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Combined assessment and regulation on ecological land use and water demand of the river system: a case study in Luanhe River, North China

D. H. Yan[1,2], G. Wang[1,2], H. Wang[1,2], and T. L. Qin[1,2,3]

[1]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
[2]Water Resources Department, China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
[3]Environmental Science and Engineering Department, Donghua University, Shanghai, 201620, China

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Correspondence to: G. Wang (hanhehebest@163.com)

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Abstract

With economic and social development, ecological water and land use of the river system were seriously misappropriated, which resulted in overall degradation of the river systems. In this study, theoretical and technical frameworks of regionalisation on the eco-environmental function of the river systems were preliminarily formulated. According to the river eco-environmental functions, Luanhe River was regionalised into four types of first-class functional areas, i.e., ecological preservation areas, habitat restoration areas, ecological buffer areas and development and utilisation areas. Combined with the main functions of all functional areas, ecological land use of the river system in Luanhe River was assessed and planned. The total area of basic ecological land use was 876.98 km^2; that of restrictive ecological land use was 1745.52 km^2; that of ecological land use of the river system returned from farmland was 284.25 km^2; and that returned from construction land was 17.35 km^2. Combined with prototype observation experiments, the average minimum ecological flow of mainstreams in upper and middle reaches of the Luanhe River was 4.896 $m^3 s^{-1}$ with the habitat method. The evaporation and seepage consumption of the river system in Luanhe River and vegetation consumption in riparian zones were about 133 million m^3 and 145 million m^3 per year, respectively. Downwards from the Panjiakou-Daheiting Reservoir system, the mainstream of the Luanhe River was the crucial reach for regulation on instream ecological water use. It was required to speed up ecological land use planning of the river system and strengthen the regulation of ecological water use in important lower reaches of the Luanhe River under the condition of competitive water demand.

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1 Introduction

As a combined system, the river system consists of river ecosystem and riparian ecosystem, of which the range can be defined as a hundred-year floodplain (Gregory, 1991). Rivers have a remarkable hydrological function, molding function and important eco-environmental functions, such as flood regulation and storage, groundwater recharge, sediment transport and salt discharge, pollutant diluting and biodiversity protection (Luo et al., 2004). In addition, with improved human ability in transforming nature, rivers gradually possess many social service functions, such as water supply, power generation, shipping, aquiculture and landscape entertainment (Liu, 2009). Determined by multifunctional characteristics of rivers, the river system inevitably becomes one of natural systems, which is most severely threatened by human beings and most intensively interfered with by human activities. In recent centuries, with the fast development of economy and sharp increase of population, the ecological and hydrological pattern of the river system has been changed by extensive economic activities. Lots of floodplain areas are developed and utilised for agriculture, aquaculture and the development of cities and towns (Jones et al., 1999; Lytle and Merritt, 2004; Morgan et al., 2007). A great reduction occurs to the ecological land use of the river with an importance in safeguarding critical ecological processes and providing critical ecosystem services. The ecological water use of the river is also seriously misappropriated, so that the river system is degrading under severe interference (Jones et al., 2010).

The earliest research on water demand of river ecological environment went back to the concern of US Fish and Wildlife Service about instream flow in the 1940s (Ward et al., 1979). Between 1960s and 1970s, many scholars had discussed the methods for determining the minimum ecological instream flow, which were applied to the assessment and planning of some famous rivers (Loar et al., 1981). Between 1980s and 1990s, more sophisticated theoretical and method systems in the calculation of instream flow had been formed (Bovee, 1986; Petts, 1996; Poff et al., 1997; Lytle and Poff, 2004; Henry, 1995; Geoffrey, 1996; Hughes, 2001). Since the middle and late

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period of the 1980s, lots of concerns were aroused by the restoration of degraded riparian ecosystems and the management of riparian buffer zones. A large number of experiments and researches, focusing on water resource protection, soil and water conservation and other basic eco-environmental functions of riparian buffer zones, had been conducted (Lowrance et al., 1985; Knopf et al., 1988; Phillips, 1989; Sweeney et al., 2004; Schoonover et al., 2005; Baker et al., 2006; Lees and Peres, 2008; Lennox et al., 2009). Some laws and policies on riparian management were formulated (Morrison, 1988; Welsch, 1991; Smith and Hellmund, 1993). However, in current resource development and eco-environmental protection, more researches on the microcosmic process are conducted than those on macroscopic aspects. There are many studies targeted at a single species, while few comprehensive studies on complicated river system exist. Researches on single function (resource function, environmental function) are assessed more than those on multiple functions, of which, the multifunctional characteristics of the river system are split. Therefore, it is urgent to perform integrated management of the river system to maintain water and eco-environmental safety, so as to fully play the multi-attribute functions of the river system.

As one of four first-class basins in Haihe River Basin, North China, Luanhe River Basin is not only an important mineral resource distribution area, but also one of the important water sources of Bohai Rim economic circle. With economic and social development, the ecological water and land use of the river system in Luanhe River Basin has been seriously misappropriated, which causes overall degradation of the river system and threatens the entire ecological and water safety of the basin. Taking the Luanhe River as an example, this study (1) assessed the ecological water demand of the river system, (2) presented and argued the theoretical and technical frameworks of regionalisation on eco-environmental function of the river system, (3) regionalised the Luanhe River with systemic identification of crucial eco-environmental functional areas in the basin, and (4) assessed the ecological land use in the Luanhe River system. Ecological instream flow was calculated with the habitat method, combining prototype observation experiments. Moreover, the habitat method is based on the theoretical framework of IFIM (instream flow incremental methodology). In this study, aquatic macroinvertebrate was taken as target species for instream flow evaluation, assuming that these species played an important role in sustaining the integrity of the aquatic ecosystem. Statistical methods were used combined with GIS techniques and approaches in the ecological land use assessment. The objective was to give some suggestions for government policy makers in planning regional eco-hydrological regulation of the Luanhe River Basin.

2 Site description

Located between 115°34′ E–119°50′ E and 39°02′ N–42°43′ N in the northeast of North China Plain, the Luanhe River Basin covers a total area of 44 700 km^2 with an average width of 103 km. Originating from the north foot of the Bayanguer Mountain in Zhangjiakou, Hebei Province, this river travels through 27 cities and counties of Hebei Province, Inner Mongolia autonomous region and Liaoning Province, finally flows into Bohai Bay. The basin is inclined from northwest to southeast. The upper reaches consist of Bashang plain and paddock plateau regions with undulating terrain shown as lots of deflation hollows. The middle reaches consist of North Hebei and Yanshan Mountain hilly areas with very deep river valleys. The lower reaches consist of Yanshan Mountain front plain and Luanhe delta plain, which are intensively influenced by human activities. The Luanhe River Basin shows diverse geomorphic types, of which, mountains, hills and basins cover about 70 % of the total basin area, plateaus and plains account for about 16 % and 12 %, respectively. In addition, river valleys, beaches, terrace and tableland are also broadly distributed in this area, where typical temperate continental climate prevails as hot and rainy in summer and cold and dry in winter. The annual mean temperature is 7.6 °C and annual active accumulated temperature no lower than 10 °C changes obviously from 2250 °C to 4000 °C. The annual mean rainfall is 520 mm with the rainy seasons from July to September every year. The river system is well developed in this basin, where nine first-class branch rivers exist with the catchment

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area more than 1000 km^2. The landscape types of the Luanhe River Basin are diverse, shown as many types of soil, such as meadow soil, forest soil, chestnut soil, brown soil, cinnamon soil and solonchak. The vegetation types of the basin mainly comprise cultural vegetation, bushwood, plateau and broad-leaved forest, and a small area of coniferous forest and meadow.

The Luanhe River has a large water volume in the Haihe River Basin. However, the development and utilisation intensity of water resources in the basin are also continuously increased with the fast increasing water demand of the regional economy. Especially since the completion and operation of the Panjiakou Reservoir, Daheiting Reservoir and other large-scale major water conservancy projects in the mainstream of the Luanhe River, great changes have occurred to the flow and sediment processes of channels in the lower reaches, which damages the physical structures of channels, causing the degeneration of river ecological functions and a reduction in biodiversity, and also leads to the erosion and recession of the modern Luanhe River delta shoreline. The ecological space of the river system is occupied by the unreasonable development and utilisation of land resources in riparian zones, exacerbating the contradiction of the land struggle between human and water. With global climate change, the runoff of the Luanhe River system is obviously decreased and the annual mean surface water resource between 2000 and 2009 is only 40.6 % of that between 1956 and 2000. In addition, emerging with the rapid development of economy, water quality problem causes the contradiction of supply and demand even harsher.

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3 Materials and methods

3.1 Materials

3.1.1 Sampling

Sampling of benthic invertebrates in the Luanhe River Basin was completed in July and December of 2010. Samples were collected in a series of sections from upper plateau reaches, middle mountainous reaches and lower plain reaches during different months under various flow conditions (21 sections in total, with a minimum of three samples per location). The locations of sampling sections in the Luanhe River Basin are shown in Fig. 2.

Firstly, study reaches were divided into several areas according to habitat types of shallow, deep stream and deep pool, where benthic animal samples were collected. The used collection tools included a 30 cm × 30 cm Surber net and a 15 cm × 30 cm grab bucket type sediment collector with primary collection areas of 0.09 m^2 and 0.045 m^2, respectively. The Surber net was applicable to mountainous areas of the Luanhe River, where the substrate compositions of river beds were cobble or gravel with a water depth no more than 0.5 m. Equipped with a 200 µm stainless steel sieve, the grab bucket type sediment collector had obvious advantages when applied to lower reaches with poor flow and sand substrate in plain areas of the Luanhe River. The samples were fixed and stored with 4 % formaldehyde. Meanwhile, it was required to record the physical property parameters of each section area, such as flow velocity, water depth, river width and the attribute of substrate composition of river beds. Moreover, the position of each sampling point was determined with GPS.

In the entire investigation, a total of 49 kinds of benthic animal were collected, belonging to 12 orders (classes) and 30 families. Among them, 36 kinds were aquatic insects, belonging to 7 orders and 21 families, accounting for 73.5 % of the total. Five kinds belonged to oligochaeta and 3 families, accounting for 10.2 %. Another five kinds were mollusk, belonging to 4 families and accounting for 10.2 %. The other four kinds

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belonged to 3 families, accounting for 8.2 %. Benthic animal communities, belonging to Chironomidae, Diptera, were identified at all sampling points with higher species abundance and dominance.

The river systems in the upper, middle and lower reaches of the Luanhe River had obvious differentiation characteristics. Gradient changes with the level of rivers occurred to geomorphology, soil, vegetation, land use type and pattern of riparian zones, substrate composition of river beds, flow features and other properties of river banks, the composition and distribution of instream biological groups. The descriptions on eco-environmental characteristics of sampling sections in different areas are listed in Table 1.

3.1.2 Crucial eco-environmental functional areas

Crucial natural preservation areas

Lots of national and provincial natural reserves are distributed along the headstreams of some important branch rivers in the mountainous areas of the upper and middle reaches of the Luanhe River Basin. With an outstanding function of water source conservation, a large area of complete typical forest or prairie ecosystem is reserved in these preservation areas. Moreover, natural preservation areas possess abundant biological resources and gene pool resources with distinct and unique biological diversity. In addition, close to Beijing and Tianjin, natural reserves play an important role in the protection of ecological safety of the Beijing-Tianjin area.

Chengde national important preservation areas for soil erosion prevention in the Luanhe River Basin

The Luanhe River Basin in Chengde is one of 16 national important preservation areas in China for soil erosion prevention, approved by the State Council in 2006. The total basin area of 23 000 km^2, accounting for 80 % of that in the upper reaches of Panjiakou Reservoir, and this basin is an important water source of the reservoir. Statistics show that during the period from 1990 to 2000, annual mean sedimentation of Panjiakou Reservoir was 12.61 million m^3, triple over the period from 1980 to 1989. By the end of 2000, accumulated sedimentation of the reservoir was 180 million m^3, accounting for 6.9 % of the modified reservoir capacity. Although the protection of forests and vegetation has been strengthened in this area and the area of forestland and grassland has been expanded greatly in recent years, the existing secondary forest still has poorer soil and water retaining capacity, while the ecosystems of forestland and grassland are still vulnerable integrally.

Duolun typical ecological vulnerable area in upper reaches of the Luanhe River

The vulnerable area is located in Duolun County, Inner Mongolia autonomous region, where lots of low hills and accumulated sand dunes exist, especially fixed and semi-fixed sand dunes and mobile sand belts. Natural secondary forest, sand meadow and natural wetlands are scattered among sand belts sporadically. In this area, the annual rainfall is only about 380 mm and average wind velocity is 3.0–3.5 m^{-1}. In a transitional agro-pasture area, Duolun County has a vulnerable ecological environment, where a very serious soil erosion problem exists with a soil erosion area up to 3283 km^2, accounting for 87 % of the total, and a large quantity of sediment flows into the lower reaches with water of the Luanhe River every year. The aggravation of soil erosion and sandstorms not only plagues this county, but also threatens the environmental quality of the Capital Beijing and the quality of drinking water in Tianjin area.

Water sources of major water supply and transfer projects

Panjiakou Reservoir and Daheiting Reservoir exist as the water sources of water diversion projects from the Luanhe River to Tangshan and Tianjin. Taolinkou Reservoir is the water source of the Qing-Qin water transfer project, and Chengde Shuangfengsi

Reservoir has been approved in this basin. With rapid economic development in upper reaches of the reservoir, total discharged industrial wastewater and urban domestic sewage are increased continuously in recent years, and the agricultural non-point source pollution is exacerbated by soil erosion. Moreover, affected by the mining industry around reservoirs in the upper reaches, water quality of the reservoirs is gradually reduced.

3.2 Methods

3.2.1 Ecological instream flow demand

Comprehensively taking into account the relationship between the characteristics of habitants preferential to living beings and river hydrological properties, habitant method based on biological principles is regarded as a more reliable quantifying method at present. In this study, a sort of habitant method-WUW (weight utilisable width method) was used to enable the study more simple and flexible to operate without considering the representativeness of sections in study reaches. Moreover, the method was principally based on the theoretical framework of instream flow incremental methodology (Midcontinent Ecological Science Center, 2001).

The suitability curve of habitant factors is prepared according to the suitability requirements of target species on flow velocity V_i, water depth D_i, substrate composition C_i and other important habitant factors (Gore, 2001; Jowett and Quinn, 1990). Corresponding to flow velocity, water depth and substrate composition of each area, respectively, suitability indexes $f(V_i)$, $f(D_i)$ and $f(C_i)$ are determined according to suitability curve, ranging from 0 to 1. For each habitant factor, 0 and 1 indicate that the condition of the current habitant is completely not suitable or completely suitable for target species, respectively. Besides, considering the influence of water quality on benthic animal, water-quality suitability index $f(W_i)$ is defined as $f(W_i)$ 1, 0.6, and 0.3, indicating clean, polluted intermediately and polluted seriously, respectively (Duan,

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2011). Finally, the habitant suitability width of each section and each target species, i.e., WUW, is calculated with Eq. (1).

$$\mathrm{WUW} = \sum F\left[f(V_i), f(D_i), f(C_i), f(W_i)\right] \times W_i \tag{1}$$

where W_i is the section width of i-th area in the study section; $f(V_i)$, $f(D_i)$, $f(C_i)$ and $f(W_i)$ are suitability indexes of flow velocity, water depth, substrate composition and water quality, respectively; and $F[\,]$ is the combined habitant suitability factor, expressed as CSF, calculated with geometric mean method.

$$\mathrm{CFS} = \left(f(V_i) \times f(D_i) \times f(C_i) \times f(W_i)\right)^{1/4} \tag{2}$$

Through establishing the relation curve between WUW and flow Q, flow threshold is determined according to the turning point of the change in WUW, and the minimum ecological instream flow demand is finally obtained.

In all benthic animal communities, Diptera, especially Chironomidae, has the highest faunal diversity, identified as the dominant species in sampling. Therefore, as a target species, Chironomidae is used for constructing the habitant suitability model of benthic animal.

3.2.2 Evaporation and seepage of the river system

In surface evaporation of the river water, evaporation depth of water body per unit area indicates evaporation capability. The following is the calculation equation on the net water demand of river evaporation consumption.

$$W_w = (E_w - P) \times H \times L \tag{3}$$

where W_w is the net water demand (m^3) of surface evaporation consumption; E_w is actual evaporation capability (mm); P is average rainfall (mm) of a channel; H is average water surface width (m); L is calculated river length (km).

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Since water surface width of a river greatly changes with runoff within a year, water surface width in a normal flow period is used as the average width to calculate surface evaporation. The data of evaporation capacity and rainfall can be obtained from adjacent meteorological stations.

Water demand of channel seepage consumption can be calculated with the groundwater dynamic method and hydrological analysis method. However, it is difficult to obtain hydrogeological parameters related to these two methods in real calculation and, thus, the water demand of seepage consumption is calculated roughly through multiplying the basic instream flow demand by a certain seepage rate. In reference to relevant researches, the seepage rate of 0.15 is used for rough estimation.

3.2.3 Water demand of vegetation in riparian zones

Water demand of vegetation in riparian zones can be simplified into water demands of forest land and grassland, calculated with the following equation:

$$W_p = E_p \times A_p \quad (4)$$

where W_p is water demand of vegetation; E_p is evaporation capacity (mm) of vegetation; A_p is the vegetation area in a riparian zone. The physiological water consumption mechanism of vegetation is very complicated, influenced by many factors, such as climate condition, vegetation condition and soil moisture condition. For convenience, the water demands of vegetation in riparian zone are classified into different vegetation-type units, according to a universal land utilisation classification system based on the relevant research results of the Haihe River Basin. The water demands of evaporation consumption in every vegetation unit are 500 mm for forest land, 330 mm for bush, 330 mm for open forest land, 350 mm for other forest lands, 300 mm for grassland with high coverage, 210 mm for grassland with medium coverage, and 150 mm for grassland with low coverage.

3.2.4 Eco-environmental functional regionalisation of rivers

Connotation of functional regionalisation

River functional regionalisation refers to a river regionalised into functional areas with different utilisation types and different environmental quality requirements, according to site condition, resource condition, development and protection situations of rivers and regional requirements of economic and social development. Based on the definite functional properties of different reaches, corresponding control indexes and limitation conditions are proposed for reasonably controlling and correctly directing the utilisation of rivers, so as to achieve the multi-dimensional purposes of environment improvement, landscape creation, ecological protection and sustainable utilisation. Thereby, the contradiction between natural ecological functions and eco-social functions is well coordinated.

Functional regionalisation system

There are lots of natural preservation areas in the upper reaches of the Luanhe River system with remarkable functions of water source conservation, ecological protective screen and biological protection. Moreover, Luanhe River Basin is one of the areas with rapid economic development in North China, where many cities are built in river valleys with urbanization process accompanied by outstanding resource demands for rivers. Therefore, it is necessary to regionalise rivers into ecological preservation areas and development and utilisation areas, in order to protect integrality of river functions as well as meet reasonable requirements of the development and utilisation of rivers. Aiming at grassland degradation and soil erosion in the upper and middle reaches, ecological function shrinkage in the plain channels of the lower reaches and other serious issues, ecological restoration and even reconstruction are required in some crucial reaches. Therefore, it is necessary to plan certain ecological restoration areas.

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Besides, considering that administrative divisions enable rivers and reaches attached to different management entities, buffer areas or transitional areas should be established to ensure the functional integrality of the river corridor systems, so as to coordinate water demand contradiction among different management entities. Moreover, buffer areas should also be established among different functional areas. Thus, the first-class eco-environmental functional regionalisation system is required to include four types of areas, i.e., ecological preservation areas, habitat restoration areas, ecological buffer areas and development and utilisation areas.

According to different water demand entities, development and utilisation areas are further divided into second-class functional areas, such as industrial water use areas, agricultural water use areas, drinking water source areas, aquiculture water use areas, landscape water body areas and wastewater discharge control areas. With different protection objects, preservation areas can be further divided into natural preservation areas and water source preservation areas.

The following are the explanations on first-class eco-environmental functional areas:

a. *Ecological preservation areas*
   Similar to the connotation of preservation areas in water functional areas, ecological preservation areas refer to the areas crucial for water resource preservation, protection of natural eco-environment and rare or endangered species, in which all development activities are forbidden. The ecological preservation areas include source water preservation areas, water sources of national and provincial natural reserves or areas of natural ecology systems with typical ecological protection value, and water sources of large-scale trans-basin, trans-provincial and in-provincial water transfer projects.

b. *Habitat restoration areas*
   Habitat restoration areas refer to the areas where river ecosystems have been damaged to some extent by human activities, which can be restored to meet the requirements of continuity and functional integrity of stream habitats under the

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support of eco-social conditions and hydro-geographic conditions. During ecological restoration process, it is essential to exert the subjective initiative to restore existing damaged ecosystems, so as to improve and restore partial structures and functions of ecosystems and realize the self maintenance of river ecosystems.

c. *Ecological buffer areas*
Ecological buffer areas are used for coordinating water demand issues among provinces and the areas with serious contradiction, in order to satisfy water demands of different entities. When ecological preservation areas and habitat restoration areas are connected with development and utilisation areas, ecological buffer areas can keep external influence off from ecological preservation areas, and connect broken habitats to realise structural integrity and functional continuity of the river systems, thereby achieving the purposes of ecological buffering and social buffering.

d. *Development and utilisation areas*
Same to the connotation of development and utilisation areas in water functional areas, development and utilisation areas mainly refer to the water areas able to meet the water demands of industrial and agricultural production, urban life, fishery industry, entertainment and so on. Development and utilisation areas mainly consist of important urban reaches within the basin and the areas with extensive water intakes and large water demand on certain agricultural irrigation or fishery production.

Functional regionalisation procedures

Combined with comprehensive planning of water resources in this basin and local economic development planning, junctions among all functional areas, such as reservoirs, boundaries between cities and counties, are determined by identifying the crucial eco-environmental functions of rivers in this basin. Then, rivers are regionalised into different eco-environmental functional areas. The coordination and rationality of

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regionalisation results should be inspected, according to the existing water functional areas, so as to correct regionalisation results. The first-class functional areas should be nominated in the form of river name, region name and functional area type. In addition, development and utilisation areas can be further divided into second-class functional areas, according to actual requirements of local economic development.

3.2.5 Assessment and planning on river ecological land use

The crucial problem for ecological land use research and ecological planning is to determine the scale and pattern of land use. Focusing on regional sustainable development, ecological land use research is committed to coordinate nature and eco-social development. Therefore, anything but environmental determinism cannot be analysed with the ecological optimization theory. Moreover, the scale and pattern of ecological land use should be particularly studied, so as to avoid potential ecological problems at a certain safe level. With different eco-environmental functions in various reaches of this basin, the required scale of ecological land use should be differentiated with areas and reaches, so as to ensure scientific and practicable regionalisation results.

Assessment on ecological land use of ecological preservation areas and ecological buffer areas of rivers

The reaches with the function of water source conservation and drinking water source preservation are mostly located in the upper reaches of mountainous areas with a small population and low river development and utilisation degree, where ecological land use can be determined with the method of planning buffer areas. In reference to surface water resource protection plan and regionalisation results of urban centralized drinking water source in Hebei Province, the areas within 200 m on both sides of the rivers are planned to be basic ecological land. Strict protection measurements are taken to forbid any forms of development activities. The areas 1 km outside the enclosure line of basic ecological land use are planned to be restrictive ecological land, in which development

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activities could not affect the eco-environmental functions of buffer zones. For reaches crossing over natural preservation areas, in consideration of protecting the integrity of habitats, the enclosure line of ecological land use should be expanded to ensure continuity of habitants, so as to protect the integrity of natural preservation areas and original landscape. The areas within 2 km on both sides of the rivers are planned to be ecological land use in this study, where any forms of developmental activities should be forbidden. The functions of ecological buffer areas are defined between development and utilisation areas and ecological preservation areas. Moreover, it can be realised simply by planning certain buffer areas. The areas within 100 m on both sides of rivers and areas and 1 km extending out from basic ecological land were planned to be basic ecological land use and restrictive ecological land use, respectively.

Assessment on ecological land use in upper and middle reaches of habitat restoration areas

The habitat restoration areas in the upper and middle reaches of the Luanhe River are mainly composed of two parts. One is the Duolun typical ecological vulnerable area, located in a transitional agro-pasture area with a vulnerable ecological environment and serious desertification and grassland degradation, where soil erosion is very common. The other is the Chengde national important preservation areas for soil erosion prevention in the Luanhe River Basin. Although high coverage of forests and grassland exists in this area, the potential threat of soil erosion still occur, due to the main vegetation type of this area as secondary forest and the unstable ecosystems of forests and grassland. Therefore, the riparian buffer zones with effective width are essential for controlling soil erosion. Research conducted by Copper (1987) and Lowrance (1988) showed that 80–100 m riparian buffer zones could effectively reduce 50–70 % of sediments. Therefore, 100 m buffer areas on both sides of the rivers are planned to be ecological land use in the habitat restoration areas of rivers.

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Assessment on ecological land use in development and utilisation areas of rivers

Most of the development and utilisation areas are located in cities, towns and other areas with high population density, where the majority of people are gathered along both sides of rivers. Most of the construction land use in riparian zones has formed in a certain scale and pattern, and a certain land space should be reserved for future urban planning and development. Therefore, the buffer areas with a certain width cannot simply be planned to be ecological land use.

There is a large proportion of present construction land use in the development and utilisation areas. For example, the construction land use in Chengde reach of the Wuliehe River mainstream accounts for 61 % of hundred-year floodplain area; for rivers in mountainous areas, the development and utilisation areas have become residential areas with high population density, while they have lost the conditions of returning to wetland landscape. Therefore, the ecological land use of development and utilisation areas is not rigidly restricted. In the comprehensive consideration of the requirements on local economic and social development, more emphasis should be put on the protection of existing ecological land use and the regulation of ecological land use pattern. Far away from the nature, urban residents prefer to semi-naturalise entertainment space. By applying flexible river banks as much as possible to reaches in cities and on the basis of natural or semi-natural design, streamside parks, wetland parks, artificial lakes and so on should be built for creating more waterfront accessible spaces for citizens.

Assessment on ecological land use of plain habitat restoration areas in lower reaches of the Luanhe River

At present, an improved flood prevention system, including levees on both sides, mounds and bank protection works, has been formed in plain habitat restoration areas of the lower reaches of the Luanhe River. In the actual utilisation of embankment areas, farmland accounts for 52.3 %, seriously occupying the ecological land use of

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rivers. Besides, since the operation of water conservancy projects greatly reduces the instream flow, riparian zones face serious desertification with desertification area, accounting for 30.4 %. Moreover, buildings and structures are established in channels illegally, and residential areas and construction sites are scattered all around the embankments, seriously affecting flood discharge. The widths of levees on both sides of the Luanhe River range from 2.5 km to 5.5 km, while flood prevention mounds, spur dikes and other control and regulation works are built in the levees. According to the flood control plan of the Luanhe River Basin, the flood control standard of mainstream is designed for resisting against flood with a fifty-year reappearance period, ensuring that the floods no higher than the fifty-year grade can flow into the sea safely from flood prevention levees. Flood prevention mounds belong to beach flood discharge areas with short-term and long-term planning standards for resisting against floods with five-year and ten-year reappearance periods, respectively, so as to ensure that middle and small floods can flow into the sea safely through flood prevention mounds. According to the planning scheme of flood control and regulation line approved by Department of Water Resources of Hebei Province, the regulation line with a total length of 75 km is planned between Luanhe Jingshan railway bridge and the river estuary in the Luanhe River embankment area.

Complying with the principle of respecting actual situations and taking the priority of flood control, ecological land use is planned within the embankment range in the mainstream of the Luanhe River. Ecological land use is planned with the regulation line and the flood prevention mounds as boundaries, respectively. The area within flood prevention mounds is defined as the protection area of basic ecological land, where enforced protection measures are taken to forbid any forms of development and occupation, so as to protect natural ecological landscape. Moreover, artificial flood pulses should be made effectively in high flow years to flood beach areas periodically, so as to gradually restore the basic eco-environmental functions of damaged channels. The restrictive development ecological land use is planned between flood prevention mounds and regulation lines. Appropriate agricultural activities are allowed in this area on the

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premise of no damage to ecological functions. The agricultural activities are guided by the policy of protection first and moderate development, while illegal building, disorderly planting and other activities affecting flood discharge are forbidden. Ecological land use to be developed moderately is planned between regulation lines and flood prevention levees, in which people are encouraged to plant trees and take other activities to protect banks ecologically, thereby effectively managing and protecting the flood prevention levees.

4 Results

4.1 Assessment on eco-water demand of the Lunhe River system

4.1.1 Minimum ecological instream water demand

The flow velocity of the Luanhe River is measured between 0 and 0.97 m s^{-1}. The suitability curve of flow velocity shows that the flow velocity suitable to Chironomidae is between 0.2–0.5 m s^{-1} and the most suitable flow velocity is about 0.3 m s^{-1}. Some types of Chironomidae can also live in still water. When the flow velocity is higher than 0.6 m s^{-1}, the suitability index declines greatly. When the flow velocity is higher than 1 m s^{-1}, the species of Chironomidae are more difficult to survive due to unresisting water flow.

The water depths at sampling points of the Luanhe River range from 0.03 m and 1.05 m. The water depth suitable to Chironomidae is almost between 0.2 m and 0.4 m, and the most suitable water depth is about 0.3 m. Although some types of Chironomidae are identified in water areas above 0.7 m, the diversity of species is reduced significantly.

The substrate composition of river beds at sampling points are generally classified into seven types, i.e., fine sand, coarse sand, fluid mud, cobble, gravel, boulder and large aquatic plants. The influence of these sediment types on biomass and its density of Chironomidae shows that the favourite substrate type of Chironomidae benthic living beings is fluid mud, among which, fluid mud river beds provide good nesting environment for burrowing type Chironomidae. When substrate changes into fine sand river beds, the diversity of Chironomidae benthic living beings sharply declines. And then, the diversity increases when the grain diameter of substrate changes into coarse sand. Due to substrate types preferred by Chironomidae benthic living beings, cobble and gravel river bed can provide wide ecological habitat conditions. The biodiversity in boulder substrate is reduced slightly, and the river bed substrate with submerged plant shows the lowest biodiversity.

Figure 6 shows the fitting curve between WUW of study sections and flow. At present, slope ratio method and curvature method are usually used for determining flow threshold, i.e., a specific slope (critical value 1 was taken generally) or the maximum curvature on WUW-Q relation curve is defined as a threshold point (Gippel, 1998; Shang, 2008). When flow is higher than the threshold flow, flow variation will influence WUW slightly. After the flow decreases to the turning point, WUW will intensely vary with the decrease of flow. In this study, the turning point is obtained based on the slope of 1. The threshold flow of 4.896 $m^3 s^{-1}$ is calculated according to the fitting function $WUW = 11.04 + 4.896 \times \ln(Q)$.

With slow, even still flow, single river bed substrate and insignificant depth change gradient, the lower reaches of the Luanhe River are not suitable for establishing suitability physical model of benthic animal. Besides, since most of the study sections are intensively distributed in the upper and middle reaches of the Luanhe River, average minimum ecological flow of 4.896 $m^3 s^{-1}$ can be used as the minimum ecological instream flow demand of channels in the upper and lower reaches of the Luanhe River. In the research conducted by Wang in 2009, calculated with monthly frequency method and ecological hydraulic method, the minimum annual ecological water demand of channels in the lower reaches of the Luanhe River was 429 million m^3, and the suitable ecological water demand was 893 million m^3. In addition, the ecological water demand and controllable indexes of the Haihe Basin had been studied in the special research on China regional ecological water demand standard, a project in the Tenth Five-Year National Science and Technology Breakthrough Plan. The minimum ecological water demand and suitable ecological water demand of channels in the lower reaches of the Luanhe River were 353 million m^3 and 746 million m^3, respectively, calculated with the channel morphological analysis method. In this study, the average value of 391 million m^3 and 820 million m^3 in the above research were taken as the controllable indexes for minimum water utilisation of rivers and water utilisation of ecology suitability, respectively.

4.1.2 Evaporation, seepage and vegetation water demand of the river system

Calculated with the method introduced in Sect. 3.2.2, 74 million m^3 of water in the entire Luanhe River system is consumed by surface evaporation. The annual channel seepage water consumption is 59 million m^3, calculated through multiplying 391 million m^3, the basic ecological instream flow in Luan County station along the lower reaches of Luanhe River, by the seepage coefficient of 0.15. The ecological water demand of vegetation in riparian zones is about 145 million m^3, calculated with the method introduced in Sect. 3.2.3.

4.2 Eco-environmental functional areas of the Luanhe River

The river eco-environmental functional regionalisation in this study focuses on the Luanhe River system with a total length of 2100 km (reservoir areas are not included), excluding the coastal river systems in the east of the Hebei Province. With a total river length of 728 km, ten ecological preservation areas are planned, mainly distributed in the areas with significant influences on ecological preservation and water supply in lower reaches, most of which are mountainous rivers and the upper reaches of major water supply reservoirs. With a total river length of 533 km, seven ecological restoration areas are mainly distributed in the upper and middle reaches of mountainous areas with serious soil erosion and the lower reaches with serious misappropriation of river

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ecological water use, due to the impoundment of reservoirs. With a total river length of 649 km, nine development and utilisation areas are planned, distributed in water areas close to cities and towns with developed industry and agriculture, leading to large and intensive water demand. With a total river length of 189 km, five ecological buffer areas are planned, mainly distributed at Hebei-Inner Mongolia provincial boundaries in upper reaches, as well as the middle buffer areas between development and utilisation areas and ecological preservation areas in inflow rivers of the Pajiakou Reservoir. The regionalisation results on first-class eco-environmental areas in Luanhe River Basin are shown in Fig. 7.

4.3 Assessment on ecological land use of the Luanhe River system

According to the planning of ecological lands in different river eco-environmental functional areas in Sect. 3.2.5, the areas of basic ecological land use and restrictive ecological land use are 876.98 km^2 and 1745.52 km^2 in the river system of the Luanhe River Basin, respectively. In addition, based on the actual situation, ecological land use suitable for development with an area of 1745.52 km^2 is planned in the habitat restoration areas of plain channels in the lower reaches of the Luanhe River. The areas of land required to be returned from farmland and construction land are 284.25 km^2 and 17.35 km^2, respectively, as shown in Table 2. For convenient table display, the ecological land use planning in habitat restoration areas of lower reaches (Table 3) is indicated separately. Among them, basic ecological land use of ecological preservation areas with the area of 669.36 km^2 is the maximum, accounting for 76.3 % of total area. The tasks on returning farmland and construction land are very tough with the area of 212.31 km^2 and 13.49 km^2, accounting for 74.7 % and 77.8 %, respectively.

Figure 8 shows the area and distribution of ecological land use in ecological preservation areas, ecological buffer areas, and habitat restoration areas in upper and middle reaches of the Luanhe River. Figure 9 shows the area of ecological land use in habitat restoration areas of plain channels in the lower reaches of the Luanher River.

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5 Discussion

5.1 Suitability of habitat suitability model

Since the reproduction and growth rule among biological communities characterised with periodicity, water demand of living beings in channels was not constant within a year, while varied with the hydrologic regime of rivers in a continuous change process (Thame, 2003; Lee, 2008). Limited by sampling data information, the constructed biological habitat physical model was mainly used for showing annual mean water demand characteristics of target species in this study. Therefore, it is necessary to continuously carry out large-scale and high-density prototype observation experiments in the next step, so as to provide support for constructing more detailed and accurate habitat models. In addition, aquatic species present great differentiation in community composition and distribution, which is determined by hydrological, ecological and environmental characteristics in different rivers. The habitat suitability model with Chironomidae in Diptera as the dominant species constructed in this study is required to be further verified in other basins.

5.2 Rationality of river eco-environmental functional regionalisation

Generally, before river eco-environmental functional regionalisation, it is required to assess the hydrology, ecology and environment of rivers comprehensively. Therefore, a set of index system needs to be established for evaluating crucial ecological functions quantitatively. This method is feasible for the research on a certain reach. However, a great difficulty is encountered in information collection, aiming at the dimension of the whole basin in this study. Therefore, the crucial eco-environmental functional areas of this basin are only qualitatively and macroscopically identified. It is necessary to assess the hydrology, ecology and environment of rivers comprehensively in subsequent researches, on the basis of massive prototype observation experiments, so as to optimize and improve river eco-environmental functional areas.

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5.3 Discussion on safe regulation of ecological land use

Aiming at the current excessively intensive development of the river systems and degradation of ecological system functions of rivers, basic ecological land use of rivers is planned for maintaining the healthy life of rivers. In this area, the natural landscape of the river system should be maintained to maximum extent, and any forms of developmental activities, such as excavation, planting and building, should be forbidden.

The restrictive ecological land use refers to a transitional area for connecting basic ecological land use and human activity areas as an important ecological barrier for alleviating the impact of human activities on river systems. The restrictive ecological land use of the ecological preservation areas in the upper reaches is mainly used for blocking and filtering nitrogen and phosphorus nutrient elements and reducing the pollution burden of water sources caused by agricultural non-point source pollution. The restrictive ecological land use of ecological buffer areas in inflow rivers of the Panjiakou Reservoir is also planned for guaranteeing the safe quality of water supplied by the reservoir. The main water demand entity of habitat restoration areas in plain channels along the lower reaches of the basin is agricultural irrigation with a low requirement on the standard of water quality. For flood control safety, restrictive ecological land use is mainly used for restraining human activities in this area from affecting the flood discharge capacity of channels. The ecological land use suitable for development is mainly used for encouraging people to actively participate in embankment maintenance and management.

A large area of land needs to be returned from farmland in the upper and middle reaches of this basin, where these areas are usually underdeveloped in economy with a large agricultural population and, thus, land is the main source of income for people. Therefore, in order to keep local residents' enthusiasm on ecological land use protection and guarantee their normal living standard, an emphasis should be put on the issues of economic compensation and job placement. Although controllable indexes are not required on farmland and construction land returning in the development and

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utilisation areas along the middle and lower reaches of basin, ecological land use protection stress is actually transferred to the upper reaches. Therefore, the upper reaches should be compensated ecologically for fairness and coordination of the contradiction between upper and lower reaches.

5.4 Discussion on safe regulation of ecological water use

The regulation of ecological water use mainly focuses on the basic ecological instream flow greatly influenced by human activities. Evaporation and seepage of the river systems and water demand of vegetation in riparian zones are natural phenomena and difficult to be regulated and controlled. The upper reaches of the Luanhe River are slightly influenced by human activities, of which the runoff is not reduced as seriously as that of the lower reaches, basically meeting the minimum ecological instream flow demand (see Fig. 10). The actual annual runoff of the Luan County Station during the period from 1956 to 2006 showed that the runoff of channels in the lower reaches of the Luanhe River met the suitable ecological water demand (893 million m^3) before 2000. However, with a gradual decrease in recent 10 years, runoff has not satisfied or reached the minimum ecological water demand (391 million m^3) (see Fig. 11). If taking the restoration of the ecosystem in the lower damaged reaches into consideration, the ecological water deficit of the river systems will be more severe. Therefore, the reaches downwards from the Panjiakou Reservoir and the Daheiting Reservoir are important regulating areas. For safe regulation on ecological water use of river systems, on the one hand, joint dispatching of existing reservoir groups in this basin should be strengthened, so as to strive for more ecological water use for channels in lower reaches by scientific management and allocation; on the other hand, water sources transferred from other places should come into service as quickly as possible and industrial water and urban domestic water in the Tianjin area could be compensated effectively through the East Route Project of China's South-to-North Water Transfer, so as to replace part of the ecological water use for improving the ecological environment of channels.

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6 Conclusions

Focusing on the main ecological and environmental problems as well as the requirements on the comprehensive ecological and hydrological regulation of rivers, combined the assessment and regulation on ecological land and water use of the Luanhe River system is researched in this study and following conclusions are reached.

The theoretical and technical framework on eco-environmental functional regionalisation of the river systems is proposed, and the Luanhe River is regionalised according to the river eco-environmental functions. Based on systematical identification on crucial eco-environmental functional areas, such as important natural preservation areas, water source preservation areas, important preservation areas for soil erosion prevention and typical ecological vulnerable areas, the Luanhe River is regionalised into four types of first-class functional areas, i.e., ecological preservation areas, habitat restoration areas, ecological buffer areas and development and utilisation areas with regionalised river lengths of 728 km, 533 km, 189 km and 649 km, respectively. The ecological preservation areas, as well as development and utilisation areas, can be divided into several second-class functional areas according to actual demands.

The assessment and planning on ecological lands of the Luanhe River system is performed on a basis of river eco-environmental functional regionalisation. The total area of basic ecological land use in the Luanhe River system is 876.98 km^2, that of restrictive ecological land use is 1745.52 km^2, that of land required to be returned from farmland is 284.25 km^2, and that of ecological land use required to be returned from construction land is 17.35 km^2. The area of basic ecological land use in ecological preservation areas is the maximum at 669.36 km^2, accounting for 76.3 % of the total, while the task for ecological land use regulation is very tough. Considering the actual requirement of regional economic and social development, ecological land use in the development and utilisation areas are not required rigidly, but the upper reaches of this basin should be compensated ecologically to some extent.

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The ecological water use demand of the river system is systemically calculated and analysed, according to water demand characteristics of ecological environment in the river system. Through constructing a large-scale physical model of the benthic invertebrate habitat, the average minimum channel ecological base flow of mainstream in the upper and middle reaches of the Luanhe River is calculated at 4.896 $m^3 s^{-1}$, and the present instream flow basically meets the threshold value. The minimum ecological water demand is 391 million $m^3 a^{-1}$ in channels along the lower reaches of the Luanhe River, and the actual annual runoff in channels of lower reaches almost fails to meet the minimum ecological water demand since 2000. Therefore, seriously influenced under the condition of competitive water demand, the regulation on ecological water use of reaches should be strengthened. The annual water demand of evaporation and seepage consumption in the Luanhe River system is about 133 million m^3, and water demand of the vegetation in riparian zones is about 145 million m^3.

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Table 1. Descriptions on eco-environmental characteristics of sampling sections in different areas.

Sampling section area	Structure of river bed and river regime	Substrate composition	Water surface width (m)	Water depth (m)	Flow velocity
Plateau area in the upper reaches	Sediment uplift type; lots of shallows; drawer-shaped section; wide and shallow; high water quality;	Fine sand, coarse sand	10 ∼ 40	0 ∼ 0.5	0.1 ∼ 0.4
Mountainous area in the middle reaches	Lots of turns; irregular channels; a large number of stagnant areas; stable river bed structure with ribwork or starry stones;	Cobble stone, gravel and aquatic plant	10 ∼ 30	0.1 ∼ 0.9	0.1 ∼ 1.0
Plain area in the lower reaches	Low slope; poor flowability; serious sediment deposition; hydrological regime greatly affected by human activities; and low water quality;	Sludge and silt	10 ∼ 25	0.3 ∼ 0.7	0 ∼ 0.2

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Table 2. Ecological land use planning of all river eco-environmental functional areas.

Functional area type	Basic ecological land use (km^2)	Restrictive ecological land use (km^2)	Land required to be returned from farmland (km^2)	Land required to be returned from construction land (km^2)
Ecological preservation areas	669.36	1271.15	212.31	13.49
Habitat restoration areas	93.45	–	33.05	1.58
Ecological buffer areas	37.90	364.77	10.19	0.32
Development and utilisation areas	–	–	–	–
Total	800.71	1635.92	255.55	15.39

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Table 3. Ecological land use planning in habitat restoration area of plain channels in lower reaches of the Luanhe River.

Basic ecological land use (km^2)	Restrictive ecological land use (km^2)	Ecological land use suitable for development (km^2)
76.27	109.60	34.78
Land required to be returned from farmland (km^2)	Land required to be returned from construction land (km^2)	
28.70	1.96	

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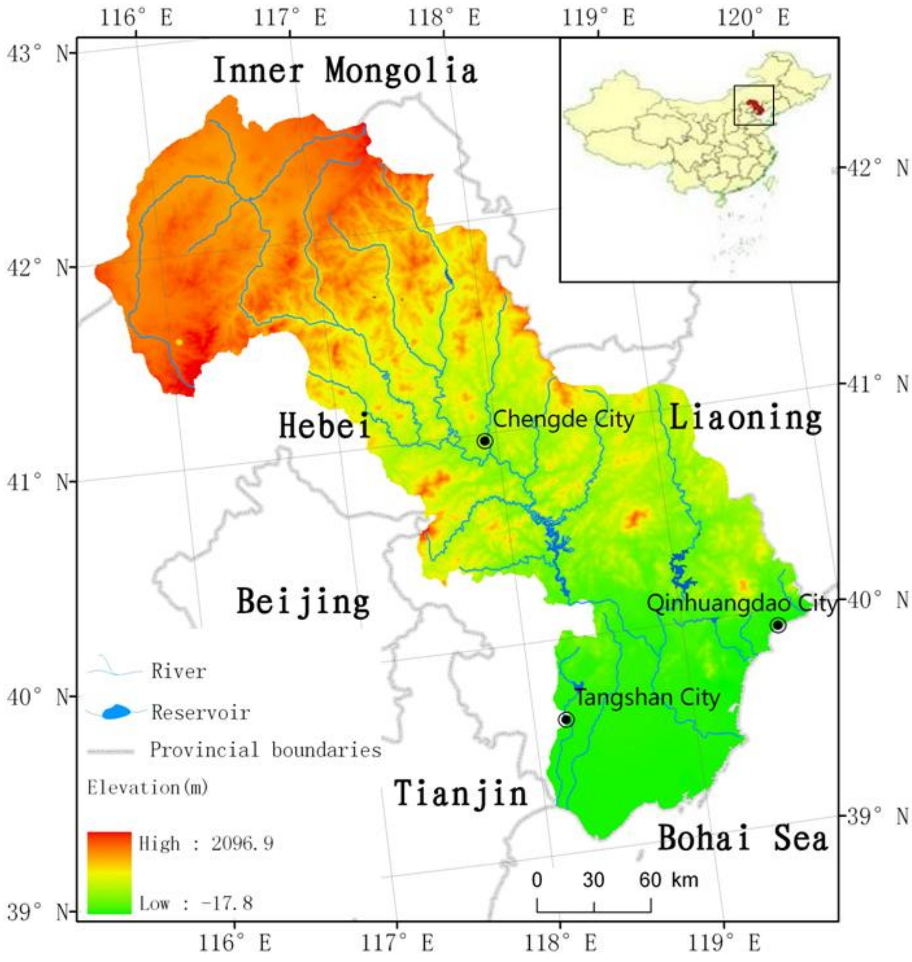

Fig. 1. Locations of study areas.

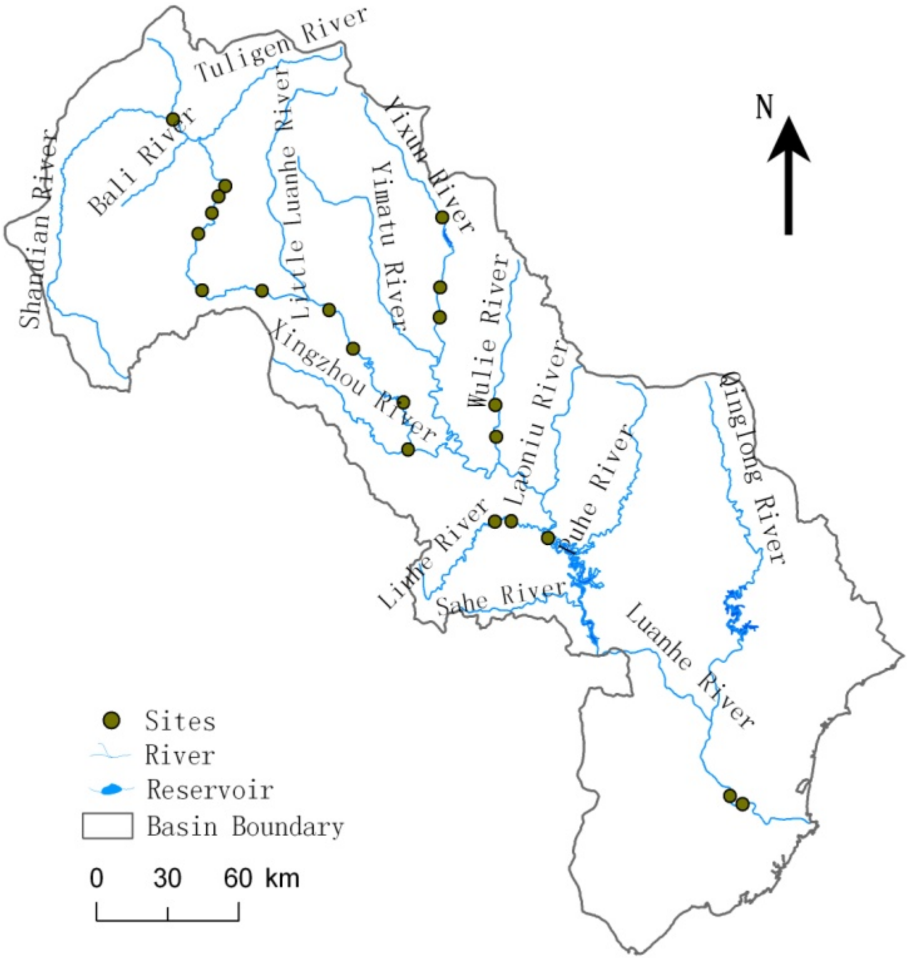

Fig. 2. Locations of sampling sections in the Luanhe River.

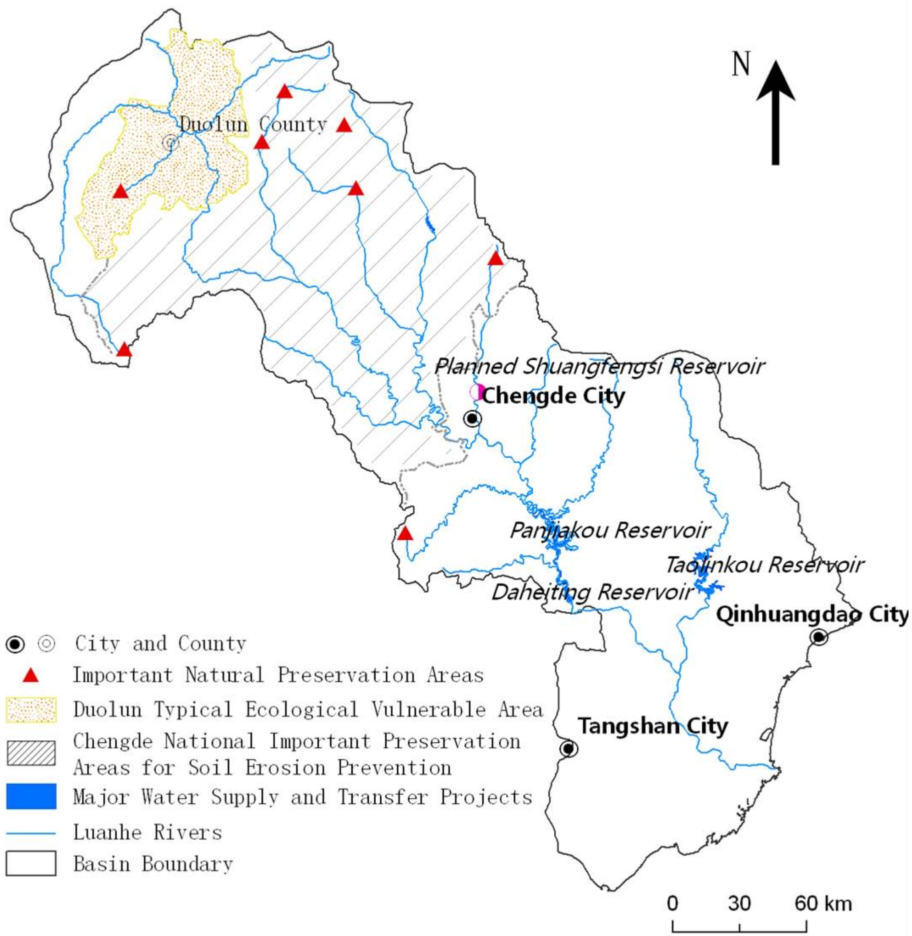

Fig. 3. Crucial eco-environmental functional areas in the Luanhe River Basin.

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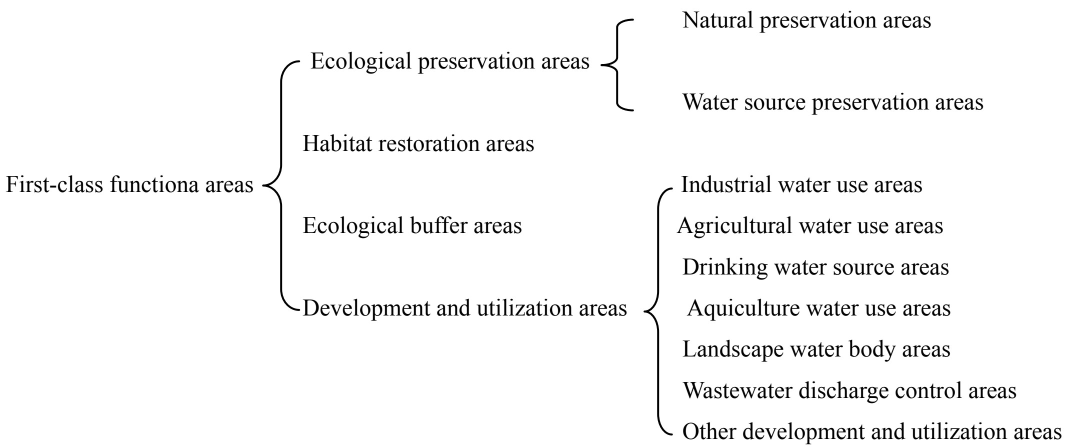

Fig. 4. Eco-environmental functional regionalisation system of the Luanhe River.

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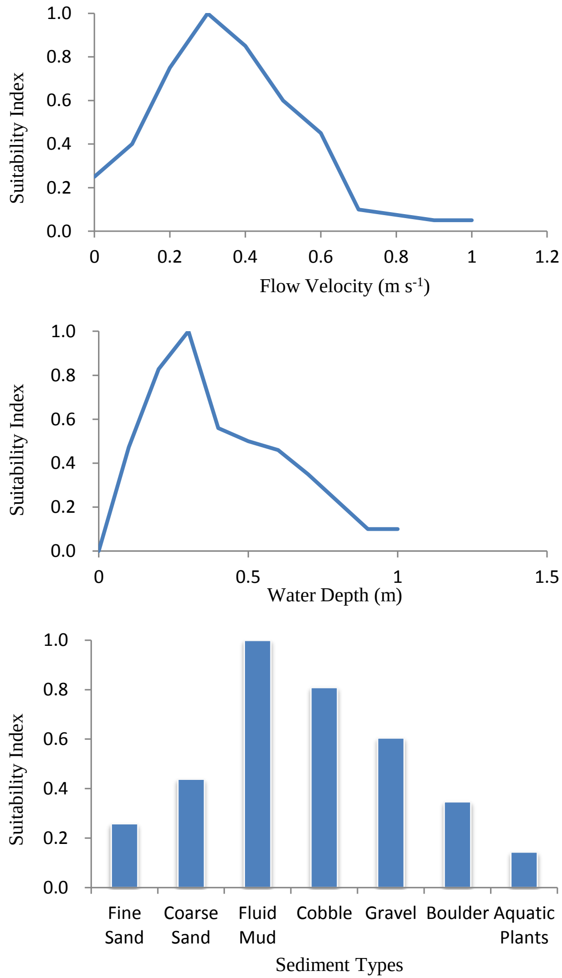

Fig. 5. Suitability model of Chironomidae, Diptera to flow velocity, water depth and substrate composition.

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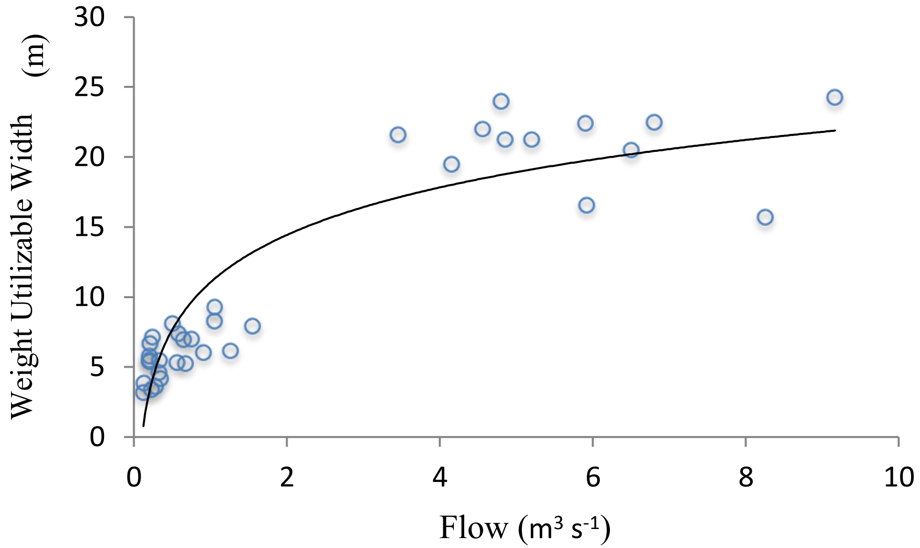

Fig. 6. Fitting curve between WUW and flow.

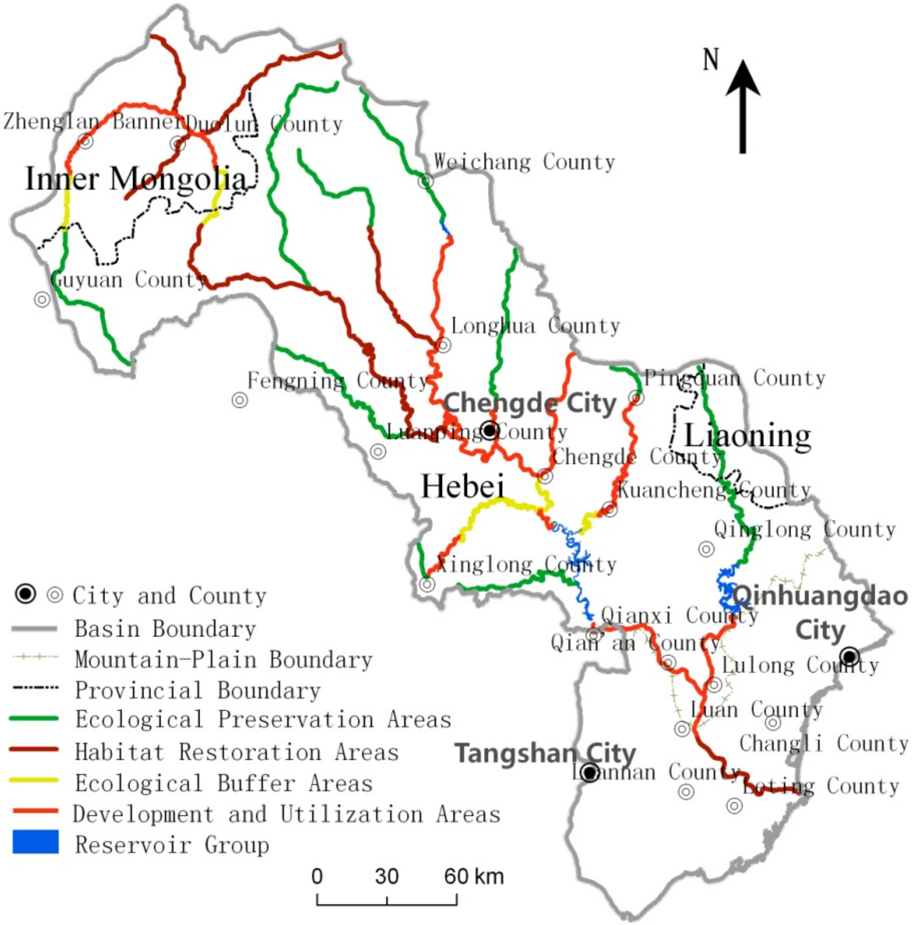

Fig. 7. First-class eco-environmental regionalisation in the Luanhe River Basin.

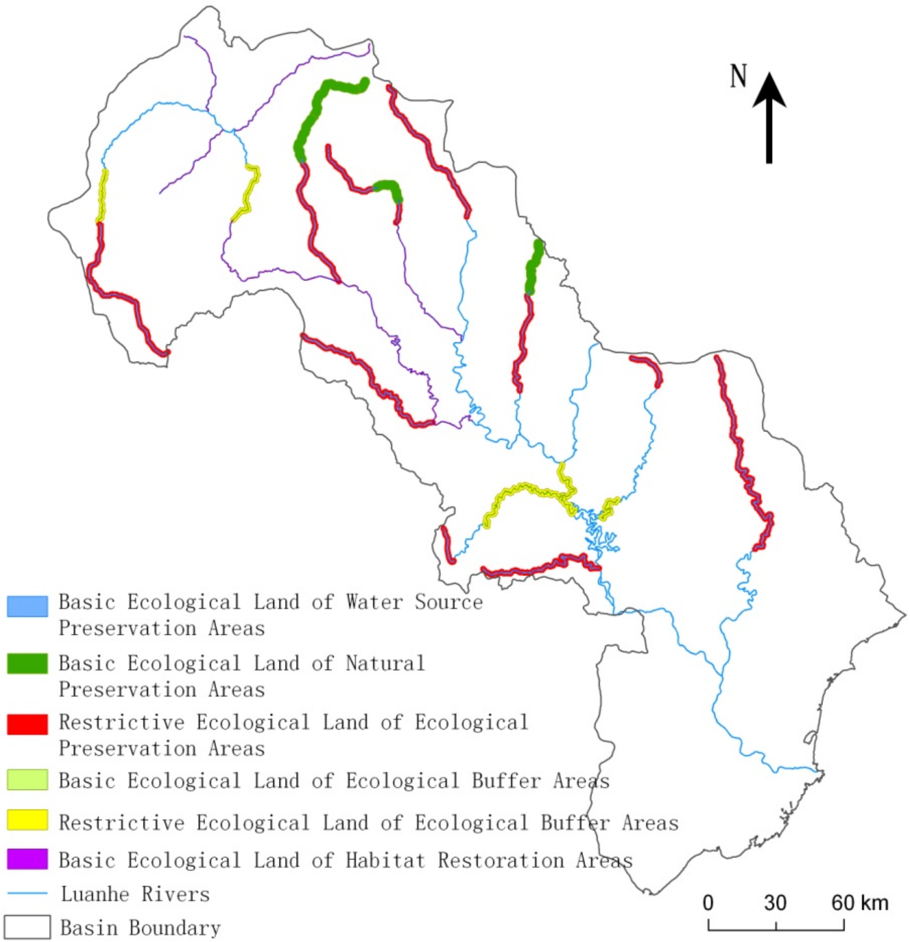

Fig. 8. Area and distribution of ecological lands in ecological preservation areas, ecological buffer area and habitat restoration areas in upper and middle reaches of the Luanhe River.

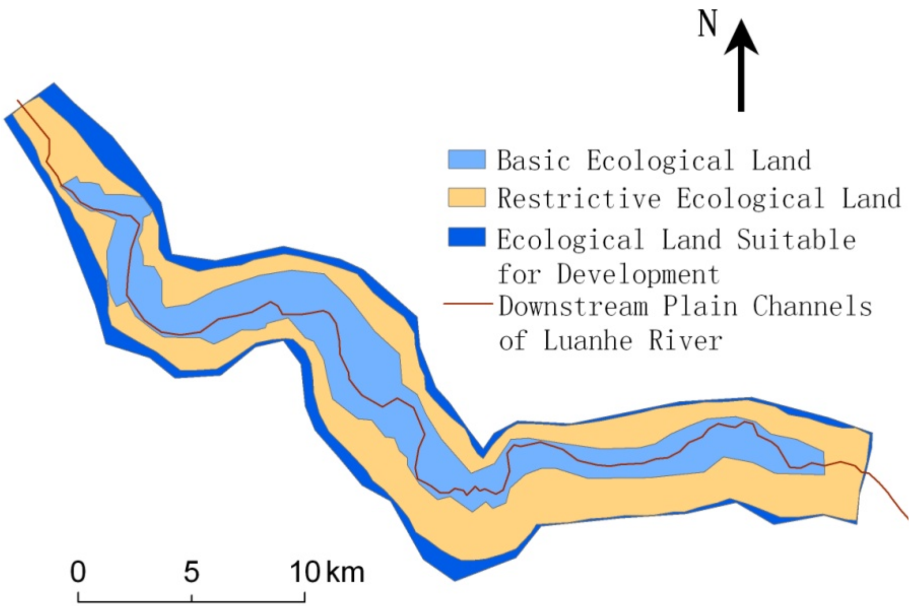

Fig. 9. Area of ecological land use of channels in lower reaches of the Luanhe River.

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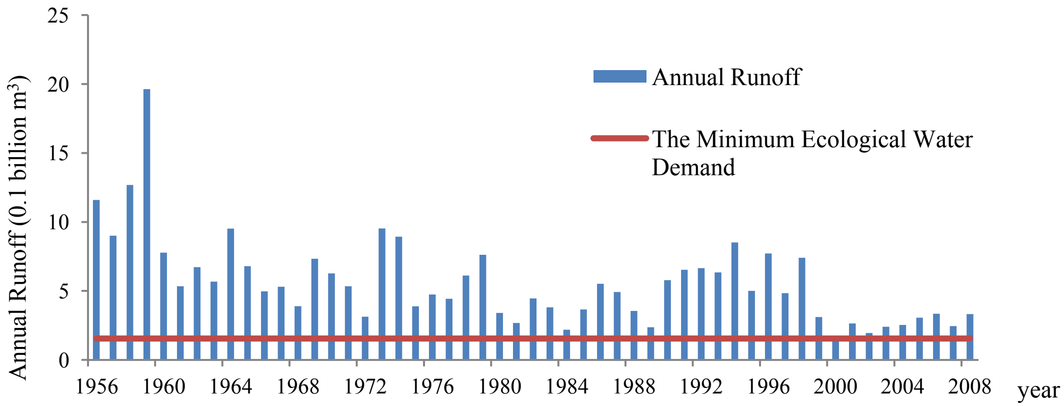

Fig. 10. Comparison between annual runoff and minimum ecological water demand of Sandaohezi Station in the upper Luanhe River.

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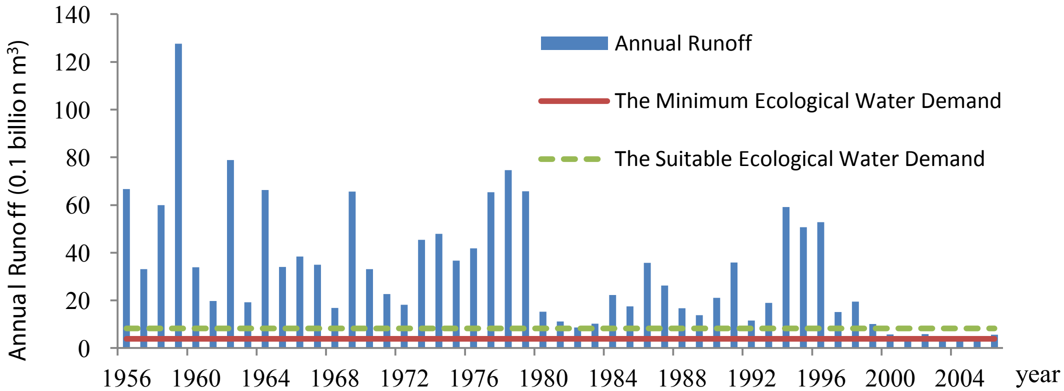

Fig. 11. Comparison between annual runoff and different levels on river ecological water demand at the Luan Country Station in lower reaches of the Luanhe River.

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