Evaluation of river connectivity based on TOPSIS model: Taking the North District Expansion Zone of Zhangjiagang Economic Development Zone in Jiangsu Province as an Example

Genting Yu 1*, Haibo Xu1, Aiju You1, Keke Hu1, Lin Hu1
1 Zhejiang institute of hydraulics & estuary, Hangzhou, Zhejiang, 310020, China
*Corresponding author’s e-mail: 15990141324@163.com

Abstract. The river system connectivity has become an important indicator of current river health assessment. The proper connectivity of river systems has the functions of allocating resources, improving water and soil environment, and preventing floods and droughts. However, it will be affected by many factors. In this paper, take Zhangjiagang, Jiangsu Province as an example, the influence degree of the structural connectivity index (expressed as static indicators) and hydroconnectivity index (expressed as static and dynamic indicators) on the connectivity of river flow system is analyzed based on the TOPSIS model. The study finds that the order of influence of each index on the connectivity of water system in the study area is: The structure connectivity index ($\alpha$, $\gamma$) is greater than hydrological connectivity index ($R_b$, $W_p$, $R_d$, $E_p$, $C_EN$), and the Closeness $Tj=(0.546, 0.546, 0.471, 0.479, 0.506, 0.519, 0.463).$ when analyzing the regional scale, we should consider the local conditions and consider comprehensively from the perspectives of structural connectivity and hydrological connectivity. The results of the study hope to provide theoretical basis for water system planning and management.

1. Introduction
With the deterioration of water resource environment, river health and comprehensive river basin management have been attached great importance. As an important indicator of river health evaluation and improvement of water resource utilization, water system connectivity has been highlighted in the national "12th five-year" strategic plan [1-2], indicating that water system connectivity has been promoted to the strategic level of national river management. Since Amoros and Roux[3] put forward the concept of water system connectivity in 1988, scholars have conducted in-depth studies on water system connectivity through multi-dimensions (meaning [4], landscape [5], hydrology [6], ecology [7], etc.). For example, Urban and Keitt[8], based on graph theory, have proved that the minimum spanning tree can be used as a powerful guide to determine the overall landscape connectivity, that is, in a large network system, the persistence of the system can be guaranteed by protecting the minimum spanning tree. J Xia et al. [9] believed that water system connectivity refers to the degree to which water flows and related substances can guarantee or enhance specific kinetic energy effects through one or more connecting channels. J H Xia et al. [10] believed that water system is a four-dimensional natural ecosystem of space and time, and its connectivity mechanism is mainly manifested as longitudinal, horizontal and vertical connectivity and dynamic in time, which extends the connectivity...
concept to the riparian zone and the transformation of surface water and groundwater. J Y Zhao et al. [11] applied the connectivity concept in graph theory to the connectivity evaluation of river-beach area system, and quantified the connectivity analysis of river-beach area system. X Y Meng et al. [12] used the connectivity evaluation of transportation network for reference, and took the index of $\gamma$ measurement in graph theory as an important index to measure the connectivity of water system. The fragility of water systems makes the water connectivity of these tree-like networks easy to be cut off by common infrastructure (such as dams, culverts) [13], and through restricting movement hindering the propagation, masking and diffusion of river biota [14], and showing significant differences in the pan-regional scale of river and lake water systems [15-16]. Obviously, the above research is lack of the key factors affecting water system connectivity evaluation, this paper will be based on TOPSIS model, taking the North District Expansion Zone of Zhangjiagang Economic Development Zone in Jiangsu Province as an Example, through the fusion of predecessors' research results, the indexes that affect the connectivity of water system are introduced and the influence degree is evaluated, so as to provide theoretical basis for the realization of multi-source complementarity, abundance and depletion regulation and later management of water resources.

2. Quantitative index of water system connectivity

2.1. Quantitative indicators of structural connectivity

The structural indicators of water system connectivity are expressed by network coefficient $\alpha$ and associativity $\gamma$, which are based on the basic elements of graph theory and quantified from the perspective of geographical structure connectivity.

(1) the network coefficient $\alpha$ reflect the actual ring formation level of river network system, which is represented by the ratio of the actual number of loops to the maximum possible number of loops [17].

$$\alpha = \frac{M - V + 1}{2V - 5}$$  \hspace{1cm} (1)

Where, $M$ is the number of edges of the river network; $V$ is the number of vertices of the river network. $\alpha$ is between 0 and 1, the larger the value is, the larger the number of drainage loops is, and the flow path variability is the highest when $\alpha$ is equal to 1.

(2) The associativity $\gamma$ represent the ratio of the actual number of edges the river network to its possible maximum number of edges [17].

$$\gamma = \frac{M}{3(V - 2)}$$  \hspace{1cm} (2)

Where, $M$ is the number of edges of the river network; $V$ is the number of vertices of the river network.

2.2. Quantitative indicators of hydrological connectivity

The connectivity of water system is not only influenced by the geographical structure but also by the hydrological process. Ambroise[18] proposed the concept of active river network in 2010, which refers to the river network at the outlet section of the basin where the part of runoff due to the hydrologic process or the connection of the outlet of the stream network is not smooth, and the hydrologic connectivity is expressed as the ratio of the active number of sides $B_1$ to the total number of $B_2$, $\frac{C_{EN}}{B_1/B_2}$. P L Li et al. [19], X Y Meng et al. [12] on the basis of urban water system, starting from the driving factors and the effect of hydraulic of drainage connected, increase the content of the hydrological connectivity evaluation, including the river network density $R_d$, surface water region ratio $W_p$, number of rivers per square kilometer $R_0$ and water flow potential $E_p$ etc, which effectively solves the drainage connected degree of comparability between different regional scale problems.

(1) The $R_d$ refers to the ratio of total length of trunk and tributary to drainage area, which to some extent reflects the influence of local precipitation, elevation drop and soil permeability on drainage development and density [27].
\[ R_p = \sum_{i=1}^{N} L_i / A \]  
(3)

Where, \( L_i \) is the length of channel \( i \), km; \( A \) is the area of the study area, km\(^2\).

(2) The \( W_p \) represents the proportion of surface water area under the average water level for years to the total area of the region, and corrects the width of river network density [19].

\[ W_p = A_w / A \]  
(4)

Where, \( A_w \) is the regional water surface area under the average water level for many years, km\(^2\).

(3) The \( R_b \) represents the number of rivers per unit area, which to some extent reflects the development status of rivers and is an important indicator parameter for the formation of tree-like network [19].

\[ R_b = s / A \]  
(5)

Where, \( s \) is the number of rivers in the region.

(4) The \( E_p \) is influenced by the channel profile, riverbed slope and the change of profile along the channel. The basic driving factors affecting water flow and its strength are introduced [12].

\[ E_p = \frac{\rho g \sum h (h_{\text{up}} - h_{\text{down}}) A}{2A} \]  
(6)

Where, \( \rho \) is the density of water, kg·m\(^{-3}\); \( g \) is the acceleration of gravity, m·s\(^{-2}\); \( h \) is the average water depth of the river reach, m; \( h_{\text{up}} \) and \( h_{\text{down}} \) are the water level at the inlet and outlet of river reach, m; \( A \) is the surface area of the river reach, km\(^2\); \( A \) is the area of the study area, km\(^2\).

It was found in the above study that scholars only compared the connectivity index parameters under different conditions, but did not find the key influencing factors of water system connectivity. This paper will make a detailed evaluation of water system connectivity under structural (static) and hydrological (static and dynamic) conditions based on TOPSIS model.

### 3. Evaluation method based on TOPSIS model

TOPSIS model is based on the setting of the most preferred and least preferred schemes, to judge multiple indicators in the decision matrix and their distances, so as to evaluate the strengths and weaknesses of each scheme. Let \( Y^* \) is the preferred scenario, that is, the maximum value of the \( j \) index in the evaluation data in the \( i \) region, which is called the positive ideal solution. \( Y^- \) is the least preferred scenario, that is, the minimum value of the \( j \) index in the evaluation data in the \( i \) region, which is called the negative ideal solution. The calculation method is as follows [21]:

\[ Y^* = \left\{ \max_{j \in \text{region}} y_{ij} \right\} \quad i = 1, 2, \ldots, m \]  
(7)

\[ Y^- = \left\{ \min_{j \in \text{region}} y_{ij} \right\} \quad i = 1, 2, \ldots, m \]  
(8)

Distance is calculated using Euclidean metric, as follows:

\[ D_j^+ = \sqrt{\sum_{i=1}^{m} (y_{ij}^* - y_{ij})^2} \]  
(9)

\[ D_j^- = \sqrt{\sum_{i=1}^{m} (y_{ij}^+ - y_{ij})^2} \]  
(10)

Where, \( y_{ij} \) is the weighted normalized value of the \( j \) index to the \( i \) region; \( D_j^+ \) (or \( D_j^- \)) are the distances between the \( j \) index and \( y_{ij}^+ \) (or \( y_{ij}^- \)); \( y_{ij}^+ \) and \( y_{ij}^- \) are the values of the most preferred scenario and least preferred scenario of the \( j \) indicator in all regions, respectively.

Proximity degree \( T_j \) is used to reflect the response degree of each index to different regions, and its value is between 0 and 1. With the increase of \( T_j \), the response degree of a certain index to connectivity increases. Here, the proximity degree can be used to study the response degree of structural connectivity index and hydrological connectivity index to the connectivity of river network, and determine the order of advantages and disadvantages. The calculation formula is as follows:
\[ T_j = \frac{D_j^+}{D_j^++D_j^-} \]  \hspace{1cm} (11)

4. Instance and analysis

Take Zhangjiagang economic development zone in Jiangsu province as an example. It is located in the south bank of the lower reaches of the Yangtze river and belongs to the plain area. On the basis of the status quo of water system, combined with network, water system planning and topography in the study area, it can be divided into three planning area, corresponding to the Da Xin, Yang She and Jin Feng, respectively. The regional data were shown in the table 1 (the data from the detailed planning of the Zhangjiagang city river and reference [19]), the partition map were in the references [19].

| Study area     | Hydrological connectivity index | Hydrological connectivity index |
|----------------|---------------------------------|---------------------------------|
|                | River network density \( R_d \) (km·km\(^{-2}\)) | Surface water region ratio \( W_p \) (%) | Number of rivers per square kilometer \( R_b \) | Water flow potential \( E_p \) | Active river network indicator \( C_{EN} \) | the network coefficient \( \alpha \) | The associativity \( \gamma \) |
| I-Da Xin       | 2.07 | 5.38 | 1.237 | 2.05 | 0.103 | 0.286 | 0.537 |
| II-Yang She    | 1.768 | 4.151 | 1.857 | 1.46 | 0.178 | 0.353 | 0.577 |
| III-Jin Feng   | 2.566 | 6.672 | 2.566 | 1.22 | 0.264 | 0.268 | 0.524 |

4.1. Calculation based on TOPSIS model

When the model is calculated, the data should be trended in the same way. It's usually a matter of turning low index into high index (the method \( X_j' = 1/X_j \) is commonly used for the transformation from low to high), and then the data with the same trend are normalized to obtain the normalized matrix \( f_{ij} \), and carried out the positive ideal solutions \( f_{ij_{max}} \), negative ideal solutions \( f_{ij_{min}} \), \( D_j^+ \) and \( D_j^- \). Finally, the proximity degree \( T_j \) is calculated as follows, and the results are shown in table 2.

\[ f_{ij} = X_j' / \left( \sum_{i=1}^{m} (X_j')^2 \right) \]  \hspace{1cm} (12)

\[ D_j^+ = \sqrt{\sum_{i=1}^{m} (f_{ij} - f_{ij_{max}})^2} \]  \hspace{1cm} (13)

\[ D_j^- = \sqrt{\sum_{i=1}^{m} (f_{ij} - f_{ij_{min}})^2} \]  \hspace{1cm} (14)

| indicators | The initial value | \( f_{ij} \) | \( f_{ij_{max}} \) | \( f_{ij_{min}} \) | \( D_j^+ \) | \( D_j^- \) | \( T_j \) |
|------------|------------------|----------------|---------------------|---------------------|----------------|----------------|----------------|
| \( R_d \) (km·km\(^{-2}\)) | 2.07 | 1.77 | 2.57 | 0.58 | 0.67 | 0.46 | 0.67 | 0.46 | 0.23 | 0.24 | 0.506 |
| \( W_p \) (%) | 5.38 | 4.15 | 6.67 | 0.55 | 0.71 | 0.44 | 0.71 | 0.44 | 0.31 | 0.29 | 0.479 |
| \( R_b \) | 1.24 | 1.86 | 2.57 | 0.77 | 0.51 | 0.37 | 0.77 | 0.37 | 0.48 | 0.42 | 0.471 |
| \( E_p \) | 2.05 | 1.46 | 1.22 | 0.42 | 0.58 | 0.7 | 0.7 | 0.42 | 0.31 | 0.33 | 0.519 |
| \( C_{EN} \) | 0.1 | 0.18 | 0.26 | 0.82 | 0.48 | 0.32 | 0.82 | 0.32 | 0.6 | 0.52 | 0.463 |
| \( \alpha \) | 0.286 | 0.353 | 0.27 | 0.6 | 0.48 | 0.64 | 0.64 | 0.48 | 0.16 | 0.19 | 0.546 |
| \( \gamma \) | 0.54 | 0.58 | 0.52 | 0.59 | 0.54 | 0.6 | 0.6 | 0.54 | 0.06 | 0.07 | 0.546 |
4.2. Evaluation of influencing factors

As can be seen from table 2, the closeness of $R_d$, $W_p$, $R_b$, $E_p$, $C_{EN}$, $\alpha$ and $\gamma$ to water system connectivity is 0.506, 0.479, 0.471, 0.519, 0.546, 0.546, respectively. Draw the spider chart shown in figure 1, it can intuitively see close to the degree of response of index. The seven indexes can be obtained on the response of the water system connectivity and order: the structure connectivity index ($\alpha$ and $\gamma$) is greater than hydrological connectivity index ($R_d$, $W_p$, $R_b$, $E_p$, $C_{EN}$). This is in line with the current stage, on the basis of the newly opened river, the connectivity of water system is also increased by increasing surface water region ratio and flow regulation.

By calculating the average proximity degree of the two types of indicators, it is found that the response degree of structural connectivity index to water system connectivity is 52.82%, and that of hydrological connectivity index to water system connectivity is 47.18%, the coefficient of variation of the average proximity degree of the two indexes to water system connectivity was only 5.64%. For the regional scale of river network, the variation amplitude is very small. Therefore, in the evaluation of water system connectivity, it is necessary to consider both structural connectivity index and hydrological connectivity index. In other words, the connectivity of water system can be expressed as $C=k_1D+k_2H$, where, $D$ is the static structural index ($\alpha$ and $\gamma$); $H$ includes static indicators ($R_d$, $W_p$, $R_b$, etc.) and dynamic indicators ($E_p$, $C_{EN}$, etc.).

5. Conclusion and prospect

Connectivity of water system is an important way to improve the allocation capacity of water resources. Since the concept of connectivity was put forward, connectivity of water system has been highly valued and become a strategy for water control under the new situation. Water system connectivity is affected by a variety of factors. The analysis by TOPSIS model shows that the order of influence of each index on water system connectivity is that the structural connectivity index ($\alpha$, $\gamma$) is greater than hydrological connectivity index ($R_d$, $W_p$, $R_b$, $E_p$, $C_{EN}$). This is consistent with the improvement of water system connectivity by increasing the index of structural connectivity through newly opened river, However, the coefficient of variation of the effect of the two indicators on the connectivity of water system is small, so when considering the regional scale, it is necessary to take into comprehensive consideration from the perspectives of structural connectivity (static) and

![Fig1. Closeness of each indicator to water system connectivity](image-url)
hydrological connectivity (static and dynamic). This is in line with the current stage, on the basis of the newly opened river, the connectivity of water system is also increased by increasing surface water region ratio and flow regulation.

At present, the research on the connectivity theory of water system in China has made a great step forward, and a series of two-dimensional wide space quantitative evaluation systems have been proposed from the macro scale, but there is no relevant research on the connectivity of natural ecosystem of river network on the micro scale, so there are still some challenges in applying the theory to the planning and management of river network. The evaluation of water system connectivity is a complicated subject. We analyzes the influence degree of quantitative index of water system connectivity in the study area, which provides a strong guiding significance for a better and comprehensive exploration of leading factors of water system connectivity. In the follow-up studies of different regions, it is still necessary to take into account water system connectivity in a comprehensive way according to local conditions, such as connectivity of time span, horizontal and vertical connectivity of river ecosystem.

Acknowledgments
This study was funded by the National Natural Science Foundation of China (NSFC) (Granted No. 51709237), the Water Resources Science and Technology Project of Zhejiang Province, China (Granted No. RA1905 and 2018F10028), We are grateful for the working environment provided by the Zhejiang institute of hydraulics & estuary, and as well as the patient guidance of professor Jihong Xia, Hohai University.

References
[1] QIAN Y.C., HE P.(2009) Research of profit distributing of general contractor and subcontractor dynamic alliances based incentive contract. Yangtze river, 40: 40-42
[2] XIANG T.Y., ZHANG N.(2017) Water resources allocation and environmental management in small watershed based on ecological water demand. Yangtze river,S2.
[3] Amoros C., Roux A.L.(1988) Interaction between water bodies within the floodplain of large rivers: function and development of connectivity. Munstersche Geographische Arbeiten,29:125-130.
[4] Pringle C.M.(2003) What is hydrologic connectivity and why is it ecologically important?. Hydrological Processes,17:2685-2689.
[5] SI H., XU Y.N.(2011) Research on planning method of urban green space core region based on landscape connectivity. Journal of Nanjing Forestry University(Natural Sciences Edition),35:51-56.
[6] Freeman, MC, Pringle, et al.(2007) Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. J AM WATER RESOUR ASSOC, 43:5-14.
[7] XIANG Y., WEI A.L., RU T., et al.(2015) Rivers System Connection and Regional Ecological and Environmental Impacts in China. China population resources and environment, s1:139-142.
[8] Urban D., Keitt T.(2001)Landscape connectivity: a graph-theoretic perspective. Ecology, 82:1205-1218.
[9] XIA J., GAO Y., ZUO Q.T., et al.(2012) Characteristics of Interconnected Rivers System and Its Ecological Effects on Water Environment. Progress in geography,10:26-31.
[10] XIA J.H., CHEN Y.M., ZHOU Z.Y., et al.(2017) Review of mechanism and quantifying methods of river system connectivity. Advances in Water Science, 28:780-787.
[11] ZHAO J.Y., DONG Z.R., ZHAI Z.L., et al.(2011) Evaluation method for river floodplain system connectivity based on graph theory. Journal of Hydraulic Engineering, 39:537-543.
[12] MENG X.Y., CHEN X., CHEN D.Y., et al.(2014) Evaluation system of urban water system connectivity. Journal of Hohai University(Natural Sciences), 42:24-28.
[13] Fullerton A. H., Burnett K.M., Steel E.A., et al.(2010) Hydrological connectivity for riverine fish: measurement challenges and research opportunities. Freshwater Biology, 55:2215-2237.
[14] Jungwirth M., Muhar S., Schmutz S.(2000) Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. Hydrobiologia, 422-423:85-97.
[15] LI Y.Y., LI J.Q., LI Z.L., et al.(2011) Issues and Challenges for the Study of the Interconnected River System Network. Resources Science, 33:386-391.
[16] Poulter B., Goodall J. L., Halpin P.N.(2008) Applications of network analysis for adaptive management of artificial drainage systems in landscapes vulnerable to sea level rise. Journal of Hydrology, 357: 207-217.
[17] XU G.L., XU Y.P., WANG L.Y.(2012) Evaluation of river network connectivity based on hydraulic resistance and graph theory. Advances in Water Science, 23:776-781.
[18] Ambroise B.(2010) Variable ‘active’ versus ‘contributing’ areas or periods: a necessary distinction. Hydrological Processes, 18:1149-1155.
[19] LI P.L., CHEN J., SUN B.X., et al. (2018) Research on Urban Water System Planning Based on Connectivity. Yellow River, 40:31-35.
[20] RUI X.F.(2004) Principle of hydraulics. China WaterPower Press, Beijing.
[21] LEI X.P., QIU G.H.(2016) Empirical study about the carrying capacity evaluation of regional resources and environment based on entropy-weight TOPSIS model. Acta Scientiae Circumstantiae, 36:314-323.