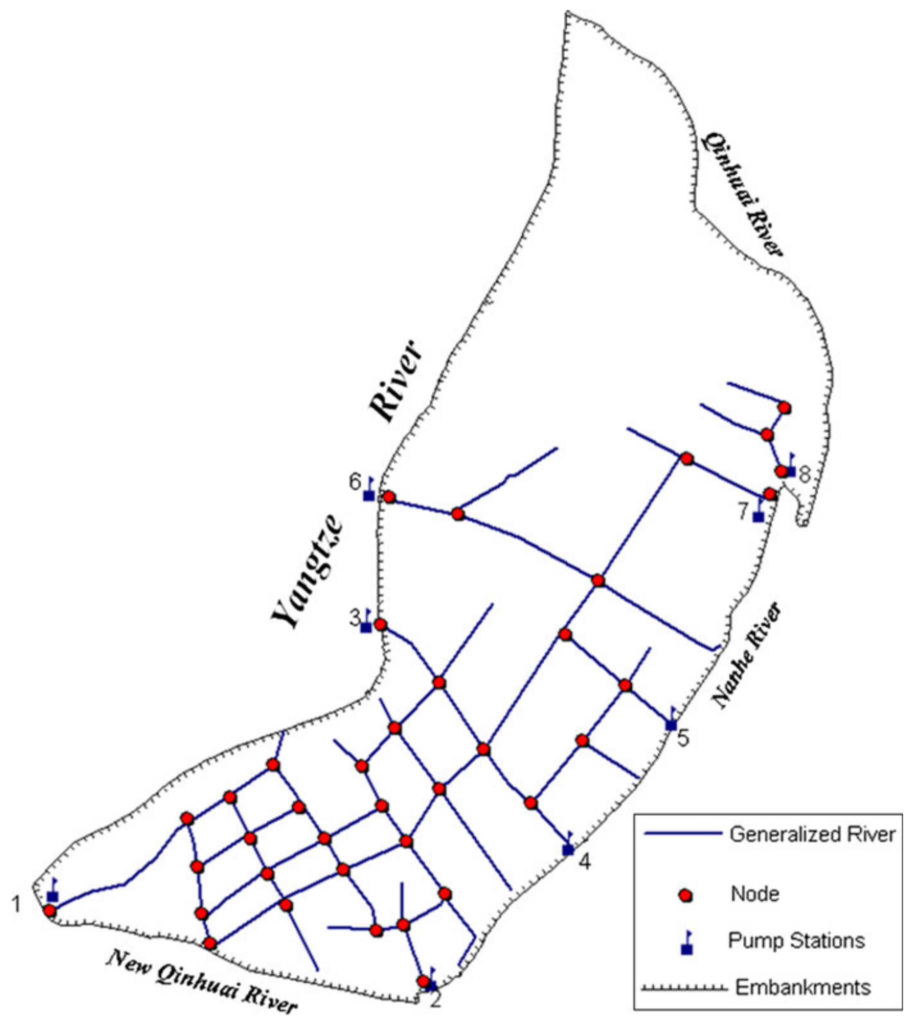

Fig. 8 Generalized river network of Hexi New Town

Table 1 Result of generalized river Network

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

equal. Therefore, q_1 in the flow chat is changed to q_1^{ii} when computing for the design capacity of a city with several pump stations. Here, *ii* is the order number of pump stations.

Case study

Research area

Nanjing City is one of the most famous and important cities in China due to its recent rapid urbanization. Hexi New Town, the right prioritized area for development located at the southwest of Nanjing City, is surrounded by the Yangtze, Qinhuai, Nanhe and New Qinhuai rivers (Fig. 7). The topography of Hexi New Town is plain and low lying, lower than the normal water level. The town prevents flooding by embankments, draining the waterlogging by pump stations. Obviously, it suffers from waterlogging disasters because the capacity of the pump stations is inappropriate. Here, the NWCM was applied for the right capacity.

Generalized river

The generalization of the inner river network was the base of the unsteady flow calculation. In the process, the main inner rivers with high transportation capacity were fully considered, while the subordinate ones were neglected. However, the subordinate rivers' storage capacity was reflected on the water surface ratio in the generalized river network. The final river network is displayed in Fig. 8 and Table 1.

Figure 8 shows eight pump stations allocated to the inner river network. More attention was paid to the node with the eight pump stations in the northern river network, which was not connected to the southern river network.

NWCM in Hexi New Town

Concentration time

In Hexi New Town, eight suppositional rivers were present instead of pump stations, connecting with the inner rivers

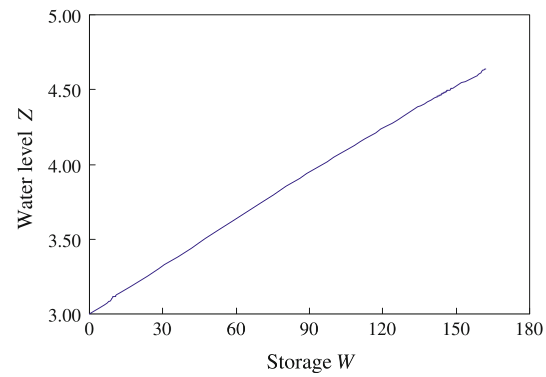

Fig. 9 Stage capacity curve in Hexi New Town

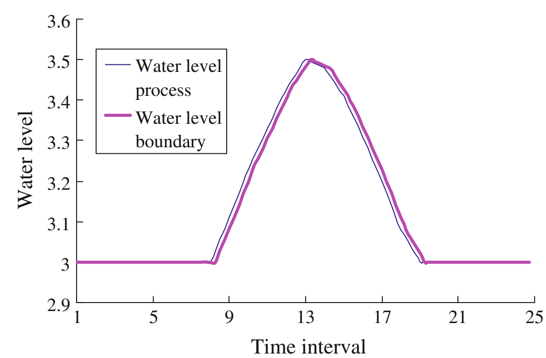

Fig. 10 Conversion for water level boundary

10 km in length. The flow process of each node with the pump station was then figured out, and the concentration time was gained using Eq. (1) (Table 2).

In the plain river network area, the concentration times of those nodes were nearly equal, the maximum of which was 0.37 h, approximately 22 min. When computing for the capacity of the pump stations by unsteady flow calculation, the time step was 15 min. The water level process was moved behind for a time step to get the water level boundary.

Water level boundary

The starting level for the drainage was fixed as 3.00 m, on which the relationship between Z and W was based and drafted (Fig. 9). To make the water level reach the maximum (3.50 m), the initial value was given as the result of the

Table 2 Concentration time of each node with pump station

Node	1	2	3	4	5	6	7	8	Average
τ (h)	0.22	0.25	0.27	0.36	0.34	0.19	0.37	0.32	0.29

Table 3 New flow process after the first trial computation

t_i	Q (t) (m^3/s)							
	1	2	3	4	5	6	7	8
1	7.67	9.55	8.78	7.28	8.33	21.4	14.7	12.9
2	5.08	6.64	5.58	5.09	5.38	11.1	8.84	6.61
3	−1.05	−1.49	−0.76	−0.06	−0.17	−2.25	0.87	−0.09
4	0.08	0.04	0.36	0.79	0.79	0.20	2.21	0.94
5	0.96	1.18	1.18	1.35	1.37	1.67	2.83	1.41
6	−0.15	−0.24	0.02	0.39	0.35	−0.65	1.24	0.19
7	−0.36	−0.50	−0.20	0.20	0.15	−1.08	0.89	−0.02
8	8.48	10.5	9.82	8.37	9.51	23.3	17.1	14.4
9	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
10	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
11	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
12	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
13	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
14	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
15	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
16	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
17	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
18	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
19	14.0	18.0	16.3	14.6	16.1	35.6	28.9	23.2
20	7.04	8.99	7.96	7.53	7.99	16.0	13.8	9.43
21	−0.53	−1.10	−0.08	0.85	0.90	1.66	3.77	1.82
22	9.48	11.6	11.1	9.77	11.10	27.2	20.6	16.6
23	6.61	8.71	7.47	7.07	7.52	15.2	12.8	9.36
24	−0.03	−0.20	0.57	1.26	1.31	1.18	3.72	2.09

tabular solution (223.3 m^3/s). Storage of each time interval was taken from Eq. (2). In accordance with the relationship of Z–W, the water level progress was easily figured out, thus moving behind for a time step to get the water level boundary (Fig. 10). The boundaries of the eight nodes with pump stations were the same because of the plain area.

Results

As seen in Fig. 6, the eight flow processes were computed by the unsteady flow calculation, then q_1 was averaged to find a new flow process $Q(t)$ (Table 3).

From the first trial computation, the maximal water level of the river network was 3.56 m, whereas that of the northern river network was 3.63 m. All these did not meet the condition to stop. Therefore, a new q_1 was fixed by Eq. (5) to find the new $Q(t)$ as the flow boundary for the next trial computation.

According to the result of the second trial computation, the Z_{max} of the southern river network was 3.54 m and that of the northern was 3.43 m. The former met the stop condition, whereas the latter did not. After fixing a new q_1 of the eight nodes to compute again, the final water level of the northern river network met the condition. The final discharge of each node with the pump station was figured out (Table 4), which was the design drainage capacity of each pump station. Demonstrably, the total capacity of the pump stations was 171.2 m^3/s in Hexi New Town, 23.3 % less than the result of the tabular solution (223.3 m^3/s), owing to the larger storage of river channels.

Table 4 Design drainage capacity of each pump station in Hexi New Town

Node	1	2	3	4	5	6	7	8
q_1 (m^3/s)	14.3	18.4	16.6	14.8	16.4	36.3	29.5	24.9

Conclusions

NWCM was proposed to calculate the design capacity of pump stations in the riverside city by converting the boundary of pump drainage into that of the water level.

Depending on the characteristic that water level is less different in a plain area with a high-density river network, the same water level boundary was fixed while the concentration time of each node was nearly equal. The NWCM found a water level process by the storage capacity curve with only one initial value, regardless of the number of pump stations in the city. The design capacity of each pump station was then confirmed after the unsteady flow calculation, which was more convenient than in the other models.

In addition, the result of the case study demonstrated that the total design capacity of the pump stations obtained by the NWCM was less than that by the tabular solution due to the full consideration for storage capacity of the inner river channels in the former method.

Acknowledgments This work was funded by the National Natural Science Foundation of China, under Grant No. 50239030. This support is gratefully acknowledged.

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