Journal of Cleaner Production 230 (2019) 55–68

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Emergy-based accounting method for aquatic ecosystem services valuation: A case of China

Qing Yang [a], Gengyuan Liu [a, b, *], Marco Casazza [c], Yan Hao [a, b], Biagio F. Giannetti [a, d]

[a] *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China*
[b] *Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, Beijing, 100875, China*
[c] *University of Naples 'Parthenope', Department of Engineering, Centro Direzionale, Isola C4, 80143, Naples, Italy*
[d] *Post-graduation Program in Production Engineering, Paulista University, Brazil*

ARTICLE INFO

Article history:
Received 5 February 2019
Received in revised form
6 May 2019
Accepted 8 May 2019
Available online 9 May 2019

Keywords:
Aquatic ecosystems
Ecosystem services valuation
Emergy
Non-monetary accounting

ABSTRACT

The importance of aquatic ecosystem services (ES) has been widely recognized. However, complexities among different aquatic ecosystems, the uncertainties of ES delivery mechanism and the lack of a unified accounting method from a production perspective still bring challenges for assessing aquatic ecosystem services valuation (ESV). To address these three concerns, this study develops a coherent accounting method on aquatic ESV. This includes: (1) an aquatic classification system ("source", "process" and "sink" type); (2) an aquatic ES classification system, which considers their formation mechanisms; (3) a set of detailed ESV accounting techniques. Aquatic ES are divided into direct services, indirect services and existing services. In addition, according to the characteristics and uniqueness of different aquatic ecosystems, the importance degree of each aquatic ES is identified. Further, the aquatic ESV accounting techniques are established to reach three study goals: (1) integration with the characteristics of specific aquatic ecosystems when measuring ESV, (2) aquatic ESV assessment from supply side, and (3) unified metric. The newly developed aquatic ESV accounting is applied to aquatic ecosystems as a case study to test this method. The results show that: (1) Sichuan has the largest aquatic ESV (1.12E+23 sej/yr); (2) Tibet has the largest aquatic ESV per unit area (5.55E+11 sej/m^2/yr); (3) Most China's aquatic ecosystems have microclimate regulation as their largest ESV per unit area. This study can fill several research gaps on aquatic ESV evaluation, providing also scientific suggestions on differentiated conservation and management policies applied to specific aquatic ecosystems.

1. Introduction

Aquatic ecosystems play a pivotal role in providing food to humans, in mitigating climate change and also in serving a nursery function for diverse species or cultural services for humans (MEA, 2005; Ouyang et al., 2018). Global estimates suggest that more than 50% of aquatic ecosystems have been already lost (Langan et al., 2018), while 60% of the remaining aquatic ecosystems are degraded or unsustainably used because of population and economic growths (MEA, 2005).

The recognition of aquatic ecosystem services valuation (ESV) is growing (Maltby and Acreman, 2011; Groot et al., 2006; Ricaurte et al., 2017). Yet, significant challenges for examining aquatic ESV still exist, due to their high variability in delivering different ecosystem services (ES) brought by their heterogeneity and specific properties (MEA, 2005; Langan et al., 2018). For example, headwaters regions are the origins of large rivers (source type). Thus, water quality is considered first when assessing the ESV (Liu et al., 2008). Rivers (process type) are the connectors among sources and sinks. Thus, the transport or loading functions are mainly considered. Lakes (sink type) can be sinks or converges of waters. This is the case either of closed lakes with an inlet but no outlet or of the outflow to a river (Gao et al., 2018). In such a case, the sediments enrichment should be considered. The second challenge is the uncertainty of aquatic ES formation mechanisms. For example, some researches apply the ES classification systems established by other studies, such as MEA, but they don't identify the ES delivery modes.

A systematic aquatic ESV assessment, uncovering the

---

* Corresponding author. State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China.
E-mail address: liugengyuan@bnu.edu.cn (G. Liu).

https://doi.org/10.1016/j.jclepro.2019.05.080
0959-6526/© 2019 Elsevier Ltd. All rights reserved.

Abbreviation

ES	ecosystem services
ESV	ecosystem services valuation
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
Max(R)	renewable resource
B	biomass
Em_{bi}	the emergy required by biomass increase in aquatic ecosystem *i* (sej/yr)
R_{li}	the renewable resources emergy in aquatic ecosystem *i* (sej/yr)
R_{ii}	the renewable resources emergy required by input biomass outside aquatic ecosystem *i* (sej/yr)
R_{oi}	the renewable resources emergy required by output biomass outside aquatic ecosystem *i* (sej/yr)
Em_{cs}	the emergy required to sequestrate carbon in aquatic ecosystems (sej/yr)
C_i	the carbon sequestrated in aquatic ecosystem *i* (g C/m^{2}*yr)
S_i	the *i*th aquatic ecosystem's area (m^{2})
UEV_{csi}	the UEV of carbon sequestration in aquatic ecosystem *i* (sej/g)
UEV	Unit Emergy Value
Em_{i}	the renewable emergy driving NPP of aquatic ecosystem *i* (sej/yr)
NPP_i	: the net primary productivity of aquatic ecosystem *i* (g C/m^{2}*yr)
Em_{sb}	the emergy applied to deposit organic matter in aquatic ecosystems (sej/yr)
OM_{ai}	the deposition of organic matter in aquatic ecosystem *i* (g/m^{2}/yr)
k_1	the fraction of deposition absorbed by aquatic plants
k_{2i}	: the conversion factor from g to kcal in aquatic ecosystem *i*
k_3	the conversion factor from kcal to J
UEV_{omi}	the UEV of organic sediment deposition in aquatic ecosystem *i* (sej/J)
k_4	the ratio of organic sediment deposition to the NPP in aquatic ecosystem *i*
Em_{gr}	the emergy used to replenish groundwater (sej/yr)
R_i	the precipitation in aquatic ecosystem *i* (m/yr)
ρ	water density (kg/m^{3})
k_i	the infiltration coefficient of aquatic ecosystem *i*
G	water's Gibbs free energy (J/g)
UEV_{gw}	the UEV of water infiltration (sej/J)
DALYs	Disability Adjusted Life Years
PDF	Potentially Disappeared Fraction
Em_{HH}	the emergy needed to reduce damages to human health (sej/yr)
M_{ij}	the ability of the *j*th aquatic ecosystem to remove water pollutant *i* (mg/kg)
NPP_j	the net primary productivity of aquatic ecosystem *j* (g C/m^{2}/yr)
S_j	the *j*th aquatic ecosystem's area (m^{2})
$DALY_{pi}$	the DALY of one individual resulted from *i*th water pollutant (cap*yr/kg)
τ_H	emergy per capital (sej/cap)
T_i	the *i*th water pollutant's turnover time (yr)
PDF_{pi}	the PDF of species caused by the *i*th water pollutant (PDF $\times$ m^{2} $\times$ yr $\times$ kg^{-1}
Em_{spj}	the emergy needed by species in aquatic ecosystem *j* (sej/yr)
Em_{mt}	the emergy required to transport materials in river ecosystem (sej/yr)
R_{ai}	the rainfall in aquatic ecosystem *i* (m/yr)
k_r	runoff rate
h_i	the average elevation of aquatic ecosystem *i* (m)
g	gravity (m/s^{2})
UEV_{rgeo}	the transformity of runoff (geopotential energy) (sej/J)
Em_h	: the emergy required to generate hydropower in river ecosystem (sej/yr)
Em_r	: the emergy contributed by rainfall to generate hydroelectricity in river ecosystem (sej/yr)
Em_{mb}	: the emergy contributed by mountain building to form hydropower in river ecosystem (sej/yr)
S_{dci}	: the catchment area of dam *i* in river ecosystem (m^{2})
R_{di}	: the rainfall in dam *i* area (m/yr)
UEV_r	: the UEV of rain (sej/g)
r_{di}	: average deviation rate in dam *i* area in river ecosystem (m/yr)
ρ_m	: mountain density (g/cm^{3})
UEV_m	: the UEV of mountain (sej/g)
Em_{mr}	: the emergy applied to regulate microclimate in aquatic ecosystems (sej/yr)
E_{ai}	: the annual evaporation of aquatic ecosystem *i* (m/yr)
UEV_{wt}	: the UEV of water transpiration (sej/J)
Em_{acr1}	: the emergy applied to reduce harms to human health resulting from climate regulation by aquatic ecosystems (sej/yr)
Em_{acr2}	: the emergy needed to reduce harms to ecosystem quality brought by climate regulation by aquatic ecosystems (sej/yr)
C_{ij}	: the *i*th greenhouse gas sequestration in aquatic ecosystem *j* (kg/m^{2}/yr)
$DALY_{gi}$	: the DALY caused by greenhouse gas *i* (capital*year/kg)
LT_i	: the lifetime of greenhouse gas *i*
PDF_{gi}	: the PDF of species resulting from greenhouse gas *i* (PDF $\times$ m^{2} $\times$ yr/kg)
NP_i	: the net production of network component *i* (J/yr)
Tr_i	: the UEV of component *i* (sej/J)
EB	: ecosystem biodiversity
EIV_i	: the ecosystem importance value of the component *i* in the network to the total emergy throughput of the system
TET	: the total emergy throughflow (sej/m^{2}/yr)
FS	forest swamp
SS	shrub swamp
M	marsh
L:	lake
R_P	reservoir or pond
RI	River
C_D	canal or ditch
BI	biomass increase
CS	carbon sequestration
GR	groundwater recharge
WP	water purification
HG	hydropower generation
MR	microclimate regulation
CR	climate regulation
Bio	biodiversity

uniqueness and features of variable aquatic ecosystems and capturing their ES formation mechanisms, is still lacking. To our best knowledge, three main methods have been applied to assess ESV: economic methods (e.g. revealed and stated preferences methods) (Costanza et al., 1997; Dias and Belcher, 2015; Mcdonough et al., 2014; Zhang et al., 2017a,b), InVEST® (Integrated Valuation of Ecosystem Services and Tradeoff) model (Ouyang et al., 2016) and emergy method (Brown et al., 2006; Huang et al., 2011).

The relevance of economic method stemmed from two seminal publications: an edited book by Daily (1997) and an article in *Nature* on the world's ESV (Costanza et al., 1997). However, economic methods are criticized for their limitations of human-centered valuation framework. Moreover, they lack of consideration with respect to the complex ES formation and delivery principles (Costanza et al., 2017), imperfect information (Norton et al., 1998) and derivation that human's well-being may derive from other sources, such as social or built capital (Costanza et al., 2014).

InVEST model, released in 2007, has been widely used in the international scope (Nelson et al., 2009; Tallis and Polasky, 2009; Papagiannakis and Lioukas, 2012). In particular, it provides a way to map and evaluate multiple ES, that can be applied to inform conservation and natural resource management. However, it is not a panacea (Bhagabati et al., 2014; Tallis and Polasky, 2009). For example, it lacks of a unified metrics, as well as of a simulation of the dynamic processes underlying many ecosystem functions (Langan et al., 2018) and of a prediction on how ecosystem services will change as ecosystems are altered (Tallis and Polasky, 2009).

The use of a production perspective to assess ESV allows to capture the dynamic processes of ecological functions and ES formation mechanisms. Under this environmental accounting framework, emergy method provides an ESV measurement approach by evaluating the biophysical flows used to support its generation, i.e. its cost of production (Odum, 1996; Franzese et al., 2017). Emergy is the available energy required, directly and indirectly, to make a service or good (Odum, 1996). When applied to assess ESV, the formation of ecosystem services are considered as an ecological thermodynamic process (Franzese et al., 2017). In particular, from a production perspective, emergy can detail and analyze material flows and energy transfer, quantify each flow and stock's environmental contributions, as well as specific biophysical and thermodynamic variables. Even if emergy was extensively applied for ESV assessment (Campbell, 2012; Turcato et al., 2015; Zhang et al., 2017a,b), it still lacks of a comprehensive assessment method, applied to different aquatic ecosystems, which can also reveal their ES formation mechanisms.

To fill this research gap, the aim of this paper is to develop a coherent emergy-based assessment method applied to aquatic ESV. Consequently, the specific scientific goals of this work are: (1) to uncover the differences and complexities of aquatic ecosystems; (2) to clarify the aquatic ES classification systems and formation mechanisms; (3) to develop a coherent emergy-based accounting technique for aquatic ESV (unified metric). Therefore, the novelties of this study are developing a systematic accounting method for aquatic ESV based on emergy analysis, and investigating aquatic ESV based on ecosystems' uniqueness and further identifying their significant services. China's aquatic ecosystems are selected as the case study to test this method. This study is organized as below: section 2 establishes the accounting method on aquatic ESV; section 3 describes the case study, the data sources as well as the evaluation results and related analyses; section 4 presents a discussion on the proposed assessment method and results; section 5 is focused on the conclusions.

2. Accounting method on aquatic ecosystem services valuation

2.1. Aquatic ecosystems classification systems

An aquatic ecosystem is an ecosystem within a water body. It mainly includes two categories: marine ecosystems and freshwater ecosystems (Alexander and Fairbridge, 1999). Marine ecosystems are differentiated from freshwater ones by an higher salt concentration, with an average salinity of 35% of water globally (Chester and Jickells, 2012). Freshwater ecosystems are divided into three basic types: (1) lentic, such as lakes and ponds; (2) lotic, including rivers; and (3) wetlands, ecosystems with saturated soil or inundated for part of the time (Vaccari et al., 2005). With respect to wetlands, they are classified into four main types: swamp, marsh, fen and bog (Keddy, 2010). Combining this classification system with China's Land Cover I and II Classification System, also due to the lack of data on marine ecosystems, aquatic ecosystems including forest swamp, shrub swamp, marsh, lake, reservoir or pond, river, canal or ditch are investigated in this study (Table 1).

2.2. Aquatic ES classification systems and key services identification

Aquatic ecosystem services are classified into direct, indirect and existing services. Direct services refer to the changes in systems' stocks and flows; indirect services are generated through ecological processes, such as co-products or by-products (Yang et al., 2018); existing services are the share of global services at local scale. The specific aquatic ES subtypes in this study are presented in Table 1.

Aquatic ecosystems can also be divided into "source", "process" and "sink" types, as shown in Fig. 1. Meanwhile, four services types: provisioning, regulating, supporting and cultural services classified by MEA (2005) are also presented in the table to provide a large significance to the ecosystem functions.

Headwaters belong to "source" type. In the case of China, they include, among others, the Sanjiangyuan region in China, as well as the headwaters of three great Asian rivers: the Yellow, the Yangtze, and the Lancang (Liu et al., 2017). Water quality and conservation are especially relevant when examining ESV (Liu et al., 2008). In fact, these areas are important habitats for several organisms, resulting in high biodiversity. Therefore, in Table 1, the symbol "●●●" is used to show the relevance of biomass increase, carbon sequestration and biodiversity for this type of ecosystems ("source" type), indicating the highest ranking in significance (classified with marks from "●" to "●●●").

With respect to river, representing a typical "process" type, the fluidity attribute is considered highly important, due to its resulting water purification, hydropower generation and materials transport capacity (Liu et al., 2011).

With respect to "sink" type, lakes and reservoirs are the sinks of rivers, with important functions, such as organic matter deposition. Swamps and marshes are not only the sinks of water, due to their low topographic relief. but, considering also wetlands, composed by trees, shrubs, grasses and so on, they support a large amount of biomass, generating a high carbon sequestration and level of biodiversity (Keddy, 2010). Thus, for wetlands ("sink" type), these ESV are of high significance, i.e. "●●●". Reynaud and Lanzanova (2017) also indicate cultural and educational values as relevant services for lakes. This is why cultural and education value of ecosystems are assessed by the carrying information, based on emergy method, where information has a higher hierarchy in systems. Therefore, "●●●" is applied to represent the importance of cultural and educational value for all aquatic ecosystems. The specific ecosystem services classification and their key services are shown

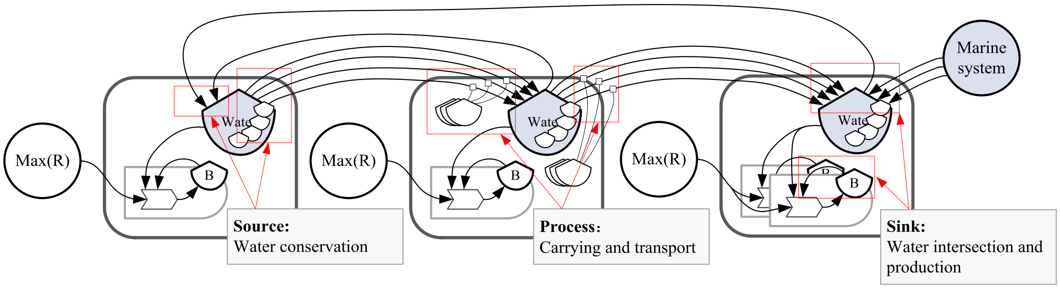


Fig. 1. The emergy diagram based on aquatic ecosystems classifications (Max(R): renewable resource; B: biomass).

in Table 1.

2.3. Diagram representation

The emergy diagram of river ES is represented in Fig. 2 as an example.

The process described by Fig. 2 starts from the carbon, absorbed from the air to plants through photosynthesis driven by sunlight, resulting in biomass increase. Carbon moves to the sediments through the death of organisms (mostly plants). The process of groundwater recharge usually occurs in the vadose zone, as a flux to the water table surface (Singh et al., 2018). Groundwater is recharged to a smaller extent by surface water (rivers and lakes) (Smerdon, 2017). Hazardous substances can be decomposed into less toxic or non-toxic substances by aquatic organisms through bioaccumulation, biosorption and phytoremediation (Vijayaraghavan and Balasubramanian, 2015). The flow of rivers can also dilute and degrade pollutants in water bodies. Meanwhile, generally because of the gravity acting on materials and/or the fluidity of runoff, river ecosystem can transport materials. Besides, driven by the geopotential energy of river and the height difference between mountains and river plains, hydropower can be generated by river ecosystems. In addition, river ecosystem can regulate climate at both micro and macro scale, due to its higher thermal capacity than soil or plants (Steeneveld et al., 2014). River ecosystems are habitats of freshwater organisms (Muneepeerakul et al., 2019), resulting in their contribution to biodiversity. At the right side of the emergy diagram, cultural and education value for river ecosystems are represented. In particular, this value affects humans' cognition, education and researches, due to its carried information.

2.4. Accounting techniques on aquatic ecosystem services

In the section, the aquatic ES formation mechanisms are presented and their ESV accounting techniques is detailed.

2.4.1. Direct services

2.4.1.1. Biomass increase. Biomass is the mass of living biological organisms in a given area at a given time (unit: kg/m^2 or t/hm^2) (Houghton, 2008). River, lake, wetland and reservoir ecosystems are included here. The specific calculation formula is:

$$Em_{bi} = MAX(R_{li}) + MAX(R_{ii}) - MAX(R_{oi}) \tag{1}$$

where: Em_{bi} is the emergy required by biomass increase in aquatic ecosystem i (sej/yr); R_{li} is the renewable resources emergy in aquatic ecosystem i (sej/yr); R_{ii} is the renewable resources emergy required by input biomass outside aquatic ecosystem i considering the fluidity of water (sej/yr); R_{oi} is the renewable resources emergy required by output biomass outside aquatic ecosystem i considering the fluidity of water (sej/yr). $MAX(R)$ is calculated as (Yang et al., 2018):

$$\begin{aligned} MAX(R) = \mathrm{MAX}\Big[\sum(&\text{solar energy, thermal energy, tide}),\\ &\text{wave energy, wind energy, rain chemical potential}\\ &\text{energy, runoff geopotential energy, runoff chemical}\\ &\text{potential energy}\Big] \end{aligned} \tag{2}$$

2.4.1.2. Carbon sequestration. Wetland peat and lake sediments are worldwide considerable carbon pools due to their generally large carbon denseness and long dwelling times though their relatively small spatial distribution globally (Downing and Duarte, 2009). It was estimated that inland waters receive 1.9 Pg C/yr from the terrestrial ecosystems, of which around 10.5% is buried in aquatic sediments (Cole et al., 2007). Lakes, rivers, wetlands and reservoirs are included here. Carbon sequestration service is defined as:

$$Em_{cs} = \sum(C_i{*}S_i{*}UEV_{csi}) \tag{3}$$

$$UEV_{csi} = \frac{(Em_i)/S_i}{NPP_i} \tag{4}$$

where: Em_{cs} is the emergy required to sequestrate carbon in aquatic ecosystems (sej/yr); C_i is the carbon sequestrated in aquatic ecosystem i (g $C/m^{2}{*}yr$); UEV_{csi} is the Unit Emergy Value (UEV) of carbon sequestration in aquatic ecosystem i (sej/g); Em_i is the renewable emergy driving the net primary production (NPP) of aquatic ecosystem i (sej/yr), which is Em_{bi} in Eq. (1); NPP_i is the net primary productivity of aquatic ecosystem i (g $C/m^{2}{*}yr$).

2.4.1.3. Sediment building. Sediment organic matter is a source of food and energy for aquatic organisms, as well as a source of "recycle nutrients" for waters productivity (Froelich et al., 1979). Meanwhile, its nutritional balance plays a significant role in material flow through ecosystems (Meyers and Teranes, 2001; Westrich and Förstner, 2007).

Sediment building service in this study refers to the organic matter building in sediments in aquatic ecosystems without eutrophication, while this service is excluded from the total service when an aquatic ecosystem is eutrophic. The particulate detritus of vegetation is the primary source of lake organic sediments (Lerman et al., 1995). Nearly all organic matter originates from plants; less than 10% come from animals (Meyers and Ishiwatari, 1995). The calculation method of sediment building can be written as:

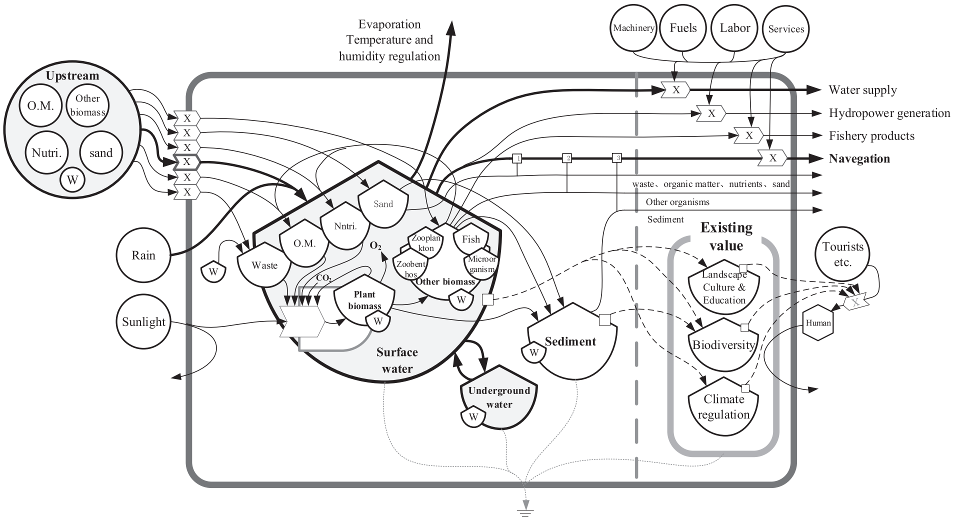


Fig. 2. The emergy diagram of river ecosystem services.

$$Em_{sb} = \sum (OM_{ai} \times k_1 \times k_{2i} \times k_3 \times S_i \times UEV_{omi}) \tag{5}$$

$$OM_{ai} = k_4 \times NPP_i \tag{6}$$

where: Em_{sb} is the emergy applied to deposit organic matter in aquatic ecosystems (sej/yr); OM_{ai} is the deposition of organic matter in aquatic ecosystem i (g/m^2/yr); k_1 is the fraction of deposition absorbed by aquatic plants, which is 0.78 (Mitsch and Gosselink, 1993); k_{2i} is the conversion factor from g to kcal in aquatic ecosystem i; k_3 is the conversion factor from kcal to J, which equals to 4186 J/kcal; S_i presents the ith aquatic ecosystem's area (m^2); UEV_{omi} is the UEV of organic sediment deposition in aquatic ecosystem i (sej/J); k_4 is the ratio of organic sediment deposition to the NPP in aquatic ecosystem i, which is 30.37% (Gale and Reddy, 1994); NPP_i is the net primary productivity of aquatic ecosystem i (g C/ha/yr).

2.4.1.4. Groundwater recharge. Surface water systems, which are formed of pervious sediments or occur in regions with particularly mobile water tables, play a special role in groundwater recharge (Silveira and Usunoff, 2009). The value is accounted as:

$$Em_{gr} = \sum (R_i * \rho * S_i * k_i * G * UEV_{gw}) \tag{7}$$

where: Em_{gr} is the emergy used to replenish groundwater (sej/yr); R_i presents the precipitation in aquatic ecosystem i (m/yr); ρ presents water density (kg/m^3); S_i indicates the ith aquatic ecosystem's area (m^2); k_i is the infiltration coefficient of aquatic ecosystem i; G is water's Gibbs free energy (J/g), which equals to 4.94 (Brown and Bardi, 2001); UEV_{gw} is the UEV of water infiltration (sej/J).

2.4.2. Indirect services

2.4.2.1. Water purification. Aquatic ecosystems have the capacity to remove contaminants from water by a variety of processes (Ostroumov, 2004), including dilution, sedimentation, aeration, absorption, floatation, chemical and biological reactions (González et al., 2014). When the concentration of pollutants exceeds the self-purification ability of water bodies, the capacity will not work (González et al., 2014; Yang et al., 2009). Hence, the self-purification capacity of aquatic ecosystems is selected to evaluate the water purification service.

Due to the self-purification ability of aquatic ecosystems, water pollutants would reduce the harmful effects on human health and ecosystem quality (Yang et al., 2018), which are respectively assessed by Disability Adjusted Life Years (DALYs) and Potentially Disappeared Fraction (PDF) of species. The detailed definition of DALYs and PDF, as well as the reasons for applying these two indicators, can be found in Goedkoop and Spriensma (2001) and Yang et al. (2018). In these studies, purification services of forest ecosystems were evaluated using these measurements. In the case of aquatic ecosystems, the specific calculation methods are defined below.

(a) Human health losses reduction

$$Em_{HH} = \sum ((M_{ij} \times NPP_j \times S_j \times DALY_{pi} \times \tau_H)/T_i) \tag{8}$$

where: Em_{HH} means the emergy needed to reduce damages to human health (sej/yr); M_{ij} presents the ability of the jth aquatic ecosystem to remove water pollutant i (mg/kg); NPP_j is the net primary productivity of aquatic ecosystem j (g C/m^2/yr); S_j is the jth aquatic ecosystem's area (m^2); $DALY_{pi}$ is the DALY of one individual resulted from ith water pollutant (cap*yr/kg); τ_H presents emergy per capital (sej/cap); T_i indicates the ith water pollutant's turnover time (yr).

(b) Ecosystem quality losses reduction

$$Em_{EQ} = \sum (M_{ij} \times NPP_j \times PDF_{pi} \times Em_{spj})/T_i \tag{9}$$

where: E_{mEQ} presents the emergy used to reduce damages to ecosystem quality (sej/yr); PDF_{pi} means the PDF of species caused by the ith water pollutant (PDF × m^2 × yr × kg^{-1}); Em_{spj} indicates the emergy needed by species in aquatic ecosystem j (sej/yr), which is expressed as local renewable resources (sej/yr) and can be calculated by equation (2); M_{ij}, NPP_j and T_i have the same meanings as the ones in equation (8).

The total water purification value Em_{wp} is the sum of Em_{HH} and Em_{EQ}.

2.4.2.2. Air purification. Aquatic ecosystems have the capacity to purify air (Em_{ap}), especially in the case of wetland ecosystems, due to the higher presence of plants than in other aquatic ecosystems (Cherry, 2011). The calculation method is similar to that of water purification. However, M_{ij} in equations (7) and (8) should be replaced with the air purification capacity of aquatic ecosystems. In parallel, $DALY_{pi}$ and PDF_{pi} in equations (7) and (8) should be replaced with DALYs and PDF caused by the i-th air pollutant.

2.4.2.3. Materials transport. Materials transport refers to the movement of solid particles, generally because of the acting of gravity on the materials and/or the movement of the fluid, in which the materials are contained (Czuba, 2018). Materials transport is significant in providing habitat for fish and other organisms in rivers (Valero et al., 2017). In this study, river and canal ecosystems have this service. Transported materials include nutrients, organic matter and sediments. Driven by geopotential energy, materials transport is assessed as follows:

$$Em_{mt} = \sum (S_i \times R_{ai} \times \rho \times k_r \times h_i \times g \times UEV_{rgeo}) \tag{10}$$

where: Em_{mt} is the emergy required to transport materials in river ecosystem (sej/yr); S_i presents the ith aquatic ecosystem's area (m^2); R_{ai} means the rainfall in aquatic ecosystem i (m/yr); ρ presents water density (kg/m^3); k_r indicates runoff rate, which is 25% (Brown and Ulgiati, 2016); h_i is the average elevation of aquatic ecosystem i (m); g is the gravity, which is 9.8 m/s^2; UEV_{rgeo} is the transformity of runoff (geopotential energy) (sej/J).

2.4.2.4. Hydropower generation. Hydroelectricity is generated in a dam, where the force of falling water is used to turn a turbine, that is connected to an electricity generator (Xu et al., 2018a). Hydropower is the most widely exploited form of renewable energy with very few greenhouse gases emissions (Solarin et al., 2019). Hydropower is derived from the combination action of runoff and elevation difference, which are driven by rainfall and mountain building respectively. Therefore, the measurement of hydropower service is:

$$Em_h = Em_r + Em_{mb} \tag{11}$$

$$Em_r = \sum (S_{dci} \times R_{di} \times \rho \times UEV_r) \tag{12}$$

$$Em_{mb} = \sum (S_{dci} \times r_{di} \times (1E+6) \times \rho_m \times UEV_m) \tag{13}$$

where: Em_h is the emergy required to generate hydropower in river ecosystem (sej/yr); Em_r is the emergy contributed by rainfall to generate hydroelectricity in river ecosystem (sej/yr); Em_{mb} is the emergy contributed by mountain building to form hydropower in river ecosystem (sej/yr); S_{dci} presents the catchment area of dam i in river ecosystem (m^2); R_{di} is the rainfall in dam i area (m/yr); ρ presents water density (kg/m^3); UEV_r indicates the UEV of rain (sej/g); r_{di} means average deviation rate in dam i area in river ecosystem (m/yr); $(1E+6)$ is the conversion factor from m^3 to cm^3, which means 1 m^3=(1E+6) cm^3; ρ_m presents mountain density (g/cm^3); UEV_m means the UEV of mountain (sej/g).

2.4.2.5. Microclimate regulation. Aquatic ecosystems form a unique microclimate, with significant cooling and humidifying effects (Bai et al., 2013; Carrington et al., 2001), due to the heightened evaporation during daytime, originating from heat capacity of water larger than that of impervious surface, soil, rock and vegetaion (Steeneveld et al., 2014). This service is accounted as:

$$Em_{mr} = \sum_{i=1}^{n} (E_{ai} * S_i * \rho * (1E+3) * G * UEV_{wt}) \tag{14}$$

where: Em_{mr} is the emergy applied to regulate microclimate in aquatic ecosystems (sej/yr); E_{ai} is the annual evaporation of aquatic ecosystem i (m/yr); S_i indicates the ith aquatic ecosystem's area (m^2); ρ means the density of water (kg/m^3); $(1E+3)$ presents the conversion factor from kg to g, which mean 1 kg equals to 1000 g; G is the water's Gibbs free energy (J/g), which equals to 4.94 (Brown and Bardi, 2001); UEV_{wt} is the UEV of water transpiration (sej/J).

2.4.3. Existing services

2.4.3.1. Climate regulation. Globally, aquatic ecosystems play an important role in regulating climate. DALYs and PDF are also applied here to measure the value of aquatic ecosystems as carbon pool to regulate climate. The specific reasons for selecting these two methods are detailed in Yang et al. (2018). The calculation formulas are:

$$Em_{acr1} = \sum C_{ij} \times \frac{DALY_{gi}}{LT_i} \times S_j \times \tau_H \tag{15}$$

$$Em_{acr2} = \sum C_{ij} \times \frac{PDF_{gi}}{LT_i} \times Em_{spj} \tag{16}$$

where: Em_{acr1} means the emergy applied to reduce harms to human health resulting from climate regulation by aquatic ecosystems (sej/yr); Em_{acr2} indicates the emergy needed to reduce harms to ecosystem quality brought by climate regulation by aquatic ecosystems (sej/yr); C_{ij} is the ith greenhouse gas sequestration in aquatic ecosystem j ($kg/m^2/yr$); $DALY_{gi}$ presents the DALY caused by greenhouse gas i (capital*year/kg); LT_i is the lifetime of greenhouse gas i; τ_H means the emergy per capita in case area (sej/cap); S_j indicates the jth aquatic ecosystem's area (ha); PDF_{gi} presents the PDF of species resulting from greenhouse gas i ($PDF \times m^2 \times yr/kg$); Em_{spj} is the emergy used to support species in aquatic ecosystem j (sej/yr), which is the local renewable resources (sej/yr) and can be calculated by equation (2). The total value of climate regulation (Em_{cr}) for aquatic ecosystem is the sum of Em_{acr1} and Em_{acr2}.

2.4.3.2. Biodiversity. At ecosystem scale, biodiversity evaluation generally depend on counts of species in different classes (Brown et al., 2006). Yet these methods have some challenges. First, the sources of biodiversity database are variable, due to the variable sampling intensities in different ecosystems or areas (Fagan and Kareiva, 1997; Peet, 1974). Moreover, they primarily fail to identify the interplays and feedbacks among ecological networks (Worm and Duffy, 2003). Therefore, Brown et al. (2006) proposed a system approach to evaluate a diversity index. This method, called emergy ecological network model (Brown et al., 2006; Campbell and Tilley, 2016), is applied here to calculate several indices. These indices, used to identify the relation between emergy and biodiversity (Campbell and Tilley, 2016), are:

$$EIV = (NP_i \times Tr_i) \Big/ \sum (NP_i \times Tr_i) \tag{17}$$

$$EB = -\sum (EIV_i \times \log_2 EIV_i) \tag{18}$$

$$TET = \sum (NP_i \times Tr_i) \tag{19}$$

where: NP_i means the net production of network component i (J/

yr); Tr_i presents the UEV of component i (sej/J); EB indicates ecosystem biodiversity; EIV_i presents the ecosystem importance value of the component i in the network to the total emergy throughput of the system; TET means the total emergy throughflow (sej/m^2/yr), and it is applied to measure the emergy required by the biodiversity in a given area (Em_{Bio}).

The transformities in equation (19) are typically computed through a linear optimization technique, as defined by Bardi et al. (2005). An example of energy transfer matrix is detailed in Fig. 6, as previously discussed by Brown et al. (2006). The advantage of such a system approach is that it can capture the hierarchical distribution of both flows and biophysical stocks through food networks (Brown et al., 2006).

2.4.3.3. Cultural and educational value. Abel offered a theoretical framework for considering the production of “culture” as a cycle, where the emergy carried by information is applied to assess the cultural value of one system in emergy terms (Abel, 2013, 2014). Due to the lack of data and a reference method to assess the cultural information carried by ecosystems, this service is not evaluated in this study.

2.4.4. The total aquatic ESV

In the case river ecosystems, runoff geopotential energy, being one of the inputs related to biomass increase, drives materials transport. This is why this carrying service is excluded from the total ESV in this study, in order to avoid double counting. Meanwhile, hydroelectricity generation (n) is also partly driven by runoff geopotential energy. It is assumed that, in a given region, the ratio between the distance from the hydropower station to the start point to the river and the total length of river is x. Therefore, there are three cases. In particular, the hydropower station is located at: (1) the start point of the river reach ($x = 0$); (2) the end point of the river reach ($x = 1$); (3) the place between start and end point ($0 < x < 1$).

In addition, for biomass increase, two cases are considered: (a) runoff geopotential energy is the largest renewable resource; (b) another energy form, such as rain or wind energy, is the largest renewable input. If case (a), the location of hydropower station should be taken into consideration in the three cases. The specific formulas of total river ESV are:

For case (a) and (1),

$$\mathrm{TESV} = \sum\left(MAX\left(Em_{bi},\ Em_{cs}, Em_{sb}, Em_{gr}\right),\ Em_{wp}, Em_{ap}, Em_{h}, Em_{mr}, Em_{cr}, Em_{Bio}, Em_{ce}\right) \tag{20}$$

For case (a) and (2),

$$\mathrm{TESV} = \sum\left((1-x) * MAX\left(Em_{bi},\ Em_{cs}, Em_{sb}, Em_{gr}\right),\ Em_{wp}, Em_{ap}, Em_{h}, Em_{mr}, Em_{cr}, Em_{Bio}, Em_{ce}\right) \tag{21}$$

For case (a) and (3),

$$\mathrm{TESV} = \sum\left(MAX\left(MAX\left(Em_{bi},\ Em_{cs}, Em_{sb}, Em_{gr}\right), Em_{h}\right),\ Em_{wp}, Em_{ap}, Em_{mr}, Em_{cr}, Em_{Bio}, Em_{ce}\right) \tag{22}$$

For case (b),

$$\mathrm{TESV} = \sum\left(MAX\left(Em_{bi},\ Em_{cs}, Em_{sb}, Em_{gr}\right),\ Em_{wp}, Em_{ap}, Em_{h}, Em_{mr}, Em_{cr}, Em_{Bio}, Em_{ce}\right) \tag{23}$$

where all the meanings of subtypes of ESV are the same as the explanation in equations 1–19.

In terms of other aquatic ecosystems, the formula of total ESV is:

$$\mathrm{TESV} = \sum\left(MAX\left(Em_{bi},\ Em_{cs}, Em_{sb}, Em_{gr}\right),\ Em_{wp}, Em_{ap}, Em_{mr}, Em_{cr}, Em_{Bio}, Em_{ce}\right) \tag{24}$$

2.5. Characteristics of research area

China's aquatic ecosystems are selected as a case study. The study period is limited to 2010, being the most recent year with available land use type data. Although China's total water resources ranks sixth worldwide, due to its population of 1.3 billion, its per capita water resources only accounts for a quarter of the world average (Gu et al., 2017). Water resources in 16 provincial regions (with respect to 34 China's current ones) are under a severe shortage level, while 6 of them are below extremely shortage level. Another characteristic is the unbalanced spatial and temporal distribution of China's water resources (Yang et al., 2015). At present, in the northern areas, the population is 47% of the total China's one, but only 19% of national water volume is available in that area. Conversely, southern China has 53% of total national population, but contributes to 81% of China's water resources (Barnett et al., 2015; Gu et al., 2017). The specific area of aquatic ecosystems in China is shown in Fig. 3. Fig. 3 shows that the Tibet has the largest aquatic areas (5.19E+10 m^2), followed by Qinghai (4.70E+10 m^2), Inner Mongolia (4.54E+10 m^2) and so on. On the contrary, Beijing has the smallest aquatic area, which is (2.69E+08 m^2), followed by Ningxia (5.20E+08 m^2) and Shanxi (5.27E+08 m^2). Due to the lack of data on Hong Kong, Macao and Taiwan, only 31 provinces in China included in this study. In addition, the specific data sources of this paper are presented in supplementary materials (section 1).

3. Results

3.1. The spatial distribution of China's aquatic ESV

The spatial distribution characteristics of China's aquatic ESV in 2010 is presented in Fig. 4.

Fig. 4 shows that Sichuan has the largest aquatic ESV (1.13E+23 sej/yr), followed by Hubei (9.87E+22 sej/yr), Guangxi (3.64E+22 sej/yr) and Hunan (3.25E+22 sej/yr). River ecosystems contribute most to these provinces' aquatic ESV, with the ratio of 99%, 98%, 99% and 98% respectively. Except for Tianjin, Inner Mongolia, Heilongjiang, Jiangsu, Shandong and Tibet, all the rest of provinces have river ecosystems as their largest aquatic ESV. Tianjin has the smallest aquatic ESV (1.87E+20 sej/yr), followed by Shanghai (3.31E+20 sej/yr) and Hainan (3.61E+20 sej/yr). Instead, the Northeast, North China and Northwest regions in China have smaller aquatic ESV.

Aquatic ESV per unit area is also investigated in this study. Fig. 4 shows that Tibet has the largest aquatic ESV per unit area (5.55E+11 sej/m^2/yr), followed by Yunnan (4.00E+11 sej/m^2/yr), Guizhou (3.29E+11 sej/m^2/yr) and Fujian (2.59E+11 sej/m^2/yr). Conversely, Shanxi has the smallest aquatic ESV per unit area

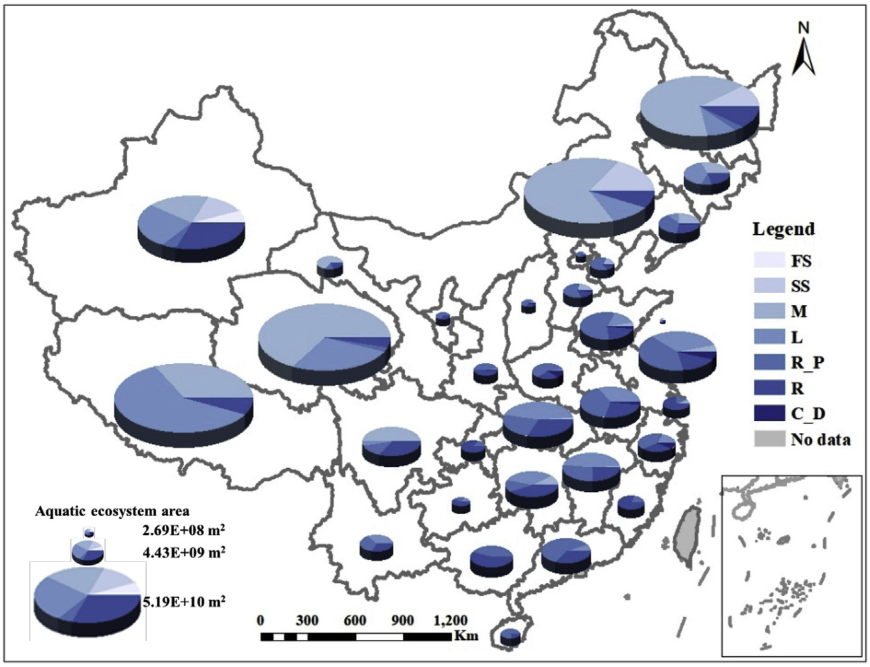


Fig. 3. The specific area of aquatic ecosystems in China in 2010 (FS: Forest swamp; SS: Shrub swamp; M: marsh; L: Lake; R_P: Reservoir or Pond; R: River; C_D: Canal or ditch) (source: Xu et al., 2018b).

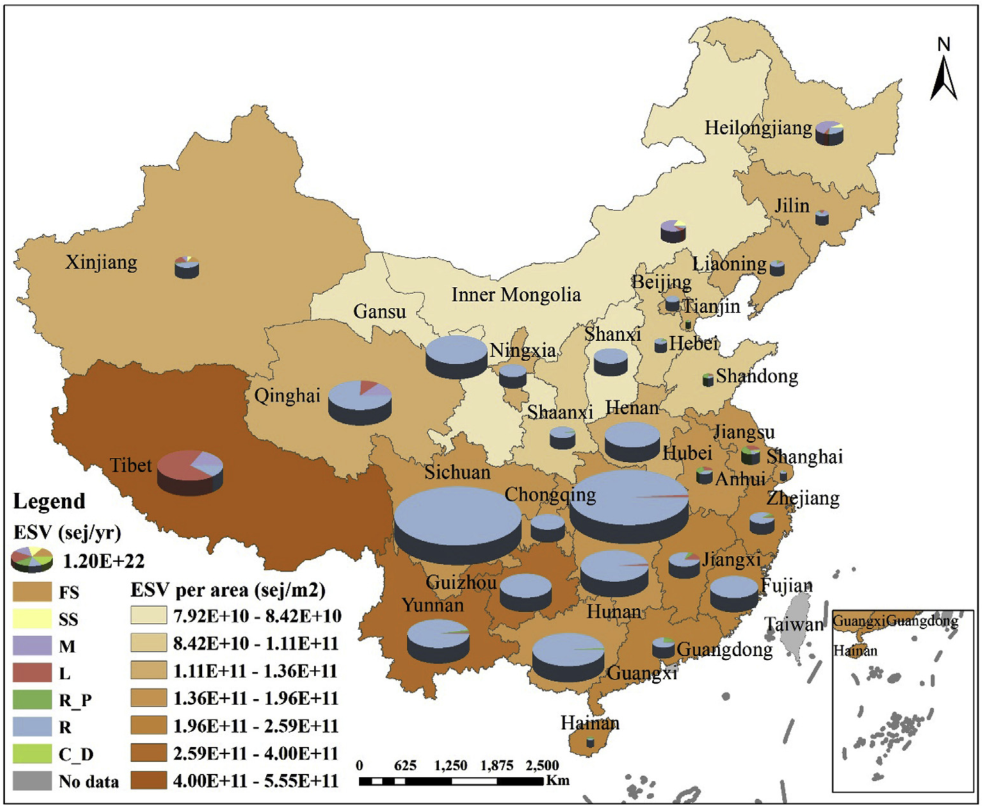


Fig. 4. The spatial distribution of China's aquatic ESV in 2010 (FS: Forest swamp; SS: Shrub swamp; M: marsh; L: Lake; R_P: Reservoir or Pond; R: River; C_D: Canal or ditch; Total: total value of all the aquatic ecosystems).

(7.92E+10 sej/m^2/yr), followed by Gansu (8.04E+10 sej/m^2/yr), Inner Mongolia (8.42E+10 sej/m^2/yr), Hebei (1.01E+11 sej/m^2/yr), Shandong (1.05E+11 sej/m^2/yr) and so on. The specific calculation process and results of China's aquatic ESV are detailed in the section 1 and 2 of supplementary materials. Since hydropower generation is partly driven by runoff geopotential energy, the calculation assumes that hydropower stations are located in the geographic center of province.

Fig. 5 shows the specific contribution of ecosystem services types to the aquatic ESV per unit area. Because most China's lakes are eutrophic (Ni et al., 2019), sediment building service is excluded from this study. Moreover, due to the lack of air purification capability of aquatic ecosystems, air purification is not assessed here. Among all the ecosystem services, for most China's provinces, microclimate regulation service is the highest in value per unit area. Conversely, carbon sequestration and climate regulation services are relatively small.

More in detail, for biomass increase, the values in southwestern China are higher than those of northwest, central and eastern China. The biomass increase values in Tibet are 1.22E+11, 1.19E+11, 1.10E+11, 1.03E+11, 9.76E+10 and 9.15E+10sej/m^2/yr for its marsh, lake, shrub swamp, river, reservoir and forest swamp respectively. Yunnan's marsh has the highest biomass increase service, with the value of 1.22E+11 sej/m^2/yr. Marsh, shrub swamp and lake in Sichuan province account most for its biomass increase service, with the value of 1.13E+11, 1.09E+11 and 1.06E+11 sej/m^2/yr. Marsh in Qinghai contributes most to its biomass increase, with the 4.93E+10 sej/m^2/yr. As in the case of carbon sequestration, Western China, including Tibet, Xinjiang and Qinghai, has larger service than central and Eastern China. This distribution trend is consistent with biomass increase. With respect to groundwater recharge, the service in the Southern regions is much larger than the rest of China. This is especially true for Jiangxi, Zhejiang, Hunan, Guangdong, Hainan, Anhui and Hubei provinces. This fact is due to the higher precipitation amount than the other provinces.

Water purification capability in eastern China, including Hainan, Shanghai, Beijing, Zhejiang, Fujian, Jiangsu, Tianjin and so on, are higher than in central and western China. This result depends on the fact that the product of aquatic NPP and emergy per capita in eastern China are larger than that of central and western areas. Western China's materials transport values are larger than central and eastern China ones. This is consistent with China's terrain, gradually descending from west to east, like a staircase. Larger hydropower generation services are mainly concentrated in southeastern China. Instead, this service in northern and western China (such as Inner Mongolia, Gansu, Xinjiang and so on) is relatively small. This depends on the fact that precipitations in southeastern China are more abundant than in the northwest.

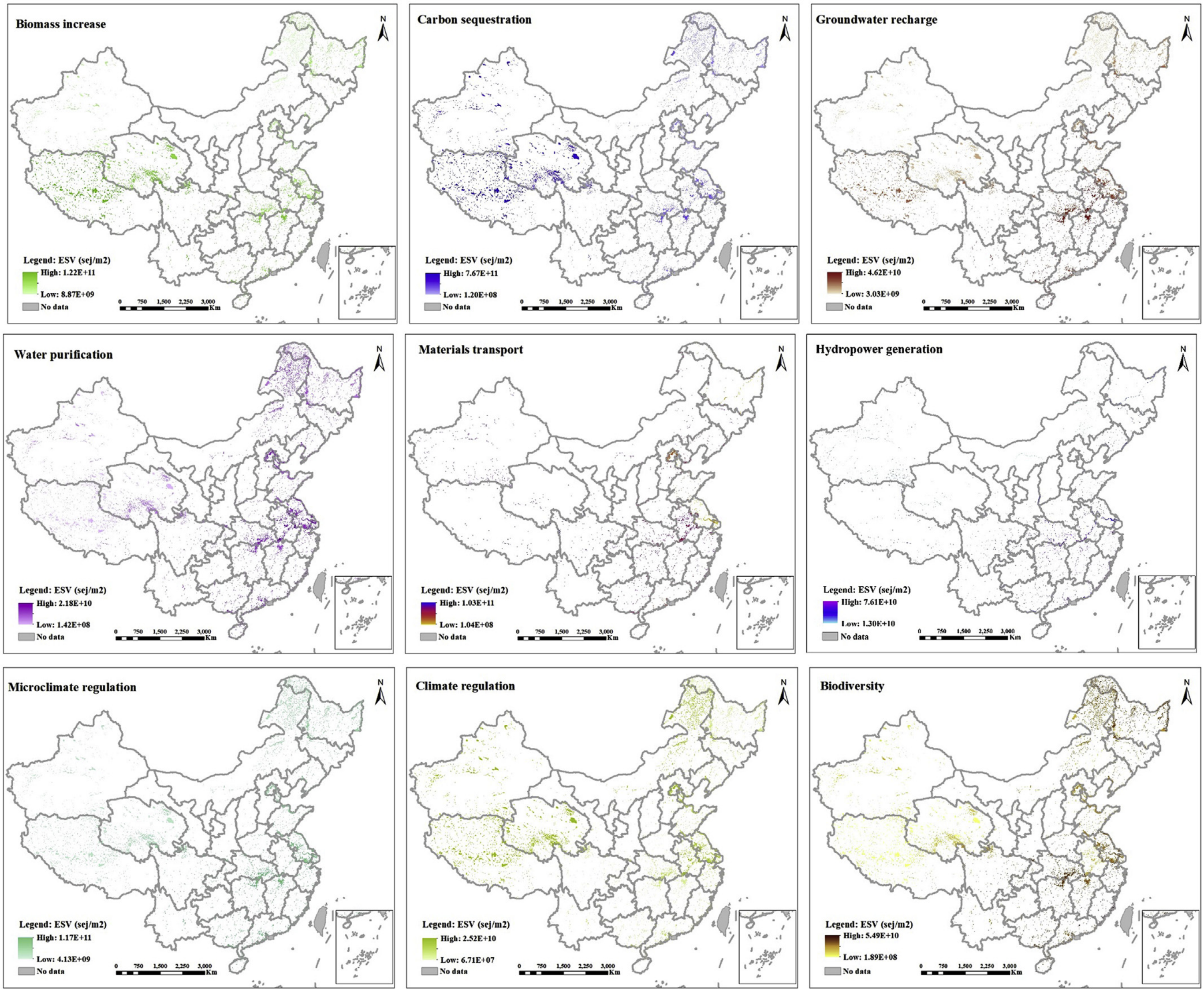

Biomass increase
Carbon sequestration
Groundwater recharge
Water purification
Materials transport
Hydropower generation
Microclimate regulation
Climate regulation
Biodiversity

Fig. 5. China's aquatic ESV per unit area in 2010.

Microclimate regulation services in southern and central China areas, such as Guangdong, Jiangxi, Zhejiang, Hubei and Hunan, are greater than that in northern and western China. This is again consistent with the distribution of China's precipitation and evaporation.

For climate regulation, Qinghai, Xinjiang, Tibet, Beijing, Ningxia, Tianjin and Shanghai have a larger service amount than other provinces, because the emergy per capita in these provinces are higher than that of west provinces (Lin et al., 2018). As in the case of biodiversity, due to the lack of data on energy transfer in all aquatic ecosystems, emergy throughflow in Florida Everglades (Brown et al., 2006) is applied to evaluate biodiversity in wetland ecosystems. The emergy throughflow in other aquatic ecosystems are obtained by using the ratio of NPP among aquatic ecosystems to infer the other emergy throughflows.

Fig. 5 shows that Southern China (e.g. Guangdong), central and eastern China (such as Fujian, Zhejiang, Hubei and Hunan), and Northeast China have relatively higher biodiversity than western provinces, such as Xinjiang, Ningxia, Gansu and so on. The characteristics of this distribution are the same as NPP for China (IGSNRR and RESDC, CAS, 2010).

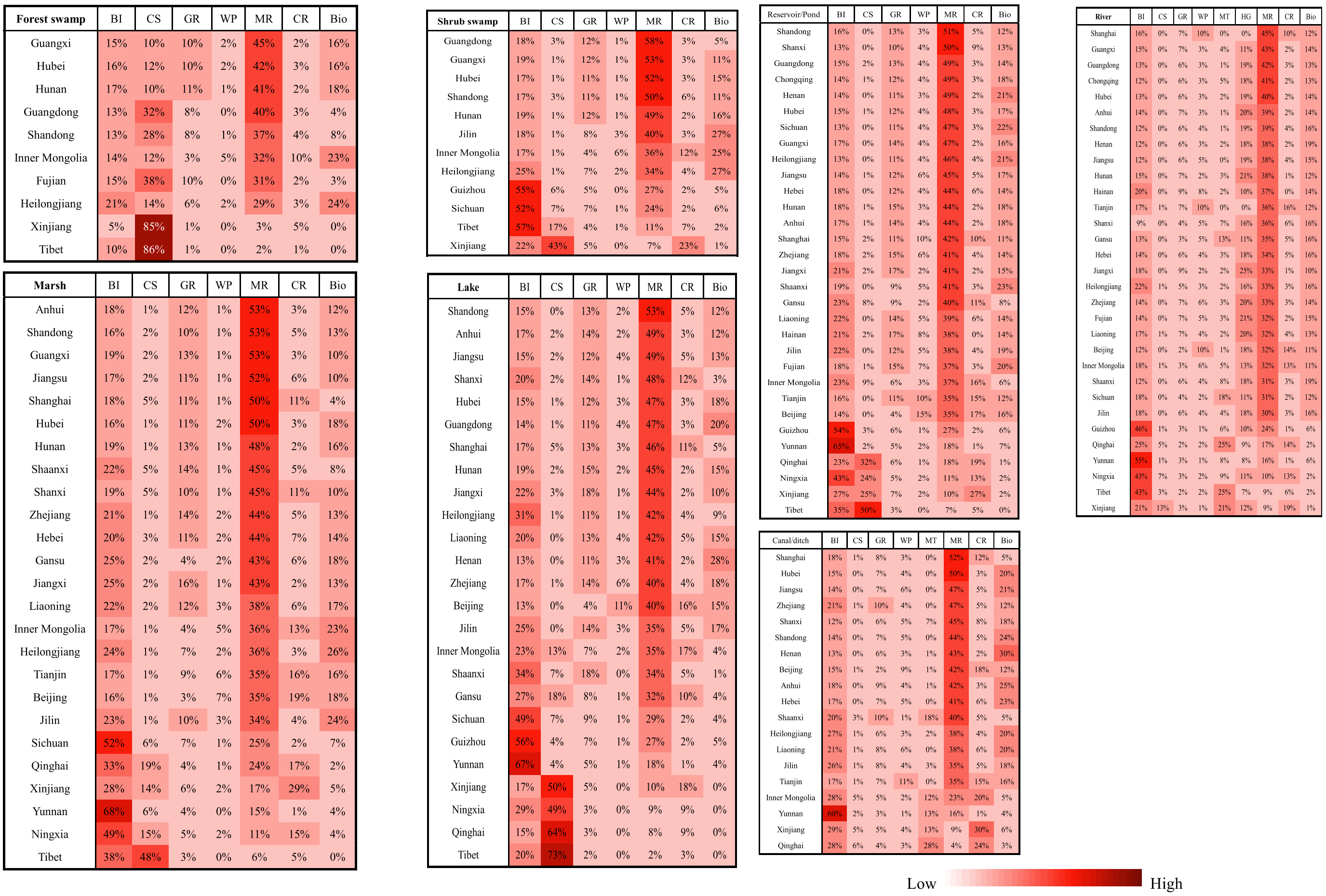
3.2. The importance degree of China's aquatic ESV

To obtain the importance degree of aquatic ESV, the subtype ESVs are applied to divide the sum of all aquatic ESVs. The results are shown by Fig. 6. The larger is the ratio of ESV, the more relevant is the importance degree. Because some provinces do not include all types of aquatic ecosystems, the results of provinces with corresponding ecosystems are presented here. Fig. 6 shows that aquatic ecosystems in most China's provinces have microclimate regulation as their most significant service.

Specifically, for forest swamp, apart from Fujian, Xinjiang and Tibet, having carbon sequestration as their most important service, microclimate regulation is of highest importance for the other provinces. Meanwhile, biodiversity also contributes a lot to the importance degree. Similarly to forest swamp, microclimate regulation has a higher significance degree for shrub swamp, with the exception of Guizhou, Sichuan, Tibet and Xinjiang, having biomass increase and carbon sequestration as their most important services.

On the other hand, biodiversity (Jilin, Inner Mongolia and Heilongjiang) is also important for shrub swamp ecosystem. Marsh ecosystem has similar importance degree distribution features to forest and shrub swamp ecosystems. For example, most provinces have microclimate regulation as their most significant aquatic service, and biomass increase, carbon sequestration, climate regulation and biodiversity are also of great importance.

These features are consistent with the identification of key functions, as described in section 2.2. Lake, reservoir/pond, river, canal/ditch ecosystems also have similar importance degree characteristics to wetland ecosystems. Besides, materials transport has a high significance degree in Qinghai and Xinjiang provinces. With regards to river ecosystem, hydropower generation is the unique service as well as the important service especially in Jiangxi, Hunan,



Forest swamp	BI	CS	GR	WP	MR	CR	Bio
Guangxi	15%	10%	10%	2%	45%	2%	16%
Hubei	16%	12%	10%	2%	42%	3%	16%
Hunan	17%	10%	11%	1%	41%	2%	18%
Guangdong	13%	32%	8%	0%	40%	3%	4%
Shandong	13%	28%	8%	1%	37%	4%	8%
Inner Mongolia	14%	12%	3%	5%	32%	10%	23%
Fujian	15%	38%	10%	0%	31%	2%	3%
Heilongjiang	21%	14%	6%	2%	29%	3%	24%
Xinjiang	5%	85%	1%	0%	3%	5%	0%
Tibet	10%	86%	1%	0%	2%	1%	0%

Marsh	BI	CS	GR	WP	MR	CR	Bio
Anhui	18%	1%	12%	1%	53%	3%	12%
Shandong	16%	2%	10%	1%	53%	5%	13%
Guangxi	19%	2%	13%	1%	53%	3%	10%
Jiangsu	17%	2%	11%	1%	52%	6%	10%
Shanghai	18%	5%	11%	1%	50%	11%	4%
Hubei	16%	1%	11%	2%	50%	3%	18%
Hunan	19%	1%	13%	1%	48%	2%	16%
Shaanxi	22%	5%	14%	1%	45%	5%	8%
Shanxi	19%	5%	10%	1%	45%	11%	10%
Zhejiang	21%	1%	14%	2%	44%	5%	13%
Hebei	20%	3%	11%	2%	44%	7%	14%
Gansu	25%	2%	4%	2%	43%	6%	18%
Jiangxi	25%	2%	16%	1%	43%	2%	13%
Liaoning	22%	2%	12%	3%	38%	6%	17%
Inner Mongolia	17%	1%	4%	5%	36%	13%	23%
Heilongjiang	24%	1%	7%	2%	36%	3%	26%
Tianjin	17%	1%	9%	6%	35%	16%	16%
Beijing	16%	1%	3%	7%	35%	19%	18%
Jilin	23%	1%	10%	3%	34%	4%	24%
Sichuan	52%	6%	7%	1%	25%	2%	7%
Qinghai	33%	19%	4%	1%	24%	17%	2%
Xinjiang	28%	14%	6%	2%	17%	29%	5%
Yunnan	68%	6%	4%	0%	15%	1%	4%
Ningxia	49%	15%	5%	2%	11%	15%	4%
Tibet	38%	48%	3%	0%	6%	5%	0%

Shrub swamp	BI	CS	GR	WP	MR	CR	Bio
Guangdong	18%	3%	12%	1%	58%	3%	5%
Guangxi	19%	1%	12%	1%	53%	3%	11%
Hubei	17%	1%	11%	1%	52%	3%	15%
Shandong	17%	3%	11%	1%	50%	6%	11%
Hunan	19%	1%	12%	1%	49%	2%	16%
Jilin	18%	1%	8%	3%	40%	3%	27%
Inner Mongolia	17%	1%	4%	6%	36%	12%	25%
Heilongjiang	25%	1%	7%	2%	34%	4%	27%
Guizhou	55%	6%	5%	0%	27%	2%	5%
Sichuan	52%	7%	7%	1%	24%	2%	6%
Tibet	57%	17%	4%	1%	11%	7%	2%
Xinjiang	22%	43%	5%	0%	7%	23%	1%

Lake	BI	CS	GR	WP	MR	CR	Bio
Shandong	15%	0%	13%	2%	53%	5%	12%
Anhui	17%	2%	14%	2%	49%	3%	12%
Jiangsu	15%	2%	12%	4%	49%	5%	13%
Shanxi	20%	2%	14%	1%	48%	12%	3%
Hubei	15%	1%	12%	3%	47%	3%	18%
Guangdong	14%	1%	11%	4%	47%	3%	20%
Shanghai	17%	5%	13%	3%	46%	11%	5%
Hunan	19%	2%	15%	2%	45%	2%	15%
Jiangxi	22%	3%	18%	1%	44%	2%	10%
Heilongjiang	31%	1%	11%	1%	42%	4%	9%
Liaoning	20%	0%	13%	4%	42%	5%	15%
Henan	13%	0%	11%	3%	41%	2%	28%
Zhejiang	17%	1%	14%	6%	40%	4%	18%
Beijing	13%	0%	4%	11%	40%	16%	15%
Jilin	25%	0%	14%	3%	35%	5%	17%
Inner Mongolia	23%	13%	7%	2%	35%	17%	4%
Shaanxi	34%	7%	18%	0%	34%	5%	1%
Gansu	27%	18%	8%	1%	32%	10%	4%
Sichuan	49%	7%	9%	1%	29%	2%	4%
Guizhou	56%	4%	7%	1%	27%	2%	5%
Yunnan	67%	4%	5%	1%	18%	1%	4%
Xinjiang	17%	50%	5%	0%	10%	18%	0%
Ningxia	29%	49%	3%	0%	9%	9%	0%
Qinghai	15%	64%	3%	0%	8%	9%	0%
Tibet	20%	73%	2%	0%	2%	3%	0%

Reservoir/Pond	BI	CS	GR	WP	MR	CR	Bio
Shandong	16%	0%	13%	3%	51%	5%	12%
Shanxi	13%	0%	10%	4%	50%	9%	13%
Guangdong	15%	2%	13%	4%	49%	3%	14%
Chongqing	14%	1%	12%	4%	49%	3%	18%
Henan	14%	0%	11%	3%	49%	2%	21%
Hubei	15%	1%	12%	4%	48%	3%	17%
Sichuan	13%	0%	11%	4%	47%	3%	22%
Guangxi	17%	0%	14%	4%	47%	2%	16%
Heilongjiang	13%	0%	11%	4%	46%	4%	21%
Jiangsu	14%	1%	12%	6%	45%	5%	17%
Hebei	18%	0%	12%	4%	44%	6%	14%
Hunan	18%	1%	15%	3%	44%	2%	18%
Anhui	17%	1%	14%	4%	44%	2%	18%
Shanghai	15%	2%	11%	10%	42%	10%	11%
Zhejiang	18%	2%	15%	6%	41%	4%	14%
Jiangxi	21%	2%	17%	2%	41%	2%	15%
Shaanxi	19%	0%	9%	5%	41%	3%	23%
Gansu	23%	8%	9%	2%	40%	11%	8%
Liaoning	22%	0%	14%	5%	39%	6%	14%
Hainan	21%	2%	17%	8%	38%	0%	14%
Jilin	22%	0%	12%	5%	38%	4%	19%
Fujian	18%	1%	15%	7%	37%	3%	20%
Inner Mongolia	23%	9%	6%	3%	37%	16%	6%
Tianjin	16%	0%	11%	10%	35%	15%	12%
Beijing	14%	0%	4%	15%	35%	17%	16%
Guizhou	54%	3%	6%	1%	27%	2%	6%
Yunnan	65%	2%	5%	2%	18%	1%	7%
Qinghai	23%	32%	6%	1%	18%	19%	1%
Ningxia	43%	24%	5%	2%	11%	13%	2%
Xinjiang	27%	25%	7%	2%	10%	27%	2%
Tibet	35%	50%	3%	0%	7%	5%	0%

Canal/ditch	BI	CS	GR	WP	MT	MR	CR	Bio
Shanghai	18%	1%	8%	3%	0%	52%	12%	5%
Hubei	15%	0%	7%	4%	0%	50%	3%	20%
Jiangsu	14%	0%	7%	6%	0%	47%	5%	21%
Zhejiang	21%	1%	10%	4%	0%	47%	5%	12%
Shanxi	12%	0%	6%	5%	7%	45%	8%	18%
Shandong	14%	0%	7%	5%	0%	44%	5%	24%
Henan	13%	0%	6%	3%	1%	43%	2%	30%
Beijing	15%	1%	2%	9%	1%	42%	18%	12%
Anhui	18%	0%	9%	4%	1%	42%	3%	25%
Hebei	17%	0%	7%	5%	0%	41%	6%	23%
Shaanxi	20%	3%	10%	1%	18%	40%	5%	5%
Heilongjiang	27%	1%	6%	3%	2%	38%	4%	20%
Liaoning	21%	1%	8%	6%	0%	38%	6%	20%
Jilin	26%	1%	8%	4%	3%	35%	5%	18%
Tianjin	17%	1%	7%	11%	0%	35%	15%	16%
Inner Mongolia	28%	5%	5%	2%	12%	23%	20%	5%
Yunnan	60%	2%	3%	1%	13%	16%	1%	4%
Xinjiang	29%	5%	5%	4%	13%	9%	30%	6%
Qinghai	28%	6%	4%	3%	28%	4%	24%	3%

River	BI	CS	GR	WP	MT	HG	MR	CR	Bio
Shanghai	16%	0%	7%	10%	0%	0%	45%	10%	12%
Guangxi	15%	0%	7%	3%	4%	11%	43%	2%	14%
Guangdong	13%	0%	6%	3%	1%	19%	42%	3%	13%
Chongqing	12%	0%	6%	3%	5%	18%	41%	2%	13%
Hubei	13%	0%	6%	3%	2%	19%	40%	2%	14%
Anhui	14%	0%	7%	3%	1%	20%	39%	2%	14%
Shandong	12%	0%	6%	4%	1%	19%	39%	4%	16%
Henan	12%	0%	6%	3%	2%	18%	38%	2%	19%
Jiangsu	12%	0%	6%	5%	0%	19%	38%	4%	15%
Hunan	15%	0%	7%	2%	3%	21%	38%	1%	12%
Hainan	20%	0%	9%	8%	2%	10%	37%	0%	14%
Tianjin	17%	1%	7%	10%	0%	0%	36%	16%	12%
Shanxi	9%	0%	4%	5%	7%	16%	36%	6%	16%
Gansu	13%	0%	3%	5%	13%	11%	35%	5%	16%
Hebei	14%	0%	6%	4%	3%	18%	34%	5%	16%
Jiangxi	18%	0%	9%	2%	2%	25%	33%	1%	10%
Heilongjiang	22%	1%	5%	3%	2%	16%	33%	3%	16%
Zhejiang	14%	0%	7%	6%	3%	20%	33%	3%	14%
Fujian	14%	0%	7%	5%	3%	21%	32%	2%	15%
Liaoning	17%	1%	7%	4%	2%	20%	32%	4%	13%
Beijing	12%	0%	2%	10%	1%	18%	32%	14%	11%
Inner Mongolia	18%	1%	3%	6%	5%	13%	32%	13%	11%
Shaanxi	12%	0%	6%	4%	8%	18%	31%	3%	19%
Sichuan	18%	0%	4%	2%	18%	11%	31%	2%	12%
Jilin	18%	0%	6%	4%	4%	18%	30%	3%	16%
Guizhou	46%	1%	3%	1%	6%	10%	24%	1%	6%
Qinghai	25%	5%	2%	2%	25%	9%	17%	14%	2%
Yunnan	55%	1%	3%	1%	8%	8%	16%	1%	6%
Ningxia	43%	7%	3%	2%	9%	11%	10%	13%	2%
Tibet	43%	3%	2%	2%	25%	7%	9%	6%	2%
Xinjiang	21%	13%	3%	1%	21%	12%	9%	19%	1%

Fig. 6. The importance degree of China's aquatic ESV in 2010 (BI: Biomass increase; CS: carbon sequestration; GR: Groundwater recharge; WP: Water purification; HG: Hydropower generation; MR: Microclimate regulation; CR: Climate regulation; Bio: Biodiversity).

Table 1
The aquatic ecosystems classification systems and their importance degree.

Aquatic ES types		Aquatic ecosystems classification			MEA,2005
		"Source" type	*"Process" type*	*"Sink" type*	
		Wetlands	River, Canal/ditch	Lake, Wetlands, Reservoir/Pond	
Direct services	(A1) Biomass increase	•••	•	•••	Provisioning
	(A2) Carbon sequestration	•••	•	•••	Regulating
	(A3) Sediment building	••	•	•••	Regulating
	(A4) Groundwater recharge	•	•	•	Regulating
Indirect services	(B1) Water purification	•	•••	••	Regulating
	(B2) Air purification	•	•	•	Regulating
	(B3) Materials transport	•	•••	•	Regulating
	(B4) Hydropower generation (n)		•••		Provisioning
	(B5) Microclimate regulation	•••	•••	•••	Regulating
Existing services	(C1) Climate regulation [a]	•••	•••	•••	Regulating
	(C2) Biodiversity	•••	•	•••	Supporting
	(C3) Cultural and educational value	•••	•••	•••	Cultural

Note: "•••" "••""•" indicate the relative importance degree of the ESV ("•••"—high, "••"—medium and "•" —low). Blank space means the aquatic ecosystems do not have the corresponding services at the left side. Hydropower generation (n) indicates nature's contribution to hydropower; "a" means the average carbon sequestrated by aquatic ecosystems per unit area, therefore all aquatic ecosystems have "•••" in the table.

Anhui, Zhejiang and Liaoning provinces. These results are also consistent with the previous identification on the ES importance in section 2.2.

4. Discussions

4.1. Uncertainty analysis

To obtain the total aquatic ESV, hydropower stations are assumed to be located in the middle point of river reaches. Actually, the exact locations of hydroelectricity stations are unknown. According to the calculation results, there are following provinces belonging to case (a): Sichuan, Yunnan, Gansu, Qinghai, Ningxia, Xinjiang, Tibet. While the rest of provinces belong to case (b). That means the uncertainty of hydroelectricity station is needed to be analyzed for provinces belonging to case (a). The uncertainty in our analysis is considered by adding two additional scenarios: case (a) and (1); case (a) and (2). The uncertainty calculation approach is detailed in supplementary materials (section 3).

Table 2 shows that, for case (a) and (1), the location of hydropower station has largest influence on Yunnan's (45.76%) river ESV per unit area, followed by Tibet (44.92%) and Ningxia (35.96%). Yet as a whole, the comprehensive uncertainty of river ESV under case (a) and (1) is 18.66%, which is relatively smaller than the uncertainties in each province, except than for Sichuan and Gansu. While, the case (a) and (2) provinces have smaller uncertainties than case (a) and (1). Yunnan has the largest uncertainty, with a ratio of 32.57%, followed by Tibet (29.37%) and Ningxia (18.03%). Yet, the comprehensive uncertainty under case (a) and (2) is 13.07%, indicating that the location of hydroelectricity has relative small influence on river ESV per unit area in this case.

Table 2
The uncertainty analysis of river ecosystem services valuation per unit area under case (a) and (1), case (a) and (2).

Provinces	This study [a]	case (a) and (1)		case (a) and (2)	
	River ESV [b]	*River ESV* [b]	*Uncertainty*	*River ESV* [b]	*Uncertainty*
Sichuan	1.70E+11	1.93E+11	13.72%	1.64E+11	−3.35%
Yunnan	3.33E+11	4.85E+11	45.76%	4.41E+11	32.57%
Gansu	1.04E+11	1.12E+11	8.19%	9.83E+10	−5.34%
Qinghai	1.02E+11	1.24E+11	22.23%	1.08E+11	6.22%
Ningxia	1.06E+11	1.44E+11	35.96%	1.25E+11	18.03%
Xinjiang	6.39E+10	7.72E+10	20.68%	6.29E+10	−1.58%
Tibet	2.00E+11	2.90E+11	44.92%	2.59E+11	29.37%
U_c [c]			18.66%		13.07%

Note: a mean the result of this study is one states of case (3); b means the river ESV is the ESV per unit area (sej/m^2/yr); c means U_c presents the comprehensive uncertainty.

4.2. The effects of hydroelectric power station on biodiversity

Hydroelectricity has side effects on biodiversity, due to flooding of lowland habitat, retard of terrestrial and aquatic migration routes resulted from dams (Lees et al., 2016). Therefore, the effects of hydropower on biodiversity is investigated here. Due to the unavailability of data on energy transfer of trophic web for river ecosystem, the energy transfer matrix of spring ecosystem set up by Odum and Collins (2003) is used here to estimate the influence of hydropower station on biodiversity, and the specific matrix is presented by Table 3.

Taking carnivore as an example, according to the matrix (Fig. 6, presented in Brown et al. (2006)), the NPP of carnivore in spring ecosystem is 167 J/m^2/yr. It is assumed that the NPP of carnivore varies from 1 to 167 under the influence of hydroelectricity. After applying the linear optimization proposed by Bardi et al. (2005), the emergy throughflow of biodiversity ranges from 2.08E+08 to 2.27E+08 sej/m^2/yr. Meanwhile, the emergy throughflow change ratio before and after hydroelectricity station construction are assumed the same as the changes from 2.27E+08 to 2.08E+08 sej/m^2/yr.

According to emergy throughflow in wetland ecosystem calculated by Brown et al. (2006) and given the ratio of NPP among wetlands and other aquatic ecosystems, the emergy throughflow of river ecosystems in China are inferred, varying from 1.17E+09 (Xinjiang) to 5.12E+10 sej/m^2/yr (Fujian). These estimated emergy throughflows in river ecosystems are the flows after the hydropower station construction. By multiplying 1.09, the ratio of 2.27E+08 to 2.08E+08, the emergy throughflow before the hydroelectricity station ranges from 1.28E+09 to 5.59E+10 sej/m^2/yr. Using these estimated emergy throughflows to multiply the river areas in different provinces, the total China's biodiversity service is 1.47E+21 sej/yr (before the hydropower station). While the biodiversity service after the station construction is 1.35E+21 sej/yr, with the decrease ratio of 9.13%. The specific calculation process is detailed in supplementary materials (section 4).

4.3. Implications for ecosystems management

In 2010, Chinese government released the notice called "Major

Table 3
The energy transfer matrix of spring ecosystem.

From	*Sun*	*Photosynthesis*	*Plants*	*Litter*	*Detritus*	*Bacteria*	*Detritivore*	*Carnivore*
To	Tr1	Tr2	Tr3	Tr4	Tr5	Tr6	Tr7	Tr8
Photosynthesis	2000	-1	0	0	0	0	0	0
Plants	0	11184	-9181	0	0	0	0	0
Litter	4000	0	0	-1	0	0	0	0
Detritus	0	0	8881	635	-8374	1600	200	167
Bacteria	0	0	0	0	5205	-1930	0	0
Detritivore	0	0	0	0	2309	75	-570	0
Carnivore	0	0	0	0	0	0	370	-167

Source: Bardi et al. (2005); Odum and Collins (2003).

Function-Oriented Zone Planning”, which classifies land into four zones (Fan et al., 2010): Development-optimized area; Development-prioritized area; Development-restricted area; Development-prohibited area. Among them, development-restricted area is also called key ecological functional area, which refers to the importance of ecosystems and the ecological security to the whole country or a large area.

At present, the ecosystems in these areas are degraded and it is necessary to restrict the development of large-scale and high-intensity industrialized towns to maintain and improve the ability of ecological products supply. This study identifies the ESV spatial distribution and key services for various ecosystems, which can be applied to provide suggestions to policy-makers for ecological function zone planning. For example, Qinghai-Tibet Plateau, having high services value of biomass increase, carbon sequestration and climate regulation, and also being the headwater of three great rivers, should be considered to restore aquatic ecosystems and to implement ecological migration, as well as to maintain its important role in sequestrating carbon and regulating climate. Significant areas of groundwater recharge, such as the middle and lower reaches of Yangtze River, should be planned as key flood regulation zones. Areas with high water purification values should reduce pollutants emissions to control the concentration of pollutions within the scope of ecosystems purification capability. Reducing sedimentation and dredging rivers should be important projects in the areas with high material transport value. Zones with high microclimate regulation services can be designed as recreation areas, such as parks, welfare home and so on, to play both their ecological and social functions. High value areas of biodiversity should maintain the aquatic areas, such as establishing national nature reserve to protect rare species. Further, areas with several significant services simultaneously can be planned as comprehensive ecological function zones to more value their roles in ecological benefits.

4.4. *Present limitations*

Due to the lack of some data on China's coastal and marine ecosystems, not all the service values of China's aquatic ecosystems are assessed in this study. In spite of this limitation, most of China's aquatic ecosystems, including swamp, marsh, lake, river, reservoir or pond, canal or ditch, are investigated in this study, highly reflecting China's aquatic ESV.

Due to the unavailability of some data, the amount of carbon sequestrated by water bodies per unit area are applied here to measure the climate regulation service, without taking the uniqueness of specific aquatic ecosystems into consideration. Future study should consider the characteristics of different aquatic ecosystems when assessing climate regulation if data available.

Finally, an evaluation method and a quantification of cultural ESV should be developed in future study to complete the assessment of China's aquatic ESV.

5. Conclusions

This study proposed an aquatic ESV evaluation method, revealing the differences and complexities of aquatic ecosystems. In particular, it provides a coherent accounting method for aquatic ecosystem services valuation from a production perspective. The proposed approach comprehensively considers the properties and complexities of different wetland ecosystems, such as the mixture of vegetation and water in swamps, the contributions of fluvial flow velocity to the materials transport, nutrients enrichment in lake ecosystems and so on. In addition, this study develop a coherent accounting method on aquatic ecosystem services valuation from supply side. The ES importance degree of different aquatic ecosystems services are also identified according to their uniqueness. Further, after analyzing the aquatic ES formation mechanism, this study establishes the accounting techniques on aquatic direct, indirect and existing services based on emergy method. Then, an accounting principle of total ESV is proposed. This work used China's aquatic ecosystems as a case study to test the developed framework.

The results indicate that Sichuan has the largest aquatic ESV, followed by Hubei and Guangxi; Tibet has the largest aquatic ESV per unit area, followed by Yunnan, Guizhou and Fujian; China's most aquatic ecosystems have microclimate regulation as the largest ESV per unit area; meanwhile biomass increase, carbon sequestration, biodiversity and climate regulation also contribute a lot to other provinces.

In conclusion, the framework proposed by this study, case study and related recommendations can provide valuable theoretical and policy insights to ESV accounting, aquatic ecosystems differential conservation and management.

Acknowledgements:

This work is supported by Sino-Italian Cooperation of China Natural Science Foundation (CNSC, No. 7171101135) and the Italian Ministry of Foreign Affairs and International Cooperation (MAECI, High Relevance Bilateral Projects), the Fund for Innovative Research Group of China National Natural Science Foundation (No. 51721093), Beijing Science and Technology Planning Project (No. Z181100005318001), National Natural Science Foundation of China

(No. 71673029) and the 111 Project (No. B17005).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.080.

References

Abel, T., 2013. Emergy evaluation of DNA and culture in 'information cycles'. Ecol. Model. 251, 85–98.

Abel, T., 2014. Culture in cycles: considering H.T. Odum's 'information cycle'. Int. J. Gen. Syst. 43, 44–74.

Alexander, D.E., Fairbridge, R.W., 1999. Encyclopedia of Environmental Science, 1 ed. Springer Netherlands.

Barnett, J., Rogers, S., Webber, M., Finlayson, B., Wang, M., 2015. Sustainability: transfer project cannot meet China's water needs. Nature 527, 295–297.

Bai, J., Lu, Q., Zhao, Q., Wang, J., Ouyang, H., 2013. Effects of alpine wetland landscapes on regional climate on the zoige plateau of China. Adv. Meteorol. 2013 (2013–11-14), 1–7, 2013.

Bardi, E., Cohen, M., Brown, M.T., 2005. Linear optimization method for computing transformities from ecosystem energy webs. In: Proceedings of the Third Biennial Emergy Analysis Research Conference, EmergySynthesis: Theory and Applications of the Emergy Methodology. Center for Environmental Policy,-Universityof Florida, Gainesville, Florida, USA.

Bhagabati, N.K., Ricketts, T., Sulistyawan, T.B.S., Conte, M., Ennaanay, D., Hadian, O., Mckenzie, E., Olwero, N., Rosenthal, A., Tallis, H., 2014. Ecosystem services reinforce Sumatran tiger conservation in land use plans. Biol. Conserv. 169, 147–156.

Brown, M.T., Bardi, E., 2001. A Compendium of Data for Emergy Computation Issued in a Series of Folios #3: Emergy of Ecosystems. Center for Environmental Policy, University of Florida, Gainesville.

Brown, M.T., Cohen, M.J., Bardi, E., Ingwersen, W.W., 2006. Species diversity in the Florida Everglades, USA: a systems approach to calculating biodiversity. Aquat. Sci. 68.

Brown, M.T., Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Model. 339, 148–156.

Campbell, E.T., 2012. Valuing Forest Ecosystem Services in Maryland and Suggesting Fair Payment Using the Principles of Systems Ecology. The Department of Environmental Science and Technology (ENST). University of Maryland, College Park, p. 239.

Campbell, E.T., Tilley, D.R., 2016. Relationships between renewable emergy storage or flow and biodiversity: a modeling investigation. Ecol. Model. 340, 134–148.

Carrington, D.P., Gallimore, R.G., Kutzbach, J.E., 2001. Climate sensitivity to wetlands and wetland vegetation in mid-Holocene North Africa. Clim. Dyn. 17, 151–157.

Cherry, J.A., 2011. Ecology of wetland ecosystems: water, substrate, and life. Nat. Educ. Knowl. 3, 16.

Chester, R., Jickells, T.D., 2012. Marine Geochemistry, third ed. Blackwell Publishing, Wiley-New Jersey.

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Downing, J.A., Middelburg, J.J., Melack, J., 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10, 172–185.

Costanza, R., d'Arge, R., Groot, R.d., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Belt, M.v.d., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16.

Costanza, R., Grootb, R.d., Sutton, P., Ploeg, S.v.d., Anderson, S.J., Kubiszewski, I., Farber, S., Turnerf, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158.

Czuba, J.A., 2018. A Lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks. Geomorphology 321, 146–152.

Daily, G.C., 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington D.C.

Dias, V., Belcher, K., 2015. Value and provision of ecosystem services from prairie wetlands: a choice experiment approach. Ecosyst. Serv. 15, 35–44.

Downing, J.A., Duarte, C.M., 2009. Abundance and size distribution of lakes, ponds and impoundments. Encycl. Inland Waters 51, 2388–2397.

Fagan, W.F., Kareiva, P.M., 1997. Using compiled species lists to make biodiversity comparisons among regions: a test case using Oregon butterflies. Biol. Conserv. 80, 249–259.

Fan, J., Tao, A., Ren, Q., 2010. On the historical background, scientific intentions, goal orientation, and policy framework of major function-oriented zone planning in China. J. Resour. Ecol. 1, 289–299.

Franzese, P.P., Buonocore, E., Donnarumma, L., Russo, G.F., 2017. Natural capital accounting in marine protected areas: the case of the Islands of Ventotene and S. Stefano (Central Italy). Ecol. Model. 360, 290–299.

Froelich, P.N., Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen, D., Dauphin, P., Hammond, D., Hartman, Blayne, Maynard, V., 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis. Geochem. Cosmochim. Acta 43, 1075–1090.

Gale, P., Reddy, K.R., 1994. Carbon flux between sediment and water column of a Shallow, Subtropical, Hypereutrophic lake. J. Environ. Qual. 23, 965–972.

Gao, Y., Wang, W., Yao, T., Lu, N., Lu, A., 2018. Hydrological network and classification of lakes on the Third Pole. J. Hydrol. 560, 582–594.

Goedkoop, M., Spriensma, R., 2001. The Eco-indicator 99: a damage oriented method for life cycle impact assessment, methodology report. In: B, V., P, C. (Eds.), The Netherlands, pp. 1–83.

González, S.O., Almeida, C.A., Calderón, M., Mallea, M.A., González, P., 2014. Assessment of the water self-purification capacity on a river affected by organic pollution: application of chemometrics in spatial and temporal variations. Environ. Sci. Pollut. Control Ser. 21, 10583–10593.

Groot, R.S., Stuip, M.A.M., Finlayson, M., Davidson, N., 2006. Valuing Wetlands: Guidance for Valuing the Benefits Derived from Wetland Ecosystem Services.

Gu, S., Jenkins, A., Gao, S.-J., Lu, Y., Li, H., Li, Y., Ferrier, R.C., Bailey, M., Wang, Y., Zhang, Y., Qi, X., Yu, L., Ding, L., Daniell, T., Williams, R., Hannaford, J., Acreman, M., Kirk, S., Liu, H., Liu, Z., Luo, L., Yan, D., Liu, X., Yu, F., Wang, D., Zhang, B., Ding, A., Xie, X., Liu, J., Ma, C., Jobson, A., 2017. Ensuring water resource security in China; the need for advances in evidence-based policy to support sustainable management. Environ. Sci. Policy 75, 65–69.

Houghton, R.A., 2008. Biomass. In: Fath, B. (Ed.), Encyclopedia of Ecology, second ed. Elsevier, Oxford, pp. 253–257.

Huang, S.L., Chen, Y.H., Kuo, F.Y., Wang, S.H., 2011. Emergy-based evaluation of peri-urban ecosystem services. Ecol. Complex. 8, 38–50.

Institute of Geographic Sciences and Natural Resources Research (IGSNRR) of Chinese Academy of Sciences (IGSNRR, CAS), Date Center for Resources and Environmental Sciences of Chinese Academy of Sciences (RESDC, CAS), 2010. China's NPP Data from 2000-2010. http://www.resdc.cn/data.aspx?DATAID=204.

Keddy, P.A., 2010. Wetland Ecology. Principles and Conservation. Cambridge University Press, Cambridge, UK.

Langan, C., Farmer, J., Rivington, M., Smith, J.U., 2018. Tropical wetland ecosystem service assessments in East Africa; A review of approaches and challenges. Environ. Model. Softw 102, 260–273.

Lees, A.C., Peres, C.A., Fearnside, P.M., Schneider, M., Zuanon, J.A.S., 2016. Hydropower and the future of Amazonian biodiversity. Biodivers. Conserv. 25, 1–16.

Lerman, A., Imboden, D., R. Gat, J., 1995. Physics and Chemistry of Lakes. Springer-Verlag, Berlin.

Lin, L., Liu, G., Wang, X., Wang, C., Liu, C., Casazza, M., 2018. Emergy-based provincial sustainability dynamic comparison in China. J. Environ. Account. Manag. 6, 249–260.

Liu, D., Cao, C., Dubovyk, O., Tian, R., Chen, W., Zhuang, Q., Zhao, Y., Menz, G., 2017. Using fuzzy analytic hierarchy process for spatio-temporal analysis of eco-environmental vulnerability change during 1990–2010 in Sanjiangyuan region, China. Ecol. Indicat. 73, 612–625.

Liu, G., Yang, Z., Chen, B., Ulgiati, S., 2011. Monitoring trends of urban development and environmental impact of Beijing, 1999-2006. Sci. Total Environ. 409, 3295–3308.

Liu, J., Xu, X., Shao, Q., 2008. Grassland degradation in the "Three-River headwaters" region, Qinghai province. J. Geogr. Sci. 18, 259–273.

Maltby, E., Acreman, M.C., 2011. Ecosystem services of wetlands: pathfinder for a new paradigm. Int. Assoc. Sci. Hydrol. 56, 1341–1359.

Mcdonough, S., Gallardo, W., Berg, H., Trai, N.V., Yen, N.Q., 2014. Wetland ecosystem service values and shrimp aquaculture relationships in Can Gio, Vietnam. Ecol. Indicat. 46, 201–213.

MEA (The Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-Being: Synthesis, Washington, D.C.

Meyers, P.A., Teranes, J.L., 2001. Sediment organic matter. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Meyers, P.A., Ishiwatari, R., 1995. Organic matter accumulation records in lake sediments. In: Lerman, A., Imboden, D.M., Gat, J.R. (Eds.), Physics and Chemistry of Lakes. Springer, New York.

Mitsch, W.J., Gosselink, J.G., 1993. Wetlands, second ed. ed. Van Nostrand Reinhold, New York.

Muneepeerakul, R., Bertuzzo, E., Rinaldo, A., Rodriguez-Iturbe, I., 2019. Evolving biodiversity patterns in changing river networks. J. Theor. Biol. 462, 418–424.

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D.R., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front. Ecol. Environ. 7, 4–11.

Ni, Z., Wang, S., Zhang, B.-T., Wang, Y., Li, H., 2019. Response of sediment organic phosphorus composition to lake trophic status in China. Sci. Total Environ. 652, 495–504.

Norton, B., Costanza, R., Bishop, R.C., 1998. The evolution of preferences Why 'sovereign' preferences may not lead to sustainable policies and what to do about it. Ecol. Econ. 24, 193–211.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley \& Sons Inc.

Odum, H.T., Collins, D., 2003. Transformities from ecosystem energy webs with the eigenvalue method. In: Proceedings of the First Biennial Emergy Analysis Research Conference, Emergy Synthesis: Theory and Applications of the Emergy Methodology. Center for Environmental Policy, University of Florida, Gainesville, Florida, USA.

Ostroumov, S.A., 2004. On the biotic self-purification of aquatic ecosystems: elements of the theory. Dokl. Biol. Sci. 396, 206–211.

Ouyang, X., Lee, S.Y., Connolly, R.M., Kainz, M.J., 2018. Spatially-explicit valuation of coastal wetlands for cyclone mitigation in Australia and China. Sci. Rep. 8.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., Jiang, L., Lu, F., Wang, X., Yang, G., Gong, S., Wu, B., Zeng, Y., Yang, W., Daily, G.C., 2016. Improvements in ecosystem services from investments in natural capital. Science 352, 1455–1459.

Papagiannakis, G., Lioukas, S., 2012. Values, attitudes and perceptions of managers as predictors of corporate environmental responsiveness. J. Environ. Manag. 100, 41–51.

Peet, R.K., 1974. The measurement of biodiversity. Annu. Rev. Ecol. Systemat. 5, 285–307.

Reynaud, A., Lanzanova, D., 2017. A global meta-analysis of the value of ecosystem services provided by lakes. Ecol. Econ. 137, 184–194.

Ricaurte, L.F., Olaya-Rodríguez, M.H., Cepeda-Valencia, J., Lara, D., Arroyave-Suárez, J., Finlayson, C.M., Palomo, I., 2017. Future Impacts of Drivers of Change on Wetland Ecosystem Services in Colombia.

Silveira, L., Usunoff, E.J., 2009. Groundwater - Volume III. Eolss Publishers Co. Ltd., Oxford, United Kingdom.

Singh, S.K., Zeddies, M., Shankar, U., Griffiths, G.A., 2018. Potential groundwater recharge zones within New Zealand. Geosci. Front. 10 (3), 1065–1072.

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. J. Hydrol. 555, 125–128.

Solarin, S.A., Shahbaz, M., Hammoudeh, S., 2019. Sustainable economic development in China: modelling the role of hydroelectricity consumption in a multivariate framework. Energy 168, 516–531.

Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., Theeuwes, N.E., 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landsc. Urban Plan. 121, 92–96.

Tallis, H., Polasky, S., 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann. N. Y. Acad. Sci. 1162, 265–283.

Turcato, C., Paoli, C., Scopesi, C., Montagnani, C., Mariotti, M.G., Vassallo, P., 2015. Matsucoccus bast scale in Pinus pinaster forests: a comparison of two systems by means of emergy analysis. J. Clean. Prod. 96, 539–548.

Vaccari, D.A., Strom, P.F., Alleman, J.E., 2005. Environmental Biology for Engineers and Scientists. Wiley-Interscience, Hoboken, New Jersey.

Valero, C., Alonso, C., De Miguel, R.J., Fernandez-Delgado, C., Garcia de Jalon, D., 2017. Response of fish communities in rivers subjected to a high sediment load. Limnologica 62, 142–150.

Vijayaraghavan, K., Balasubramanian, R., 2015. Is biosorption suitable for decontamination of metal-bearing wastewaters? A critical review on the state-of-the-art of biosorption processes and future directions. J. Environ. Manag. 160, 283–296.

Westrich, B., Förstner, U., 2007. Sediment Dynamics and Pollutant Mobility in Rivers. Springer, New York.

Worm, B., Duffy, J.E., 2003. Biodiversity, productivity and stability in real food webs. Trends Ecol. Evol. 18, 628–632.

Xu, B., Chen, D., Behrens, P., Ye, W., Guo, P., Luo, X., 2018. Modeling oscillation modal interaction in a hydroelectric generating system. Energy Convers. Manag. 174, 208–217.

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., Wu, S., 2018. Remote Sensing Monitoring Data Set for Land Use and Cover in China. Data Registration and Publishing System of Resource and Environment Science Data Center of Chinese Academy of Sciences. https://doi.org/10.12078/2018070201. http://www.resdc.cn/.

Yang, G., Wang, J., Shao, W., Wang, H., 2015. The relationship between China's coal resource development and water resource. Energy Procedia 75, 2548–2555.

Yang, S., Hu, H., Hao, Z., 2009. Trend forecast for the influence of the three gorges project on the water environmental capacity of Dongting lake. In: Asia-pacific Power & Energy Engineering Conference.

Yang, Q., Liu, G., Brown, M., Casazza, M., Campbell, E., Gianneti, B., 2018. Development of a new framework for non-monetary accounting on ecosystem services valuation. Ecosyst. Serv. 34, 37–54.

Zhang, B., Shi, Y.T., Liu, J.H., Xu, J., Xie, G.D., 2017. Economic values and dominant providers of key ecosystem services of wetlands in Beijing, China. Ecol. Indicat. 77, 48–58.

Zhang, J., Wang, Y., Wang, C., Wang, R., Li, F., 2017. Quantifying the emergy flow of an urban complex and the ecological services of a satellite town: a case study of Zengcheng, China. J. Clean. Prod. 163, S267–S276.