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River channel network design for drought and flood control: A case study of Xiaoqinghe River basin, Jinan City, China

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ABSTRACT

Vulnerability of river channels to urbanization has been lessened by the extensive construction of artificial water control improvements. The challenge, however, is that traditional engineering practices on isolated parts of a river may disturb the hydrologic continuity and interrupt the natural state of ecosystems. Taking the Xiaoqinghe River basin as a whole, we developed a river channel network design to mitigate river risks while sustaining the river in a state as natural as possible. The river channel risk from drought during low-flow periods and flood during high-flow periods as well as the potential for water diversion were articulated in detail. On the basis of the above investigation, a network with "nodes" and "edges" could be designed to relieve drought hazard and flood risk respectively. Subsequently, the shortest path algorithm in the graph theory was applied to optimize the low-flow network by searching for the shortest path. The effectiveness assessment was then performed for the low-flow and high-flow networks, respectively. For the former, the network connectedness was evaluated by calculating the "gamma index of connectivity" and "alpha index of circuitry"; for the latter, the ratio of flood-control capacity to projected flood level was devised and calculated. Results show that the design boosted network connectivity and circuitry during the low-flow periods, indicating a more fluent flow pathway, and reduced the flood risk during the high-flow periods.

1. Introduction

Urbanization affects the processes that control streamflow of river channels (Rose and Peters, 2001). Greater runoff, higher peak discharges, more rapid response times, and variations in sediment production often occur during urbanization (Bledsoe and Watson, 2001; White and Greer, 2006), posing great risks on ecology and flood control for river managers (Gregory, 2002). The risks are further exacerbated by the river flow fluctuations over time, typically with cyclic variations on a seasonal, annual and interannual basis (López-Moreno et al., 2008). For example, during low-flow periods, on-going water resources abstraction results in gradual reduction of flow available for instream uses, which, in turn, trigger a number of environmental effects, including increased sedimentation, aggravated water pollution, decreased aquatic biota, and declined recreational landscape (Smakhtin, 2001). During high-flow periods, intense rainfall increases river runoff and peak discharges, posing more challenges on flood protection. More seriously, the global warming and related climate changes are predicted to occur over the next century, which will significantly increase the weather-related risks (Muller, 2007); especially, this trend would aggravate periodic and chronic shortfalls of water and trigger a rise in the frequency and intensity of extreme storm events (Browning-Aiken et al., 2007; Mujumdar, 2008).

Therefore, a necessary strategy to reduce urban river risks induced by urbanization and climate change is to take rainfall variations into account for improvements. There are two opposite methodologies of river improvements. The first is to use traditional engineering techniques, such as river channelization, and construction of dams and reservoirs. Second, a more sustainable approach can be taken to address the challenges of urban effects on stream flows and sediment yield, such as channel restoration in parts of the selected basin (Morris and Moses, 1999; Henshaw and Booth, 2000; Asakawa et al., 2004; Clifford, 2007). Nevertheless, most of the engineering projects have generally been applied in a piecemeal manner over relatively short reaches, without a sound understanding of the broader spatial context (Harper et al., 1999; Gregory, 2002; Brouwer and van Ek, 2004). Such reactive strategies

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are not the most efficient and cost-effective way to achieve improvement success in ecological terms (Brierley et al., 2002). As a result, defining a basin-framed ‘vision’ is a critical early step in effective river improvements (Chin and Gregory, 2005; Schmandt, 2006).

This alteration, when taken in the context of a river network as a population of channels and their confluences (Benda et al., 2004), allows the development of a river channel network to regulate the spatial distribution of water resources and further impose river improvements throughout a river basin. The interest in river channel network has been concentrated on analyzing its topological structure by descriptive measures, for example, discussing the relationship between river channel network morphometry and river reach hydrologic and geomorphic characteristics (Moussa, 2008), and exploring how river channel network structure imposes effects on ecological patterns, such as riverine habitat organization (Benda et al., 2004), fish assemblage structure (Hitt and Angermeier, 2008), and riparian vegetation distribution (Shaw and Cooper, 2008). However, combining structures of graphs and algorithms to find optimal network paths (Poulter et al., 2008) or predicting streamflow statistics with river channel network models (Young et al., 2000; Liu and Weller, 2008) have also been explored. The well-developed application of graphs and algorithms allows us to design an artificial river channel network to address risks of a single river reach by supplementing the removed connection in urban areas, where the real state of basin is one of highly fragmented and largely modified transfers (Graf, 2001). Although a few endeavors have been made to design artificial networks composed of open water channels, storage ponds, and constructed wetlands to relieve urban flood water (Wang et al., 2006a,b), the valid method to link various elements within a river channel network for urban river management is far less developed.

This paper explores how such a channel network can be developed and applied to the basin of Xiaoqinghe (XQH) River in the City of Jinan, China to address the consequences of drought and flood presented by urbanization and climate change during low-flow and high-flow periods, respectively. The City of Jinan has alternating high-flow (June–September) and low-flow (October to next May) periods, corresponding to flood-dominated and drought-dominated regimes. According to Ren et al. (2008), due to climate change, since 1950s, especially after 1990, limitation of water supply has been largely intensified during low-flow periods; meanwhile, flood frequency and intensity also increase apparently during high-flow periods in east China. However, poor planning for emergencies and the lack of structured contingency plans fails to mitigate inundation and water shortages during times of rainfall variations in the study area. Efforts are required to design an artificial river channel network comprising open channels, lakes, reservoirs and wetlands to redistribute water resources within river channels and in turn to reduce risks of flood and drought.

The objective of this study is to 1) propose river channel network scenarios for low-flow and high-flow periods; 2) introduce the shortest path algorithm of graph theory to optimize the low-flow network; and 3) evaluate the risk-relieving capacity of the networks designed for low-flow and high-flow periods.

2. Study area

The city of Jinan (Fig. 1A) is bordered by the Tai Mountain to the south and the Yellow River to the north, with a strongly higher topography in the south than in the north. Hilly areas, piedmont clinoplain, and alluvial plains lie across the city from south to north. Altitude within the area ranges from 23 m to 975 m above sea level, with a highly contrasting relief. The semi-humid continental monsoon climate throughout the city is characterized by cold, dry winters and hot, wet summers. The average annual precipitation is 636 mm, with 75% during the high-flow periods. The average annual temperature is 14.3 °C. The average monthly temperature rises to the highest point in July, ranging from 26.8 °C to 27.4 °C, and drops to the lowest point in January, ranging from -3.2 °C to -1.4 °C.

The rivers flowing through this city belong to the Yellow River basin in the southwest, the XQH River basin in the central district, and the Haihe River basin in the northeast (Fig. 1B). The XQH River basin covers half of the whole urban area. The streams within the XQH River basin are used for navigation, irrigation, and stormwater drainage.

XQH River, the mainstream of the basin, originates from western suburb of the city, flows from southwest to northeast parallel to the Yellow River, and eventually enters the Bohai Sea. The XQH River has a total length of 237 km and a catchment area of 10,572 km^2, of which 70.3 km and 2824.1 km^2 are in the urban districts of Jinan City. There are 27 tributary streams flowing into or out of the XQH River. Most of the streams begin in southern mountains and flow north to the mainstream. Rainfall is the main water source of the streams. The streams to the north of XQH River are mostly flood-discharging channels. The lakes and reservoirs all over the basin (Fig. 1C) have been exploited for water resources development and recreational services.

The uneven distribution of rainfall makes a clear distinction between the low-flow and high-flow periods within a year, which in turn imposes river risks on the XQH River basin. During low-flow periods, scarce rainfall and on-going water resources development usually result in zero flow for instream use in the XQH River and its streams to the south. During high-flow periods, the sharp increases of flow rate, high slope, and narrow cross sections all contribute to flood inundation, especially along the XQH River, Xingji Stream, and Xiujiang Stream (Yu and Wang, 2006). A series of measures have been implemented to fight against flood and drought (Table 1). However, the engineering structures either suffer from a lack of maintenance or have inadequate flood-control capacity. Furthermore, a systematic water management plan is absent for this basin.

3. Methods

The river channel network in a basin is composed of all the river channels in the basin that are interconnected in an orderly fashion (Liu and Weller, 2008). The topology of river channel networks can be efficiently described using graph theory algorithms, which have been developed initially for electrical circuits and transportation networks (Albert and Barabasi, 2002). Graph theory is an organized branch of mathematics, it uses graphs to model situations that occur within certain kinds of problems (Chartrand and Zhang, 2006), and hence gains wide applications to domains of Computer Science, Operational Research, Electronics, Chemistry, Physics, Geography and Environment, and other social sciences (Bu et al., 2002). Main work on geographical and environmental applications of graph theory is concentrated on analyzing topological structure of stream networks and transportation networks. Recent rapid expansion of graph theory permits computational methodologies develop from simple descriptive measures to structure combination and algorithms for finding optimal network flows (Cliff et al., 1979).

The networks in graph theory are composed of “edges” and “nodes”, which in hydrologic terms are river channels and confluences respectively (Poulter et al., 2008). In the broader definition used in this study, nodes refer to channel confluences, river headwaters, lakes, reservoirs and wetlands; and edges represent natural and artificial river channels.

Using the digitalization method of ArcView GIS 3.2, we extracted nodes and edges of the natural river channel network within

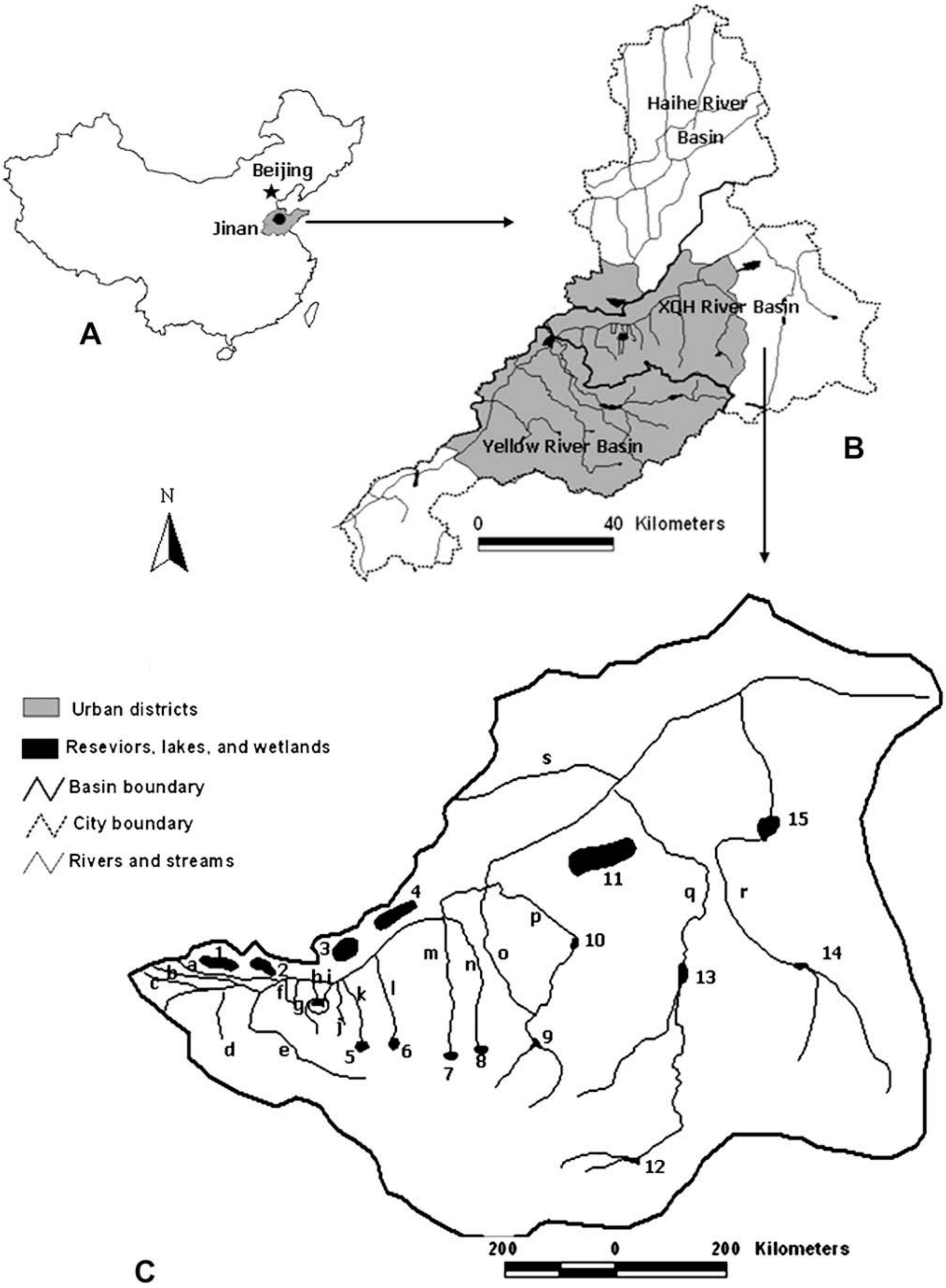

Fig. 1. (A) Location of the City of Jinan; (B) Location of the Xiaoqinghe River basin that covers half of the whole urban district; (C) Natural river channel network within the basin of Xiaoqinghe River (N-n). 1) Meili Wetlands; 2) Yangjuan Wetlands; 3) Shanghuashan Wetlands; 4) Xiahuashan Wetlands; 5) Jiangshuiquan Reservoir; 6) Mengjia Reservoir; 7) Xiaoguan Reservoir; 8) Ganggou Reservoir; 9) Langmaoshan Reservoir; 10) Duzhang Reservoir; 11) Baiyun Lake; 12) Duozhuang Reservoir; 13) Dazhan Reservoir; 14) Xinglin Reservoir; 15) Yazhuang Lake. a) Beitaiping Stream; b) Hongxigan Stream; c) Nantaiping Stream; d) Lashan Stream; e) Xingji Stream; f) Gongshang Stream; g) the moat; h) Xiluo Stream; i) Dongluo Stream; j) Liuhang Stream; k) Quanfu Stream; l) Daxinshi Stream; m) Hancang Stream; n) Liugong Stream; o) Yangjia Stream; p) Juye Stream; q) Xiujiang Stream; r) Luohe Stream; s) Dashaliu Stream.

the XQH River basin from a topographic map (1:740,000) in JEPG format (2006) provided by the Water Resources Bureau of Jinan City (WRBJC).

3.1. For low-flow periods

3.1.1. Designing river channel network

Almost all river reaches within the XQH River basin begin in mountains and receive rainfall and underground spring as their water sources. During low-flow periods, there is inadequate water for instream use for the XQH River and its south tributaries because of slight rainfall and lowered groundwater table. Given that the XQH River has been supplemented from the Yellow River with existing structures for years, we only need to organize a river channel network to replenish water for the tributaries.

The instream flow requirements (IFR) were calculated for tributaries to investigate their risks to drought. IFR are typically reserved for maintenance of biodiversity and protection of habitat; the minimum IFR usually mean the basic flow that maintains the existence of aquatic environments with a continuum structure that

Table 1
Stream length, water source, river risk, and risk-relieving measure surveyed for Xiaoqinghe River and its tributaries.

Name	Stream length (km)	Water source	River risk	Risk-relieving measure
Xiaoqinghe	120.3	Rainfall	Drought and flood	(1), (3), (4)
Nantaiping	11.4	Yellow River	No risks	
Hongxigan	15.0	Yellow River	No risks	
Beitaiping	17.9	Yellow River	No risks	
Lashan	8.2	Rainfall	Drought	No measures
Xingji	27.9	Rainfall	Drought and flood	No measures
Gongshang	9.6	Xiaoqinghe River	Drought	No measures
Xiluo	2.9	Spring and rainfall	Drought	(5)
Dongluo	3.2	Spring and rainfall	Drought	(5)
The moat	8.8	Spring and rainfall	Drought	(5)
Liuhang	8.2	Rainfall	Drought	No measures
Quanfu	12.7	Rainfall	Drought	(2)
Daxinshi	16.8	Rainfall	Drought	(2)
Hancang	23.5	Rainfall	Drought	(2)
Liugong	25.2	Rainfall	Drought	(2), (6)
Yangjia	24.5	Rainfall	Drought	(6)
Juye	42.3	Rainfall	Drought	(2), (6)
Xiujiang	81.6	Rainfall	Drought and flood	(2), (6)
Luohe	66.0	Rainfall	Drought	(2)
Dashaliu	30.7	Yellow River	No risks	

Note: risk-relieving measures include (1) river or stream channelization; (2) construction of reservoirs to store runoff; (3) construction of levees to protect flood from outburst; (4) diversion of water from the Yellow River to replenish drying river reaches; (5) closure of nearby waterworks to protect underground water sources; (6) greening of banks to conserve water.

provide physical habitat for biodiversity (Tang et al., 2004). Herein, replenishing IFR for tributaries will produce potential ecological benefits for the whole basin. Usually, instream flow is obtained empirically from a series of historic data. In China, for regions lack of water resources, IFR are calculated using the following formula (Wang et al., 2007):

$$Q_h = \min\{Q_i\}, \tag{1}$$

where Q_h is the minimum IFR (10^8 m^3), it will maintain the flow continuity and basic ecological functions of a stream; Q_i is the flow discharge during low-flow periods in the year of i (10^8 m^3); i is the statistic year, $i = 1970, 1971, \ldots, 2006$.

A river channel network was then designed to redistribute water resources spatially and temporally with water-diversion channels that address the drought problem during low-flow periods. The design was accomplished in three steps, i.e., 1) investigating river channel risk to drought and analyzing water-diversion potential; 2) selecting available water sources (reservoirs, wetlands, lakes and headwaters) or conjunctions as network nodes to supply water for the river channels subject to drought threat; and 3) connecting the selected nodes with edges that represent artificial channels or natural corridors, to form the designed river channel network that was different from the natural one.

3.1.2. Optimizing channel network with the shortest path model

Compared to the natural river channel network, the designed one embodies more nodes and links, with boosted degree of network connectivity and circuitry, or complexity (Forman and Godron, 1986). Theoretically, a complex network provides alternative routes for material transportation, implicating the effectiveness of linkages (Dramstad et al., 1996). Practically, a complex network has to be connected with more loops, links and nodes, increasing constructing and management costs. The contrast between theory and practice calls for an optimizing approach to reduce redundant loops, links and nodes within complex networks. Therefore, we improved the topology of the designed river channel network by applying the shortest path algorithm of graph theory.

A directed graph G_d is a pair of (V, E), where V is a set of nodes and E a set of unordered pairs of (i, j) that denote the directed edges. The i and j are initial and terminal nodes respectively, which together are called endpoints of (i, j) (Chen, 1976). If each edge of G_d is weighted with one or more real numbers, then the directed graph can be called a directed network, or simply a network. Therefore, a directed network N is defined as:

$$N = (V, E, W), \tag{2}$$

where $V = \{1, \ldots, n\}$ is the set of n nodes, $E \subset N \times N$ is the set of edges, and associated with each edge $(i, j) \in E$ is a vector weight $w_{ij} \in W$.

In the above network N, the path from origin edge to destination edge $p\ (u, v)$ consists of a group of edge series $(e_0, \ldots, e_k)$, in which $u = e_0$, $v = e_k$. The weight of the path is the sum of weights of all edges. The shortest path between the edges u and v is defined as the path with the least weight among all the paths between these two edges. The shortest path model can be described as follows (Xie and Xing, 2000):

$$\begin{aligned} &\min \sum_{(i,j)\in A} w_{ij}x_{ij} \\ &\text{s.t.} \quad \sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(j,i)\in A} x_{ji} = \begin{cases} 1, & i = s, \\ -1, & i = t, \\ 0, & i \neq s, t. \end{cases} \\ &x_{ij} \geq 0, \end{aligned} \tag{3}$$

where the decision variable x_{ij} is a 0–1 variable. If $x_{ij} = 1$, the edge (i, j) is on the route s–t; if $x_{ij} = 0$, the edge (i, j) is not on the route s–t.

To solve the above optimization model, lengths have to be assigned to edges firstly. Herein, the edge length was defined as "integrative resistance", referring to hydraulic resistance and economic cost. In view of hydraulic conditions, the flow along a channel is related to slope (Rinaldo et al., 2004), the geometry of a channel and the frictional force (Poulter et al., 2008), which can be seen from the Manning Equation that states flow velocity within an individual open channel (Lin, 2008):

$$v = \frac{1}{n} R^{2/3} i^{1/2}, \tag{4}$$

where v is the mean velocity in section, n is the Manning roughness coefficient, R is the hydraulic radius of the channel, and i is the friction slope, under steady flow conditions, the friction slope is assumed to be equal to bed slope (Chow et al., 1988). According to the "Code for Design of Irrigation and Drainage Engineering" (GB50288-99), the designed channel will surely maintain flow steady, so i refers to bed slope in this paper. It has also been proposed that the optimal river channel network is toward the state of minimum energy dissipation, which is determined by edge length in addition to flow discharge (Paik and Kumar, 2008). Actually this is understandable from the equation as follows:

$$t = l/v = l \times n \times R^{-2/3} \times i^{-1/2}, \tag{5}$$

where t is time period of flow movement along the channel, l is the channel length. The higher the resistance is, the longer the flow moves along the channel, and the more energy dissipation is.

Economic cost mainly comes from two aspects: channel excavation and construction of water control structures. The engineering quantity of channel excavation further relates to channel length and section dimension. Because all newly added channels are assumed to have the same flow rate of 8 m^3/s, the total IFR of the nine target streams (Table 2), they have the same section dimension. Then only channel length determines the economic cost of channel excavation. As for water control structures, according to the "Code for Design of Irrigation and Drainage Engineering" (GB50288-99), water-drawing structures (including water-drawing sluice, desilting sluice, and diversion dike) are to be built at the head of water-transferring channels, thus all designed channels have similar water control structures and relative economic cost. Consequently, the overall economic cost is mainly determined by channel length. In addition, construction of the channel network requires land occupation, which converts agricultural areas to river channels or ecological based habitat, interrupts the original agricultural ecosystems, and further arouse social conflicts. Ecosystem interruption and social conflicts both arouse externalities and indirectly increase the economic cost of this engineering. Externalities can be decreased by reducing engineering quantity; therefore, channel length not only determines the direct engineering cost but also the potential cost produced by externalities.

The "integrative resistance" was then explained as:

$$W = l \times n \times R^{-2/3} \times i^{-1/2}, \tag{6}$$

$$R = \frac{A}{X} = \frac{(b + mh) \times h}{\left(b + 2h\right)\sqrt{1 + m^2}}, \tag{7}$$

where W is the "integrative resistance", A is the cross-sectional area of the channel, X is the wetted perimeter, b is the channel width, and h is the water depth, m is the slope coefficient. Herein connecting two sites with a river channel has to consider length, slope, roughness and geometry. In China, channel slope is generally designed between 1/10,000 and 1/28,000 (Li, 2006), which is small enough to be neglected. In practice, the manning roughness coefficient reflects the roughness of channel sidewalls, and can be simply determined by building materials (Tang et al., 2007); hence, all designed channels are assumed to have the same roughness, because they will be built with the same materials under nearly same geological conditions and similar flow rates. Therefore, the channel roughness can also be neglected. For a rectangular channel, $m = 0$, the hydraulic radius R can be simplified as:

$$R = \frac{A}{X} = \frac{b \times h}{b + 2h} = \frac{b}{\alpha + 2}, \tag{8}$$

$$b = \alpha \times h = \alpha \times \beta \times Q^{1/3}, \tag{9}$$

where α is the ratio of channel width to water depth, β is an empirical coefficient, Q is the flow discharge of channel (m^3/s). According to the "Code for Design of Irrigation and Drainage Engineering" (GB50288-99), $\beta = 0.76$, and when $m = 0$, $\alpha = 2$ is the optimal value. Q is designed as the total water requirements of 8 m^3/s (Table 2). R is then equal to 0.76 after calculation. Because all designed channels have the same hydraulic radius, R can also be neglected. We concluded from the above analysis that, for the integrative resistance W, only channel length l is the significantly effective factor for the basin of Xiaoqinghe River.

This study then defined w_{ij} as the length of edge (i, j), the values of w_{ij} were measured on the digitalized map. For convenience of calculation and description, w_{ij} was classified into six levels; basically one level contained two kilometers for hilly areas and three kilometers for plains (Table 3). The label-setting algorithm was then employed to calculate the least length with the Bellman Formula (Xie and Xing, 2000):

$$\begin{cases} u_s = 0, \\ u_j = \min\limits_{i \neq j}\{u_i + w_{ij}\}, \end{cases} \tag{10}$$

where s is the initial node, and u_j the length of the shortest path between nodes i and j. Based on the calculations, edges with longer length between every pair-nodes, if existed, were considered redundant and thus removed from the designed channel network. Finally, the remaining nodes and edges formed the optimized river channel network.

3.1.3. *Assessing the effectiveness of network linkage*

If a river reach is struggling against drought, the network was expected to effectively divert water from other water bodies to the drying one. Therefore, the functional effectiveness of the artificial river channel network can be assessed by linkage effectiveness. The linkage of various elements within the network can be explained with circuitry and connectivity (Cook, 2002). Connectivity is a measure of the extent to which nodes are connected. This study employed the "gamma index of connectivity", the ratio of the number of links in a network to the maximum number of links possible as given in the following formula (Forman and Godron, 1986; Cook, 2002).

$$\gamma = L/L_{\max} = L/3(V - 2) \quad (V \geq 3, V \in N), \tag{11}$$

where γ is the gamma index of connectivity, L the number of linkages, and V the number of nodes.

Network circuitry is described as the extent to which loops or circuits are present in the network. This study used "alpha index of circuitry", which measures the number of loops present divided by the maximum number of loops possible as in the following formula (Forman and Godron, 1986; Cook, 2002).

$$\alpha = (L - V + 1)/(2V - 5) \quad (V \geq 3, V \in N), \tag{12}$$

where α is the degree of network circuitry.

The indices of α and γ were calculated for analysis of the natural, designed and optimized channel networks, respectively.

Table 2
Calculation of the minimum IFR for tributaries of the Xiaoqinghe River.

Stream	IFR (10^8 m^3)	Flow rate of IFR (m^3/s)	Stream	IFR (10^8 m^3)	Flow rate of IFR[a] (m^3/s)
Lashan	0.129	0.622	Daxinshi	0.132	0.638
Xingji	0.237	1.144	Hancang	0.004	0.019
Gongshang	0.199	0.959	Liugong	0.015	0.073
The Moat	0.110	0.532	Yangjia	0.002	0.011
Xiluo	0.351	1.692	Juye	0.072	0.347
Dongluo	0.122	0.587	Xiujiang	0.099	0.479
Liuhang	0.184	0.889	Luohe	0.071	0.341
Quanfu	0.198	0.953			

[a] Flow rate of the IFR is the IFR divided by time interval of low-flow period.

Table 3
Level of edge weight determined by channel length for plains and hilly areas.

Weight level	Channel length l (km)	
	For plains	For hilly areas
0	Natural channels	
1	$0 < l \leq 3$	$0 < l \leq 2$
2	$3 < l \leq 6$	$2 < l \leq 4$
3	$6 < l \leq 9$	$4 < l \leq 6$
4	$9 < l \leq 12$	$6 < l \leq 8$
5	$12 < l \leq 15$	$8 < l \leq 10$
6	$l > 15$	$l > 10$

Table 4
Exploitable upper-reach reservoirs used as water sources for several streams.

Stream	IFR (10^8 m^3)	Reservoir	Available storage[a] (10^8 m^3)
Yangjia	0.002	Langmaoshan	0.021
Juye	0.072	Duzhang	0.088
Xiujiang	0.099	Dazhan	0.040
		Duozhuang	0.071
Luohe	0.071	Xinglin	0.037

[a] Available storage is the difference between storage at the beginning of the year and storage at the end of the year.

3.2. For high-flow periods

3.2.1. Designing river channel network

Within the basin, XQH River, Xingji Stream, and Xiujiang Stream are particularly vulnerable to flood risks during high-flow periods (Table 1). The designing steps are similar to those for low-flow periods, while the results are different.

Only one artificial channel is available to divert stormwater from the Lashan Stream, Xingji Stream and Xiujiang Stream, respectively. Flood water of the XQH River can be discharged from a number of channels, which were constructed by the full use of lakes and wetlands (Fig 5); they are expected to be put into use simultaneously since only one or two flow paths would be far from being capable to protect from flooding at a safe level. Given the above, we assume that no redundant channels exist in the network and the optimization practice is unnecessary for the designed network of high-flow periods.

3.2.2. Assessing the network flood-relieving effect

The peak discharge risk within a river reach diminishes through retention wetlands, reservoirs, levees, and flood-diverting channels within the designed network. Therefore, we used four variables to represent flood-control capacity as in the following formula:

$$\begin{aligned} E &= C/(P \times 3600t), \\ C &= C_w + C_r + F_l \times 3600t + F_c \times 3600t, \end{aligned} \tag{13}$$

where E is the ratio of flood-control capability to target flood level, representing the flood-control effect of the designed network for high-flow periods, it is a >0 variable, if $E \geq 1$, the network is capable enough to eliminate flood risk completely; t is flood duration, hour; 3600 is a coefficient of unit conversion, an hour is 3600 s; C is the total flood-control capability of the designed network which incorporates all possible flood-protection works, 10^4 m^3; P is the target peak discharge, m^3/s; C_w is the flood storage capacity of retention wetlands, 10^4 m^3; C_r is the flood storage capacity of reservoirs, 10^4 m^3; F_l is the flood-withstand standard of levees, m^3/s; and F_c is flow rate of river channels diverting flood directly to other river reaches, m^3/s.

Notably, P represents the peak discharge of a certain standard of flood, which is projected conforming to the “Chinese National Standard for flood control” (GB50201-94). In this study, the standard of 100-year return period was set for the mainstream segments in the urban districts, and 20-year return period for the other segments of the mainstream and its tributaries.

With reference to the “Feasibility study report on the comprehensive control project of the XQH River, Jinan City” provided by

Table 5
Investigation into water-transferring availability and designed flow path for streams subject to drought risk during low-flow periods.

Stream	Flow path[a]	Water-transferring investigation
Lashan Stream	6–10; 9–10	The Yufu Stream and Wohushan Reservoir are the two available water sources.
Xingji Stream	1–2–5–11; 9–10–11; 6–10–11	Besides the Yufu Stream and Wohushan Reservoir, the Jinxiuchuan Reservoir is another water source, yet the hilly topography and long distance from the reservoir to Xingji Stream frustrate the possibility to connect them directly. The midway Fenshuiling Waterworks, which receives water from the reservoir, can be used as a transfer station.
Gongshang Stream	9–10–11–12; 6–10–11–12	The U-shaped artificial channel receives water from the Xiaoqinghe River. Thus the most economic approach is increasing source flow from the mainstream.
The moat	1–2–5–7	The three streams are fed by springs, indicating two water-transferring ways. One is recharging groundwater as an underlying way; the other is supplying surface water as an immediate way. In detail, water is discharged from the Jinxiuchuan Reservoir, flows through the Xingji Stream till the middle reach, and diverges into two paths. One path is to connect the moat for surface water supplementing. The other is along the Xingji Stream to its lower reach within the high permeability zone, where water leaks to recharge the springs.
Xiluo	(9,13); 6–(10,13); 1–2–5–7–13;	
Dongluo	1–2–5–7–13–14; (9,14); 6–(10,14)	
Liuhang	1–2–4–8–15; 1–3–4–8–15; 1–2–5–7–8–15; (9,15); 6–(10,15)	Water is discharged from the Jinxiuchuan Reservoir, and then diverges into three paths. One is along the Xingji Stream; another is by the Jiangshuiquan Reservoir; the last is by the Mengjia Reservoir.
Quanfu	1–2–4–16; 1–3–4–16; (9,16); 6–(10,16)	The small storage capacity of their own reservoirs (Jiangshuiquan Reservoir and Mengjia Reservoir) is not self-sufficient, so water is extracted from the Jinxiuchuan Reservoir to the two small reservoirs to, in turn, replenish the two streams.
Daxinshi	1–2–4–16–17; 1–3–17; 1–3–4–16–17; 1–2–4–8–15–16–17; 1–2–5–7–8–15–16–17; (9,17); 6–(10,17)	
Hancang	18–19–20–24; 21–22–23–24	The upper-reach reservoirs are too small to supply themselves; besides, under their lower reaches are important groundwater sources. Thus, one way is to divert flow from the Langmaoshan Reservoir to the upper-reach reservoirs to feed the two streams. The other way is to divert flow from the Duzhang Reservoir to the lower reaches to recharge underground water resources. In case of water shortage happening to the Duzhang Reservoir, water is transferred from the Baiyun Lake to replenish it.
Liugong	18–19–23; 21–22–23	
Yangjia	18–22; 28–21–22	The three streams all have large reservoirs or lakes along them for water storage and, if allocating properly, can meet the water demand by themselves without borrowing from other water sources.
Juye	18–21; 28–21	
Luohe	29–30	
Xiujiang	25–26–27; 28–27	Water is discharged from the Dazhan Reservoir and flows along the natural channel to supply for the upper reach; water is diverted from the Baiyun Lake to guarantee the water demands of its lower reaches.

[a] (m, n), the flow path passing through all the continuous nodes of $m, m+1, \ldots, n-1, n$; refer to Fig. 2 for the node numbering.

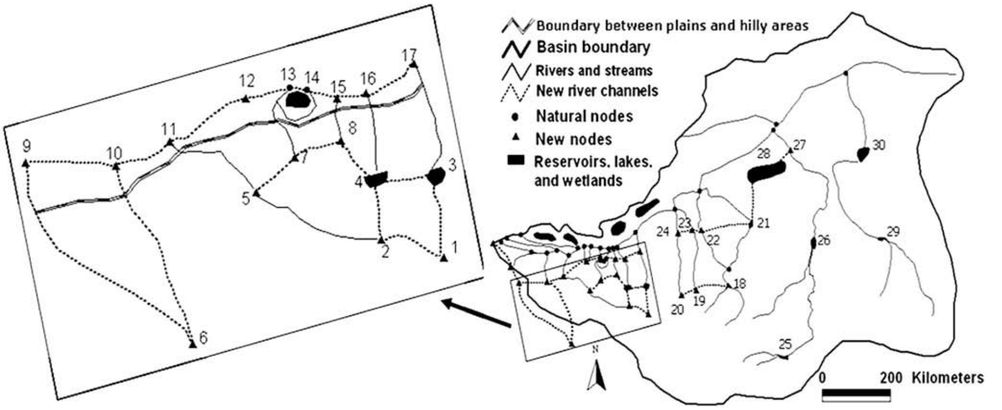

Fig. 2. Designed channel network for low-flow periods (N-dl). The subnetwork in the rectangle is relatively complex and needs to be optimized with the shortest path model. 1) Fenshuiling Waterworks; 2) headwater of Xingji Stream; 5) a turning point on the Xingji Stream; 6) WohushanReservoir; 7) headwater of the moat; 8) headwater of Liuhang Stream; 9) a turning point on the Yufu Stream; 10) headwater of Lashan Stream; 11) another turning point on the Xingji Stream; 12) Fenghuang Sluice on the Gongshang Stream; 13) confluence of Xiluo Stream and the moat; 14) confluence of Dongluo Stream and the moat; 15) a turning point on the Liuhang Stream; 16) a turning point on the Quanfu Stream; 17) a turning point on the Daxinshi Stream; 22) a turning point on the Yangjia Stream; 23) a turning point on the Liugong Stream; 24) a water intake on the Hancang Stream; 27) a water intake on the Xiujiang Stream.

WRBJC, we divided the mainstream into five segments: 1) from the headwater to the Lashan Stream confluence; 2) from the Lashan Stream confluence to the Xingji Stream confluence; 3) from the Xingji Stream confluence to the Daxinshi Stream Confluence; 4) from the Daxinshi Stream Confluence to the Juye Stream confluence; 5) from the Juye Stream confluence to the lower reaches.

4. Results

4.1. For low-flow periods

4.1.1. Designing river channel network

Nine streams were selected as the targets that need water replenishing from the Yellow River basin after calculation of the minimum IFR (Table 2), they are the Lashan Stream, Xingji Stream, Gongshang Stream, the Moat, Xiluo Stream, Dongluo Stream, Liuhang Stream, Quanfu Stream, and Daxinshi Stream. Because the Yangjia Stream, Juye Stream, Xiujiang Stream and Luohe Stream all have reservoirs on their upper reach, and can self-supply their own IFR without water replenishing from out of the basin (Table 4). The other two streams of Hancang and Liugong both have small enough IFR to be neglected (Table 2).

Exploitable water sources and water-transferring scenarios of target streams were then investigated (Table 5). Despite being beyond the study basin, Yufu Stream and its upstream Wohushan Reservoir have been developed as a flow path recharging water into the XQH River. Consequently, the flow path is adopted to replenish flow for most of the tributaries. In particular, Yufu Stream, a perennial stream with plentiful runoff, is an important water source. We laid out a long channel starting from the Yufu Stream, extending east to the Daxinshi Stream.

To articulate the above scenarios with graph theory, we selected nodes and linked them to design a river channel network based on the natural network (Fig. 2). Water-drawing structures (including water-drawing sluice, desilting sluice, and diversion dike) are to be built at all of the nodes except 12, 25, 26, 29, 30.

4.1.2. Optimizing river channel network

According to the original design, almost all tributaries, especially those in the urban districts, have more than one flow path to receive water diverted from other water bodies (Table 5), implicating that some paths with longer length may be redundant. Both the Hancang Stream and Liugong Stream have two flow paths: one is to replenish water for the two above surface streams, the other is to recharge groundwater. Yangjia Stream, Juye Stream and Xiujiang Stream all have two flow paths, of which only one is artificial; and thus none of them is redundant.

Network optimization was performed for the subnetwork in the rectangle in Fig. 2, which is relatively complex (Table 5). The originally proposed river channel subnetwork in Fig. 3 was optimized to a simpler one in Fig. 4.

4.1.3. Assessing the network linkage effectiveness

Using formulas (11) and (12), the indices of α and γ were calculated and compared between natural, designed and optimized

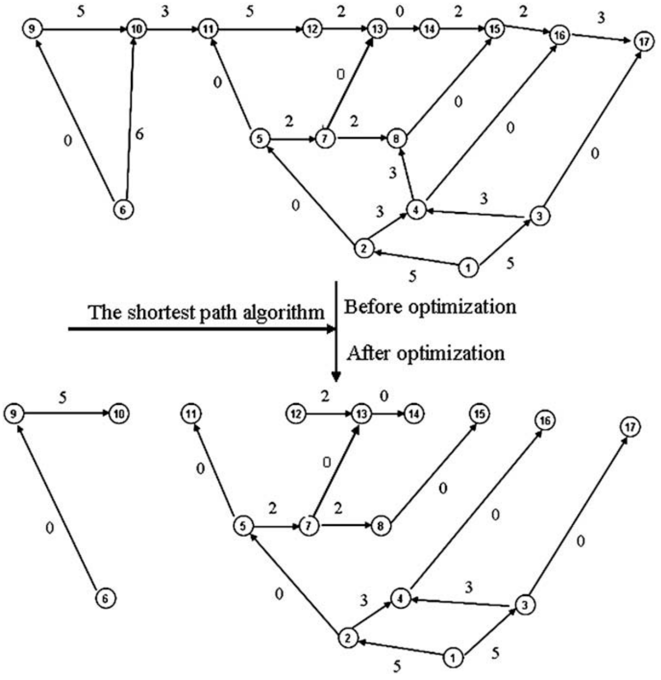

Fig. 3. Optimization of the subnetwork. Edges of (4, 8), (6, 10), (10, 11), (11, 12), (14, 15), (15, 16), (16, 17) were excluded from the originally designed subnetwork using the shortest path model.

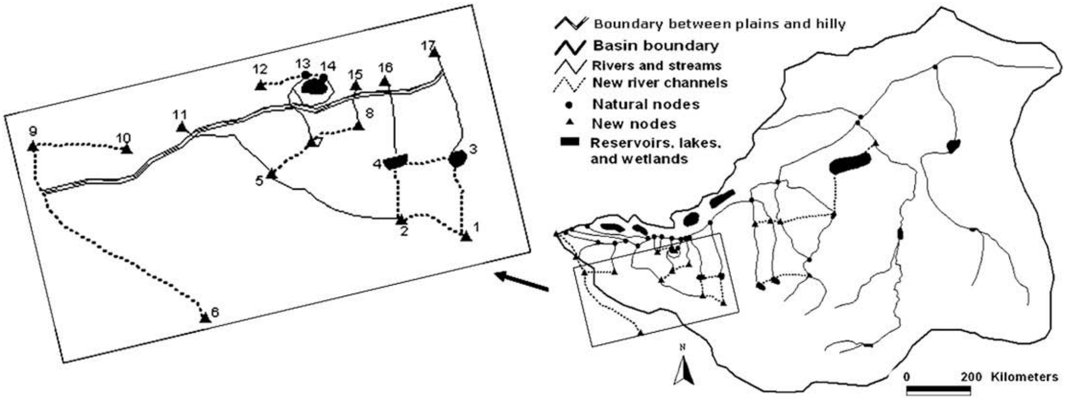

Fig. 4. Optimized channel network for low-flow periods (N-o). N-o contains less nodes and edges than N-dl.

networks for low-flow periods (Table 6). The two indices both rise up in artificial networks, implicating the improved linkage effectiveness.

In N-n, 32 nodes and 37 edges translate into a nearly loopless network with relatively high connectivity. N-dl is characterized by much higher connectivity and circuitry than N-n. N-o is produced by 49 nodes and 68 edges, with α and γ at 0.22 and 0.48 respectively, which are slightly smaller than that of N-dl, resulting from the exclusion of edges and nodes from N-dl by the shortest path model. Compared to N-n, the added 17 nodes and 31 edges of N-o give the intensified connectivity and especially improved circuitry.

4.2. *For high-flow periods*

4.2.1. *Designing river channel network*

Flood-retainable wetlands and reservoirs, and available flood-relieving scenarios were first investigated (Table 7), and then nodes were selected and linked to divert flood from the four river reaches to other waters during high-flow periods (Fig. 5). According to Xiong (2005), sluices are needed to control flow rate at water inlet and outlet of water bodies, in other words, in actual engineering design, sluices are needed at nodes in Fig. 5.

4.2.2. *Assessing the network flood-relieving effect*

Using formula (13), the index of E was calculated for N-dh (Table 8). Results show that the designed network is notably effective to relieve peak discharges for all river reaches imperiled by flood. Flood risk reduces to at least half of its original level, even to zero for the Xiujiang Stream.

At least, half of the possible flood risk shall be calmed (e.g. the Xingji Stream and Segment 3 of the XQH River); even for Xiujiang Stream and Segment 1 of the XQH River, the potential flood risk shall be removed completely.

Table 6
Assessment of network effectiveness by calculating the indices of α and γ for N-n, N-dl and N-o during low-flow periods.

Index	Network		
	N-n	N-dl	N-o
α	0.08	0.27	0.22
γ	0.40	0.52	0.48

5. Discussion

5.1. *Design of networks*

Networks are ubiquitous in the natural and engineered worlds; and it has been realized that commonalities do exist in the structures and dynamics of natural and manmade networks, and structural features modulate network's dynamics (Wan et al., 2008). Based on the theoretic study, one can hope that, a good network design would significantly improve the network dynamic performance by exploiting its topology. Heretofore, however, the graph-theoretic studies (Bu et al., 2002) have largely focus on evaluating the impact of the graph structure on the network performance, and fail to reach the applied research of network design. This study attempts to find a graph-theoretic way to address the general procedure of conducting a network design. Take the low-flow period network for example; its main dynamic performance is to transfer water resources to the tributaries of Xiaoqinghe River, which can be improved by tightening its structural connectedness, just as the transportation networks (Cliff et al., 1979). Similarly, in the communication network engineering, the role played by a network's graph in system design begun to gain attention (Kelly, 2003; Gevros and Crowcroft, 2004), and Wan et al. (2008) also justified that network performance must be shaped/optimized through the use of the network topology.

In low-land basins around the world, raising water levels or infilling channels is an important engineering measure to reduce drought, and has been proved feasible (Querner and van Lanen, 2001). Compared to infilling channels, raising water levels attracts more interests from engineers, and many replenishing engineering are then pointing toward underground recharge by finding appropriate hydrogeologic zone, which rarely involves surface river channel networks (Gates et al., 2008; Myers, 2009). As for the method of infilling channels, the question of selecting surface flow paths is usually randomly and subjectively solved. As in the city of Wuhan, China (Guo et al., 2006) and Taicang, China (Xu et al., 2007), the concept of network has been incorporated into the urban water system plans, yet neither study articulates how to appropriately add new channels. To strengthen the scientific basis of network design, this study used the shortest path algorithm to find the optimal flow path. Generally speaking, the shortest path algorithm can be used to measure not only the length of a path, but also the costs, risks and other properties associated with the path (Smith, 1982). It is hence applicable to a river channel network for finding paths with target optimal properties, and "length" here does not traditionally mean distance, but is created as an integrative property involving

Table 7
Survey of available retention waters and design of flood-relieving scenarios for river reaches subject to flood risk during high-flow periods.

Stream	Retention waters	Flood-relieving investigation
Upper to middle reaches of XQH River	Meili Wetland Yangjuan Wetland Shanghuashan Wetland Xiahuashan Wetland	The four low-land wetlands retain flood, while the left-bank tributaries deliver flood to the Xiaoqinghe River, increasing flood threat to the trunk. Consequently, several channels are to connect the trunk and left-bank tributaries to the four wetlands, then to the Yellow River.
Lower reach of XQH River	Yellow River	Flood water is diverted from the reach to the Yellow River directly.
Xingji Stream	Quanfu Stream	Flood water is diverted from the headwater to the Quanfu Stream, then to the Yellow River
Xiujiang Stream	Duozhuang Reservoir Dazhan Reservoir Baiyun Lake	Flood water is retained by two reservoirs and the Baiyun Lake, and then transferred to the Xiaoqinghe River.

hydrologic and hydraulic, engineering and economic conditions, which is specifically applicable to hydrologic systems.

To mitigate flood risk, such hard engineering as construction of levees, straightening of channels, place of cement revetment are traditional and still predominant measures in China, however, their adverse effects on hydrological, ecological and economic conditions have largely been realized and alternative interventions with minimized effects are recommended (Brouwer and van Ek, 2004; All, 2005). The network design for high-flow periods in this study, points toward exploiting retention wetlands instead of implementing hard engineering to relieve flood risk. Wetlands can provide the services of water storage and peak-flow attenuation for stormwater treatment (Ogawa and Male, 1986; DeLaney, 1995), and enhanced stormwater treatment wetlands exist where ecological and treatment objectives are simultaneously met (Knight, 1996; Otto et al., 2001). The flood treatment measures in this study not only make use of wetlands but also organize them in a network within the whole basin, which attempts to maintain the continuity and integrity of a hydrologic system. Early in 1980s, the concept of river continuum has been addressed (Vannote et al., 1980; Naiman et al., 1987); yet traditional piecemeal flood treatment has led to disappearance of natural hydrologic convergence (Ogawa and Male, 1986). Cohen and Brown (2007) found that the basin-scale planning of stormwater collection and treatment systems using hierarchical wetland-river networks can permit annual retention improvements of 31%.

5.2. Assessment of networks

As is known to all, river networks are among nature's most common fractal patterns (Yan et al., 2008), and as an open dissipative system, the river network naturally evolves into Spanning, loopless configurations characterized by minimum energy dissipation (Banavar et al., 2001; Paik and Kumar, 2008). For the networks of low-flow periods, however, N-n is a nearly loopless network, while N-dl and N-o are both characterized with much intensified connectivity and especially improved circuitry, indicating that the original river network basically maintains its natural status, but the artificial networks seem deviate from the evolving laws of natural river networks. It is true, after understanding that the network design for low-flow periods is to satisfy not natural laws but the functional objective of water conveyance. Rinaldo et al. (2004) also argues that the absolutely optimal river network structure is realistic only under precise physical requirements. This suggests that other branching structures occurring in nature (e.g. looping) may possibly arise through optimality to selective pressures. Herein, under the pressure of water redistribution, the designed network is more like a transportation network than a hydrologic one. According to Cliff et al. (1979), transportation networks whose vertices are all highly interlinked are likely to display wheel-lie graphs rather than tree-like graphs or chin-like ones. On the other hand, the parameters of γ and α increase with values as the graph becomes more interconnected. Therefore, the network design for low-flow periods achieves its goal under the law of water conveyance.

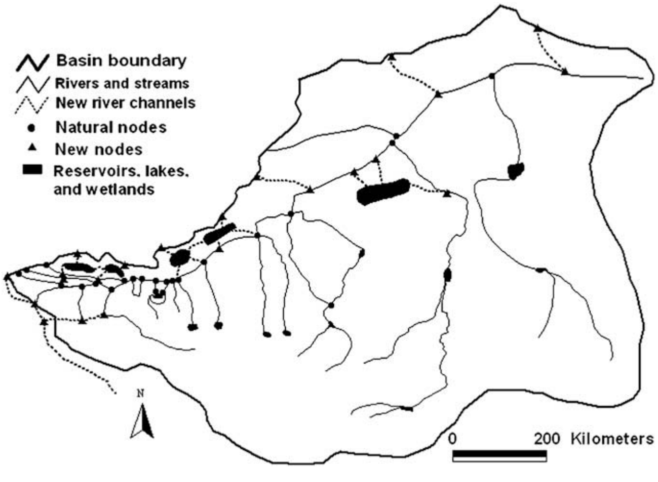

Fig. 5. Designed channel network for high-flow periods (N-dh).

Although the above parameters have specific structural meanings, they frequently take on the same value for graphs with very different topological properties (Cliff et al., 1979). This suggests a possibility that, some nods and edges might be removed from a network, but relevant structural parameters still keep unchanged or change slightly. In this study, N-dl was simplified to N-o by optimization with 4 nodes and 7 edges removed, reduced by 13% and 15%, respectively; while the connectivity and circuitry changed slightly. Hence, the optimization procedure not only reduces redundant edges and nodes but also maintains the network function.

The success of drought mitigation is determined not only by the connectedness of water flow paths but also by the flow rate they convey. To make sure that each target stream can be met with IFR, we assigned the flow rate of 8 m^3/s (total sum of IFR for all streams) to each artificial channel, because it needs to transfer water to a couple of target streams but not the specific one.

To analyze the effectiveness of N-dh is to assess its ability to balance flood-relief capacity and projected flood level. The capacity is gained by the flood-protection level of levees and flood storage capacity within the whole basin (Wu and Tang, 2007). Results show that the flood-relieving function of N-dh is evident. Notably, the flood-control capacity for XQH River predominantly result from existing levees, which still work even without the network; while for the Xingji Stream and Xiujiang Stream, the flood-control capacity come from wetlands, reservoirs and channels, which cannot work without the design. It can then be concluded that, the

Table 8
Assessment of flood-relieving effect of the designed network for high-flow periods by calculating *E*, the ratio of total flood-control capability (*C*) to peak discharge of projected flood level (*P*).

		C_w (10^4 m^3)	C_r (10^4 m^3)	F_l (m^3/s)	F_c (m^3/s)	C (10^4 m^3)	t (h)	P (m^3/s)	E
XQH River	1	600	0	51	0	1921.9	72	70	1.06
	2	450	0	209	0	5867.3	72	345	0.66
	3	324	0	343	0	9214.6	72	669	0.53
	4	585	0	523	0	14,141.2	72	771	0.71
	5	0	0	703	150	22,109.8	72	1030	0.83
Xingji Stream		0	0	0	200	1728	24	387	0.52
Xiujiang Stream		2700	2055	0	0	4755	24	330	1.67

Data of F_l, P and t come from "Feasibility study report on the comprehensive control project of the Xiaoqinghe River, Jinan City"; Data of F_c was estimated referring to the flow of left-bank tributaries of Xiaoqinghe River.

design is more effective for the tributaries than that for the mainstream. Reason for this is that the designed network is built up with both natural waters (wetlands and river reaches), and artificial structures (reservoirs and levees). The design is hence not a completely natural restoration work but an attempt to avoid further adverse interventions on the environment. In fact, the combination of natural waters and artificial structures has gained prevalent acceptance in urban stormwater management, such as best management practices (Bäckström et al., 2002; Marsalek and Chocat, 2002; Wang et al., 2006a,b).

5.3. Management implications

This network design is meant to restore ecological regimes of the target natural streams by recharging them with ecologically based flows, and combine nature-like look and ecological process into artificial channels by paving the revetment with vegetation and natural materials instead of absolutely hard materials. Just as other restoration engineering, this design will produce great positive ecological and environmental benefits: fish repopulation, water purification, waterfront greening, and nutrient transportation (Yang, 2005; Nagayama et al., 2008). Nevertheless, the ecologically based engineering may cause the opposite problem as well: negative effects of reestablished ecological processes on socioeconomic land uses (Buckley and Crone, 2008), such as converting agricultural areas to river channels or habit for native plants will not only interrupt the original agricultural ecosystems but also arouse negative attitudes and defensive actions of surrounding landowners. The social conflict will impede our ecological engineering from achieving its goal, and also reduce ecological benefits in economics (Armsworth et al., 2006). In economics, the concept of externalities is used to describe the effects of activities on individuals not directly involved in those activities. The negative effect of our ecological engineering on local landowners is such a typical example. Consequently, we figured out several technical and management measures to incorporate social conditions and conflict resolution into this network design to promote favorable ecological and social compatibility. When the negative social effects generated by ecological engineering are also undesirable to ecologists, the negative externalities are considered indirect, when the effects are generated by intended ecological activities, the negative externalities are considered direct (Buckley and Crone, 2008). In the network design for low-flow periods, flood is a potential risk to local landowners, but flood is not the goal of our design though it may exist after artificial channels are constructed, thus flood is considered the most significant indirect negative externalities. We recommend ecological revetment instead of hard materials built along artificial channels, because ecological revetment is more effective and sustainable for flood control (Chen et al., 2007). Direct negative externalities are more difficult to resolve than indirect (Buckley and Crone, 2008). The construction of artificial channels will have to occupy agricultural areas and cause economic lost to local farmers. To resolve the direct externalities, implementing social–ecological interactions is the first step, community participation is required, such as distributing surveys to farmers to judge their satisfaction to the engineering and seek suggestions, clearly presenting overall outcomes including benefits and uncertainties to local farmers. Only in this way, a stable outcome is likely to come out, and other researchers also point out the importance of social–ecological cooperation (Higgs, 1997; Folke, 2007). Internalization and compensation is the second step, local government agencies or management board for the engineering purchase farmland from willing sellers, and pay them fair market price. If they like, local farmers can also be employed as labors in the ecological activities to increase their income. In China, direct money compensation or grain subsidy for relevant residents is a general strategy (Luo, 2009).

In addition, river has conventionally been managed within administrative rather than natural boundaries, in a fragmented rather than holistic manner (Gourbesville, 2008). As a consequence, boundary rivers are unregulated or managed under rules that differ from one to another political jurisdiction. The design of river channel network in this paper adopts river basin at the management scale, which corresponds to natural ecosystem processes (Blackmore, 1995). As argued by Schmandt (2006), an integrated basin management can serve four goals: provide an adequate supply of water for natural and human uses, maintain and improve water quality, restore biodiversity, and support regional sustainable economic development. None of these goals has been achieved by the current management plans for the XQH River basin. The first goal, to which endeavors in this study are dedicated, is even hindered by the lack of scientific understanding of instream conditions. Hence, for the XQH River basin, a proper monitoring protocol on hydrological, ecological, and physical conditions needs to be devised as soon as possible.

6. Conclusion

We applied graph theory to a channel network methodology to design and identify major flow paths that provide unique management opportunities. Our approach represents a close-to nature and cost-effective method for designing large river channel networks. However, the designed river channel network in this study is implemented in a transportation-oriented manner and permits relatively large engineering quantity, it is better to be applied to basins in simple terrains with homogenous hierarchy of stream networks and regular network structure, such as, artificial system of irrigation ditches.

To find the optimal flow path, we consider hydraulic and economic properties of a path conceptually, but only channel length is involved practically, because the objective of this paper is network design but not channel design. Nevertheless, this optimization procedure can be better applied to river basins where the topography, such as slope, elevation, and distance, is detailed by digital elevation models, and necessary hydrological data are available. The shortest path algorithm we have used to optimize network links can also be modified to select or design other fluvial routes if the length of the shortest path algorithm is designed in a multi-category and numerically based manner. For example, it can be used to identify major underground flow paths or pollutant removal path, if the length involves geological conditions or environmental capacity or other integrative properties.

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