

Geocode-Based Aquatic Habitats in Hierarchical System of the Yellow River Basin

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ABSTRACT. Riverine systems are primary habitats for aquatic species. Great efforts have been made to understand interaction between aquatic organism and various environmental factors in specific reaches of a river, yet little was known about how to identify habitats in river networks. In this paper, a comprehensive approach was proposed for identification of aquatic habitats in hierarchical river systems in terms of integrated geocodes synthesized through over-layer of multiple factors such as geologic periods, climatic conditions, water sources, geomorphic characteristics and river patterns. Using this approach in the Yellow River Basin over an area of 758,600 km², six groups of aquatic habitats were classified by clustering of 85 geocodes, and 313 sub-habitats were further identified by considering both surface composition (e.g., lithological features and soil texture) and topographic property (e.g., elevation and slope) in the loess geomorphic regions. Consequently, the contribution of the headwater streams to diversity of aquatic habitats among rivers and mid-sized rivers to the diversity within a river has been revealed by coupling of the geocode-based habitats and the river networks. The present study is of significance to efficient capture of habitat diversity and better understanding of biodiversity in rivers of different stream orders.

Keywords: geocodes, habitats, hierarchical river system, identification, Yellow River

1. Introduction

River systems are of great significance not only to transportation of water (Huang and Loucks, 2000; Milly et al., 2005), sediment (Huang, 1998; Syvitski et al., 2005; Qin et al., 2007; Li, et al., 2008), and other associated materials (Li, et al., 2009; Regnier et al., 2013) from land to ocean, but also to providing habitats for aquatic species (Benda et al., 2004). River networks are hierarchical systems consisting of rivers of different orders. The degree of stream branching can be characterized by different stream-ordering rules (Horton, 1945; Strahler, 1952, 1957; Shreve, 1966; Huang, et al., 2006; Li, et al., 2010; Lv, et al., 2010), in which Horton and Strahler stream-ordering schemes are most commonly used. The structure properties of river networks have been long concerned from mathematic, hydrological, and geomorphological perspectives since 1940s. It has been found that the topological parameters (e.g., number of rivers and bifurcation ratio) and morphological parameters (e.g., river length, basin area) of rivers with different stream-orders follow some geometric laws (Horton, 1945), along which, self-similarity in natural

river networks has also been confirmed (Zanardo et al., 2013; Fan et al., 2017a; Wang et al., 2018). Moreover, the fractal dimension was introduced to describe the dendritic nature of river networks (Veltri et al., 1996; Zhang et al., 2015). More recently, interactions between hierarchical river networks and natural processes including climate change (Zanardo et al., 2013), water and sediment balance (He et al., 2012; Czuba and Fofoula-Georgiou, 2015), geomorphic evolution (Lave, 2015), greenhouse gases emissions (Hotchkiss et al., 2015), and biological communities (Campbell and McIntosh, 2017) were investigated. In particular, aquatic habitat conditions (Baatrup-Pedersen et al., 2017), and distribution (Ceola et al., 2014), diversity (Rice, 2017), and dispersal (Swan and Brown, 2017) of stream communities all appeared to have remarkable correspondence with structure properties of river networks. Since the hierarchical structure of river networks causes substantial ecological responses, it is essential to take structure properties of river networks into account when depicting riverine habitat characteristics.

Great efforts have been made to identify riverine habitats in terms of physical attributes. Climate factors (He, 2017), hydraulic parameters (Buffagni et al., 2000), geomorphic factors (Inglis et al., 2008), land cover characteristics (Ardli and Wolff, 2009), and channel morphological metrics (Whited et al., 2013) have been selected for habitat descriptions. With the increasing human disturbance on rivers, habitat quality evalu-

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ation systems for urban rivers (Boitsidis et al., 2006; Zeng et al., 2007) as well as rivers impacted by reservoirs (Ma et al., 2014) were also investigated. Ni and Gao (2011a, b) proposed a comprehensive riverine habitat identification system which combined information of geologic period, climatic condition, water sources, and geomorphic features. Similarly, Mckenna et al. (2015) characterized riverine habitat conditions based on a spatially universal framework composed with multi-dimension variables including climate, stream flow, stream geometry, geology, land cover, and water temperature.

Although aquatic habitats and river networks in various catchments are separately investigated in previous studies, less efforts have been made to describe habitats in the context of hierarchical river systems. In this paper, an integrated framework (Figure 1) was established for identification of aquatic habitats in terms of stream orders, which could well describe hierarchical characteristics of riverine habitats originally defined with geocodes synthesized through over-layer of multiple factors. Consequently, riverine habitat diversities corresponding to different stream-orders could be identified, which is helpful to accurate capture of biodiversity patterns and deeper understanding of community assembly mechanisms.

2. Study Area

The Yellow River, the second longest river in China, has a total river length of 5,464 km. Yellow River originates from Qinghai-Tibet Plateau, flows through seven provinces and two autonomous regions of China, finally injects into Bohai Sea. The Yellow River Basin is distributed in 95°53' E ~ 119°05' E, 32°10' N ~ 41°50' N, with a total area of 758,600 km² (Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014). The Yellow River Basin shows diverse climate patterns, including humid climate in the southeastern area, the semi-arid climate in the central part, and the arid climate in the northwestern region. It flows through one of the largest and thickest loess deposits in the world where soil erosion is severe (Ni et al., 2014), and has the largest average annual sediment yield (1.6×10^{12} kg/yr during 1919 ~ 1960) and sediment concentration (35 kg/m² during 1919 ~ 1960) in the world (Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014). Heterogeneous source of water and sediment is another remarkable characteristic of Yellow River (He et al., 2009). The middle reaches of Yellow River located between Hekouzhen and Sanmenxia are the major source areas of sediment, occupying 89.1% of the total sediment yield and 28% of the total runoff. The upstream reaches of Yellow River located above Hekouzhen and Sanmenxia account 62% of the total runoff, and only 8.6% of the total sediment yield (Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014).

3. Methodology

3.1. Extraction of Drainage Networks

Drainage networks were extracted from the 30m resolu-

tion Aster GDEM (Available at <http://reverb.echo.nasa.gov/reverb/>) by a high efficient method based on a sized-balanced binary search tree (Bai et al., 2015). The extraction procedure comprises five steps: (1) pretreatment to fill local depressions; (2) determination of flow directions; (3) accumulation of up-slope areas; (4) identification of drainage channels based on threshold values of critical source area and local slope, and (5) vectorization of geographic features. In this study, we set the threshold values of critical source area (number of grid cells) and local slope as 20 and 0.01, respectively.

3.2. River System Hierarchy

The Strahler stream-ordering scheme (Strahler, 1952, 1957) was used, in which first-order rivers are headwaters without bifurcation. When there is a confluence, the streamorder of downstream rivers obeys the following rules:

$$n_d = \begin{cases} n_1 + 1, & \text{for } n_1 = n_2 \\ \max(n_1, n_2), & \text{for } n_1 \neq n_2 \end{cases} \quad (1)$$

where n_d is the stream order of the downstream river, and n_1 and n_2 are the respective stream orders of the upstream rivers at the bifurcation.

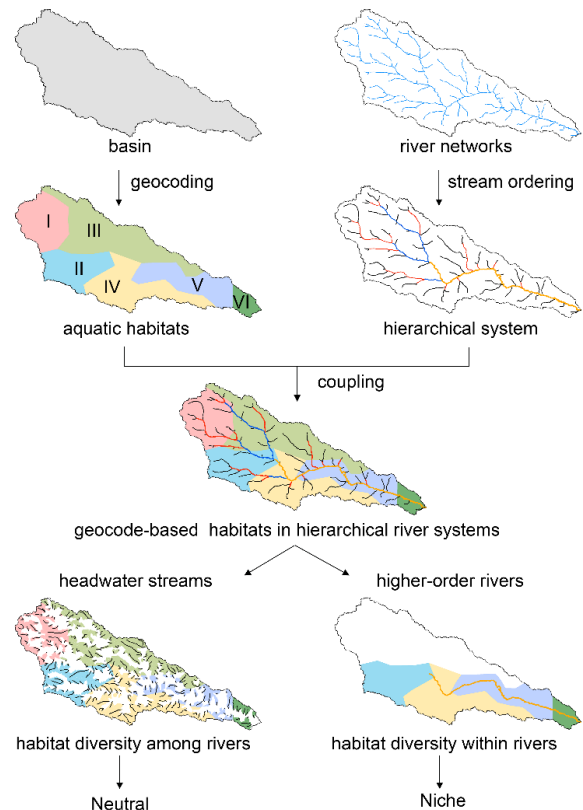


Figure 1. Framework for geocode-based aquatic habitats identification in river networks.

3.3. Integrated Geocodes System Coupled with Stream Order

With the spirit of Ni and Gao (2011a, b; An et al., 2016; Xin et al., 2017; Zhang et al., 2017), we proposed a comprehensive approach to identify the aquatic habitats in the hierarchical river system in terms of an integrated geocodes system for all stream orders (Table 1). The geocodes were synthesized through overlay of environmental factors including geologic period, climatic condition, water source, geomorphic characteristics and river pattern.

3.3.1. Geologic Period

The geological history of rivers records formation, development, and evolution of rivers. Most modern rivers were generated in Quaternary period when large scale of glacier developed, and the glacier meltwater might provide a new type of water source for rivers. In the Yellow River Basin, arid and cold climate resulted in deposition of loess sediment. Freshwater organisms were spatially divided, and distributed scope of the cold-water species expanded during this period.

3.3.2. Climatic Condition

From a geospatial perspective, rivers in different regions correspond to different climate conditions dominated by precipitation and temperature. Hence, rivers could be spatially classified in terms of tropic and subtropic climate, temperate climate, frigid climate, and plateau climate (Liu, 2010; Xin et al., 2018). In the Yellow River Basin, the temperate climate could be further subdivided into monsoon climate of medium latitudes and temperate continental climate.

3.3.3. Water Source

Water sources of rivers are also closely related to hydrological characteristics (e.g., flow regime) of rivers. Rivers in temperate climate regions may have multiple water sources including glacial permafrost, precipitation, and groundwater. However, rivers supplied by glacial permafrost tend to have a spring flood since thaw out of glacier often happens in spring, while those supplied by precipitation mostly have a flood period in summer. Groundwater would be major water sources for inland rivers distributed in arid regions or rivers in areas with high permeability (e.g., loess landform regions). However, rivers in plateau climate regions are mainly supplied by snowmelt of glacier or lakes and swamps.

3.3.4. Geomorphic Characteristics

Modern rivers may flow through areas with fluvial, karst, loess, and glacial permafrost landforms (Tian, 2009). The surface soil texture and lithologic composition would influence the properties of streambed sediment and the salinity of water body. On the other hand, topographic condition is the main driver to shape the river pattern.

Rivers flowing through loess landforms are mainly distributed in arid and semi-arid regions, and often correspond to extensive groundwater system. Considering loess sediments are product of weathering and freeze-thaw action, stream-bed sediments of these rivers are fine-grained with high porosity. Moreover, rivers flowing through glacial permafrost regions are mostly covered with moraine, and the stream-bed sediments are composed of glacial debris. Exchange of surface runoff and groundwater flow are weak due to barrier action of permafrost.

3.3.5. River Pattern

Rivers are conventionally classified into straight, meandering, braided, and anastomosed patterns from their plane views. The straight river is not stable and mainly distributed in restricted valley regions, while meandering river is of idealized pattern for evolution of a stable channel. However, braided and anastomosed rivers with multiple-channels are often characterized with frequent change of flow courses due to lower longitudinal gradient, higher sediment load, and poorer resistance of bank materials.

3.4. Identification of Aquatic Habitats

In the established integrated geocode system, the environmental factors could largely determine aquatic habitats in rivers. For a hierarchical analysis, each of the factors could be further defined by several sub-factors with quantitative gradation. Hence, representative riverine habitats were firstly identified in terms of geocodes generated by overlay of geologic periods, climatic conditions, water sources, geomorphic characteristics and river patterns, which were further classified into six groups via the *k*-Modes clustering algorithm (Huang, 1997, 1998). In view of the importance of both topographic properties and surface material compositions under the general category of loess landform in the Yellow River Basin, riverine habitats could be further identified in greater details based on morphological parameters including elevation, slope, lithological features, and soil texture.

Table 1. Integrated Geocode System for All Stream Orders

Stream order	Geocode	Environmental factors				
		Geologic period	Climatic condition	Water source	Geomorphic feature	River pattern
1~10	1	early Pleistocene	tropics & subtropics	precipitation	fluvial	straight
	2	middle Pleistocene	monsoon climate of medium latitudes	groundwater	karst	meandering
	3	late Pleistocene	temperate continental	lakes & swamps	loess	braided
	4	Holocene	plateau	glacier	glacial permafrost	anastomosed

3.5. Quantification of Environmental Factors and Data Sources

3.5.1. Geological Period

According to Dai (1983), Yellow River was generated in three stages of Quaternary period for different reaches, namely the Middle Pleistocene for riverhead–Yinchuan and Longmen-Taohuayu reaches, the Late Pleistocene for Yichuan-Longmen reach, and the Holocene for reach from Taohuayu to estuary.

3.5.2. Climatic Condition

The Yellow River Basin were divided into areas with tropical and sub-tropical climates, monsoon climate of medium latitudes, temperate continental climate, and plateau climate based on climatic regionalization map of China at 1:36 million resolutions (Liu, 2010).

3.5.3. Water Sources

Frozen Soil Map of Qinghai-Tibet Plateau at 1:3 million resolutions (Li and Cheng, 1996; National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China available at <http://www.geo-data.cn>) was used to quantify rivers supplied by snowmelt of glacier.

Regions where rivers are supplied with lakes and swamps were determined through the 1 km resolution Global Lakes and Wetlands Database (Lehner and Döll, 2004).

Regions where rivers were supplied by groundwater were quantified via the 1 km resolution aridity index (*AI*) (Middleton et al., 1992). In regions where $AI < 0.2$, runoff of rivers is supplied by groundwater since the ratio of actual evaporation to precipitation is equal to unity (Liu, 2014) when $AI = 0.2$, which implies all precipitation is consumed by evaporation instead of converting into runoff.

Rivers in the remaining regions were considered to be supplied by precipitation.

3.5.4. Geomorphic Characteristics

The loess geomorphic regions were firstly identified via the loess distribution map of China at 1:25 million (Liu, 1985) resolutions, and the glacial permafrost regions by Frozen Soil Map of Qinghai-Tibet Plateau at 1:3 million resolutions (Li and Cheng, 1996). The remaining regions for rivers to flow through were identified as fluvial geomorphic regions.

Sub-habitats were further identification in terms of sub-factors such as mean values of elevation and slope of rivers derived from the 30m resolution Aster GDEM (Available at <http://reverb.echo.nasa.gov/reverb/>). The lithologic distribution of the Yellow River Basin was derived from 0.5° resolution lithological map (Hartmann and Moosdorf, 2012) which is available at <https://doi.pangaea.de/10.1594/PANGAEA.788-537>. The soil texture was quantified based on fractions of sand and clays (Davis and Bennett, 1927). Information of

fractions of sand and clays were obtained from the 0.00833° resolution soil particle-size distribution map (Wei et al., 2012) which was available at <http://globalchange.bnu.edu.cn/research/soil>.

3.5.5. River Pattern

The sinuosity (*S*), defined as ratio of the length along its winding path and the straight length from source to outlet, was used to distinguish straight rivers from meandering rivers. As $S > 1.2$, rivers are regarded as meandering, and the remaining rivers are taken as straight rivers (Chen, 1992).

4. Results and Discussions

4.1. Hierarchical Yellow River Networks

Figure 2a illustrates the drainage networks of Yellow River Basin with stream order larger than 4. Ten spatially nested hierarchical orders are derived according to the Strahler stream-ordering rule. According to Strahler (1952), 899,415 rivers are identified, with catchment area ranging from 0.1 to 1,000,000 km². Large rivers with high stream-order form the backbone, and small rivers with low stream-order formulate the detailed network.

4.2. Hierarchical Yellow River Networks

By overlay of environmental factors including geological period (Figure 2b), climatic condition (Figure 2c), water source (Figure 2d), geomorphic characteristics (Figure 2e) and river pattern (Figure 2f) in the Yellow River Basin, 85 integrated geocodes were synthesized for 899,416 rivers with stream-order ranging from 1 to 10.

Furthermore, six groups of representative riverine hab-

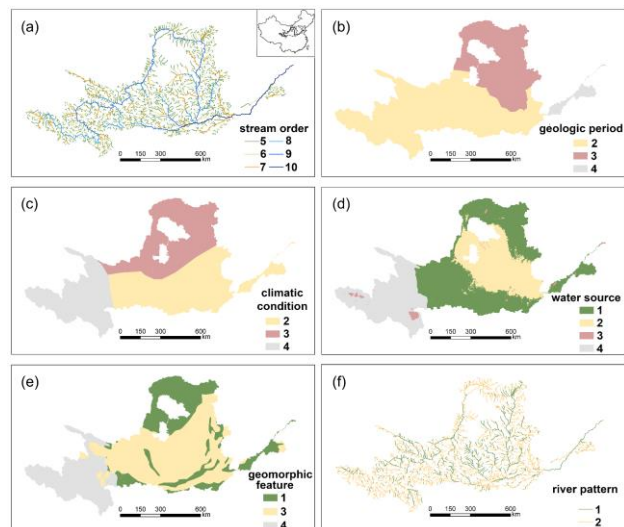


Figure 2. Distribution of: (a) Yellow River networks with different stream orders, (b) geologic period, (c) climatic condition, (d) water resource, (e) geomorphic characteristics, and (f) river pattern.

habitats were identified (Figure 3) after classification of geocodes (mainly according to climatic condition, water source, geomorphic characteristics) derived over the whole basin based on the *k*-Modes clustering algorithm. The corresponding geocodes for each of six groups were provided in Table 2.

The group I and group II include two types of riverine habitats with plateau climate and glacial permafrost landform. The plateau rivers in these regions are characterized by low water temperature due to vertical zonation, and thereby saline-tolerant species, cold water species, and extreme climatic species. On the other hand, rivers with V-shaped valley are seldom found in these groups since land surface cannot be deeply incised due to the existence of permafrost, and bed materials are composed of debris with larger range of grain sizes. In addition, riverside has no large plants and the moss is widely developed. However, the major difference of rivers in groups I and II are the water sources. Rivers in group I is mainly supplied with glacier meltwater which is highly related to the temperature, demonstrating apparent seasonal fluctuation of flow. Those in group II are primarily supplied with lakes and swamps with less seasonal fluctuation of run-off.

The group III and group IV summarize typical riverine habitats with monsoon climate of medium latitudes and loess landform. The monsoon climate of medium latitudes shows obvious seasonal variation, hot and rainy in summer but cold and dry in winter, leading to seasonal biological life cycle. In loess geomorphic region, high sediment concentration is often observed in rivers due to severe soil erosion, leading to low transparency of flow water and weakening the photosynthetic

intensity of the producers. Meanwhile, the living space of benthos is limited due to the fine-grained loess sediment. Therefore, biodiversity would not be high in these river basins. Rivers in group III show apparent seasonal variations of runoff than those in group IV due to different water sources from precipitation and groundwater.

The group V and group VI cluster riverine habitats with fluvial landform. Rivers in Group V are mostly distributed in middle and lower areas of the Yellow River. In middle area of the basin, coarse-grained sediments provide sufficient living environments for benthos and fishes. The alternate appearance of pools and riffles lead to distribution of both lotic species and lentic species in this area. Meanwhile, the poor-riffle systems are a high-quality spawning grounds of fishes (Li et al., 2012). In lower area of the basin, a great quantity of sediment deposited, leading to the raise of riverbed, which would greatly influence the diversity of benthos as well as fishes (Fu et al., 2010). Rivers in group VI are located in arid grasslands corresponding to temperate continental climate with scarce precipitation, thus, rivers are mainly supplied by groundwater.

4.3. Identification of Sub-habitats in the Loess Landform Region

It can be found that geomorphic characteristics of river systems play a leading role in classification of the riverine habitats. However, under the same landform unit, there are still a variety of geomorphic features, which can be determined by two major factors, one is the topographic feature, and the other is the surface material composition. The topographic feature determines the river branching structure (Perron et al., 2012) and fluvial morphology (Wohl, 2014), while the surface material composition can affect sediment properties some associated hydrochemical characteristics in rivers (Boluwade and Madramootoo, 2015).

Taking the area of loess landform as an example, we can give reasonable descriptions on river habitats for fish communities based on more detailed geomorphic parameters such as elevation, slope, lithology, and soil texture (Figure 4a ~ 4d).

From a topographic perspective, elevation is an important factor for distinguishing plains (< 200 m), hills (200 ~ 500 m) and mountains (> 500 m) (Tian, 2009), which also influences other physical-chemical parameters including slope, water temperature, dissolved oxygen, and pH (Kisi et al., 2013). As illustrated in Figure 4a, the elevation in the loess landform region determines a longitudinal gradient along with the flow direction of the mainstream, causing corresponding change of fish assemblages. Elevation plays a key role in determining species compositions of fish assemblages (Askeyev et al., 2017). In high altitude regions with extreme climatic conditions, there would be some endemic species such as cold-water species like trout, salmon, and char (Isaak et al., 2015). Species richness is found either increase (Askeyev et al., 2015, 2017) or decrease (Carvajal-Quintero et al., 2015) gradually with increasing elevation. It also has been reported

Table 2. Geocodes in Six Groups of Representative Aquatic Habitats

Group No.	Geocodes
I	24441, 24442
II	24341, 24342
III	22131, 22132, 23131, 23132, 32131, 32132, 42131, 42132
IV	22231, 22232, 32231, 32232, 42231, 42232
V	22111, 22112, 23111, 23112, 32111, 32112, 33111, 33112, 42111, 42112
VI	23211, 23212, 33211, 33212

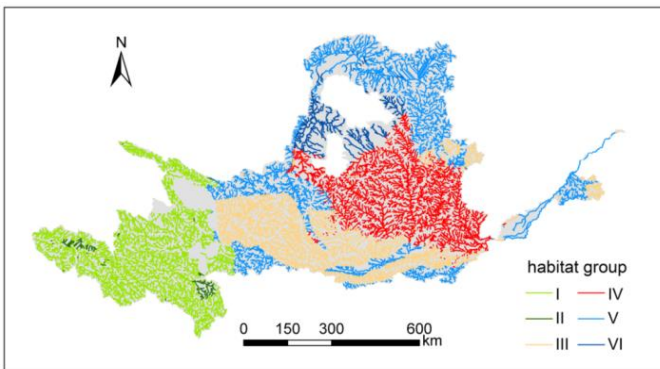


Figure 3. Six groups of representative riverine habitats in the Yellow River Basin.

that nearly 90% of the fish species were recorded in regions with elevation between 250 and 1,250 m (Jaramillovilla et al., 2010). Moreover, elevation also reflects the impact of human activities on the fish community. In general, abundance of fishes in the areas of high altitude would be promoted by better aquatic environments considering the less anthropogenic impacts in the upper rivers (Wu et al., 2014).

Slope is another important indicator of landform. As illustrated in Figure 4b, the steep lands (e.g., slope > 15°) are distributed in upstream regions of the primary or the secondary tributaries of the Yellow River. These areas mainly correspond to loess hilly-gully areas and rocky mountain areas with strong water erosion, thin soil layer, and exposed rock surface (Zhang et al., 2015) since soil is easily eroded during flood period. However, flat areas with small slope (e.g., slope < 15°) mainly correspond to loess depositional landforms e.g., loess tablelands and loess ridges, where water erosion process is weak and sediments are usually fine (Tian, 2009). Meanwhile, the slope can influence the distribution of fishes with different body sizes. Average body length and weight of fishes in the steep areas are larger than those in flat areas (Shepherd et al., 2009; Ru et al., 2010) since the steep areas more correspond to riffles, in which case, small fishes would be severely disturbed.

Figure 4c maps the lithological distribution of the loess landform region, 61% of which are covered with uncon-

solidated loess sediment. The remaining areas are distributed with different rocks including volcanic rocks, plutonic rocks, carbonate sedimentary rocks and metamorphic rocks (Hartmann and Moosdorf, 2012), whose mineral compositions would determine major ion concentrations contained in water and total dissolved solid (TDS), and provide required elements for the growth of aquatic organisms. The basic rocks with low content of SiO₂ and high content of Ca²⁺, Al³⁺, Mg²⁺, would lead to high alkalinity and alkalinity of water, while the acid rocks with high content of SiO₂ would result in acid water body (Wang et al., 2008). The limestone regions also correspond to high value of pH, and are mainly distributed with carbonate-preferred organisms. There is a clear separation in fish community structure between rocky-and soft-bottom habitats, that is, fish communities in rocky-bottom habitats are dominated by permanent non-commercial species, whereas the dominant species in soft-bottom habitats are juvenile fishes and commercial species (Pihl and Wennhage, 2002).

Distribution of soil texture properties in loess landform region which is quantified by fractions of sands and clays are mapped in Figure 4d. Coarse sediments (clay fraction < 25%, sand fraction > 55%) are distributed in the middle area of the Yellow River, and source areas of the major tributaries; whereas sandy clay, loamy clay, and silty clay whose clay fraction larger than 25% are mainly distributed in the confluent area of the major tributaries. Grain sizes of sediments on riverbed

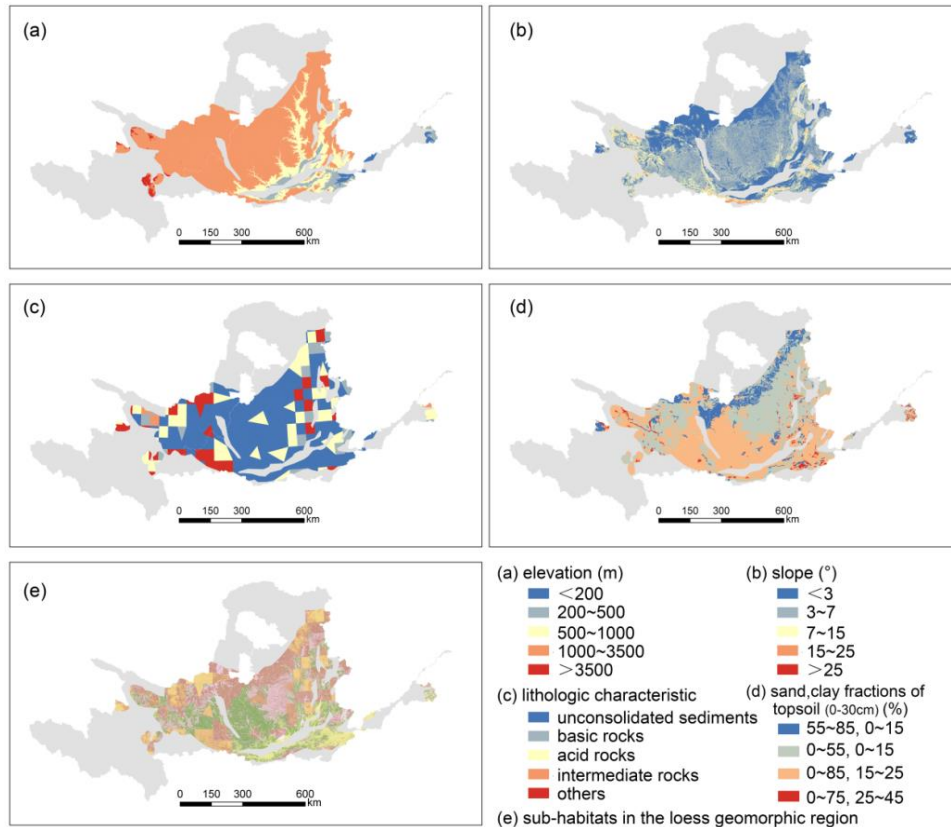


Figure 4. Distribution of: (a) elevation; (b) terrain slope; (c) lithologic characteristic; (d) sand and clay fractions of topsoil (0 ~ 30m), and (e) sub-habitats in the loess geomorphic region identified based on overlay of (a) ~ (d).

surface are essential to spawning habitat quality of fishes (Riebe et al., 2014). Grain size of sediments is required coarse enough to resist water erosion (Tang, 2004) and to allow flowing through of the oxygen-rich water, but also required fine enough to enable female fishes to move sediments for structuring redds and deposit their eggs in the riverbed (Kondolf et al., 1993). Fishes with larger body size often make more riverbed area for spawning since they are more capable of moving larger sediment beneficial to higher fecundity (Riebe et al., 2014). Furthermore, grain size of sediment is the major influencing factor of juvenile fish distribution at small scale. Smaller fishes have a preference for fine-particle sediments, whereas larger fishes have less selectivity even if pebbles and granules are less common options for them (Stoner and Abookire, 2002).

Overlay of the aforementioned four geomorphic factors generates 313 sub-habitats (mean area of 1,212 km²) in the loess landform region, covering a total area of 380,163 km² (Figure 4e). The Characteristics of fish community corre-

sponding to different geomorphic factors were displayed in Table 3.

4.4. Coupling of Aquatic Habitats and Topological Structure

Spatial attributes could also be interpreted in terms of stream order. Using the Strahler stream-order scheme, ten orders of rivers are classified in the Yellow River Basin, which are expected to be correlated with aquatic habitats controlled by channel elevation, slope, fraction of sediments (clay and sand).

Figures 5a and 5b show that both mean and median values of channel elevation and slope decrease with stream order (particularly from order 1 to order 7). The mean value of channel elevation decreases from 2,199 to 192 m when the stream order increases from 1 to 10. The mean value of channel slope decreases from 12.28° to 8.01° from order 1 to order 10, and reaches the minimum value (5.82°) at 7th order. These results quantify the relationship between topographic

Table 3. Characteristics of Fish Community Corresponding to Different Geomorphic Factors

Geomorphic conditions		Fish community
Factor	Grade	
elevation	low	eurythermal species
	high	endemic species
slope	low	smaller-sized fishes
	high	larger-sized fishes
hardness of riverbed materials	low	juvenile fishes; commercial species
	high	non-commercial species
alkalinity of rock	low	silicate-preferred species
	high	carbonate-preferred species
grain size of sediment	low	smaller fishes; lentic species
	high	higher fecundity of fishes; lotic species

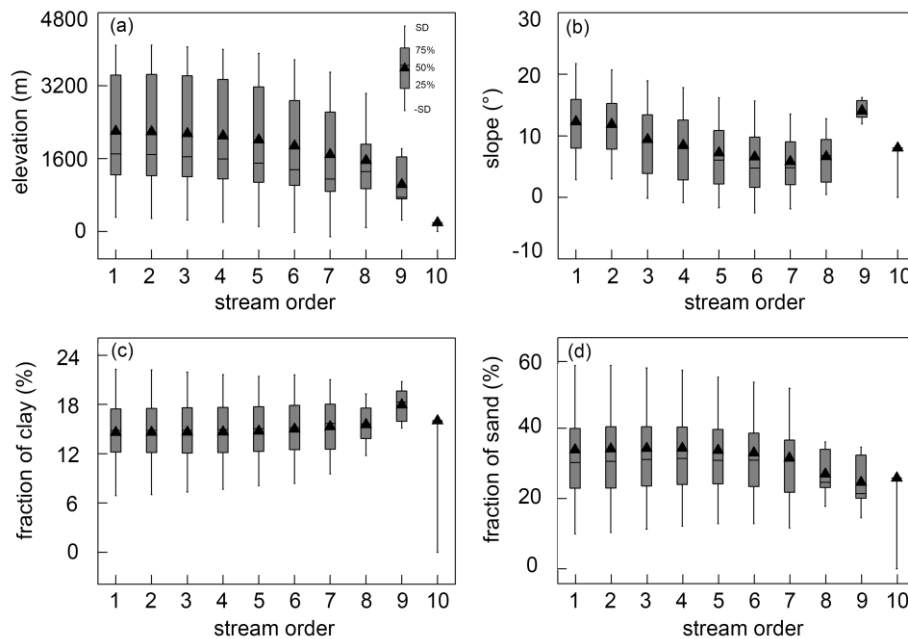


Figure 5. Relationship between (a) elevation and stream order; (b) slope and stream order; (c) fraction of clay and stream order; and (d) fraction of sand and stream order.

conditions and hierarchical properties of rivers. Low-order rivers more correspond to habitats with higher elevation and steeper slope, and flat habitats with low altitude more frequently occur in high-order rivers.

Figures 5c and 5d illustrate the fraction of clays and sands respectively in response to ten orders of rivers. For order 1 ~ 10, the mean value of fraction of clay increases from 14.6 to 17.96%, and reaches the maximum when stream order reaches 9. Mean value of fraction of sand reduces from 33.86 to 24.62% and reaches the minimum when stream order gets to 9. It seems that the greater stream-order is, the finer sediments would be encountered in the aquatic habitats in the Yellow River Basin.

Coupling of topographic features and surface material compositions is helpful to understand spatial distribution of riverine habitats in terms of stream orders, and hierarchical analysis based on primary geomorphic issues/factors would be of particular use to identify ecological responses in the context of river networks.

4.5. Diversity of Riverine Habitats with Different Stream Orders

4.5.1. Diversity of Riverine Habitats among Rivers

The diversities of riverine habitats described by the geocodes are highly relevant to stream orders. Figure 6a illustrates 85 independent geocodes (N_G) screened from thousands of generated outputs over the whole Yellow River Basin. Coupling with rivers from order 1 to 10, the N_G simply decreases from 83 to 10, in which the N_G for headwater (1st ~ 3rd order herein) streams takes 96 ~ 98% of the total.

Headwater streams present greater N_G due to two main reasons. Firstly, both number (N) and length (L) of lower-order streams are much larger as shown in Figures 6b and 6c. The number of rivers reduces from 711,641 to 1, and the total length of rivers decreases from 694,718 to 1,396 km with increase of stream orders from 1 to 10. Headwater streams contribute about 95% of the total number and 79% of the total length of rivers, suggesting their irreplaceable role in promoting diversity of riverine habitats. Secondly, headwater streams are more spatially isolated due to the branching structure of river networks. The spatial isolation of low stream-order rivers could be quantified by an index called fractal dimension (D) (Mandelbrot, 1967) with the box counting algorithm (Beauvais and Montgomery, 1997):

$$D = \lim_{\epsilon \rightarrow 0} [\log N(\epsilon) / \log(1/\epsilon)] \tag{2}$$

where $N(\epsilon)$ is the number of boxes of side length ϵ required to cover the set.

Fractal dimensions for each of the ten orders of rivers are illustrated in Figure 6d, from which we can see that the value of D also decreases with increasing stream order. Furthermore, D and N_G are found positively correlated ($R^2 = 0.49$). On the average, N_G decreases by 22% with per-unit decrease of D . The low-order streams with higher fractal dimension are capable of spreading to extensive areas from the tips of a dendritic fluvial network, which leads to pronounced habitat variations among headwater streams.

Since headwater streams present greater among-stream discrepancies in local habitat characteristics than larger rivers,

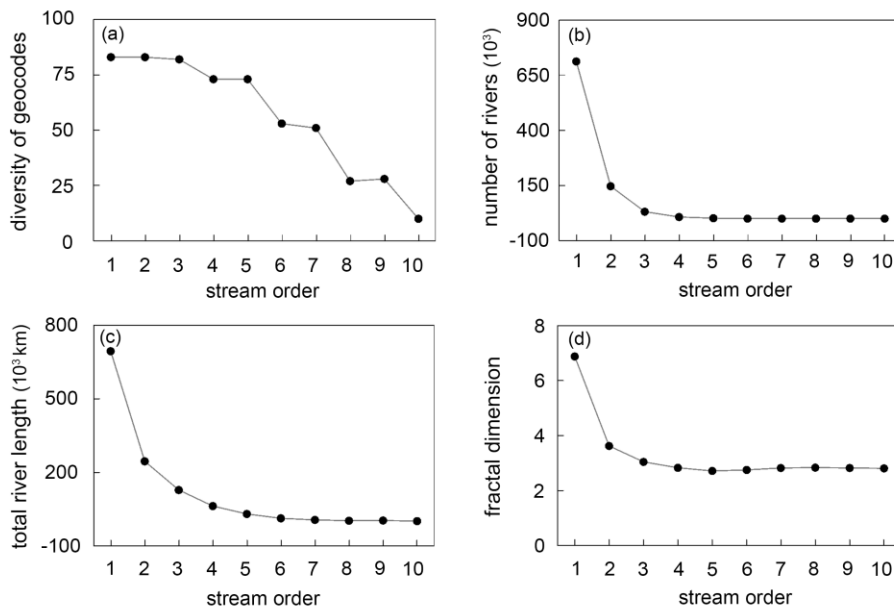


Figure 6. Hierarchical properties of (a) diversity of geocodes among rivers, (b) number of rivers, (c) total length of rivers, and (d) fractal dimension.

there is a high degree of variability in species composition among headwater streams which is known as β diversity (Whittaker, 1960). The significant contribution of headwater streams to biodiversity (especially β diversity) has been reported recently (Besemer et al., 2013; Biggs et al., 2017; Baattrup-Pedersen et al., 2017), which is further confirmed in the present work though traditionally headwater streams have been considered depauperate (RCC, Vannote et al., 1980) on stream network biodiversity.

4.5.2. Diversity of Riverine Habitats within a River

Rivers could be segmented into reaches in terms of geocodes which reflect spatial heterogeneity of principal environmental factors within a single river, leading to habitat fragmentation which is characterized by two indexes FI_1 and FI_2 respectively defined as follows:

$$FI_1 = N_I/N \tag{3}$$

and

$$FI_2 = L_I/L_2 \tag{4}$$

where N_I is number of reaches, and N is number of rivers of specific order; L_I and L_2 are average length of rivers and reaches of specific order, respectively.

Figures 7a and 7b illustrate both FI_1 and FI_2 for ten orders of rivers. Increase of FI_1 (from 1.02 to 13.67) and FI_2 (from 1.07 to 14.33) reveal that degree of habitat fragmentation of rivers grows with increasing stream order (1st ~ 9th but except the 10th). For clarity, another two parameters (D_{G1} and D_{G2}) are further introduced to present the average habitat diversity within a river:

$$D_{G1} = N_G/N \tag{5}$$

$$D_{G2} = N_G/L \tag{6}$$

As illustrated in Figures 7c and 7d, D_{G1} increases from 0.01 to 1,000 when stream order increase from 1 to 10, while D_{G2} increases with stream order for order 1 ~ 8, and decreases

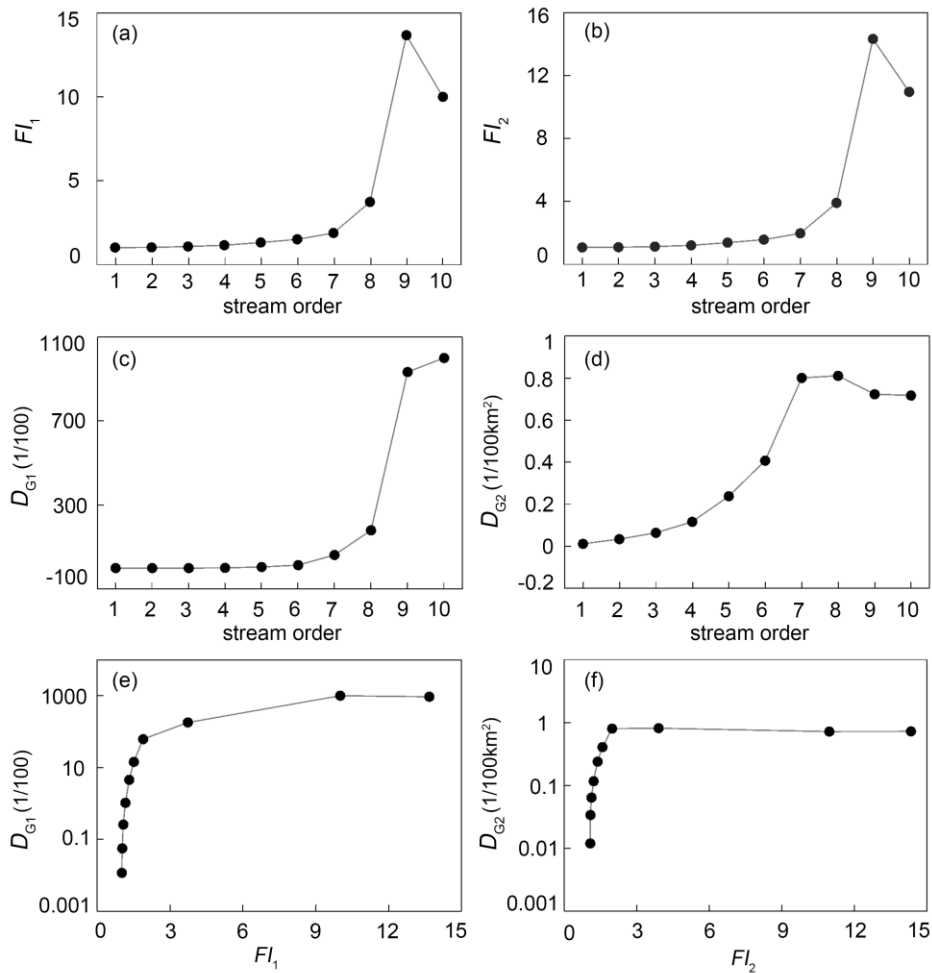


Figure 7. Characterization of fragmental degree of rivers (a) FI_1 , and (b) FI_2 , geocodes (c) D_{G1} , and (d) D_{G2} within a river, and their relationship (e) D_{G1} and FI_1 , (f) D_{G2} and FI_2 .

from order 8 to order 10. This implies that a low-order stream exhibits more homogeneity of habitats, but a high-order river tends to present heterogeneity of habitats. And higher heterogeneity of habitats within a river indicates a higher complexity of riverine habitats.

The relationship between river fragmentation and average habitat diversity within a river are also investigated (see Figures 7e and 7f). In the perspective of number of rivers with given stream orders (Figure 7e), D_{G1} slowly increases (from 0.03 to 0.09) for rivers from order 1 to 4, then rapidly increases (0.22 to 1.24) from order 4 to 7, and followed by a decrease (from 0.63 to -0.18) for rivers from order 7 to 10. With increase of the stream order, the positive feedback of habitat diversity within a river is declined to degree of habitat fragmentation of rivers. In the perspective of length of rivers with given stream orders, similar relations are found between D_{G2} and FI_2 (Figure 7 f). Overall, the habitat diversity within a river of lower stream-order (1 ~ 3) is generally small and getting higher for moderate stream-order (4 ~ 7).

The highest environmental heterogeneity of rivers with moderate orders demonstrates an increase of ecological diversity from headwaters to mid-sized streams. Existing literatures on fishes (Muneepeerakul et al., 2008) and diatom (Stenger-Kovács et al., 2014) confirm the view of enhance local diversity (characterized by alpha diversity, Whittaker, 1960) corresponding to stream order.

4.6. Implications for River Ecology

Interaction between dendritic river networks and habitat diversity is one of the major concerns on biodiversity. For example, previous studies have indicated the consequences of underestimation for biodiversity in river networks when small streams are ignored (Benstead and Leigh, 2012). Our systematic study on the role of headwater streams as well as mid-sized rivers on differentiation of aquatic habitats is helpful to get insights into biological responses in river networks. The coupling of habitats and river networks could be implemented through geomorphic properties, in particular factors describing surface materials and topographic conditions, and thereby allows to investigate the community assembly mechanism in the hierarchical aquatic systems.

The present work is potentially useful for explaining the controversy about dominant driving force of community construction and biodiversity in terms of Niche and Neutral theories in riverine habitats. Niche-based theory of community assembly believes that community construction is a screening process, in which local species are selected from large-scale species reservoirs through multiple environmental filtering and biological interacting (Shea and Chesson, 2002), whereas the neutral theory of biodiversity assumes that community diversity is only the result of diffusion and random action, which is independent with species attributes and environmental factors (Hubbell, 2005; Liu et al., 2017; Sun et al., 2017; Yu et al., 2017). More recently, some attempts have been made for reconciliation of these two theories (Niu et al., 2009; Fan et al., 2017b). Our study reveals that Neutral theory is

more suitable for describing aquatic habitats with homogeneous geographical features, and headwater streams (with lower stream orders) become dominant to the topologic structure of river networks. However, Niche theory is more appropriate for describing aquatic habitats with varied climatic and geographic conditions, and larger rivers (with higher stream orders) should be the major concern because of increasing habitat heterogeneity and diverse response of biological community.

5. Conclusions

An integrated approach is proposed for identification of aquatic habitats in river networks in terms of geocodes derived from geologic periods, climatic conditions, water sources, geomorphic characteristics and river patterns. In particular, 6 groups of aquatic habitats in the Yellow River Basin have been classified, and 313 sub-habitats were further derived with consideration of both topographic condition and surface material composition in the loess geomorphic regions. By coupling the generated habitats with river networks in the Yellow River Basin, the role of rivers with different stream orders has been systematically examined, in particular the contribution of headwater streams to diversity of aquatic habitats among rivers and mid-sized rivers to the diversity within a river, which also allows a better understanding of assembly mechanisms of biological communities in hierarchical river systems.

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Notation List

AI : aridity index, a function of precipitation and potential evapo-transpiration.

S : sinuosity, ratio of the length along its winding path and the straight length from source to outlet.

N_G : number of independent geocodes.

N : number of rivers of specific order.

L : total length of rivers of specific order.

D : fractal dimension.

ε : side length of box.

$N(\varepsilon)$: the number of boxes of required to cover the set.

N_I : number of reaches.

L_1 : average length of rivers of specific order.

L_2 : average length of reaches of specific order.

FI_1 : parameter of habitat fragmentation, $FI_1 = N_I/N$.

FI_2 : parameter of habitat fragmentation, $FI_2 = L_1/L_2$.

D_{G1} : average habitat diversity within a river in terms of number of rivers, $D_{G1} = N_G/N$.

D_{G2} : average habitat diversity within a river in terms of river length, $D_{G2} = N_G/L$.

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