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Connecting regional landscapes by ecological networks in the Greater Pearl River Delta

Yongzhong Guo[1] · Youzhao Liu[1]

Abstract Landscape degradation and habitat fragmentation present one of the most pressing environmental issues associated with human development and the overuse of resources. Ecological networks are claimed to be effective for maintaining and improving landscape connectivity. Although there have been several methods of designation (such as the target species method), the present study builds a regional ecological network via a landscape ecological approach for the purpose of enhancing and restoring landscape connectivity. Using ArcGIS overlay and least-cost path algorithms, the study integrated relevant environmental and socioeconomic data into GIS projects to find optimal solutions for establishing a regional ecological network to act as a framework for improving landscape connectivity. After the addition of riparian protection areas and stepping stones, the resulting landscape configuration map depicts a potential approach to regional ecological connectivity. Further studies are needed, such as integrating this regional nature protection conceptualization with the urban development land use framework.

Keywords Landscape connectivity · Ecological network · Landscape planning · Core area · Corridor · GIS · Greater Pearl River Delta

✉ Yongzhong Guo
simonyzg@hotmail.com

Youzhao Liu
yzliu@njau.edu.cn

[1] College of Public Administration, Nanjing Agricultural University, Nanjing 210095, China

Introduction

The ecological network spatial concept emerged at the beginning of 1990s, when habitat loss and fragmentation became increasingly serious as consequences of human land use and urbanization. Ecological networks (EN) arose from a desire to maintain biodiversity and ecological processes through the approaches of maintaining and/or enhancing habitat/landscape connectivity.

The theoretical background to ENs synthesizes ideas from island biogeography, metapopulation theory, and the broader perspective of landscape ecology discipline (Boitani et al. 2007; Théau et al. 2015). The term ecological network refers to a set of ecosystems that are linked by a flow of organisms in a spatially coherent system and that also interact with the landscape matrix within which they are embedded (Opdam et al. 2006). An EN can also be defined as a system of nature reserves and their interconnections that makes a fragmented natural system coherent in order to support biological diversity and ecological processes. An EN is composed of core areas, buffer zones, and ecological corridors (Jongman 2003). Core areas have mostly been identified by traditional nature conservation policies such as the Yellowstone National Park; ecological corridors are various linear landscapes that maintain natural connectivity by connecting core areas and may vary in shape and size from wide to narrow, meandering to straight, continuous to discontinuous (stepping stones); a buffer is a zone peripheral to a core area or ecological corridor, within which restrictions are placed upon resource use to enhance the conservation value of the core area/corridor (Jongman 2004).

To date, various approaches have been employed in framing and designing ENs, since different countries or regions have different geographic, natural, and

socioeconomic conditions; and different professionals (ecologists, geographers, planners, politicians, and the public) perceive the landscape from their own perspectives. According to Hepcan and Ozkan (2011), three network types can be discerned: greenways, geo-ecological networks (landscape approach), and bio-ecological networks (species-specific approach).

Battisti (2013) suggests that there are two principal arenas in the field of EN studies: the site-based approach usually emphasizes a landscape study area according to administrative/political boundaries, whereas the target-oriented arena focuses on the ecological behaviors of the targeted species. Although some relationships must exist between the specific species and focused landscape area, the knowledge gap between the professionals of these two arenas and the lack of related scientific tools and co-operation have hindered an integrated approach to combine them.

Perhaps the most comprehensive comparison of different approaches to EN studies was presented by Théau et al. (2015) in an innovative empirical investigation conducted in southern Quebec, Canada. The authors chose three subfields (agricultural, mixed, and forested) within the Saint-Francois River watershed and designed six conceptual approaches according to three categories: single-species (indicator and umbrella species approach), multi-species (multi-scales and ecological continuums approach), and landscape-based (ecological continuums and biodiversity approach). By using a comprehensive index-thematic indicator (TI) to represent the total effective value of the three components of sustainable development (environmental, economic, and social), the resulting 18 maps and corresponding radar charts indicated that the landscape-based ecological continuum approach is one of the best approaches for designing and implementing ENs for sustainable landscape development.

With regard to intensified human development and rapidly urbanizing regions globally, it seems that the landscape-based approach of EN design can be a good choice. In this paper, we chose the landscape-based approach to develop a regional EN for regional nature conservation that, in turn, functions as an important part of the overall regional landscape planning framework, combining nature conservation and human development.

Study area and data

The Greater Pearl River Delta (PRD) study area is a relatively isolated region located in the central coastal area of southern China. The study area (21.6–24°N, 112–115.4°E) covers an area of 44,891.2 km^2 and had a population of 61.861 million in 2010. It consists of 11 prefecture-level

and upper administrative/political units: nine prefecture-level cities (Guangzhou, Shenzhen, Zhuhai, Huizhou, Dongguan, Zhongshan, Jiangmen, Foshan, and part of Zhaoqing); and two Special Administrative Regions (SARs, considered provincial level political units), namely Hong Kong and Macau (Fig. 1).

With temperate climate, abundant surface water, and loamy soils, the study area is productive. Agriculture flourished in the past. Guangzhou (the capital of Guangdong Province) was always considered the most important commercial and cultural center of southern China, and Hong Kong remains one of the dominant metropolises worldwide, with similar economic and cultural roles to those of New York and London.

Data were obtained from various sources; Table 1 illustrates the types and origins of data used to identify core areas and create a cost surface for identifying ecological corridors.

The land cover map was produced by using nine Landsat OLI (Operational Land Imager) images (paths 121, 122, 123; rows 43, 44, 45) in 2013, issued by the United States Geological Survey (USGS). Using ERDAS IMAGINE 9.2, and by referring to the Pearl River Delta Land Use Map published by the Department of Land and Resources of Guangdong Province (2013), we allocated the image data to five classes: built-up, barren land, surface water, agricultural land, and forest. To test the accuracy of classification, the Accuracy Assessment tool in ERDAS 9.2 was utilized, and 500 classified sample points within the study area were compared with the Pearl River Delta Land Use Map. The overall accuracy of the land cover classification was 91.67%, and the Kappa index was 0.87. The results clearly meet the minimum standard of 85% stipulated by the USGS classification requirement (Anderson et al. 1976; Dewan and Yamaguchi 2009; Weng 2002).

As a result of technical difficulties in extracting normalized difference vegetation index (NDVI) results from the OLI images of Landsat 8, a set of TM (Thematic Mapper) images from Landsat 5 in 2003 were used to obtain vegetation density, utilizing the NDVI function in ERDAS 9.2. The resulting vegetation density classes were defined as high intensive (0.7–1.0), moderate intensive (0.5–0.7), low intensive (0.3–0.5), sparse (0–0.3), and no vegetation (−1 to 0).

Digital elevation model (DEM) data were used to derive slope and elevation layers. By partitioning administrative areas into town level, and by using population census data from governmental agencies in 2010, we created a 328 town-level unit population density map layer based on population/area calculation. Settlement locations were determined from the centroids of built-up land areas on satellite images. Road network data were obtained from publications and were updated by referring to the most recent satellite images and to Yahoo maps.
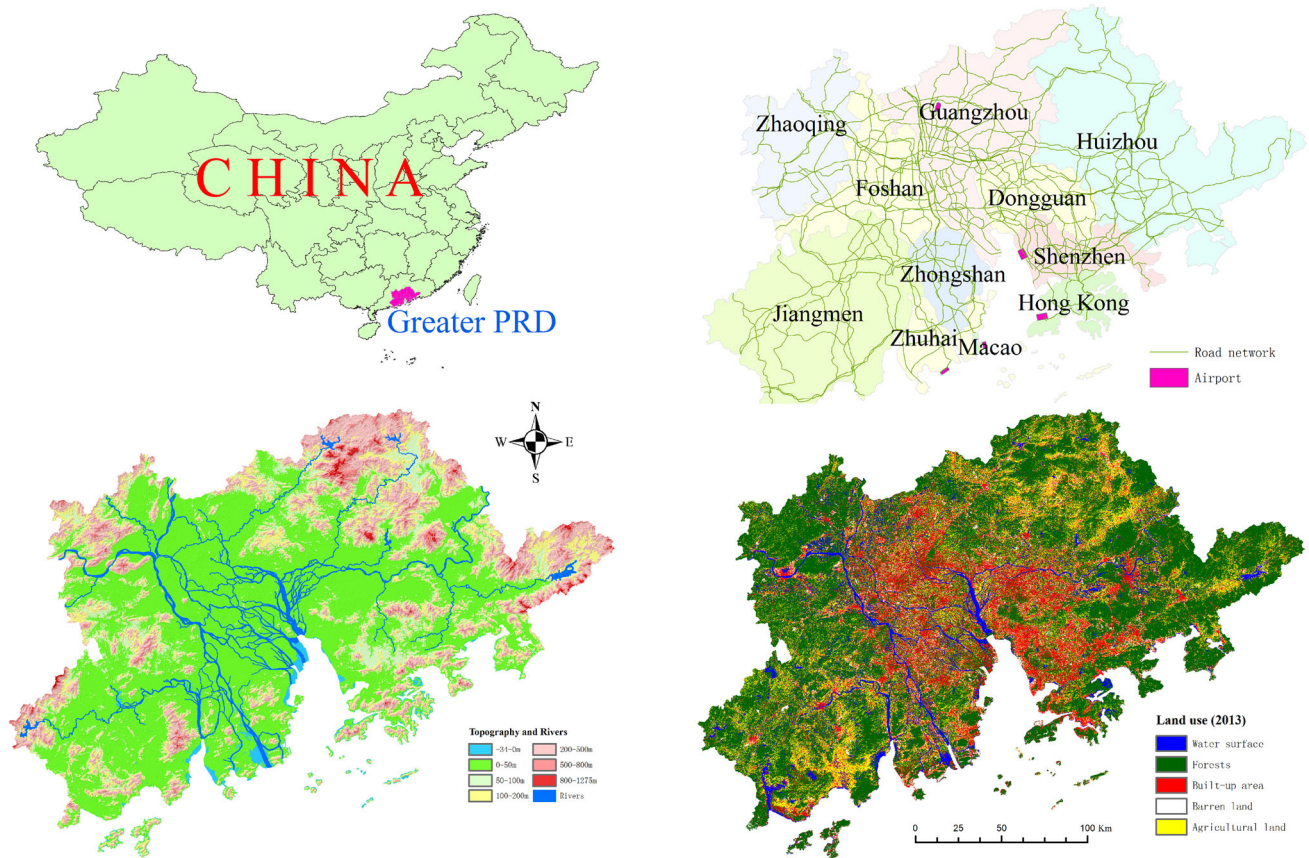
Fig. 1 Geographic context of Greater Pearl River Delta

Table 1 Data sources

Data	Derived from
Land cover	USGS Landsat 8 OLI images 2013
Vegetation density	NDVI of Landsat 5 TM images 2005
Topography (elevation and slope)	Digital elevation model, Chinese Academy of Sciences
Human population density	Guangdong Province Government Statistics 2010
Road network	Guangdong Province album, Landsat OLI images
Settlement locations	Guangdong Province album, Landsat OLI images

Projections of all the data layers were converted to the Landsat OLI coordinate system and materialized into ArcGIS 9.3 (ESRI 2008) projects in a projected coordinate system of UTM Zone 50 N, WGS 1984, with a grid cell size of 30 m.

Methodology

The approach was based on regional landscape ecological analysis. No target species were specified as proxies because of the great difficulty of finding relative animal information. It is postulated that general forest mammals (Singleton et al. 2002) behave as proxies to move through or inhabit the regional landscape-based ENs.

Constructing this regional EN involves the following principal stages:

Delineating the areas of land (core areas) to connect.

Identifying pairs of core areas to be connected.

Delineating ecological corridors that connect the identified core areas.

Deciding buffer zones to enhance and protect the delineated core areas and corridors.

The methods, data sources, and rules are detailed below.

Identification of core areas

Core areas were identified through a technological framework decided by integrating seven data layers via the overlay analysis module in ArcGIS: land cover, vegetation density,

Table 2 Data layers used to identify core areas

Data layer	Weighting
Land cover type	4
Vegetation density	2
Population density	1
Road density	1
Distance to settlement	1
Distance to road	1
Distance to river	2

human population density, road density, distance to settlement, distance to road, and distance to river (Table 2). All of the data layers were formatted in grid type and were normalized and reclassified between values of 1 (lowest) and 10 (highest). Generally factor weighting is somewhat subjective, but also can refer to expert's research results. In this study, factor weightings were assigned to each of the seven layers based on the findings of Hepcan and Ozkan (2011). Ultimately, the total core area value was calculated using Eq. (1):

$$\text{Total core area value} = \sum_{i=1}^{7} F_i \times W_i, \tag{1}$$

where F_i is the score of factor i contributing to the creation of the total core area value, while W_i is the weighting of factor i contributing to the total value. The ArcGIS Raster Calculator tool was used to sum the values to create a surface layer representing the total core area value (Fig. 2). The resulting pixel values range between 11 (lowest, not suitable) and 96 (highest, very suitable). It is reasonable to differentiate the thresholds of nature value zones among different areas affected by human activities. Considering the great differences in anthropocentric environmental impact, habitat loss, fragmentation, and land protection between the central, highly urbanized region and the remote agricultural periphery, a core area value of at least 70 was chosen as the threshold for deciding core areas within the central portion of the Greater PRD, while a threshold of at least 73 was used in the peripheral region.

To date, there is no universally accepted method for deciding the minimum size of the core area; different thresholds have been chosen according to differing study scopes and practitioners: 8 km^2 (Spencer et al. 2010), 20 km^2 (Hoctor et al. 2000), 15 km^2 (Hepcan and Ozkan 2011). In the present study area, a minimum size of 10 km^2

Fig. 2 Core value

Core value
- 11 – 50
- 50 – 60
- 60 – 70
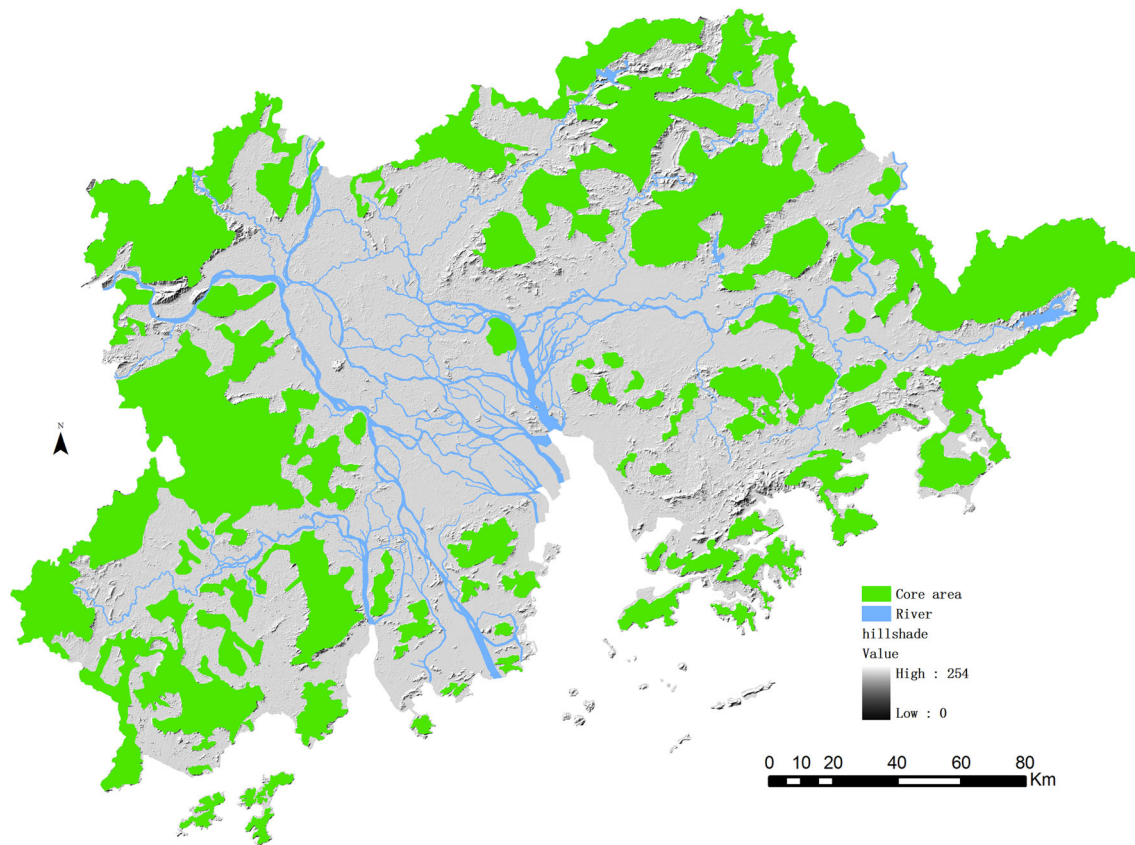- 70 – 73
- 73 – 96

0 10 20 40 60 80 Km
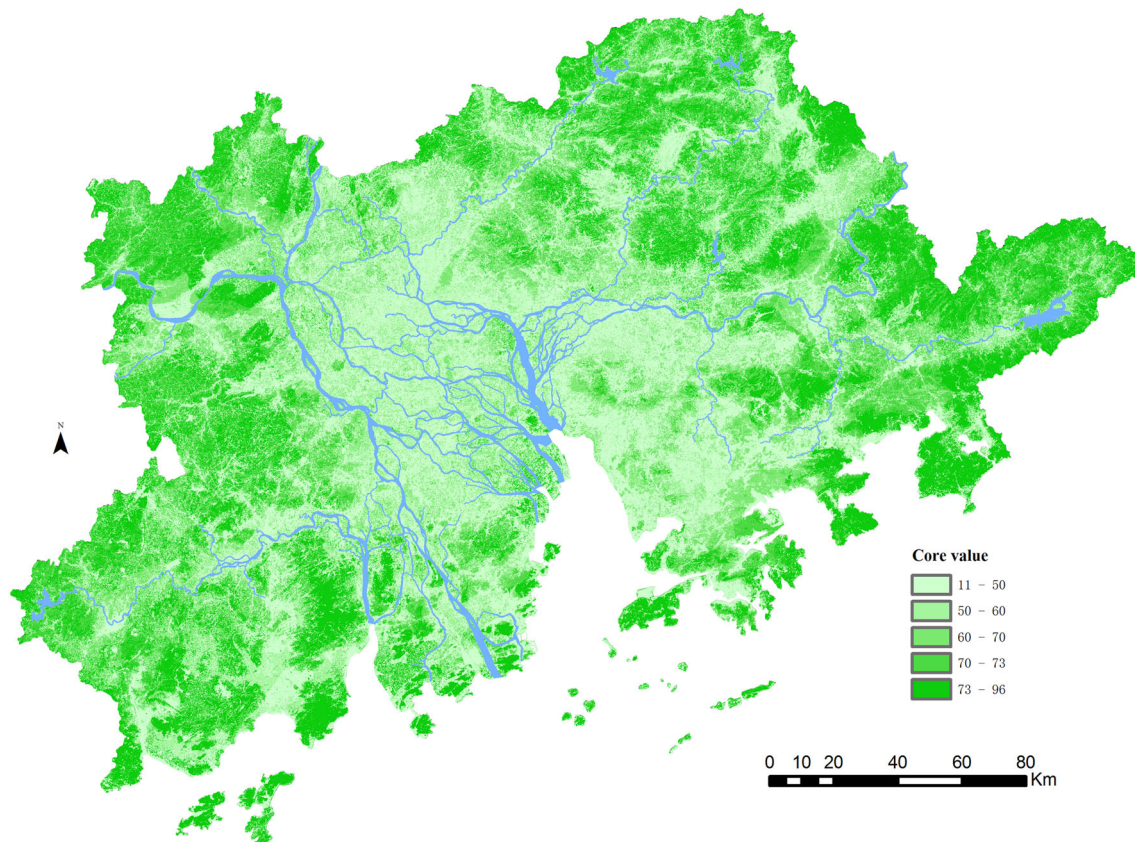
Fig. 3 Core areas

was used, depending upon the environmental and ecological characteristics of the study region. Eventually, 59 core areas were designed, ranging in size from 10.77 to 3134.32 km^2 (Fig. 3).

Determining pairs of core areas to be connected

An edge-to-edge principle (rather than centroids) was used to select pairs of core areas to be connected. The edge-to-edge method is more realistic and robust to the variety and complexity of real-world patches that are often convoluted and topologically complex (Theobald 2006). By referring to Landsat images and the topology of the patches, eye scanning was the main method for deciding the locations of source and destination pixels, with the aim of establishing a least-cost path function or locating the road fragmentation crossings.

To draw linkages on the map, a "stick" term was created to represent connection between two core areas, indicating which core areas need to be connected using least-cost path modeling or road fragmentation measures (Beier et al. 2011; Theobald 2006).

Each core area does not necessarily need to connect to every other patch (Beier et al. 2011). The following rules

were used to select pairs of core areas that should be connected:

1. Connect every core area to at least one neighbor.
2. Each core area should be connected to its nearest neighbor.
3. For most patches, an edge-to-edge approach should be used to connect patches.
4. Road fragmentation sticks should be designed to cross linear obstacles where the facing edges of two core areas are separated only by roads.
5. No stick should be present where there are large rivers (wider than 200 or 300 m), wide open water bodies such as reservoirs or sea surface (more than 1 km), or urban land areas of more than 1–2 km.
6. For large core areas (especially if topologically complex), more than one stick should be connected to its neighbors.
7. Draw a stick where land cover between the paired patches is similar to that of neighboring core areas, even if the distance is somewhat longer, or connectivity can be achieved by alternative sticks.

These rules were based on Spencer et al. (2010) but not confined to their regulations, since specific land mosaic
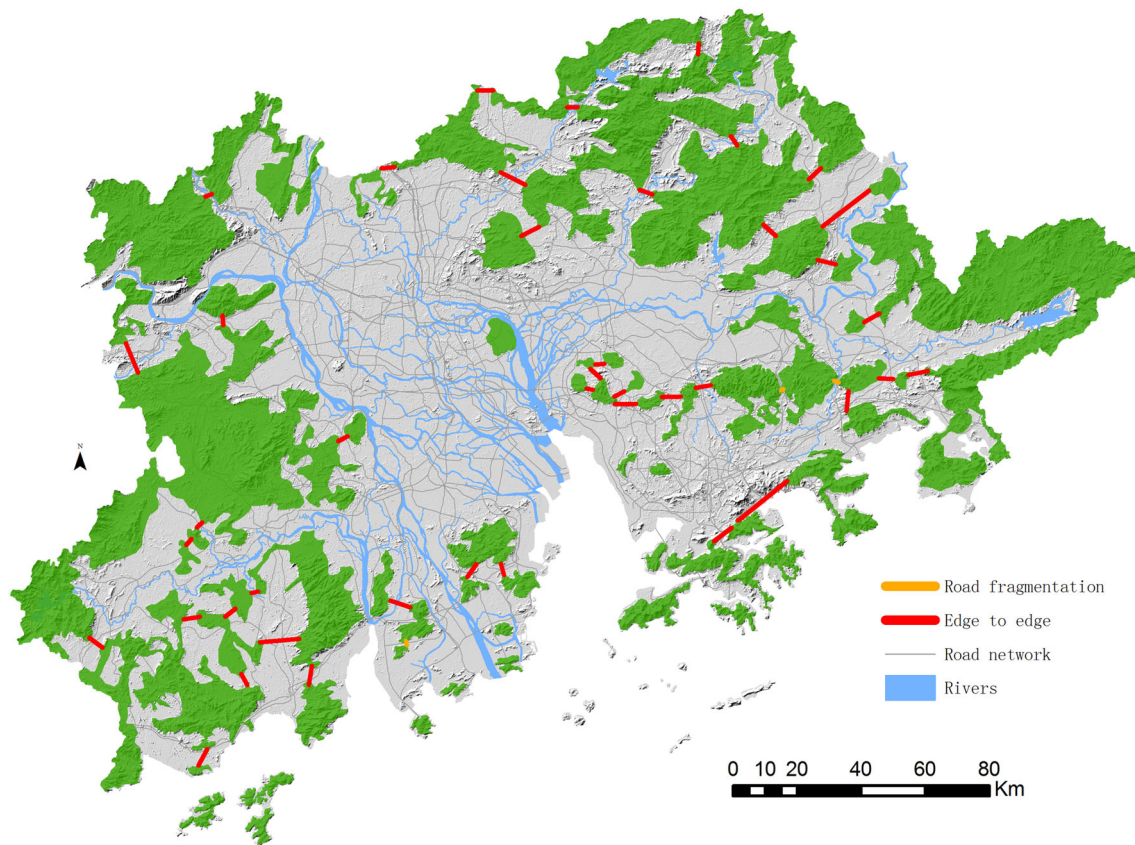
Fig. 4 Sticks for ecological networks

conditions request specific solutions, and our research chose an edge-to-edge approach instead of connecting core areas from centroid to centroid.

In accordance with the above rules, 45 sticks were designed to connect 46 core areas, as shown in Fig. 4.

Calculating cost surface

Before performing the least-cost path function, a general cost surface for ecological movement within the Greater PRD study area must be provided. The approach to calculate the regional cost surface was broadly similar to those used by other researchers (Singleton et al. 2002; Spencer et al. 2010). The cost surface represents the per-pixel cost of movement across the landscape; i.e., the opposite meaning of landscape permeability defined by Singleton et al. (2002, p 2): "the quality of a heterogeneous land area to provide for passage of animals". As mentioned previously, it is not possible to estimate movements of particular focal species. Therefore, a cost surface layer was used as a proxy, based on landscape characteristics representing the overall resistance of the landscape to ecological flows.

Factors contributing to the total value of the cost surface include land cover, vegetation density, human population density, road density, elevation, and slope. Because of the primary role of landscape naturalness in influencing ecological processes, land cover was assigned three times the weighting of other factors. Four of the six factors (land cover, vegetation density, elevation, slope) were scored by referring to the results of Singleton et al. (2002). As a result of technical obstacles and the difficulty of obtaining more detailed data, the population density and road density data were graded at equal intervals, from 1 (lowest density) to 10 (highest density). In Table 3, cost values represent the difficulty for organisms or ecological processes to move through the landscape. Cost values were calculated according to Eq. (2):

$$\text{Cost value} = \sum_{i=1}^{6} F_i \times W_i, \tag{2}$$

where F_i is the score of factor i contributing to the creation of the cost value, while W_i is the weight of factor i contributing to the cost value. The ArcGIS Raster Calculator tool was used to combine all of the data layers to produce a total cost surface (Fig. 5).

Table 3 Values for calculating cost surface

Data layer	Weight	Permeability	Cost value
Land cover type	3		
Forest		1.0	0
Agriculture		0.3	7
Built-up		0	10
Surface water		0	10
Barren land		0.3	7
Vegetation density	1		
High intensive		1	2
Moderate intensive		0.8	4
Low intensive		0.6	6
Sparse		0.4	8
No vegetation		0.2	10
Elevation (m)	1		
0–100		0.6	10
100–500		0.8	8
>500		1	6
Slope (°)	1		
0–20		1.0	6
20–40		0.8	8
>40		0.6	10
Population density (class)	1		
1		10	1
2		9	2
3		8	3
4		7	4
5		6	5
6		5	6
7		4	
8		3	8
9		2	9
10		1	10
Road density (class)	1		
1		10	1
2		9	2
3		8	3
4		7	4
5		6	5
6		5	6
7		4	7
8		3	8
9		2	9
10		1	10

Delineating least-cost corridors

Corridors can be defined as a strategy for bridging the gap between structural connectivity and functional connectivity. Matrix heterogeneity influences movement among patches. Species movements and other ecological processes are influenced not just by distances but by the characteristics of the matrix such as land cover type, topography, and human disturbance. Progress has been made from structural representations to notions of functional connectivity of landscapes (Theobald 2006).

Although there is little agreement on the best methods for identifying or designing ecological corridors, the least-cost path is the most popular method for designing ecological corridors. This computes the minimum cumulative cost at each destination landscape cell back to the nearest source cell (Theobald 2006). The primary input to a least-cost model is the cost surface. Factors contributing to the cost surface involve land cover, topography, human activities, and so forth. The first to explore this method were Knaapen et al. (1992) who defined and quantified the possibility of successful ecological processes among isolated landscape patches by calculating the "minimum cumulative resistance" through the product of the distance and the resistance of the landscape.

In this study, two ArcGIS Spatial Analyst tools—Cost Weighted and Shortest Path—were used to identify least-cost corridors. The Cost Weighted tool used the previously obtained cost surface as input, resulting in a cost distance layer and a cost direction layer. These two data layers, and the previously determined source point and destination point layers, were then used as input data to calculate the Shortest Path (least-cost path) by using the Shortest Path tool. The resulting 45 least-cost paths would subsequently be widened.

Previous studies used differing criteria to define the widths of the determined least-cost paths. Harrison (1992) suggested that corridor width should be estimated from data on home-range sizes and shapes, and may depend upon corridor length. Accordingly, the minimum corridor widths for many forest mammals range between 1 and 12 km on the basis of their home-ranges. Beier et al. (2006) suggested that there are many reasons for wide ecological corridors, such as animals needing sufficient area to support resident metapopulations over time while crossing between core areas; wide linkages buffering against edge effects, and enhancing the ability of biota to respond to climate change, etc.; when designing the South Coast Missing Linkages in California, the authors used a corridor width of 2 km. Furthermore, Hoctor et al. (2000) chose to widen ecological corridors in Florida up to 25% of the corridor's length, and Hepcan et al. (2011) used a parameter of 15% of linkage length.

In the present study, when determining the corridor widths in the outer east, north, and west portions of the study area, a width of 3 km was taken for paired core areas whose relative distance were shorter, or for pairs where at least one of the partners was small. A width of 5 km was
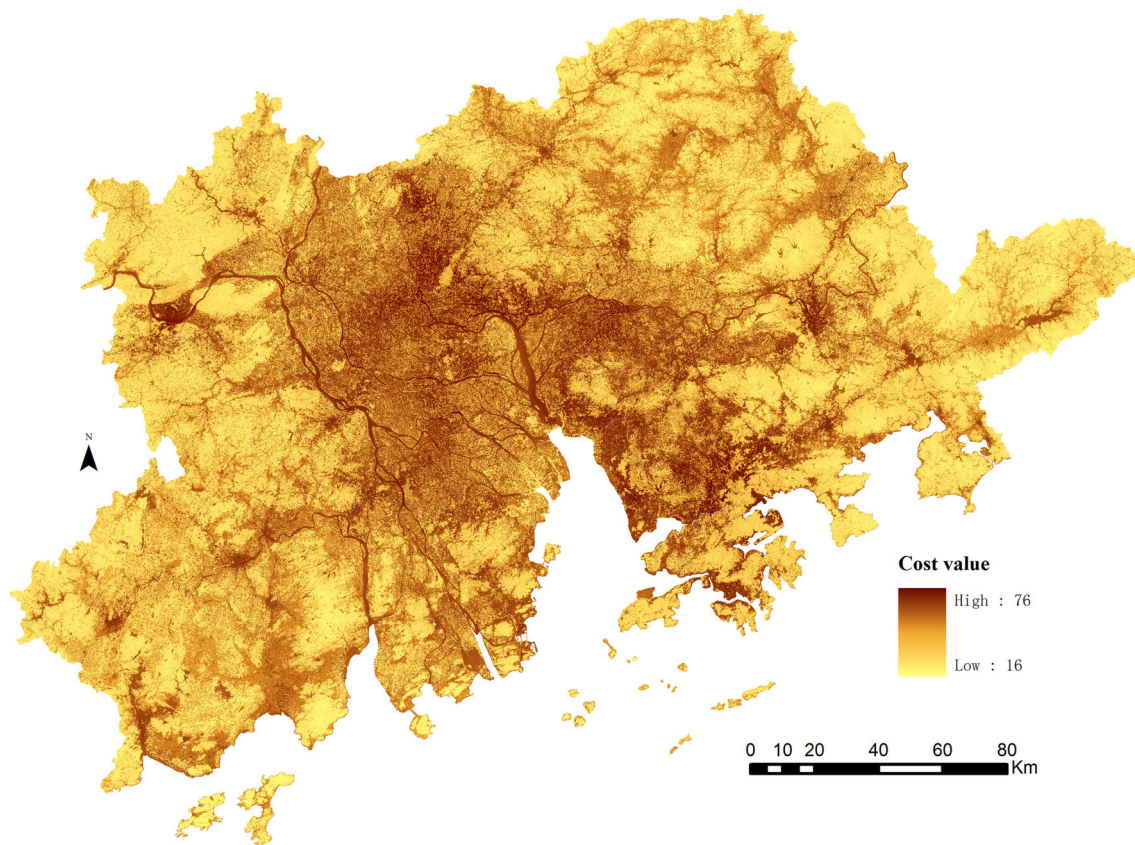
Fig. 5 Cost surface value

Table 4 Designed corridor widths in Greater PRD

Type	Width (km)	Location and background
Longer	5	Peripheral natural or agricultural area
Connecting two large core areas	5	Peripheral natural or agricultural area
Shorter	3	Peripheral natural or agricultural area
Connecting at least one small core area	3	Peripheral natural or agricultural area
Longer	1	Inner highly urbanized area
Shorter	1	Inner highly urbanized area
Road crossing	1	Inner highly urbanized area

assigned to pairs of core areas whose relative distances are longer, or to pairs of core areas that were both large in area. However, for some portions of the inner central area of the Greater PRD, the distribution of urban development meant there were insufficient landscapes to be protected as routes for animals. Therefore, it was decided to define a narrower corridor width of 1 km within the highly urbanized central area, even in cases where the relative distance was long, considering that there are already insufficient remaining natural forestry landscapes, and that rapid urbanization is continuing in the area. Road fragmentation crossings were also assigned a width of 1 km (Table 4).

Improving connectivity of the Greater PRD regional landscape by extending ENs

Riparian connectivity protection areas

Vegetation along major river corridors is the second-most important priority for nature conservation. Forman (2008a, b) suggested a five-class order of nature conservation priorities, illustrated by the patch–corridor–matrix model: (1) A few large, natural vegetation patches; (2) Vegetation along major streams; (3) Connectivity between large patches; (4) Small patches/corridors scattered across less suitable matrix; and (5)

Small patches/corridors clustered around large patches. This means that, next to large patches, river corridors are the most important element in nature protection strategies. Furthermore, rivers themselves act as connectivity corridors that maintain species mobility and other ecological processes, especially for aquatic species and amphibians. Furthermore, river routes, when combined with dense natural vegetation of adjoining land on both riverbanks, protect against erosion, and inputs of dissolved mineral nutrients and toxic chemicals from the surrounding matrix.

The Pearl River system consists of the rivers Xi, Bei, Pearl, and Dong, which converge at the mouth of the Pearl River. The Tan River drains into the South China Sea but is also channelized with the Xi River. Hence, the Greater PRD mainly comprises the lower sections of the Xi, Bei, and Dong rivers, and the entire systems of the Tan River and Pearl River. Although there is a dense and complex network of flows within the topographical delta, the water channels of the five rivers can be distinguished. These five river systems function as aquatic ecological systems; they connect many of the proposed ecological core areas and ecological corridors while also maintaining aquatic habitats and flows for species and important ecological processes. To illustrate the contributions that these rivers, their branches, and adjacent vegetation can make to both terrestrial and aquatic connectivity, these riverine corridors and adjacent vegetation cover should be incorporated into the system for maintaining regional nature connectivity.

For the purpose of implementing this riparian connectivity protection scheme, simply including the water routes of these rivers and their tributaries and designing the widths of adjoining vegetation buffers are more efficient than least-cost modeling for mapping connectivity (Spencer et al. 2010). The five main river channels (total length 1300 km) and associated tributaries were depicted, and a buffer of 2 km was assigned on each side of the channel. As discussed previously, there are no universal criteria for designating the widths of ecological corridors or for the present riparian connectivity designation (blue–green corridor). Furthermore, a width of 2 km was selected here solely to simplify the mapping process. In reality, there should be wider blue–green corridors within the upper river reaches in the mountainous peripheral areas of the Greater PRD, and narrower vegetation strips along lower reaches on the plain inner Greater PRD zone because of the large anthropogenic developmental pressures, while in some metropolitan areas the river banks have already been developed and it is not possible to designate vegetation strips.

Stepping stones

Stepping stones are small, natural vegetation patches scattered throughout a less suitable matrix, which facilitate the movement of certain species, provide some protection, and may even enhance species richness if near a large patch of natural vegetation (Forman 2008a, b). The Greater PRD includes dozens of small, isolated hills scattered across the PRD. Some are located near large patches, whereas others are dozens of kilometers removed from any patches. These isolated hills serve as stepping stones and should be incorporated into the regional nature conservation system. Furthermore, patches with "core area value" larger than 70 within the inner Greater PRD zone might also be designated as stepping stones, especially the patch located near the mouth of the Dong River.

Results

Figure 6 presents the EN map for the entire Greater PRD, which is composed of 46 core areas (ranging from 10 to 3000 km^2) connected by 45 corridors, resulting in seven networks. Although the total area of the 59 core areas is 16,546.2 km^2 (accounting for 36.86% of the 44.891.2 km^2 Greater PRD), 13 patches (492.94 km^2) were not linked as part of the networks, owing to their isolated or remote locations, the presence of urban areas, or open water obstacles. As a result, the total area of the connected networks is 16,757.73 km^2 (37.33% of the study area), with corridors covering 704.47 km^2 (1.57%) and connected core areas covering 16,053.26 km^2 (35.76%).

Within the Greater PRD, large rivers resulted in fragmentation of the terrestrial areas, making it impossible to link the entire area into a single EN. Thus, seven discrete ENs are proposed (Table 5; Fig. 7). These seven networks can be defined according to two zones: the central inner/developed zone and the peripheral outer/natural zone.

Central inner zone ENs

The central inner zone comprises approximately one-third of the Greater PRD study area. It stretches west from Sanshui city east to Huizhou metropolitan area; and it ends at the mouth of the Tan River (southwest) and Daya Gulf (southeast).

This inner zone contains three (networks 5–7) and a half (the western portion of network 2) networks, which comprise 18 core areas connected by 15 corridors. These networks are located in the eastern area and the southern edge of the inner zone. The core areas are small patches of 10–350 km^2. The corridors are narrow and primarily cross agricultural land or other less natural landscape matrices. Owing to the predominance of built-up land uses, these three simple, small networks (networks 5–7) are isolated from each other. Even the western portion of network 2 mainly consists of small patches and corridors with less
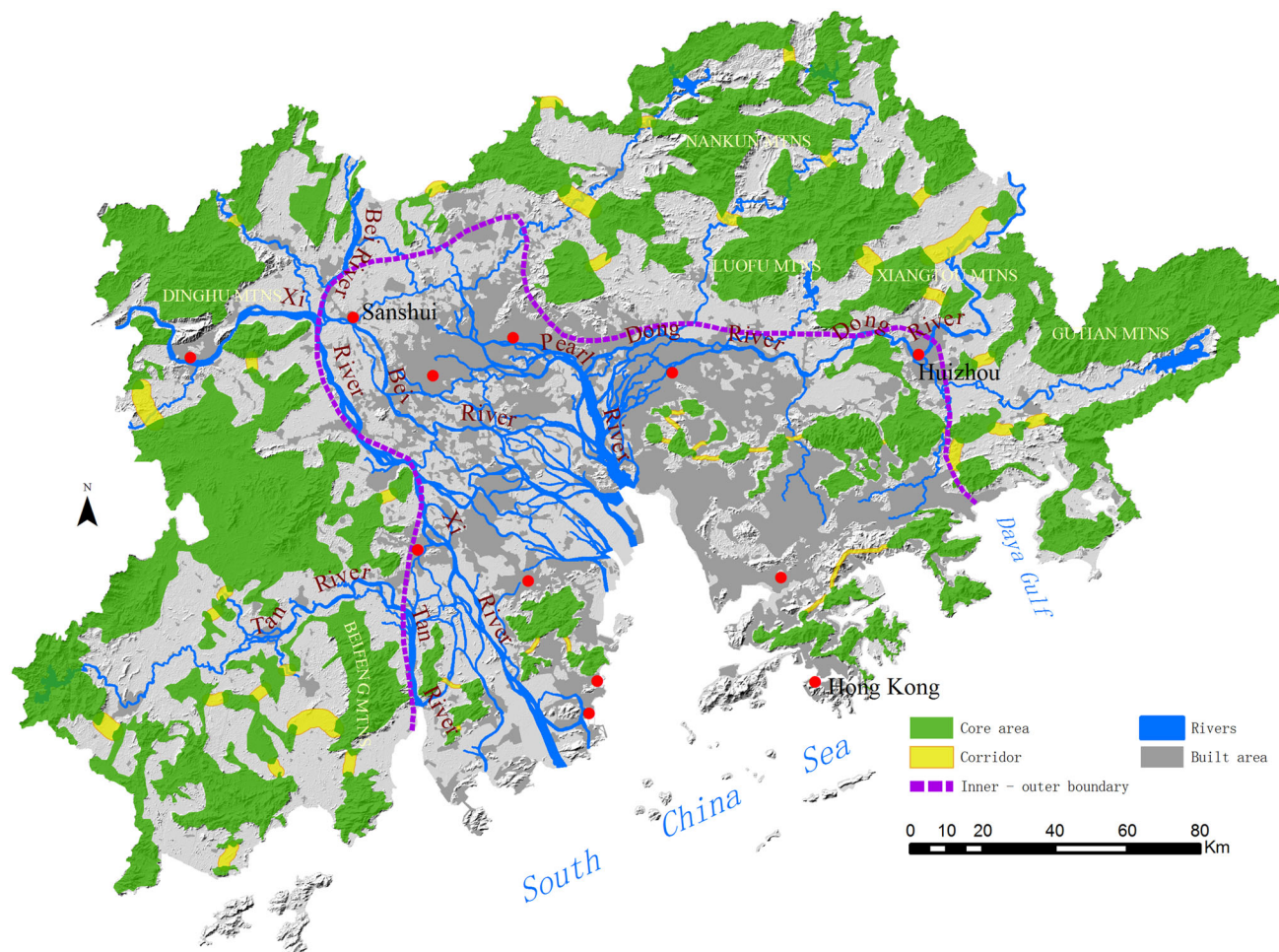
Fig. 6 Ecological network map

Table 5 Proposed ecological networks

Network name	Area (km²)	Area ratio (%)
Network 1	5701.61	12.7
Network 2	3617.99	8.06
Network 3	4926.64	10.97
Network 4	1498.37	3.34
Network 5	163.76	0.37
Network 6	280.42	0.62
Network 7	568.94	1.27
Total	16,757.73	37.33

natural characteristics. Another distinct characteristic is that none of the networks extend across the central plain area of the PRD, since this region is already converted to agricultural and urban land uses, and there are almost no hilly landscapes that can maintain natural vegetation. Furthermore, one of the two corridors within network 7, which is the longest corridor (about 22 km) in the Greater PRD region, must cross the border between Hong Kong

and Mainland China, resulting in a cross-border fencing challenge for the implementation of connectivity planning.

The fast-growing urbanization within this inner zone is the primary impediment to maintaining, restoring, or enhancing landscape ecological connectivity. Protecting the remaining natural landscapes within the small hills, riparian areas, and wetlands should be adopted as one of the main tasks in sustaining and enhancing ecological connectivity; in comparison, constructing the proposed corridors seems more difficult.

Peripheral outer-zone ENs

The peripheral outer zone covers approximately two-thirds of the Greater PRD study area. It extends from the east corner, through the northeast, northwest, and west, to the southwest corner of the study area, and is shaped like a fan-like surrounding the inner U-shaped central/developed zone.

The peripheral outer zone contains 28 core patches of 12–3000 km², which are linked by 30 corridors. The core
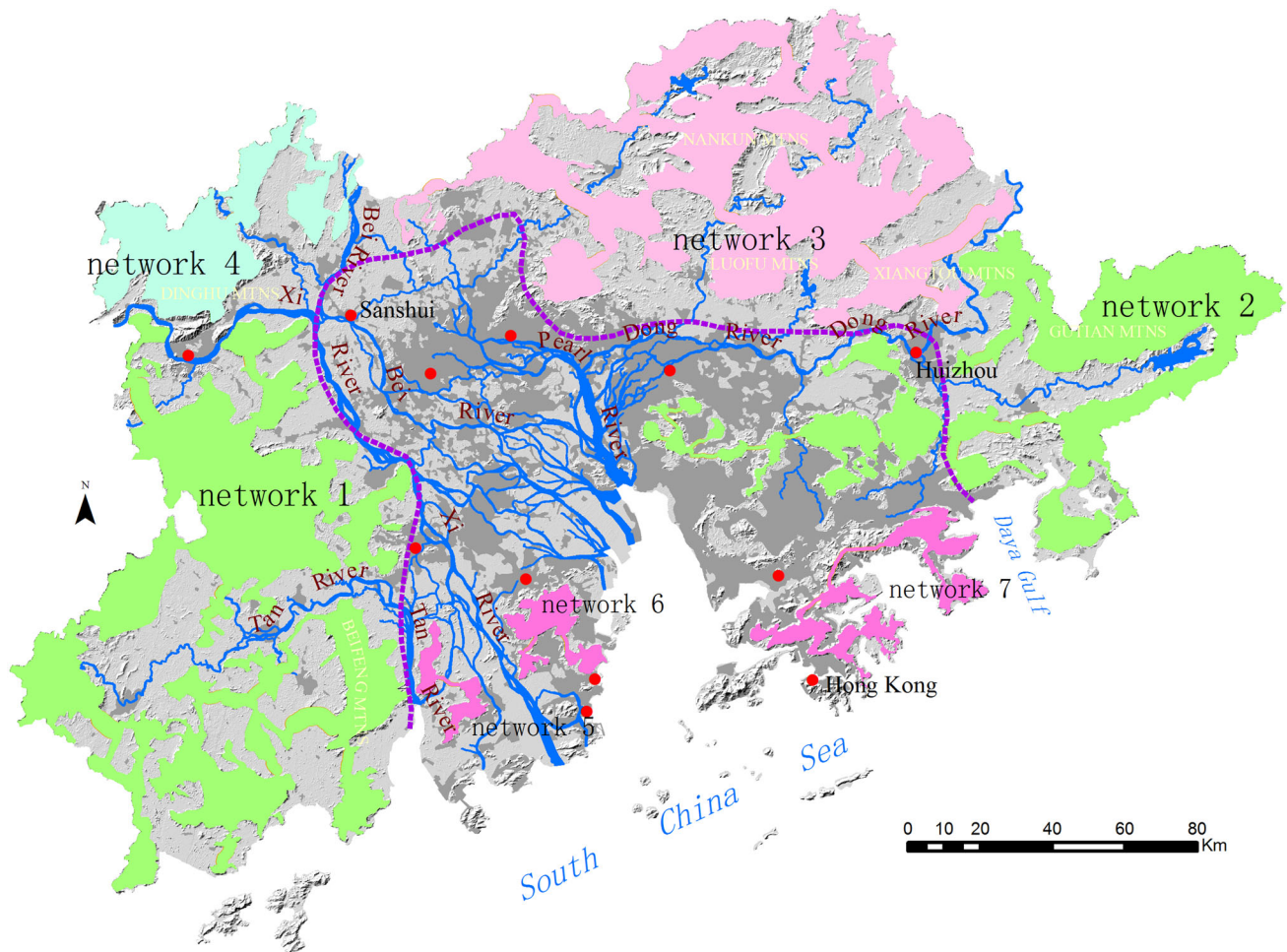
Fig. 7 Seven proposed ecological networks

areas are generally large, ecologically intact, and well protected, and they are often covered by evergreen forests and woodlands, some with shrubland. Each of the four networks (networks 1, 3, 4, and the eastern portion of network 2) has at least one core patch with an area of 1000 km² or more. Most core areas are associated with designated parks, wilderness areas, or wildlife refuges. The most important protected core areas are covered with dense forests, usually on higher mountains.

As a result of the edge-to-edge approach to designing linkages, the corridors are often relatively short, except for a few longer linkages in network 1 and network 3 and particularly a corridor in network 3 of approximately 20 km (next to the longest corridor, linking Hong Kong and mainland China). Ecological corridors generally cross areas of natural land cover, but some must traverse agricultural land or small rivers and streams, or even cross local roads.

A major focus of connectivity planning in this subregion should be maintaining and protecting the large core patches. These extensive core patches can protect aquifers,

connected stream headwaters, large home-range species, viable populations of interior species, and can mitigate natural disturbances (Forman 2008a, b). Sustaining and enhancing these large core areas are paramount for functional connectivity planning within this study area. Another approach is to improve road-crossing structures such as overpasses or underpasses, considering that road fragmentation and urbanization are likely to degrade and possibly imperil this peripheral area.

Extensions

Figure 8 presents the entire extended regional nature protection scheme including the regional EN and extensions. The total area of the designed 11 stepping stones is 237.65 km², covering 0.53% of the Greater PRD study area. All these stepping stones are located within the central inner zone. Although the suggested blue-green corridors have a total length of 1300 km and their widths were assigned to be 4 km, it is unrealistic to sum a digital figure to express the coverage they occupy since there should
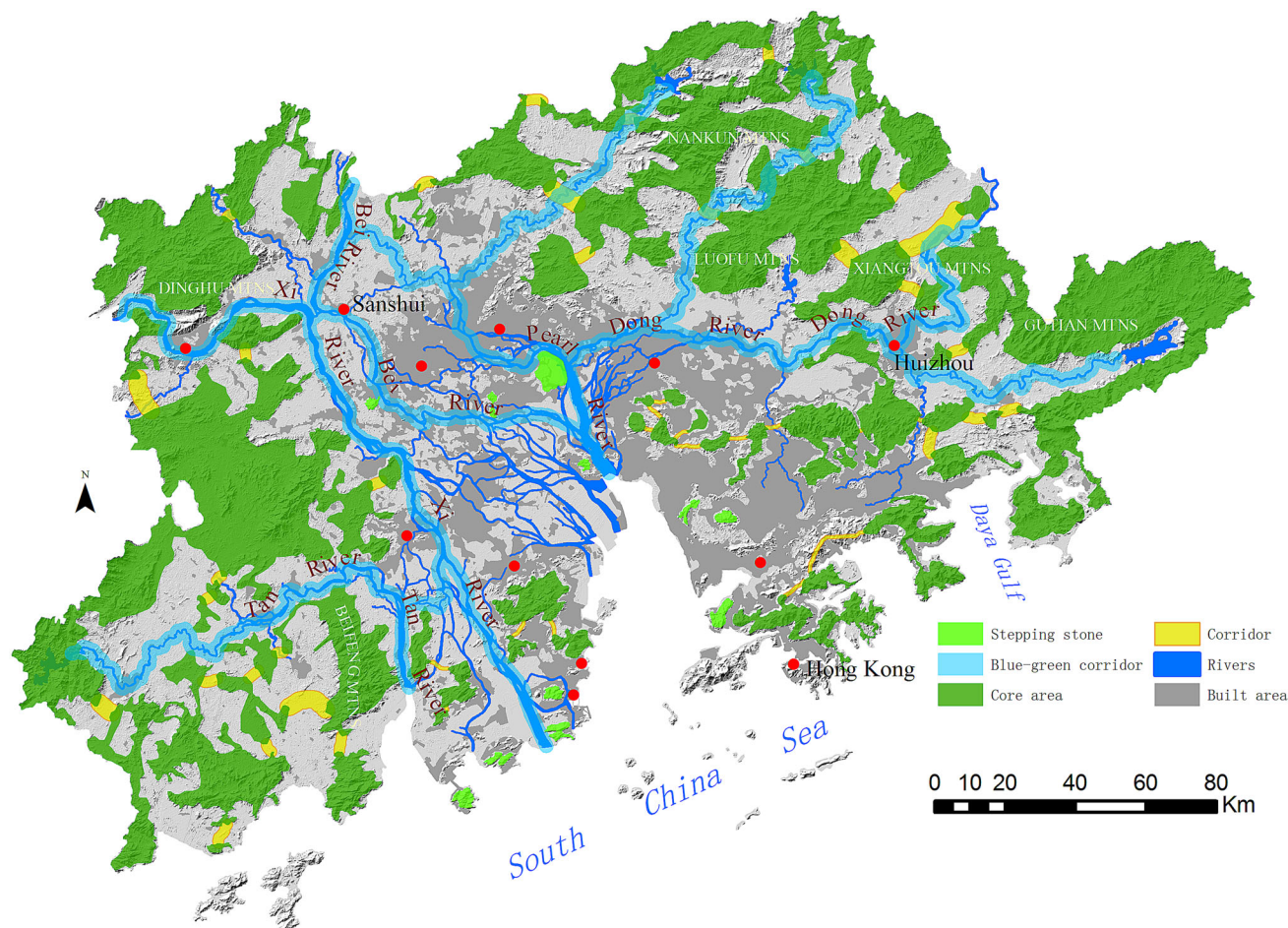
Fig. 8 Extended ecological network map

be different widths along different river reaches. In fact, this a conceptual vision instead of a detailed designation.

Discussion and conclusions

This study employed GIS technology to examine how a landscape ecology approach might be employed to establish a regional EN. Core areas were identified using an overlay method (Spatial Analyst module) in ArcGIS to integrate multiple data layers. Ecological corridors were delineated in the GIS via a least-cost path algorithm. The resulting map represents a regional EN embedded in the regional landscape, against the background of human land use. However, some further issues need to be addressed.

Within the Greater PRD, there are already nature protection areas such as Beifeng Mountains National Forest Park, Nankun Mountains National Forest Park, Gutian Nature Protection Area, and the Xiangtou Mountains Nature Protection Area. Additionally, some local endangered plants and animals are protected by governmental agencies,

such as pangolin in the Beifeng Mountains and silver pheasant in Gutian Nature Protection Area. However, in the present study, as a result of the lack of reference materials and maps, these were not included in the GIS layers used to produce the core area results. Further consultation with biologists or ecologists will improve knowledge in these fields and help to incorporate such data into future research projects.

According to classical definitions, an EN should include three basic spatial elements: core area, corridor, and buffer zone. Certainly, buffer zones are indispensable for designing a holistic EN, primarily for reasons of edge effects. To date, there are no universally accepted criteria for defining buffer widths. Weber et al. (2006) assigned ecological corridors of 175 m width in their study for Maryland's Green Infrastructure; Hepcan et al. (2011) defined a corridor width of 500 m when establishing ENs of Çeşme–Urla Peninsula in Turkey; Beier et al. (2008) recommended a width of up to 300 m in terrestrial systems and 50 m in aquatic systems. In practice, different buffer widths are required for different situations.

We did not assign specific buffer widths when designing the corridors and core areas in this study of the Greater PRD area. For corridors, widths of 1–5 km have already been assigned to corresponding corridors in previous studies. This includes buffers to counteract edge effects. For core areas, large patches can take widths of up to 300–500 m, while a narrower buffer zone is more realistic for small patches, considering their relative areas and the land use pressures from the surrounding matrix. In short, the designation of buffer widths is landscape-specific, determined by the practical landscape situation and by human land uses and development.

Globally, it seems that researchers usually define their study areas according to administrative units—such as within a country, province, county, or city boundary. This is convenient but often fragments a natural region between different administrations. This is also the case in the greater PRD study area: the 44,891.2 km^2 terrestrial area (including islands) contains 10.5 prefectural-level administrative units, but divides biota and landscapes (mountain ranges, coastlines, and river routes) between the Greater PRD and neighboring regions. When defining ENs, the range is arbitrarily restricted to these administrative boundaries. Ecological systems extend beyond the predefined study boundaries, into neighboring areas. Consequently, it is imperative that the established EN should be incorporated into an integrated system that includes neighboring regions. For example, the proposed identical networks 2–4 could be linked together into a whole network if the study area were enlarged in scope to include the upper watersheds of the Dong and Bei rivers. Such proposals were not included in the present study, but could form part of future work.

This Greater PRD EN can serve as a basis for a regional nature conservation system that integrates ENs with other aspects of conservation such as stepping stones and a riparian protection system, which we tried in the preceding section.

The overlaps between different protection elements (core areas, corridors, riparian areas, and stepping stones) were excluded from the GIS analysis. The final total area of extended ENs is 21,513.8 km^2, accounting for 47.92% of the entire Greater PRD. The addition of the riparian protection areas and stepping stones is indispensable for regional landscape connectivity conservation. The proposed core areas and terrestrial corridors are connected via many riparian corridors through otherwise inhospitable matrices, and a few projected stepping stones are located between or near the protected core areas. Maintaining and enhancing these riparian areas and stepping stones should be a focus of the entire regional landscape connectivity strategy.

The establishment of ENs constitutes only the physical portion of strategic regional landscape planning; further research and the construction of a human land use framework are needed to manage a holistic land use system. At the regional scale, geographic and economic concepts such as central place theory or location theory can be integrated and applied into landscape planning strategies. This should be one way of achieving breakthroughs in academic studies and landscape planning professions.

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