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A New Approach for the Health Assessment of River Systems Based on Interconnected Water System Networks

ZHAO Junkai[1,3], LI Lixian[1], ZHANG Aishe[1], LI Jiufa[2,*], GUO Qiuxia[1]

1. College of Tourism and Territorial Resources, Jiujiang Key Laboratory of Surveying and Maping on Land 3S Technology Application, Jiujiang University, Jiujiang, jiangxi 332005, China;
2.Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China;
3. Jiujiang Key Laboratory of Basin Management and Ecological Protection, Jiujiang, jiangxi 332005, China

Abstract: Interconnected river system networks is a national water conservancy strategy in China and focus of research. Here we discuss the classification system, material and energy exchange between rivers and lakes, various dynamic flows and ecological functions of river-lake interconnected relationships. We then propose a novel method for the health assessment of river systems based on interconnected water system networks. In a healthy river system there is “material and energy exchange” and it is the first and foremost relationship of material and energy exchange between rivers and lakes. There are unobstructed various “flows” between rivers and lakes including material flows (water, dissolved substances, sediments, organisms and contaminants), energy flows (water levels, flow and flow velocity), information flows (information generated with water flows, organisms and human activities) and value flows (shipping, power generation, drinking and irrigation). Under the influences of nature and human activity, various flows are connected by river-lake interconnection to carry material and energy exchange between rivers and lakes to achieve river-lake interactions. The material and energy exchange between rivers and lakes become one of the approaches and the direct driving forces of changes in river-lake interconnected relationships. The benignant changes in river-lake interconnected relationship tend to be in relatively steady state and in ideal dynamic balance.

Key words: interconnected water system network; classification system; material and energy exchange; ecological function; health assessment of river system; river-lake system

1 Introduction

Climate change and human activities affect water cycles and water resource transformation (Wang *et al.* 2016; Devkota and Gyawali 2015), seriously affect the health of river systems and are of increasing interest to the public (Wang *et al.* 2010; Deng *et al.* 2015). River drainage is an important part of the land water cycle system, is the main carrier of water resource formation and transformation, and is an important constituent element of ecology and the natural environment. River-communicating lakes within the river-lake system are natural reservoirs and have complex hydraulic connections. Lakes linking to rivers play the role of connector, converter and water accumulator (Wang *et al.* 2011). Relationships between rivers and lakes are very closely within the water system network, and changes and adjustments in these relationships are momentous factors in maintaining healthy rivers and healthy relationships between rivers and lakes. Therefore, it is of crucial significance to understand river-lake interconnected relationships, comprehend a classification system, and study the assessment methods of river system health.

2 The river-lake interconnected relationship

Different water bodies are interconnected by open channels, undercurrent, culverts and various pore channels are collec-

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*__Corresponding author:__ LI Jiufa, Email: jfli@re.ecnu.edu.cn

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tively termed water-area-interconnections. For example, the interconnection between two seas (Bering Strait, Malacca Strait, Strait of Gibraltar, the Suez Canal, Panama Canal and Kiel canal), rivers and lakes, streams and rivers, between rivers and oceans and lakes and rivers all belong to water-area-interconnections. The river-lake interconnected system is a compound type. As the interconnected water system network discussed in this paper, it includes the interconnected relationship between rivers and lakes, streams and rivers, and lakes and loughs.

Many river-lake interconnected projects have been constructed. Examples in China include the Dujiangyan Irrigation Project, Zhengguo Canal and Lingqu Canal more than 2000 years ago. The Beijing-Hangzhou Grand Canal in China was the longest and earliest canal and it was the largest engineering project globally (Hangou Canal begun construction in 486 B.C.). The North-to-South Water Diversion Project was built in California in 1935, and the Snowy Mountains Water Diversion Project in Australia in 1949. European countries interconnected by the Rhine, the Elbe and Maas Rivers flowing from south to north constructed lateral canals as water control projects in 1950s (Li *et al.* 2011b). A modern example is the South-to-North Water Diversion Project in China.

Zhang, *et al*. (2010) discussed the meaning of connected water systems. Li, *et al*. (2011) considered that the interconnected water system network was a generic extensive regional scale concept, showed obvious differences at different spatial scales. They also pointed out that three main functions of river-lake interconnection networks are to advance the ability of water resource allocation, improve the ecological environment of the river-lake system and enhance the ability against floods and droughts (LI *et al.* 2011a). Later, Cui, *et al*. (2012) refined and consummated the above three main functions to secondary functions, forming the functional system of interconnected water system networks (Cui *et al.* 2012b). Xia, *et al*. (2012) refined the connotation of river-lake interconnection as “on the basis of natural and artificial river-lake water systems, it will keep, remodel or build the water flow connected channels to meet certain function target, and to keep relatively stable flowing water bodies and associated conditions of the circulation of materials” (Xia *et al.* 2012). The connotation and theories of river-lake interconnection are broad, of wide influence and feature many uncertainties. Current research on related theories and technology remains explo-ratory.

3 Types of river-lake interconnected relationships

The river-lake interconnected relationship, also known as the interconnected water system network, generally includes the relation in outflow region and interior drainage area. It not only covers the relationship between rivers and natural lakes but also the relationship between rivers and artificial lakes (reservoirs), and between artificial canals and lakes. It incorporates the connection relation within drainage basins and cross-basin interconnected relation. For instance, the Yangtze River and Dongting Lake, Yangtze River and Poyang Lake, Yellow River and Eling Lake or Zhaling Lake, Zambezi River and Lake Malawi, Colorado River and Lake Mead, Mackenzie River and Lake Athabasca or Great Bear Lake all belong to the interconnection relation in outflow region. The Nile and Nasser Lake (Aswan Dam), Missouri River and Garrison Reservoir, Tennessee River and Kentucky Reservoir, Yangtze River and Three Gorges Reservoir, and Yellow River and Xiaolangdi Reservoir are relations between rivers and reservoirs. In China, the Beijing- Hangzhou Grand Canal and Nansi Lake, South- to-North Water Diversion Project and the Yangtze River together with the Huai River, Yellow River and Hai River, and Rhein-Donau Canal and Rhine and Danube in Germany are the relation among artificial rivers, lakes and river systems and cross-basin river-lake interconnected relationships.

(1) From the angle of the interconnected water system, the river-lake interconnected relationship can be divided into cross-basin and inter-basin interconnected relation. For example, the relationship between the Rhein-Donau Canal and Rhine, Danube River and lakes along it, the Chinese South-to-North Water Diversion Project, Luanhe-Tianjin Water Diversion Project, Datong River into Qinwangchuan Project in Gansu and the lakes along it, are parts of the cross-basin interconnected water system network.

(2) From the perspective of different paths in the hydrologic cycle, it can be divided into two categories, one is the relationship in outflow region and the other is the relationship in interior drainage area. Outflow basin refers to the interconnected relationship between oceanic rivers and lakes along rivers. For example, Dongting Lake and Yangtze River, and Poyang Lake and Yangtze River. The relation in interior drainage area is the interconnected relationship between inland rivers and lakes along rivers, such as the Tarim River and Taitema Lake, Buha River and Qinghai Lake.

(3) From the ways of river-lake interconnection, it covers natural connections and artificial connections. The relationship between river and natural lake belongs to the former one. The relationship between river and reservoir and that between artificial canal and lake (such as the Beijing-Hangzhou Grand Canal and Nansi Lake) are included in the latter category.

(4) Dimensions can be divided into watershed dimension, cross-watershed dimension and international rivers dimension (Table 1). International river (the cross-border river) and other dimension interconnected water system networks will overlap in some way from the perspective of research purposes and objects, corresponding research theory will be similar or identical.

Table 1 Dimension classification of interconnected water system networks and theoretical basis

Dimension	Implication	Illustration	Examples of River-lake Interconnection Project	Main Theoretical Basis
International Rivers Dimension	Cross-border river catchment (international river system)	Nile, the Rhine, the Danube, the Ganges River, the Lantsang River, the Volga River, etc.	Aswan Dam, the Tehri Dam in the Ganges River, the canals connecting the Rhine and the Danube.	Theory of water cycle, water quantity and energy balance in mainland and watershed dimension, joint exploitation and utilization of water resource, harmonious development, river health, river-lake relation evolution, sustainable development theory in international river catchment.
Cross-watershed Dimension	Interconnection of water system in crossing watersheds	Canals connecting different river systems or the water diversion projects, etc.	South-to-North Water Diversion Project, the ancient Beijing-Hangzhou Grand Canal, the Luanhe-Qingtao Water Diversion Project in China.	Theory of water circulation, water quantity and energy balance in region and watershed dimension, sustainable utilization of water resource, watershed harmonious development, river health, river-lake relation evolution, region sustainable development theory in watershed.
Watershed Dimension	Interconnection of water system within watershed	Branches flowing into main stream, Dongting Lake and Poyang Lake and the Yangtze River, the Xiaolangdi Reservoir and the Yellow River, etc.	Three Gorges Dam. The Xiaolangdi Reservoir, the Dujiangyan Irrigation Project.	The theory of region and water circulation in watershed dimension, water balance and energy balance, the theory of the sustainable utilization of water resource, river health, the relationship of river-lake relationship and region sustainable development.

4 Material and energy exchange in river-lake systems

In river-lake systems there exist material and energy exchange between rivers and lakes, such as water, dissolved substances, suspended solids, and contaminants. When the river-lake interconnected relation changes, the exchange flux of the material and energy exchange between rivers and lakes changes. On the contrary, the interconnected relationship of river-lake systems will be affected when the material and energy exchange alters. As long as there are water flows between rivers and lakes, material and energy exchange will occur, and corresponding material flows, energy flows, information flows and value flows exist. It is these flows that make the river-lake system have its normal ecological function and maintain ecological balance.

4.1 Material exchange between rivers and lakes: material flow

While carrying dissolved substances, sediments, microorganisms, contaminants and various materials, water flows keep flowing between rivers and lakes. Aquatic animals such as fish swim freely between rivers and lakes. Therefore, the material exchange in river-lake systems is realized. And this kind of material exchange is called material flow between rivers and lakes. It is the material flow that plays an important role in the formation and change of natural geographical environments such as hydrology, landforms and ecosystems in a watershed. It also has a great influence on the production and lifestyle of human beings. In the traditional agricultural society, humans used to migrate to wherever water and grass were available for it was convenient for human’s production and life nearby water sources. For the same reason, many modern metropolises are built in the middle and lower reaches of rivers and in the coastal areas of lakes and seas such as Paris, London, New York, Shanghai, Wuhan, Nanjing and Changsha. On the one hand, humans derive necessities from rivers and lakes such as water, dissolved substances, sediment and other materials, fish and aquatic plants. On the other hand, the fertile alluvial plains in the middle and lower reaches of rivers were formed by regular river floods which also tended to provide favorable conditions for human agricultural production.

4.2 Energy flows and value flows between rivers and lakes

Upstream water of a river contains a certain amount of internal energy, and the potential energy can be used directly or transformed into other forms energy while water flows to lower locations. Therefore, in river-lake systems, flows not only are the material flows, but also are the energy flows. Usually energy flow can be reflected by common elements of hydrology, such as water level difference, flow and flow velocity (Zhong *et al.* 2008). Generally, the larger the water level difference, the larger the amount of kinetic energy will be transformed by potential energy, and the quantity of energy flow will be larger. The greater the flow is, the higher the flow velocity is, and the corresponding energy flow will be more. Human beings filled with wisdom have long been aware and use energy flow to create value and benefit society. And thus, value flow is created. For instance, the SHUIPAI device was invented in the Eastern Han dynasty to make use of water energy value during iron-making processes. The shipping value is utilized when ships sail in rivers. The kinetic energy value is also used when ships move downstream, and it saves a lot of manpower and material. Modern hydropower stations are water conservancy projects that take advantage of the kinetic energy of water flow to convert it into electricity. It shows that there are energy flows and value flows between rivers and lakes.

4.3 Information exchange between rivers and lakes: information flows

There are human activities and biological information exchanged in river-lake systems. For example, frogs, fish and some aquatic organisms finish individual reproduction and development process by the support of flow carrying life information. Some fish in the middle and lower reaches of the Yangtze River have migratory behavior, and it is a typical example of information flows. Among these fish kinds, herring, grass carp, chub, bighead carp, elopichthys bambusa, and ochetobius elongatus kner are potamodromous. Hilsa herring, coilia ectenes, eel and Chinese sturgeon are diadromous. They breed in the river-lake system and grow in the sea, or they multiply in the sea and develop in rivers and lakes, and they swim between rivers and lakes to complete migration and life multiplication (Zhao *et al.* 2011). Furthermore, human activities also transfer a large amount of information between rivers and lakes. For instance, ships sailing in rivers become one carrier of all kinds of information transmission such as fishing, cargo delivery, transportation, travel, visiting friends and relatives and scientific investigation.

Thus, all these flows are flowing day and night and fully reflect the basic characteristics of river-lake interconnections. The fluxion of all flows follows the mass conservation law and the law of energy conservation in nature, and complies with the hydrologic cycle principle. The river-lake system has a great contribution to improving regional natural geographical environments and makes possible human social and economic development.

5 Material and energy exchange between rivers and lakes is a process and performance of river-lake interactions

In an interconnected river-lake system, the interactions between rivers and lakes are achieved by various flows through water, dissolved substances, sediment and other material exchanges as mediums. Whereas, in actual river-lake systems, due to power stations, sluices, dams and other hydraulic engineering, the process of material and energy exchange between rivers and lakes is greatly impacted. In addition to water and sediment exchange between rivers and lakes, the interactions include exchange among dissolved substances, contaminants and water quality, changes in erosion and deposition in wetlands and bottomlands caused by material and energy exchange variation, fish diadromous reproduction and growth, migratory bird wintering in river-lake wetlands, and the interactions cover the lake adjustment of high and low flow and coactions among human shipping, power generation, and social and economic development. The existing research illustrates interactions between rivers and lakes. For example, on the basis of analysis of hydrological data, Zhao, *et al*. (2011) established the experience formula for the intensity of water quantity exchange between rivers and lakes. This explains interactions in river-lake systems (Zhao *et al.* 2011). With the application of quantitative methods, Guo, *et al*. (2012) compared the operation of the Three Gorges Reservoir with regional climate change and how they impact interactions between the Yangtze River and Poyang Lake (Guo *et al.* 2012).

6 A case to illustrate in the middle and lower reaches of the Yangtze River

6.1 The basic approach of the evolution of natural river-lake interconnected relationship is material and energy exchange

While carrying dissolved substances, sediment and contaminants, runoff flows into lakes, and after regulation and storage of the lakes water outflow will have a low sediment concentration. Discharge with high energy produces erosion or deposition effects on riverbeds, and the river-lake interconnected relation changes slowly, the material and energy exchange between rivers and lakes is achieved simultaneously. In China, the Jing River reach belongs to the main stream of the Yangtze River. Jing River's Three Outlets (outlets of Songzi, Taiping and Ouchi are called Three Outlets), is the tie that connects the Yangtze River and Dongting Lake in China and is a typical and complex river system network (Fig. 1). A large amount of sediment is captured by the Three Gorges Reservoir the upstream of the Yangtze River, the sediment content of the water near the dam in lower reaches decreases rapidly, sediment carrying capacity is not saturated, the water course is eroded, thus the discharge capacity is increased, and the water level is decreased at the same flow. As a result, water and sediment diversions in Jingjiang River's Three Outlets are decreased, and sediment flowing from the Yangtze River into Dongting Lake is reduced. Deposition variation in Dongting Lake is mitigated and the relationship between river and lake is adjusted accordingly (Xu *et al.* 2009). In addition, there are measured data showing that great quantity of sediment flow into Poyang Lake due to water flowing backward from the Yangtze River, and most sediment is deposited on the river channel between Hukou and Xingzi, therefore, the process of material and energy exchange between the Yangtze River and Poyang Lake is affected (Fig. 1) (Gao *et al.* 2014). Material and energy exchange between rivers and lakes is the carrier of material, energy, information and value, and it is the basic approach of relational changes between river and lake. Nevertheless, human activities tend to be a very important intervention power that gives rise to changes (Kristensen *et al.* 2014).

6.2 The direct power of the evolution of natural river-lake interconnected relationships is material and energy exchange

The scouring and silting evolution trend of river- communicating lakes will be influenced by changes in water and sediment conditions for inlet runoff over the long term. In flood and dry seasons in watershed, due to different water and sediment conditions with different water levels, discharges and so on, flow power conditions and sediment carrying capacity are different, thus the interconnected relationship between rivers and lakes undergoes unceasing change. According to data from 1951 to 2005, the annual average of the total sediment quantity flowing into Dongting Lake from Jing River's Three Outlets (the Outlet of Songzi, Taiping, Ouchi, and Tiaoxian were called "Four Outlets", the Outlet of Tiaoxian was blocked off in the winter in 1958. Hereafter, "Four Outlets" became Three Outlets) and Four Rivers (Xiang River, Zi River, Yuan River, and Li River) in Hunan was 1.56×10^8t. Three Outlets occupied 81.2% of the total inflow sediment quantity, while Four Rivers only accounted for 19.8%, and the annual average of sedimentation load for years was 1.14×10^8 t (Gao *et al.* 2013; Nakayama *et al.* 2013). As a result, the water interchange state between Dongting Lake and the main stream of the Yangtze River changed from flood storage condition to stability, and then to water supply condition over nearly 60 years (Zhao *et al.* 2014). The river-communicating lakes (Dongting Lake and Poyang Lake) in the middle and lower reaches of the Yangtze River play an underestimated complementary role to provide water supply to the main stream (Dai *et al.* 2008), and the amount of the main stream runoff is the principal factor controlling the process of material and energy exchange in river-lake system (Zhao *et al.* 2014). Here we can see that the material and energy exchange is the direct power of the river-lake interconnected relationship change.

We can draw the conclusion that changes in river-lake interconnected relationships follows certain natural laws and is influenced intensely by human activity. Through various ways, river-lake interconnected relationships are transformed and induced by humans to evolve toward the direction of improving eco-environments and human social and economic development in order to achieve harmonious coexistence between people and water and between people and the environment.

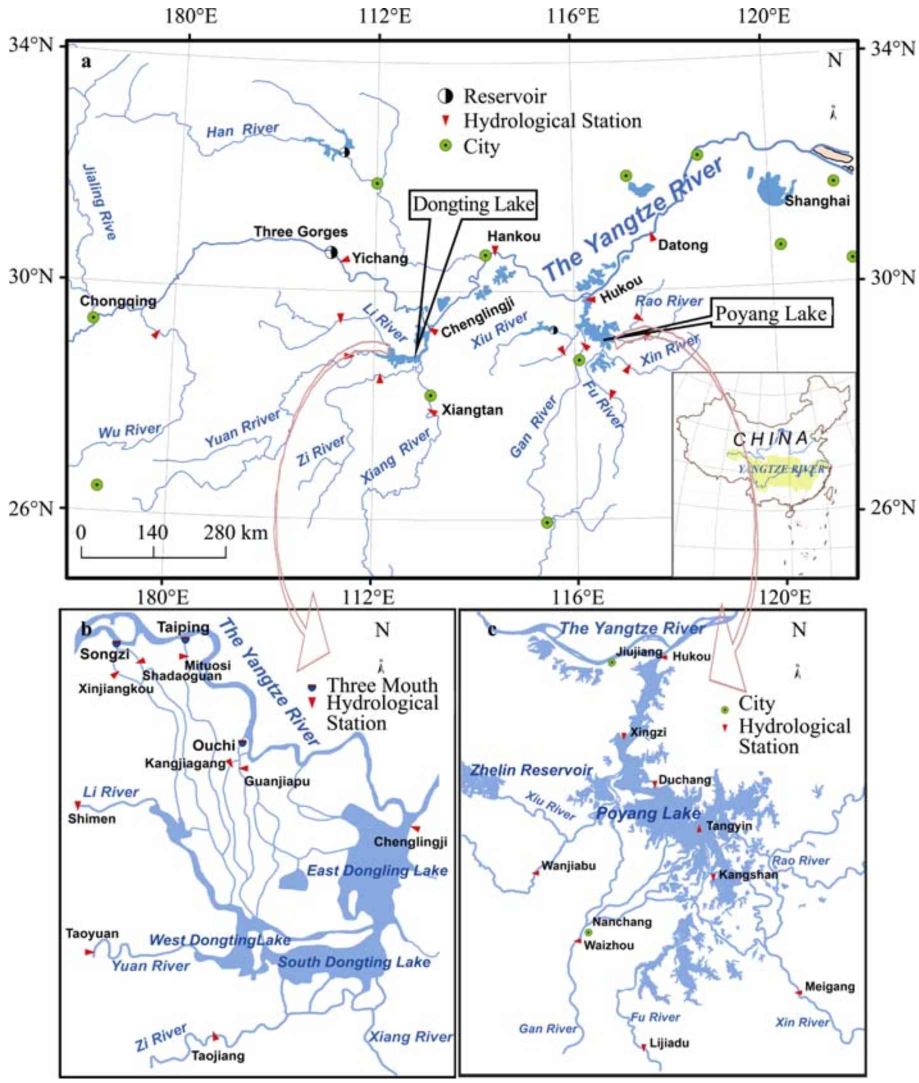

Fig.1 Map of river system connections between the Yangtze River and Dongting Lake, Poyang Lake

7 Ecological functions of river-lake interconnected systems

The inner-basin or cross-basin river-lake (reservoir) interconnected water system network constitutes one special and complex river-lake system. It consists of rivers, lakes (reservoirs), land, people and other factors, forming complicated relations with each other. (These relations include the relationship between water and people, river and lake, earth and man and water and land). All these related elements are connecting and influencing each other and they are jointly playing the ecological functions of the river-lake system. The river-lake ecosystem, namely wetlands ecosystem, is one of the three major ecosystems worldwide, one of the most important ecological environments, and the main channel of material circulation, energy flow and information exchange between terrestrial and aquatic ecosystems. It is an indispensable natural resource for human survival and development. Wetland ecosystems not only provide abundant water resources for people but also have many social service functions such as aquaculture, electricity generation, shipping, irrigating, flood controlled and prevented and water entertainment. They play a vital supporting and safety role in human social development are the foundation of human survival and modern civilization (Flint *et al.* 2017).

8 Epilogue

The interconnected water system network is formed by water bodies such as rivers and natural lakes within watersheds or artificial lakes (large reservoirs), also named river-lake (reservoir) systems. This system covers rivers, lakes (reservoirs), land and people and each factor is interrelated, mutually influences and interacts with each other. The evolution of river-lake interconnected systems follows certain natural laws, and it strongly impacted by human activity. In a river-lake system network, there are kinds of flows between rivers and lakes. These flows include material flows (water, dissolved substances, sediments, organisms, contaminants), energy flows (water levels, flow, flow velocity), information flows (information produced with flow, organism, human activities) and value flows (shipping, power generation, drink, irrigation). Under the influence of natural factors and human interventions (all kinds of water conservancy projects), various flows are connected by river-lake interconnections and material and energy exchange between rivers and lakes that achieves river-lake interactions and whole system evolution. The evolution of interconnected water system networks finally tends to be in a relatively stable state at a certain period, namely, the ideal state of dynamic balance.

In a healthy river-lake system, some chain reactions will occur as feedback when any element within the river-lake system alters, thus whole systematic functions are affected including anti-flood, ecology, resource utilization and environmental protection within catchments. The good relationship of river-lake interconnected systems based on material and energy between rivers and lakes is a new approach to the assessment of river system health.

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基于河湖水系连通的流域水系健康评价新思路

赵军凯[1,3]，李立现[1]，张爱社[1]，李九发[2]，郭秋霞[1]

1. 九江学院旅游与国土资源学院，九江市国土测绘与3S技术应用重点实验室，江西 九江 332005；
2. 华东师范大学 河口海岸学国家重点实验室，上海 200062;
3. 九江市流域管理和生态保护重点实验室，江西 九江 332005

摘　要：河湖水系连通作为新时代国家治水方略被提出，成为科学界的一个研究焦点。通过河湖连通关系的类型、“量质交换”、诸动态“流”和生态功能的讨论，提出基于河湖连通关系的河流健康评价的一个新思路。认为在健康的河湖连通系统中，河湖之间存在着良性的“量质交换”，它是河湖之间最基本的物质和能量交换关系；河湖之间的物质流（水、溶解物质、泥沙、生物，污染物等）、能量流（水位、流量、流速等）、信息流（随水流、生物和人类活动而产生的信息流动等）和价值流（航运、发电、饮用和灌溉等）畅通无阻；诸种“流”在自然和人类活动的影响下，以河湖水系连通为纽带，进行河湖之间的“量质交换”，实现河湖相互作用；“量质交换”是河湖连通关系演变的途径和动力源泉；良性的河湖连通关系演化最终趋于相对稳定状态，即动态平衡。

关键词：河湖水系连通；分类体系；量质交换；生态功能；河流健康评价；河湖系统