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ORIGINAL PAPER

Incorporating landscape connectivity into household pond configuration in a hilly agricultural landscape

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Abstract Manmade ponds are common landscape features in rural areas and also important habitats for maintaining biodiversity. However, they are vulnerable to anthropogenic activities, land-use changes, and habitat degradation; many ponds being filled or (re)created arbitrarily. Little attention has been paid to quantifying the spatial structure of these manmade ponds at a landscape scale, nor to their potential functional benefits in promoting ecological flows and interactions between habitats for whole-ecosystem integrity. In this study, we investigated the patch-based landscape connectivity of household ponds, a particular type of domestic pond prevalent in hilly rural areas of China, by using least-cost path modelling and graph theory based network analysis. A hierarchical network was modelled consisting of 4606 individual ponds, 373 pond patches and 772 potential links within a 1.5-km threshold distance. Network importance analysis revealed that the largest pond patch contributes 24.5 % to network building and that patches with larger areas are generally more important. In contrast, the importance of the simulated links is only 2.3 % at most, indicating that the network has spatial redundancy which can strengthen resilience to uncertain disturbances. Our study moves beyond network simulation and importance assessment by directly relating the connectivity analysis to a real construction context through the incorporation of a spatially explicit land suitability analysis. This approach systematises the analysis of pond landscapes and guides integration with the wider landscape matrix. It provides operational spatial suggestions for holistic landscape planning across local to regional scales.

Keywords Functional connectivity · Land suitability · Graph theory · Pond engineering · Three Gorges Reservoir Region

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Introduction

Ponds are comparatively small artificial or natural shallow-water bodies (lentic ecosystems). Although they do not receive as much attention as other significant running water systems, the total area of all ponds globally is 100 times greater than the total area of larger lakes (Oertli et al. 2005). They are common landscape features and habitats across all types of terrestrial environments worldwide. Recent studies have highlighted their notable impacts on catchment hydrology, sedimentology, geochemistry and

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ecology (Smith et al. 2002). Ponds are among the most efficient best management practices (BMPs) for treating non-point-source pollution (Harrell and Ranjithan 2003; Park et al. 2012; Youn and Pandit 2012). Additionally, ponds are crucial habitats for maintaining regional floral and faunal diversity, especially for amphibians, reptiles and aquatic plants in landscapes where wetland habitats have been severely reduced (Allentoft and O'Brien 2010; Shulse et al. 2010).

Pond building is of particular interest to Asian countries, especially in rural areas where there is an imbalance in rainfall distribution geographically and seasonally and local people rely heavily on ponds for water collection and storage. Chinese people have a long history of building and utilising ponds, such as the well-known dike-fish pond system in Southeast China (Ruddle and Zhong 1988). There is a stronger desire for ponds in hilly areas, especially now to ameliorate climate change and associated extreme weather events such as droughts and flooding. More than 180,000 small manmade ponds exist across the hilly region of Chongqing Municipality (Southwest China) (CQWRB (Chongqing Water Resource Bureau) 2015). Because of the topography and the summer monsoon, they conveniently harvest rainwater for family supply and crop irrigation during the dry season. Many household activities rely on such ponds, e.g. for clothes washing, food cleaning, livestock drinking water, irrigation, fire control, and recreation, so they are known as "household ponds" (*dangjiatang*, see Chen et al. 2014, Fig. 1). The large number of ponds within a mosaic of forests, farmland and local settlements across the region form a distinctive, variegated ecocultural landscape.

Despite their importance in supporting ecosystems and livelihoods, ponds are created for individual domestic needs and site selection is somewhat arbitrary (wherever is convenient for irrigation or family usage) (Chen et al. 2014). According to elderly local people in Chongqing, most household ponds were actually built during the 1950s and 1960s when the land was collectively owned in China. Pond construction was organised by communes or local governments as an important part of water infrastructure throughout the rural areas. The main purpose of the ponds was agricultural irrigation at that time. During subsequent generations, those original ponds have undergone dynamic changes. Some are maintained well with regular dredging operations, but some have been filled in to provide more land. Since then, new ponds have also been constructed by individuals or families because China has implemented a land contractual operation system. Individuals have the right to decide where to build on their land and what size the ponds should be.

There seems to be a lack of systematic and network perspectives on the whole pond system and the wider services they can potentially provide. Most twentieth century conservation focused on maximising biodiversity within reserves (Shafer 1990); however, in recent decades, the emergence of theories on the biodiversity "spillover" effect (Gell and Roberts 2003), metapopulation dynamics and metapatch concepts (Freckleton and Watkinson 2002), source–sink dynamics (Dias 1996), and environmental continuity and connectivity analysis (Ayram et al. 2015; Urban et al. 2009) have promoted conservation management beyond habitat borders and as a networked system on a regional scale (Brose 2010). Such a shift offers new insights into how we can better organise the spatial distribution of ponds in terms of augmenting biodiversity.

Landscape connectivity analysis and patch-based graph theory provide powerful tools for addressing issues related to complex network structure and the interactions and flow efficiency between landscape elements (Urban et al. 2009). Landscape connectivity has been defined as the degree to which the landscape facilitates or impedes movement among resource patches (Taylor et al. 1993). A well-connected ecological network is believed to facilitate energy and resource fluxes, species dispersal, genetic exchange between patches, and to contribute to the maintenance of ecosystem biodiversity and integrity (Brudvig et al. 2009; Hagen et al. 2012). There are two main types of connectivity (Crooks and Sanjayan 2006): (1) structural or physical connection—the tangible substance that links habitats, such as rivers and greenway corridors, and (2) functional connection—the behavioural responses of individuals, species or ecological processes to the landscape. Functional connectivity is generally maintained by "stepping stones" between landscape elements or habitat patches. This is a practical approach for conservation in contemporary cultural landscapes due to the increasing difficulty in maintaining physically continuous corridors when competition for productive land is so intense.

Various landscape algorithms and graph theory have formulated meaningful indices to characterise landscape structure and functional connectivity, and these are being increasingly applied to facilitate conservation-oriented land-use planning in human-dominated landscapes (Adriaensen et al. 2003; Pascual-Hortal and Saura 2006; Urban and Keitt 2001). In graph theory, the landscape is abstracted into a graph comprising sets of nodes (habitat patches) and links. Two nodes that are separated by a distance less than a defined threshold distance are considered to be connected by links (Brose 2010; Urban and Keitt 2001). Links, which may or may not have physical correspondence in the landscape, represent the capacity for individual movements or ecological flows between pairs of nodes in the case of functional connection (Pascual-Hortal and Saura 2006). One of the important contributions of graph-based simulations is to identify the cut-nodes and

Fig. 1 Photos showing household ponds

cut-links which, if removed, would disconnect a critical component in a landscape (Urban and Keitt 2001). Despite the widely acknowledged application of connectivity theory to various types of habitats (Ayram et al. 2015) such as forest (García-Feced et al. 2011; Gurrutxaga et al. 2011; Yang et al. 2014) and urban green space (Kong et al. 2010), to our knowledge, not much research has specifically highlighted the phenomenon of the large quantity of "randomly" built household ponds, their ecological significance in species-habitat conservation, and the corresponding conservation imperatives for the wider regional landscape.

Accordingly, here, we propose a framework using network analysis approaches combined with real-world contexts for pond system assessment and network (re)development. Most studies pertaining to pond system conservation use amphibians (i.e. frogs, toads, turtles) as focal species since they are indicators of habitat quality and their movement patterns and habitat selection have been widely studied (e.g. Allentoft and O'Brien 2010; Fischer et al. 2015; Luo et al. 2003). Importantly, their special water–land life cycles effectively link up terrestrial with aquatic systems and thereby benefit comprehensive landscape planning. Here, we use a locally common pond-dwelling frog (*Rana limnocharis*) in our agriculture-dominated hilly landscape as a focal species (Dash and Mahanta 1993; Wu et al. 2011). Taking Hanfeng Lake valley (Chongqing Municipality) in the Three Gorges Reservoir Region (TGRR) as a case study, this framework applies a combination of least-cost analysis, graph-theoretic techniques, and land suitability analysis, so that planners and policy makers can conveniently determine the priorities of maintaining current ponds (as habitat patches) and adding new ponds (as stepping stones) for overall landscape connectivity in the region. Compared to other applications of similar methods and metrics, we did not focus on assessing pond habitat loss but on strengthening and improving the connectivity by directly relating connectivity analysis to tangible spatial planning practices.

Methodology

The optimisation of a pond network includes the identification and evaluation of the existing pond system, the simulation of more connected spatial configurations, and the hierarchisation and prioritisation of important ponds and functional connectivity. This involves creating a least-cost path (LCP) model with ArcGIS 10.3, Linkage Mapper Toolist (McRae and Kavanagh 2011), and a graph theory-based network model utilising the ArcGIS 10.3 and Conefor 2.6 software (Saura and Torné 2012). The overall analysis framework is shown in Fig. 2. Because the habitats of the focal amphibian species involve both aquatic and land environments, we adopted the "metapatch" concept following Zetterberg et al. (2010). In our case, the metapatch included the pond(s) and surrounding upland environments, referred to as the "annual home range" or "territory" supposedly needed to supply all the resources for the species through the year (Decout et al. 2012; Powell and Mitchell 2012; Zetterberg et al. 2010). The simulated pond patches were then used as habitat sources (nodes) for further graph network analysis. Therefore, our pond landscape connectivity development is performed on patch-based graphs rather than individual ponds forming the network.

Study area

The study area (107°42′–108°54′E, 30°41′–31°42′N) is Hanfeng Lake valley of the Pengxi River catchment located in the heart of the TGRR. In the centre, the valley encompasses a densely populated urban area—Kaixian County, which is a new town relocated to higher ground above the filled reservoir (Fig. 3). As a reservoir margin town, Kaixian is experiencing unprecedented socioeconomic development.

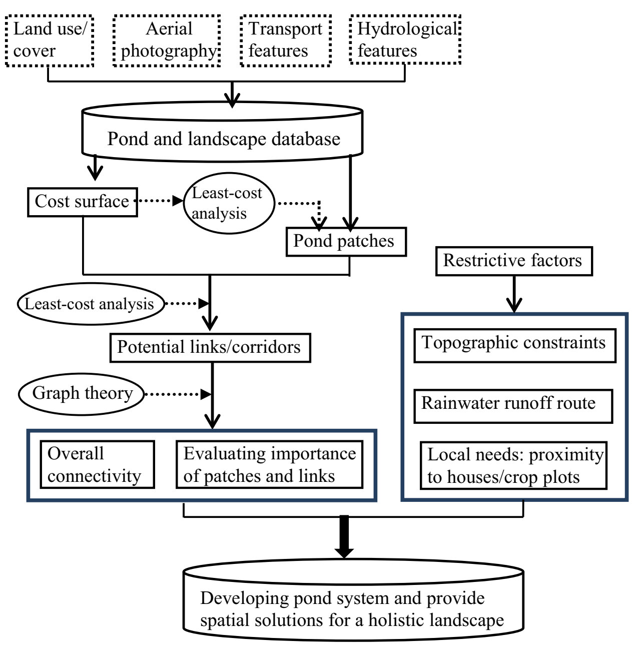


Fig. 2 Scheme of the proposed framework to optimise a household pond landscape network

More than two million people live here, and the majority are farmers. The land use across the catchment is heterogeneous, including intensive urban built-up areas, orchards, vineyards, maize crops, small reservoirs and soil conservation forests (pine and cypress), shrublands, scattered villages, as well as a large number of household ponds. Agriculture activities have been curtailed in the region over recent decades due to the nationwide Grain for Green Program and the ongoing Ecological Barrier Zone of TGRR project at elevations between 175 and 275 m (State Council of China 2011). The existing ponds may have suffered from inappropriate manipulation for ecological restoration projects, with many ponds being drained and filled for planting.

Pengxi River is one of the most important primary tributaries and recharge sources of the Yangtze River. The studied valley is 773.5 km^2 in area and characterised by a diverse topography of low-elevation river valleys (the lowest is 158 m a.s.l.), foothills and mountain ranges (the highest is 1162 m a.s.l.). The valley has a northern subtropical humid monsoonal climate with an average annual precipitation of 1200 mm, 60–80 % of which is concentrated between April and September. The mean air temperature is 18.2 °C, and there are less than 20 frost days per year. The prevailing soil types are paddy soils (below 173 m) and purple soils that support subtropical broad-leaved evergreen forests as the regional climax community.

Because of the humid climate, complex mountainous topography and negligible impacts from Quaternary glaciation, the TGRR is biogeographically diverse on both national and global scales (Wu et al. 2004). Its flora accounts for one-fifth of all seed plants in China, including a number of ancient, endemic and rare species from the tropical, subtropical and temperate zones. The region's fauna is represented by a varied assemblage of both terrestrial and aquatic vertebrates, with more than 850 species. The Chongqing section alone (80 % of the entire TGRR) has 33 amphibian species (Duan et al. 2000), accounting for 9 % of the Chinese total (Xie et al. 2006). It has been reported that Kaixian County has 17 amphibian and 23 reptile species, with a high density of $101/10^4$ km^2, more than 144 times China's average density ($0.7/10^4$ km^2) (Luo et al. 2003). The study area is in the heart of a biodiversity hotspot.

Data process

We used a digital land-use/cover map of the Pengxi River catchment (2013) to characterise the landscape matrix. This data was generated by processing multitemporal SPOT imagery (10 m resolution) and 2012 high-resolution (0.5 m) satellite aerial photography, updated by the latest Second National Land Survey in China which conforms to the Chinese standard land-use/cover typology. We then

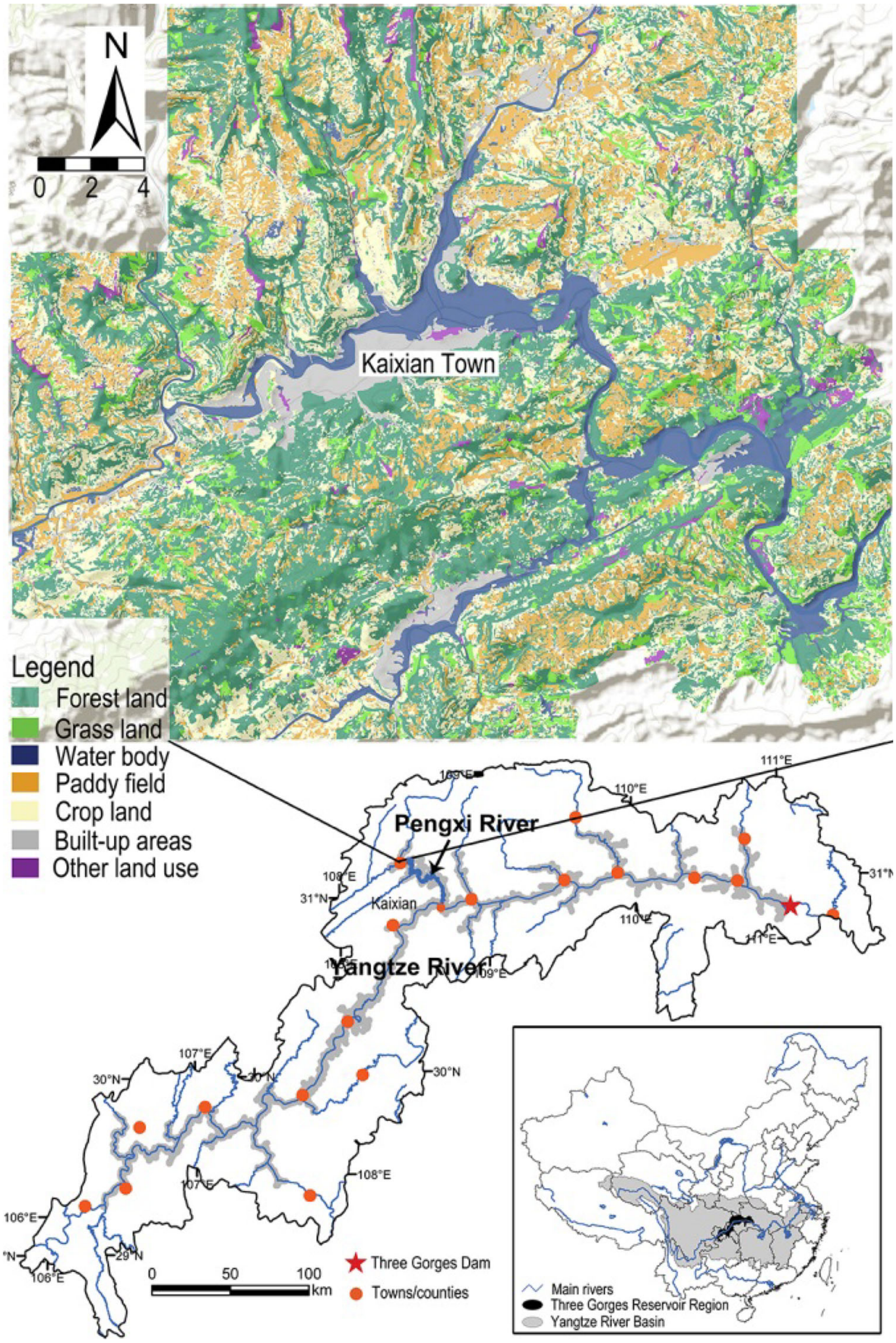


Fig. 3 Location of the study area

overlaid the land-use/cover data with 2015 high-resolution (0.5 m) satellite aerial photography in order to more accurately delineate household ponds and other water body boundaries (lakes, rivers and reservoirs). Because household ponds were dug manually, they generally do not occupy large areas. Based on the construction experiences of local farmers, we only selected ponds with surface areas of less than 1 ha as our study objectives.

The digital map was also verified through ground-truthing during the vegetation survey in 2014–2015 and visually interpreted in vector format with a minimum polygon size of 7 m^2 by ArcGIS. Twenty-five land-use/cover types were identified and mapped in detail (see the "Appendix"). Other topographical information, such as elevation and slope, was derived from the digital elevation map (DEM 1:2000).

We also incorporated linear transport features (highways, rural roads) and narrow drainage ditches into the land-use/cover map because the former are potential barriers for species movement (Carr and Fahrig 2001) and the latter are proven to facilitate amphibian movement and maintain population viability in farmland (Herzon and Helenius 2008; Mazerolle 2005). In addition, we considered water depression plots in natural low-lying lands as temporary ponds for cost-surface modelling since such ephemeral swamps could provide transient opportunities for amphibian dispersal (Bishop-Taylor et al. 2015; Decout et al. 2012).

Modelling pond patches and potential network structures

The LCP model is commonly used to determine the least expensive movement routes of species, defined as resistance value times the migration distance (for details refer to Adriaensen et al. 2003). We used this model twice: once for delineating pond patches which were used for nodes in the spatial graph analysis; and again for identifying links between these patches. This model mainly involves two types of GIS-based data—a source layer and a cost surface—conducted in Cost distance of Spatial Analyst and Linkage Mapper Toolist (GIS plug-in) in ArcGIS.

Defining pond patches

From a practical perspective, all of the household ponds were designated as potential breeding sites for source data input. A cost surface is based on assumptions regarding the permeability of the landscape matrix for the particular species. Ideally, this should be assessed from field data on species movement, but such data are difficult to collect (Ayram et al. 2015). This has resulted in a large number of studies relying entirely or in large part on collective expert opinion (Ayram et al. 2015; Johnson and Gillingham 2004). Different experts may assign different values and therefore affect the reliability of the network simulation (Rayfield et al. 2010). Therefore, in this study we adopted the landscape development intensity (LDI) index (Brown and Vivas 2005), which is a measure of human disturbance to ecosystems, to quantify the relative cost of land-use/-cover types. This index calculates the energy use (all nonrenewable energies, such as electricity, fuel, fertiliser, pesticides, and water) per unit area based on land-use/cover data. It has been proven to be a reliable measure of the level of anthropogenic disturbance and surrogate for biological community quality (Lane and Brown 2007). Several studies indicate that it has a positive relationship with pollutant loading and a significant negative relationship with biodiversity (Chen and Lin 2011; Feld et al. 2009; Mack 2006). Additionally, LDI can be spatially explicit, taking the form of grid cell layers with pixel values, which suits the features of cost surface maps well. Because of these merits, it is useful for estimating the relative cost values of land-use/cover types (Chen et al. 2015). Higher scores mean a more developed landscape with a greater influence of human activity and consequently greater resistance to species movement (see the "Appendix").

The output is a cost distance raster map, where each cell has a cumulative cost value indicating the cost distance to the closest pond sources. With reference to other studies (Decout et al. 2012; Safner et al. 2011), we established the borders of the annual home range within a maximum cost distance of 1.5 km. This distance in fact corresponds to the 90 % probability for a metapatch covering individuals' annual activities (Zetterberg et al. 2010). The resulting annual dispersal zones along with ponds formed the pond patches, which were used as nodes for further graph analysis.

Identifying potential network structures

In comparison with the annual home range, which actually represents the short-distance dispersal within the habitat patch (intrapatch connectivity), the ecological network aims to facilitate long-distance dispersal between habitat patches (interpatch connectivity). Based on previously assigned cost values and simulated pond patches, we further calculated least-cost paths as potential links between patches.

Evaluating and prioritising habitats and links

The LCP model can identify all potential linkages which have the least impedance values when travelling through each cell between sources. But it has little information on which and to what extent the identified patches or linkages contribute to the overall connectivity of the network (Pascual-Hortal and Saura 2006; Urban et al. 2009). We adopted graph-theory based indices proposed by Pascual-Hortal and Saura (2006, 2007) to evaluate the importance of patches and linkages and to further prioritise the critical landscape elements.

To improve many connectivity indices simply based on graph algorithms (e.g. α, β, γ indices), Pascual-Hortal and Saura (2006) further integrated the attributes of habitats (e.g. areas, species richness, habitat quality or quality-weighted area) into a single measurement, the integral

Table 1 Landscape connectivity indices based on graph theory

Index	Formula and explanation
Number of links (NL)	All connections between habitat nodes in the landscape under a certain threshold distance
Number of components (NC)	A component is a set of patches connected to each other but isolated from others. As a landscape gets more connected, it will present fewer components
Integral index of connectivity (IIC)	Here, n is the total number of patches (nodes) in a landscape, and a_i and a_j are the attributes of patches i and j (we used pond area size). l_{ij} is the number of links in the shortest path (LCP in this case) between patches i and j, and A_L is the total landscape area in our case. $0 \leq \text{IIC} \leq 1$. When IIC $= 0$, there are no links between nodes based on a certain threshold distance. When IIC $= 1$, all of the landscape is occupied by one habitat. When applying the area attribute, A_L is often very large, which causes IIC to be extremely low. In order to avoid this, we used its numerators IICnum to assess the overall connectivity. Its values range from 0 to the square of A_L
Node importance ($d\text{IIC}_{\text{node}}$) $d\text{IIC}_{\text{node}}\,(\%) = \frac{\text{IIC} - \text{IIC}_{\text{node\_remove}}}{\text{IIC}} \times 100$	Here, IIC is the overall connectivity value when all nodes are present, and $\text{IIC}_{\text{node\_remove}}$ is the value after removing a single node from the landscape (i.e. after a certain habitat patch loss). The higher this value is, the more important the node is for configuring a functional network
Link importance ($d\text{IIC}_{\text{link}}$) $d\text{IIC}_{\text{link}}\,(\%) = \frac{\text{IIC} - \text{IIC}_{\text{node\_remove}}}{\text{IIC}} \times 100$	Here, IIC is the overall connectivity value when all links are present, and $\text{IIC}_{\text{link\_remove}}$ is the value after removing a single link from the landscape. The higher this value is, the more important the link is for configuring a network

index of connectivity. Table 1 summarises the indices we adopted in our study.

Two types of approaches are usually used to determine a threshold distance for graph analysis. The first is based on reported behavioral characteristics of the selected species, such as breeding, nesting, or maximal migration distance one time. For example, Minor and Urban (2007) used a distance of 1.5 km as the threshold distance representing the maximum distance travelled by a forest bird (*Hylocichla mustelin*). Pereira et al. (2011) built the pond graphs based on a dispersal distance of 2 km for the European turtle (*Emys orbicularis*), while travelling distances of 1.5–3 km were observed for the common frog (*Rana temporaria*) through radio tracking in a network of suitable stepping stones (Decout et al. 2012; Safner et al. 2011). The second approach is based on sensitivity analysis. Generally, a series of distances (e.g. 1, 5, 10 and 25 km) that are broadly representative of different species groups with variable dispersal capabilities are selected to find the stable point or optimal point that satisfies the needs of planning and management (Devi et al. 2013; García-Feceda et al. 2011).

Here, we combined these two approaches. First, based on other amphibian studies, we focused on the distance ranges of 1.5–3 km to measure this species' long-distance dispersal capacity. Second, in order to detect which distance is effective for network analysis and optimal for landscape planning, we calculated the connectivity indices at varying distances from 0.5 km to the length of the longest simulated least-cost path in 0.5-km intervals in the Conefor 2.6 software package. For some points with abrupt changes, 100-m or even 50-m intervals were used to accurately delineate the change.

From a practical perspective of the feasibility and convenience of restoring or creating new ponds, three restrictive factors were considered in this study: topography, rainwater collection and proximity to farmers' houses. According to our observations, no household ponds were built on slopes greater than 35°. As the primary purpose of a household pond is to collect rainwater, it is more efficient to place ponds on or close to water runoff routes. Therefore, we performed rainwater reticulation simulation based on local storm events over a decade (1999–2011). Additionally, we set a 50-m buffer around the houses. The buffer zones are prioritised when adding new ponds as stepping stones.

Results

Spatial pattern of pond patches and potential linkages

There are 4606 household ponds with an area of 7.2 km^2. The average density is 6 ponds/km^2. The minimum area is 37 m^2, with more than 55 % under 1000 m^2. Small area and high dispersion are the spatial characteristics. Based on the annual home range simulation, these ponds were clustered into 373 pond patches, which represented the nodes for further landscape graph analysis (Fig. 4).

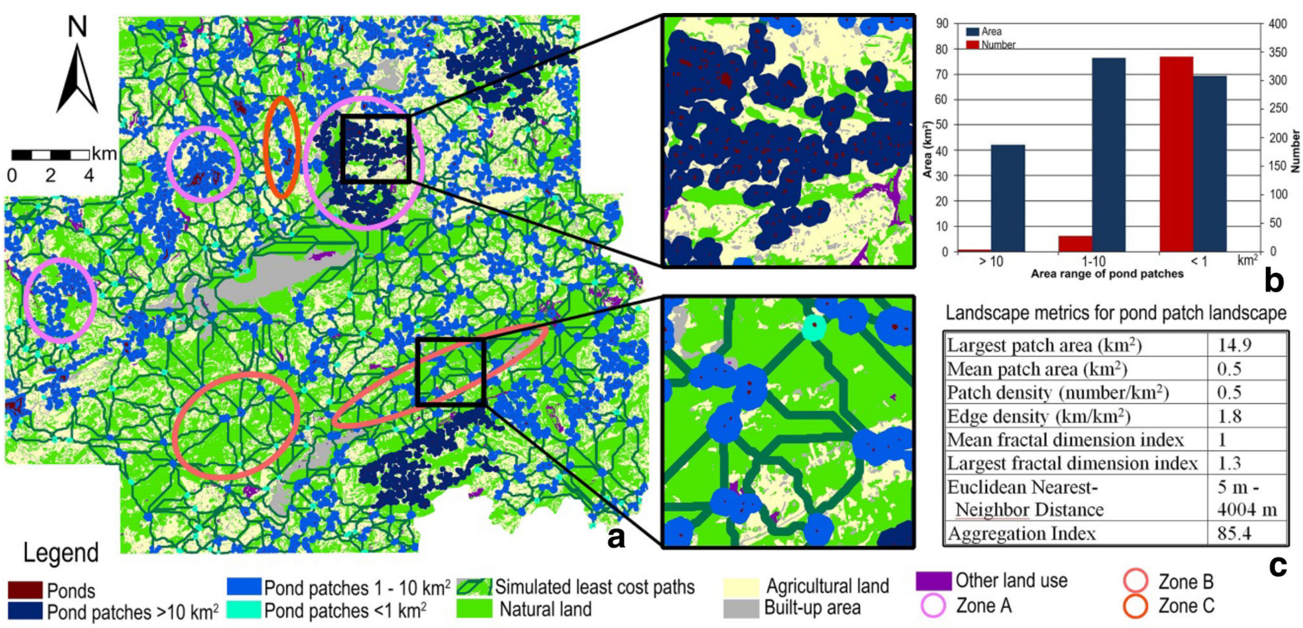
The spatial pattern of pond patches is interpreted in Fig. 4. The total pond patch area is 187.7 km^2, accounting for 24.3 % of the study area and ranging widely from 2256 m^2 to 14.9 km^2. The most complex patch's fractal dimension is larger than 1.3 ($1 \leq Fra \leq 2$), indicating a highly convoluted shape. The aggregation index is 85.4 ($0 \leq Agg \leq 100$), indicating that the pond patch landscape has fairly high clumpiness.

Therefore, several distinct characteristics can be observed: (1) large and contiguous pond patches comprising many small and evenly dispersed ponds are concentrated in the permeable agricultural matrix (e.g. zone A in Fig. 4); (2) small and unconnected pond patches, including those with only one pond, occur mainly in forest or urbanised landscapes (e.g. zone B in Fig. 4); (3) some pond patches present a narrow linear shape. They contain a series of cascading ponds which are generally perpendicular to the hill contour for optimal water supply management (e.g. zone C in Fig. 4).

Based on the LCP analysis, a fairly dense network was formed with all 373 pond patches connected by a total of 1029 potential links. The LCP lengths ranged widely from 10 to 10770 m, differing from the range of Euclidean distances: 5–4004 m (Fig. 4).

Determination of optimal threshold distance and prioritisation of the pond patch network

As shown in Fig. 5, link number (NL) positively increases with threshold distance and becomes saturated at about 2 km. The greater the distance, the more NL and the fewer landscape components (NC) are formed, as shown in Fig. 6. For distances of 0.5 to 1.5 km, the NC decreases dramatically from 113 to 5, and it becomes steady at 1 above a distance of 2 km. Landscape planners are generally confronted with the need to choose a suitable threshold distance when building an ecological network. If the distance is set too short, there will be more isolated components and fewer links within the landscape, indicating that the landscape will be more fragmented. Such a configuration cannot satisfy the goal of functional network construction. In contrast, when the distance is set too long, the entire landscape becomes connected, acting as one component. This would be economically unrealistic for planning. In the present case, it appears that a threshold distance falling in the range 1–1.5 km is optimal for both focal species dispersal and realistic needs. Based on the above analytical results and other studies, we chose 1.5 km as the threshold distance, which allowed the pond patches to be aggregated into five independent components connected by 772 links (accounting for 75 % of all potential links).



Largest patch area (km^2)	14.9
Mean patch area (km^2)	0.5
Patch density (number/km^2)	0.5
Edge density (km/km^2)	1.8
Mean fractal dimension index	1
Largest fractal dimension index	1.3
Euclidean Nearest-Neighbor Distance	5 m - 4004 m
Aggregation Index	85.4

Fig. 4 **a** Map of the pond patch distribution pattern and the least-cost paths between patches. **b** Graph of patch size range versus total area (in *blue*) and number (in *red*). **c** Table of landscape metrics depicting the spatial pattern of pond patches

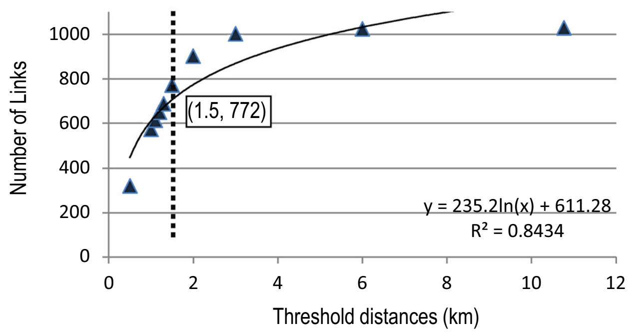


Fig. 5 Response of the link number index to variation of the threshold distance

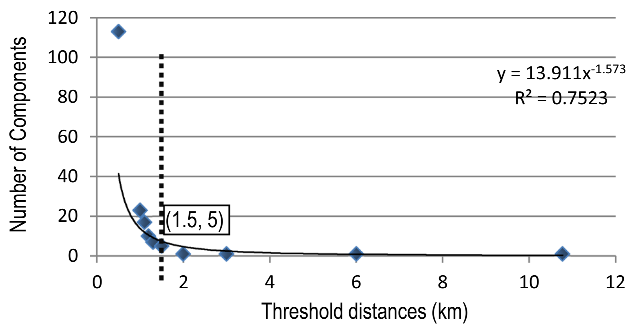


Fig. 6 Response of the component index to variation in the threshold distance

Among the five components, component I hosts the most pond patches and links, which are well connected and form a maximum complexity network (Fig. 7b). In comparison, other components simply consist of a couple of patches and links, which cannot form a network. These isolated components are mainly distributed in the most homogeneous areas of forest landscape matrix, while component I was located in agricultural areas. This pattern emphasises the close relationship between household pond habitats and human agricultural activities.

The most important pond patch is node ID 258 in component I (Fig. 7a). If it is removed, the whole landscape connectivity (IIC) decreases by 24.5 %, accounting for nearly a quarter of the whole importance among all 373 patches. Figure 7 shows that it has a large area (13.7 km^2) and owns 13 links with surrounding patches. The two most important links are between patches 258 and 204 and between 258 and 114, but with importance values of only 2.3 and 2.2, respectively. If they are removed, the whole landscape connectivity (IIC) only slightly decreases, by 2.3 and 2.2 % respectively. From Fig. 7, it can be seen that these two comparatively important links are within the complex landscape component I but are not the only links connecting the involved patches. If they are cut out, there are still alternative links, so the whole landscape connectivity is not significantly affected.

Based on the importance values, we ranked the pond patches and simulated links according to natural breaks in ArcGIS as summarised in Table 2 and Fig. 8. For either patches or links, the most critical class occupied a small fraction of the total number, all around 1 %. However, although the number of important patches is limited (4 for class 1 and 5 for class 2), they contribute the largest proportion of the area, with 38.2 % cover.

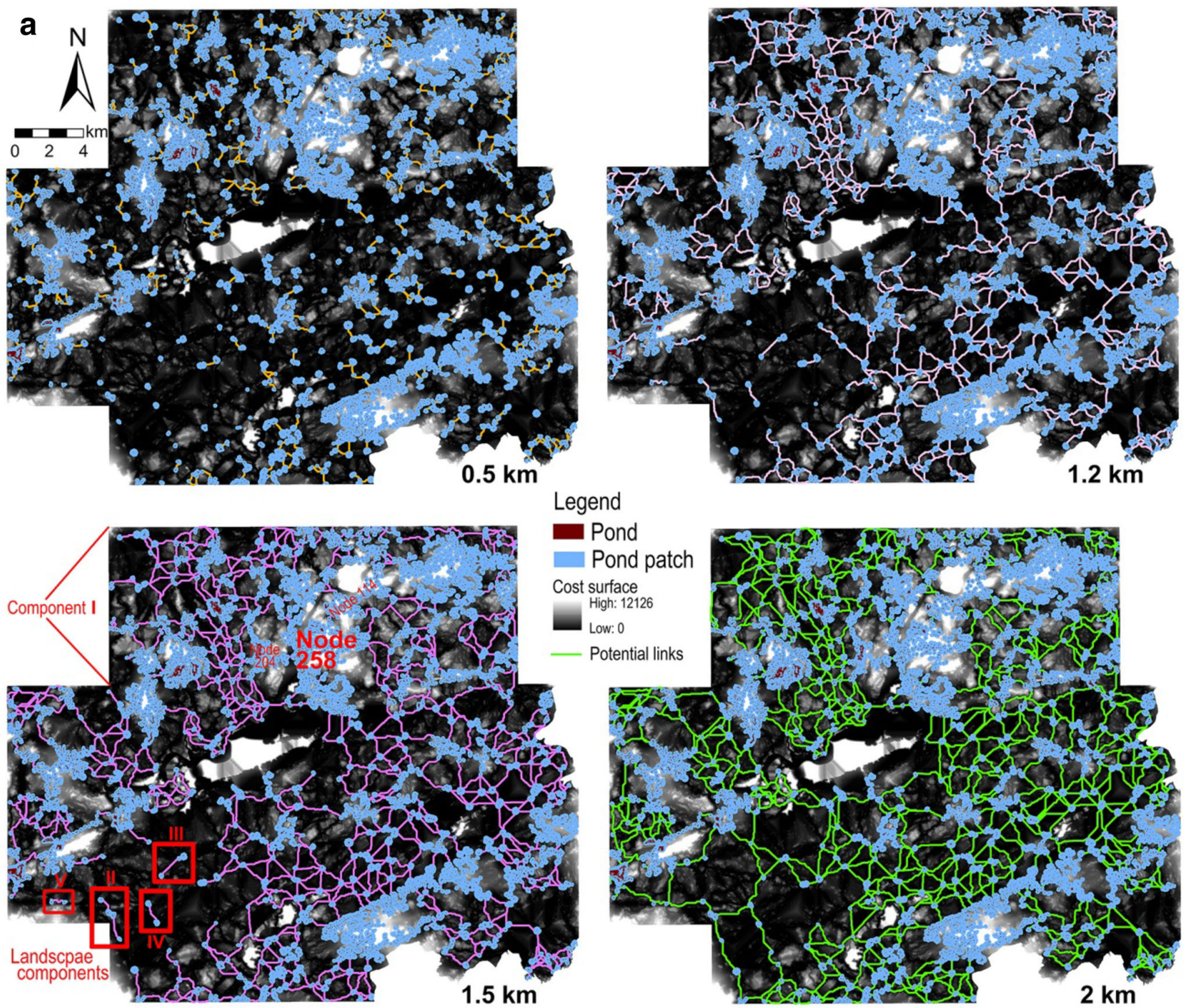
We further examined the relationship between the importance value of the patch and its area and found a strong positive linear relationship (Pearson's = 0.961, $P = 0.01$). There is also a positive linear relationship (Pearson's = 0.391, $P = 0.01$) between the importance value of the link and the total area of patches at the two ends of the link. We presume that patches with larger areas contain more species, and this in turn generates greater population dynamics between patches.

Scenario creation and improvement potentials

Four scenarios in response to land suitability were generated by overlapping the importance classification of both pond patches and links with the spatial distribution of restrictive factors (Fig. 8). These maps represent different foci and provide alternative spatial arrangements and priorities for planners in order to make pond network building more operational. Since our study was performed in gentle hill terrain, 96.8 % of the area (749 km^2) has a slope of <35°. In contrast, suitable areas for rainwater collection and the 50-m buffer zone around houses contribute only 93 and 256 km^2, respectively. Unsurprisingly, the comprehensive scenarios, considering all restrictive factors, produced the least suitable land (26 km^2) for pond network configuration. Figure 8 also shows examples of suggested locations for new ponds that would enhance the network. Through this spatially explicit visualisation, land-use decision makers can identify relatively high-quality pond habitats and choose the best opportunities to maintain or restore pond connectivity for the wider landscape.

Discussion

This study combined least-cost path modelling and graph theory based network analysis to generate spatially explicit assessments of landscape functional connectivity for household ponds in rural south China. Our focal or proxy species is the local amphibian *Rana limnocharis*, which plays a significant role in linking energy flow and nutrient cycling across aquatic and upland ecosystems and yet is sensitive to landscape fragmentation, and therefore acts as an environmental indicator (Ruggiero et al. 2008; Smith et al. 2002; Whiles et al. 2006). The reported studies of



b Statistics of five components at 1.5 km threshold distance

Component	Patches number	Patches area (km^2)	LCPs number	LCPs length (km)
I	365	186.56	767	509.4
II	2	0.31	1	1.2
III	3	0.43	2	1.7
IV	2	0.15	1	0.6
V	2	0.25	1	0.8

Fig. 7 **a** Results of pond patch connectivity simulation for various threshold distances; **b** table of statistics for the patches and links of each component obtained with a threshold distance of 1.5 km

species movement patterns have largely been conducted on endangered or rare species. However, modelling this comparatively widespread species may fit into more realistic land-use planning requirements for long-term benefits of multiple populations of interest as well as general ecosystem health (Watts et al. 2010). In addition, the unique attributes of amphibians (involving various ecosystems) will ensure a more holistically connected landscape. Furthermore, several land-use restrictions were incorporated into the connectivity assessment. By doing so, we can enhance understanding of household pond landscape patterns in terms of ecological connectivity and their contribution to comprehensive regional plans.

Household pond functional networks

Notwithstanding possible errors from simplification, uncertainties, and difficulties in validation, a graph-based approach proved to be robust and useful for understanding the landscape pattern and the potential ecological processes

Table 2 Importance value classification of pond patches and links

Rank	Importance value range	Number	Percentage by number (%)	Area (km^2)/length (km)	Percentage by area/length (%)
Class 1 (patches)	>10	4	1.1	49.2	26.2
Class 2 (patches)	5–10	5	1.3	22.5	12
Class 3 (patches)	1-5	32	8.6	50.9	27.1
Class 4 (patches)	0.5–1	28	7.5	16.7	8.9
Class 5 (patches)	<0.5	304	81.5	48.8	25.8
Class 1 (links)	>1	11	1.4	6.9	1.3
Class 2 (links)	0.1–1	53	6.9	38.4	7.5
Class 3 (links)	<0.1	708	91.7	468.4	91.2

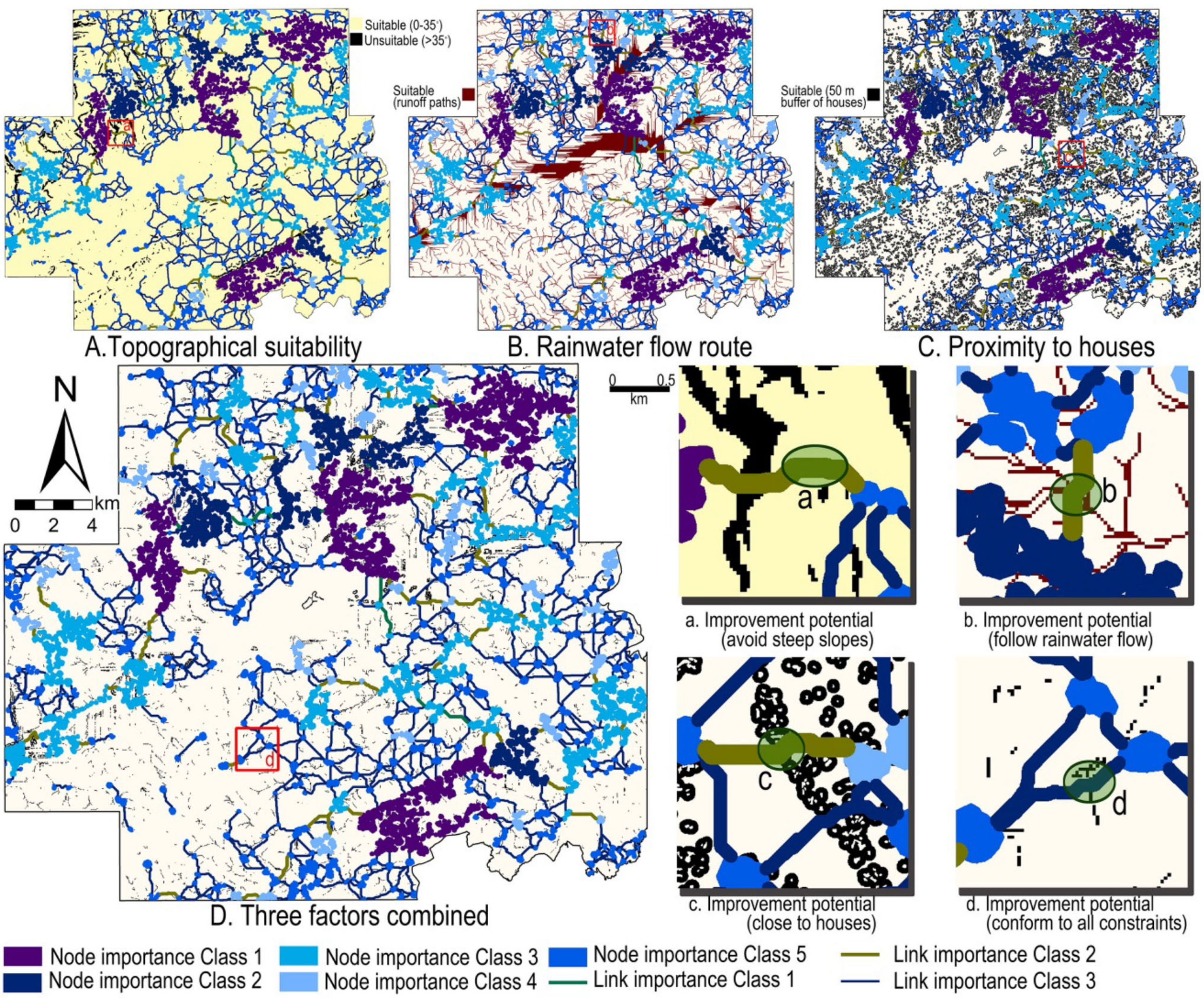


Fig. 8 Four scenarios (topographical suitability, rainwater collection, proximity to houses, and all combined) showing the relationship between the spatialised importance of pond patches and links of networks in the context of various restrictive conditions, as well as the corresponding potential improvements

between the elements. This is a valuable technique for land-related planning as it requires comparatively little data. Previous graph theory studies have largely focused on structural connectivity presented by Euclidean distances. More recently, attention has been drawn to functional connectivity, which allows planners to associate the target areas with the whole landscape matrix. Our results demonstrate the influences of various landscape matrix characteristics on graph mapping and functional connectivity simulation. First, it impacts on the size, shape and distribution of patches. As shown in Fig. 4, large contiguous patches consisting of many smaller ponds were formed within agriculture-dominated landscapes, whereas small patches with few ponds were more sporadically distributed amongst forested land.

Second, our study area is actually a type of mixed agriculture–forest landscape within hilly terrain, which is distinct from large-scale continuous agricultural land such as that in a homogeneous cultivated plain. This feature (with more forest patches in the landscape matrix) endows the network with more spatial redundancy (i.e. network resilience) due to more patches with small cost values. Figure 7 shows that the primary component I is such a well-connected network that it does not even contain cut-nodes or cut-links which would disconnect a component if removed (Galpern et al. 2011). However, even though the majority of the links we simulated in this study are not important in terms of maintaining the overall importance index, they may be of interest to land planners who would like to explore alternative or redundant backup routes for ensuring whole-system resilience (Zetterberg et al. 2010), especially in areas experiencing rapid infrastructure development.

Towards an operational solution

Although the integrated application of LCP modelling and graph-theoretical approaches has become compelling for exploring and identifying functional connectivity, how to incorporate simulated functional connectivity within real construction contexts and associated demands remains a challenge. In essence, the functional connectivity is composed of stepping-stone patches which are scattered along LCPs between the comparatively large patches of source habitats (Vogt et al. 2009). Source habitats generally receive much publicity as they maintain highly diverse and abundant species and have high aesthetic value, and are therefore targeted for preservation during rapid land-use change. By comparison, the values of stepping-stone patches are often overlooked and are therefore more easily encroached upon by human activities. Identifying the optimum location of stepping-stone patches and quantifying their contribution and priority to the whole-network connectivity can effectively increase the robustness and feasibility of land planning and management practices.

One promising way is through integrating real construction requirements with spatial modelling, such as by considering land-parcel cost assessment for grassland restoration (Torrubia et al. 2014), or overlaying land property data (i.e. building blocks, natural areas, etc.) with network options within urban landscapes (Zetterberg et al. 2010). In our study, we combined the widely used land suitability analysis with network analysis. Both of these generate spatially explicit solutions that are helpful when practitioners need to consider tradeoffs between different scenarios, the context of target locations and conservation efficiency. The methodological framework proposed in our study can be tailored or expanded to meet different connectivity objectives.

Many other studies also highlight the issue of prioritisation in the planning process (Devi et al. 2013). It is important to understand not only how the overall target system is connected and affected by various realistic scenarios, but also where critical patches or links are situated. Network evaluation using the Conefor Sensinode tool provides a direct way to diagnose priorities for decision-making, as shown in Fig. 8. Furthermore, the identified priority areas can be restrained or enhanced by information on landform, soil, and other physical (such as man-made ditches in our study) and/or socioeconomic (such as transportation features) properties. We can then obtain a final map of important and suitable patches and links for improvement or maintenance.

It should be noted that, in this study, we did not use the species distribution information as a criterion to screen the ponds for analysis, as other studies have done (Decout et al. 2012; Pereira et al. 2011). Instead, we involved all the household ponds. Our findings should therefore be regarded as potential functional networks from a practical and cost-effective planning perspective. However, since comprehensive land-use plans proceed in a progressive and hierarchical way (from regional to detailed local), we suggest that available empirical data should be incorporated, not just for the purpose of testing model results, but also for further priority setting and establishing which patches are important as sources and sinks and the relevant weighted links for maximising ecological flux. Additionally, we did not use individual ponds as patches for network analysis. Instead, we applied pond clusters (i.e. annual home range) based on unique amphibian habitat requirements to represent patch-based graphs. This allows a holistic perspective of the landscape and better fits into planning programs which are, by nature, underpinned by patch-based analysis.

Index-based cost surface evaluation

Although the approach used here represents a reliable, flexible and spatially consistent framework for establishing ecological connectivity for the pond landscape, some limitations and potential improvements for future studies should be noted.

Strictly speaking, the resistance cost values in LCP modelling should be derived from behavioral or experimental studies of species movement patterns. However, most of those studies have relied on expert opinion because of a lack of empirical data (Ayram et al. 2015). We innovatively used a landscape development intensity index as a substitute for resistance, assuming a negative relationship between the anthropogenic disturbance and the permeability of the landscape. One of the main advantages of such index-based cost value assignment is that it overcomes the subjectivity inherent in the expert scoring approach and intensive field data collection. Similar to Baldwin et al. (2010) and Alagador et al. (2012), who used values of the human footprint index for resistance values, we regard such index-based cost value assignment as an effective alternative to expert opinion or species-based data.

However, it is necessary to point out that the LDI coefficients used in this study were based on calculations derived from USA cities. The parameter inputs, such as land use/cover, energy consumption data and associated socioeconomic circumstances, obviously vary from region to region and depend on the study scale. For example, there is one type of "agriculture with high intensity" in the original LDI system, but that type is not applicable in our hilly study areas, where most cropland is small scale and scattered across the landscape. Therefore, it is better to modify the LDI coefficients based on the local situation. Additionally, it should be pointed out that the two stages of annual home range identification and LCP simulation applied the same cost surface based on the LDI index. These two stages actually represent two different ecological processes of short- and long-distance movement of species. Using the same land-use/cover map and the associated cost surface may cause problems since the two different dispersal movements may be affected by different environmental/ecological factors (Marco et al. 2011) and are also scale dependent (Angelone et al. 2011). This issue should be addressed in future research.

Conclusions

Building household ponds is an intriguing spontaneous family-based engineering activity that is prevalent in China and other Asian countries (Ichinose et al. 2007). Ponds are endowed with multiple functions for families, differentiating them from western farm ponds which are predominantly employed for irrigation. Household ponds are spatially explicit reflections of lives and work styles of local people on the land. In a sense, they epitomise and embody long-established human wisdom in dealing with living environments and are crucial to maintaining a heterogeneous landscape for biodiversity as well as production. In contemporary theory, the large number of ponds potentially allows more and diverse services to be accommodated if the ponds are arranged well within the development matrix. This requires a landscape ecological understanding of pond system structure and of dynamic interaction with other ecosystems. Based on a patch-based network analysis of species–habitat interactions, our study is the first attempt to theoretically explore and analyse household pond connectivity in a hilly agricultural landscape. By shifting the focus from effects on single ponds to a whole-system approach, our study goes to the patch-landscape scale—the level at which virtually all landscape engineering and management takes place.

The integrative approaches used in this study provide new insights into the building of functional networks into real-world development and constraints. Although there are still thousands of small household ponds in the region, the increased movement of young rural labourers to cities over the last decade has led to lax pond maintenance, which has caused the number of ponds and their quality to decline. However, in order to overcome water shortages in the mountainous regions, local governments are now taking more direct actions and formulating associated policies to ensure the ponds are sustained, such as by organising so-called Household Pond Renovation Programs across the whole region. Our results on the hierarchical networks of pond landscapes along with land constraint analysis provide practical suggestions for policy makers, land-use planners and resource managers who wish to identify critical elements, improve or add new habitats, and to optimise their placement.

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Compliance with ethical standards

Declaration All experiments and surveys comply with the current laws of the country in which they were performed.

Appendix

Land-use/cover classification used in this study

First level	Second level
Natural land	Forest land
	Other woodland
	Shrub land
	Scenic spots
	Grassland
	Reservoir water
	Pond
	River
Agricultural land	Crop land
	Paddy field
	Orchard
	Tea plantation
	Other perennial plantation
	Natural pasture
	Artificial pasture
	Agricultural facility land
Built-up area	Village
	Port land
	Highway land
	Built-up land in town
	Mining land
	Rural road
	Hydraulic building land
Other	Bare area
	Inland beach

Evaluating the relative cost surface based on the landscape development intensity index

Land use/cover used in LDI	Land use/cover used in this study	LDI coefficient
Natural system	Forest land, other woodland, shrub land, grassland, inland beach	1.00
Natural open water	Pond, river, reservoir water, temporary ponds	1.00
Tree plantation	Tea plantation, other perennial plantation	1.58
Recreational/open space—low intensity	Scenic spots, bare land, inland beach	1.83
Unimproved woodland pasture (with livestock)	Natural pasture	2.02
Improved pasture (without livestock)	Not applicable	2.77
Improved pasture—low intensity (with livestock)	Not applicable	3.41
Citrus	Orchard	3.68
Improved pasture—high intensity (with livestock)	Artificial pasture	3.74
Row crops	Crop land, paddy field	4.54
Single family residential—low density	Agricultural facility land, hydraulic facility land, rural roads	6.9
Recreational/open space—high intensity	Port land	6.92
Agriculture—high intensity	Not applicable	7.00
Single family residential—medium density	Not applicable	7.47
Single family residential—high density	Village	7.55
Mobile home (medium density)	Not applicable	7.70
Low-intensity commercial	Not applicable	8.00
Institutional	Tertiary education, hospital, cemeteries	8.07
Mobile home (high density)	Not applicable	8.29
Industrial	Industrial, mining land	8.32
Multi-family residential (low rise)	Not applicable	8.66
High-intensity commercial	Commercial	9.18
Multi-family residential (high rise)	Built-up land in town	9.19
Central business district (average 2 stories)	Not applicable	9.42
Central business district (average 4 stories)	Central business district	10.00
Linear transport features added to the land-use/cover map		
Highway (4 lane)	Highway (4 lane)	8.28
Highway (2 lane)	Highway (2 lane)	7.81
Ditches	Channels, drainages, etc.	1
Water depression (as temporary swamps)		1

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