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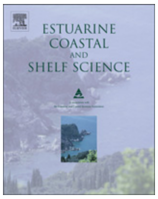

Valuing the effects of hydropower development on watershed ecosystem services: Case studies in the Jiulong River Watershed, Fujian Province, China

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ABSTRACT

Hydropower development brings many negative impacts on watershed ecosystems which are not fully integrated into current decision-making largely because in practice few accept the cost and benefit beyond market. In this paper, a framework was proposed to valuate the effects on watershed ecosystem services caused by hydropower development. Watershed ecosystem services were classified into four categories of provisioning, regulating, cultural and supporting services; then effects on watershed ecosystem services caused by hydropower development were identified to 21 indicators. Thereafter various evaluation techniques including the market value method, opportunity cost approach, project restoration method, travel cost method, and contingent valuation method were determined and the models were developed to valuate these indicators reflecting specific watershed ecosystem services. This approach was applied to three representative hydropower projects (Daguan, Xizaikou and Tiangong) of Jiulong River Watershed in southeast China. It was concluded that for hydropower development: (1) the value ratio of negative impacts to positive benefits ranges from 64.09% to 91.18%, indicating that the negative impacts of hydropower development should be critically studied during its environmental administration process; (2) the biodiversity loss and water quality degradation (together accounting for 80–94%) are the major negative impacts on watershed ecosystem services; (3) the average environmental cost per unit of electricity is up to 0.206 Yuan/kW h, which is about three quarters of its on-grid power tariff; and (4) the current water resource fee accounts for only about 4% of its negative impacts value, therefore a new compensatory method by paying for ecosystem services is necessary for sustainable hydropower development. These findings provide a clear picture of both positive and negative effects of hydropower development for decision-makers in the monetary term, and also provide a basis for further design of environmental instrument such as payment for watershed ecosystem services.

1. Introduction

Hydropower development has multiple spatial, temporal and interactive effects on the watershed hydrologic, environmental, ecological and socioeconomic aspects stemming from reservoir inundation, flow manipulation and river fragmentation (Nilsson et al., 2005). Although hydropower is usually regarded as a kind of clean energy, its negative impacts on water quality, estuary sedimentation, habitat, landscape, biodiversity and human health during development are generally well known and critically studied, especially comprehensively reviewed by the World Commission on Dams (Puff et al., 1997; Jansson et al., 2000; WCD, 2000; Andreas et al., 2002; Gehrke et al., 2002; Dudgeon, 2005). International academic community focuses more on mitigation of its negative environmental impacts (Woltemade, 1991; Harada and Yasuda, 2004; Bednarek and Hart, 2005; Richter and Thomas, 2007) rather than its environmental policy dimension such as the environmental instruments design (Fearnside, 2005). On the other hand, discussions on the dam's economic impacts are traditionally

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Table 1
The evaluation models for hydropower development effects on watershed ecosystem services. Remark: (1) "P", "N" and "V" stand for positive, negative and variable effects respectively. Some effects are variable in general, taking Culture indicator as an example, a cultural or natural tourist attraction might be submerged or disappear because of the reservoir inundation, however, new scenic spots might come up because of dam construction or large water surface. (2) Valuation model for the effect on nutrient cycle is not available.

Watershed services		Indicator	Effect type[1]	Method	Model explanation	Evaluation model equation	Letters in equation
Provisioning	Water supply	P	Municipal water supply	Shadow project method	Value of water supply increment is valuated with the cost reduction of pumping water	$V_w = P_w \times Q_w$	V_w is the benefit on Municipal water supply, P_w is the reduced cost of water pumping, and Q_w is the annual quantity of water consumption
		P	Irrigation benefit	Shadow price method	The shadow value is the increased production value from ensured farmland irrigated by hydropower plant	$V_i = \alpha \times P_s \times S_r$	V_i is the irrigation benefit, P_s is the average value per unit farmland, S_r is the area of ensured farmland irrigated, and α is the sharing coefficient
	Agriculture production	N	Foodstuff supply	Market value method	The average unit value of farmland versus flooded farmland areas produces a loss of foodstuff supply	$V_p = P_s \times S_p$	V_p is the loss of foodstuff supply, P_s is the average value per unit farmland, and S_p is the flooded area of farmland
		P	Aquiculture	Market value method	The increased breeding income due to the hydropower project is the benefit of reservoir breeding	$V_{fish} = \sum P_i \times Q_i$	V_{fish} is the profit of reservoir breeding, Q_i is the variation in quantity of breeding, and P_i is the market price of breeding specie
		N	Forestry production	Market value method	The average unit value of woodland and flooded woodland areas produces a loss of forestry production	$V_{wood} = \sum P_i \times Q_i$	V_{wood} is the woodland production loss, Q_i is the variation in quantity of wood production, and P_i is the market price per unit wood production
	Shipping industry	P	Shipping benefit	Market value method	The length of ameliorative fairway multiplies the reductive unit transportation cost equal to the increased shipping benefit	$V_{ship} = \beta \times P_c \times L \times Q_c$	V_{ship} is the shipping benefit, P_c is the reductive unit transportation cost, L is the length of ameliorative fairway, Q_c is the annual freight volume, and β is the sharing coefficient
	Hydroelectric power	P	Hydroelectric power generation	Market value method	The benefit of hydroelectric power generation is the multiplying product of the on-grid power tariff and its annual average quantity of hydroelectric power generation	$V_e = P_e \times Q_e$	V_e is the benefit of hydroelectric power generation, P_e is the on-grid power tariff, and Q_e is the annual average quantity of hydroelectric power generation
Regulating	Flood regulation	P	Flood regualation benefit	Shadow price method	The output value of protected agriculture could be considered as the benefit of the flood regulation service	$V_{flood} = \gamma \times P_s \times S_f \times C_a$	V_{flood} is the agriculture benefit due to flood regulation of the hydropower project, γ is the sharing coefficient, P_s is the average value per unit farmland, S_f is the farmland area ensured per unit storage, and C_a is the reservoir storage
	Water regulation	N	Water flow break up	Opportunity cost approach	The industrial opportunity value created by water reflects the loss of water flow break up	$V_K = P_K \times L_K$	V_K is the loss of water flow break up, P_K is the potential industrial value created per unit water, and L_K is the accumulated reductive volume of water supplied in the dry season
	Fluvial transportation	N	Reservoir sedimentation	Project restoration method	The damage of reservoir sedimentation is valuated as sedimentation removing cost	$V_r = P_r \times S_r \times Q_r$	V_r is the loss of reservoir sedimentation, P_r is the removal cost per unit sedimentation, S_r is the sediment concentration, and Q_r is the quantity of sedimentation
		N	Land formation by sedimentation	Opportunity cost approach	The opportunity value loss of estuarine land reflects the land formation loss by sedimentation	$V_g = P_g \times S_g$	V_g is the value loss of estuarine land or coastline erosion, P_g is the opportunity cost per unit estuarine land or coastline, and S_g is the eroded estuarine land area or coastline length
	Soil conservation	N	Soil erosion	Project restoration method	The soil erosion restoration cost could be considered as the damaging function value of soil erosion	$V_{se} = P_{se} \times S_{se}$	V_{se} is the loss of soil erosion, P_{se} is the restoration cost per unit eroded area, and S_{se} is the increased area of soil erosion
		N	Geological hazard	Project restoration method	The cost of controlling a geological hazard	$V_h = P_h \times S_h$	V_h is the loss due to geological hazard, P_h is the unit restoration cost, and S_h is the increased area of geological hazard
	Environmental decontamination	V	River water quality	Shadow price method	Sewage treatment plants can replace the function of water self purification. Therefore, the cost of wastewater treatment reflects the damage value of water self purification	$V_{wq} = P_{ww} \times Q_{wq}$	V_{wq} is the loss of water purification, P_{ww} is the treatment cost per unit wastewater by a sewage treatment plant, and Q_{wq} is the volume of polluted water
		P	Regulation of local micro-climate	Shadow price method	Air conditioners can replace the service of local climate regulation. Thus, the power consumption of air conditioners could be considered as the value of local climate regulation	$V_c = P_c \times Q_c$	V_c is the benefit of local micro-climate regulation, P_c is the municipal electricity price, and Q_c is the power consumption of the air conditioners

Cultural	Aesthetic value Tourism	V	Recreation & entertainment	Travel cost method	Travel costs to the tourist spot near the hydropower facility reflect the aesthetic value	$V_t = P_t \times Q_t$	V_t is the increased profit of recreation and entertainment, P_t is the average visitor cost of each visitor, and Q_t is the increased visitor number
	Education & scientific research	V	Education & scientific research	Shadow price method	The investment on educational facilities and the funding on scientific research show the service value of education and scientific research	$V_{er} = \sum F_i$	V_{er} is the value of education and scientific research, and F_i is the average annual investment or funding for education programs or scientific research programs in this area
Supporting	Primary production	N	Organic matter production	Market value method	The value created by biological mass energy resources is the sevice value of organic matter production	$V_o = P_o \times Q_o \times M$	V_o is the loss of organic material from primary production, R_e is the annual generation capacity per unit organic material, M is the annual loss of organic material, and P_e is the municipal electricity price
		N	CO_2 sequestration & O_2 release	Market value method	All green plants sequestrate CO_2 and release O_2. Thus, the service value is the unit value of CO_2 sequestration & O_2 release multiplied by the green coverage	$V_t = P_t \times Q_t$	V_t is the loss of CO_2 sequestration & O_2 release, P_t is the unit values of CO_2 sequestration & O_2 release, and Q_t is the green coverage inundated by the reservior
	Nutrient cycle^2	N	Nutrients	–	–	–	–
	Habitat	N	Biodiversity	Contingent valuation method	Stakeholders' willingness-to-pay for biodiversity could indicate the function value of habitat diversity for biota	$V_b = P_i \times Q_i$	V_b is the loss of biodiversity, P_i is the stakeholders' average willingness-to-pay, and Q_i is the number of stakeholders

limited to the market values (Bhatia et al., 2007); there is still a knowledge gap of the value of its negative impacts on watershed ecosystem services. Thus the external diseconomy of hydropower development has not been fully realized by policy-makers in practice; therefore, has not been internalized to the operating cost of developers around the world.

Recently payments for ecosystem services (PES), a voluntary transaction where a well-defined ecosystem service is being "bought" by at least one buyer from at least one provider (Wunder, 2005; Boyd and Banzhaf, 2007), has been widely adopted as an effective tool for watershed conservation such as providing water for downstream users with desirable quality, flood mitigation, carbon sequestration or forest conservation for the local, regional or international interests (Landell-Mills and Porras, 2002; Pagiola, 2002). However, there are few literatures discussing the PES for watershed hydropower development. The existing dispute of PES is how to determine the basic payment criteria, i.e., at what price the hydropower developers should compensate for its negative impacts on both upstream and downstream watershed ecosystem services. Therefore, the key step to determine PES criteria is the valuation of its effects on watershed ecosystem services.

In this paper, we propose a framework for valuing hydropower development effects on watershed ecosystem services. The main components of this framework include the watershed ecosystem services classification, effects identification, and valuation models selection. This framework was applied to three hydropower development cases of Jiulong River Watershed in southeast China.

2. Methods and materials

2.1. Methods

Ecosystem services are flows of materials, energy, and information from natural ecosystems to produce human welfare, since the mid 1990s especially after Costanza et al. (1997), there are increasing interdisciplinary work reported on the theories and practices of the definition, classification, quantification, valuation, and payments in the global, regional and local scales (Beaumonta et al., 2007; Engel et al., 2008; Fisher et al., 2009). A large number of ecosystem services have been identified, and various categorizing approaches have been developed in different studies with different purposes (Costanza et al., 1997; De Groot et al., 2002; Millennium Ecosystem Assessment, 2003; Farber et al., 2006; Wallace, 2007). In this study, we grouped ecosystem services into 4 categories including provisioning, regulating, supporting, and cultural services, which is established by Millennium Ecosystem Assessment (2003). The watershed ecosystem services were further identified as 15 sub-categories and 21 indicators (Table 1).

Various valuation methods have been used to estimate the value of ecosystem services (Fish, 1981; Freeman, 2003). Shadow project method (Garrod and Willis, 1999), market value method (Roddewig and Rapke, 1993), opportunity cost approach (Turner et al., 1998), project restoration method (Wilson and Carpenter, 1999), travel cost method (Hoevenagel, 1994), and contingent valuation method (Sagoff, 1998) were applied in this study with corresponding models (Table 1).

2.2. Case studies in the Jiulong River Watershed

The target watershed for this study is the Jiulong River Watershed. Jiulong River, the second largest one in Fujian Province, is located in the southeast of China (116°46′55″E–118°01′17″E, 24°23′53″N–25°53′38″N). It has three tributaries with the length of about 258 km and flows from its sources in Longyan and Zhangzhou, eastwards into Xiamen Bay at Xiamen. The whole watershed with the area of

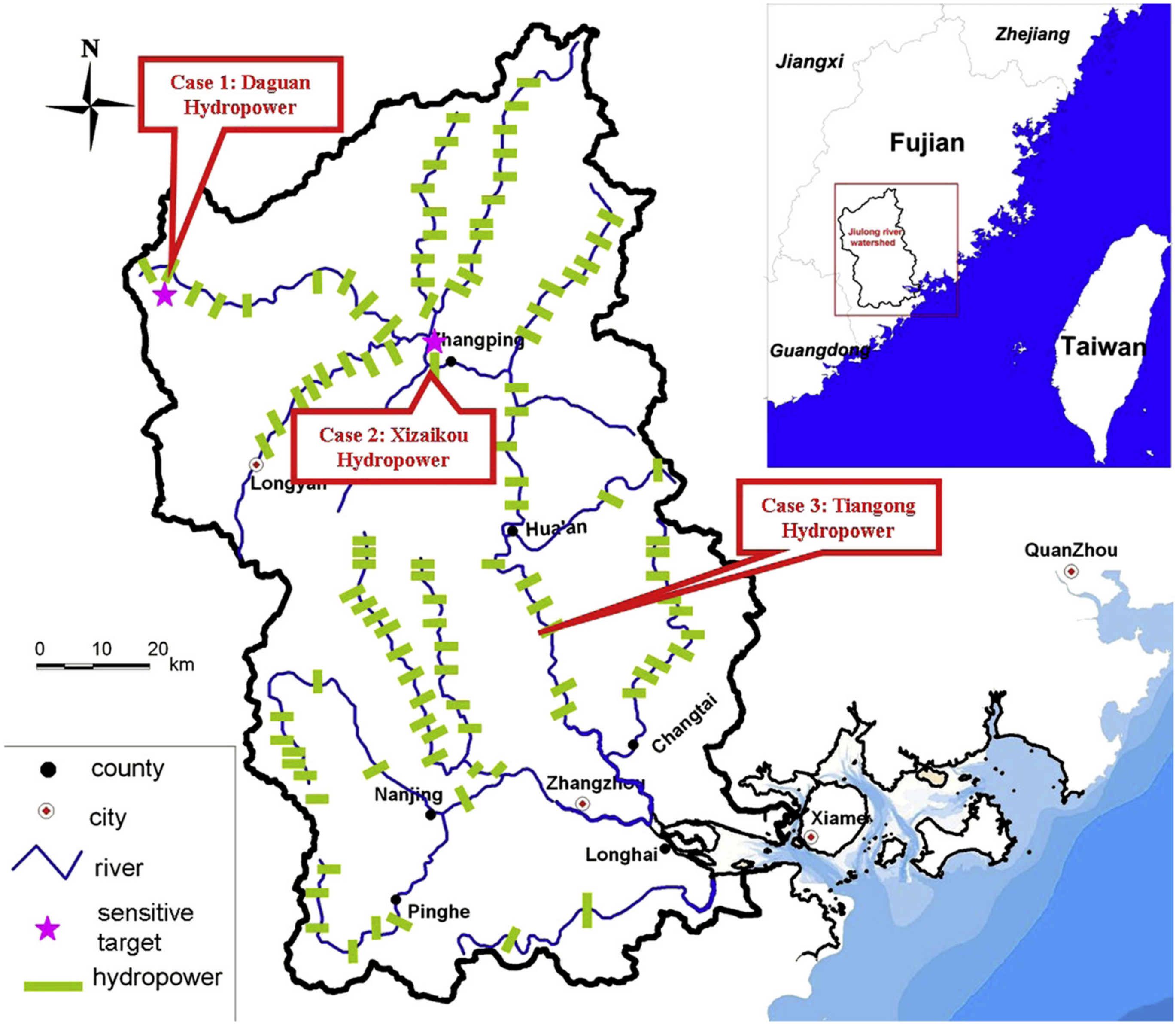

Fig. 1. Map of the Jiulong River Watershed and location of the three case studies.

14,741 km^2, is one of the most developed areas in Fujian. Besides the main water source for drinking, industry and agriculture, Jiulong River is also the important hydroelectricity source for the Watershed. Therefore, over 130 hydropower stations in the Jiulong River were constructed and more are being proposed to meet the increasing energy demand. This high density hydropower development brings more pressures on the watershed ecosystem with increasing population and rapid urbanization in the past 30 years (Fig. 1).

Table 2

The positive benefits of hydropower development to watershed ecosystem services (10^4 Yuan). Remark: (1) all results are the net present values in 2007. (2) "0" means that this indicator is NOT affected in this case; "N/A" means the effects cannot be evaluated because of model absence or data gap.

Case1: Daguan hydropower				Case 2: Xizaikou hydropower				Case 3: Tiangong hydropower			
Rank	Indicator	Percentage	Result	Rank	Indicator	Percentage	Result	Rank	Indicator	Percentage	Result
1	Hydroelectric power generation	95.08	+2726.20	1	Hydroelectric power generation	95.92	+2133.60	1	Hydroelectric power generation	94.72	+1404.00
2	Irrigation benefit	2.94	+84.39	2	Flood control benefit	2.08	+46.30	2	Irrigation benefit	3.08	+45.63
3	Flood control benefit	1.95	+55.79	3	Municipal water supply	1.04	+23.21	3	Flood control benefit	2.06	+30.55
4	Aquiculture	0.03	+0.92	4	Irrigation benefit	0.83	+18.45	4	Aquiculture	0.14	+2.08
5	Municipal water supply	0	0	5	Aquiculture	0.12	+2.75	5	Municipal water supply	0	0
6	Shipping benefit	0	0	6	Shipping benefit	0	0	6	Shipping benefit	0	0
7	Regulation of local micro-climate	N/A	N/A	7	Regulation of local micro-climate	N/A	N/A	7	Regulation of local micro-climate	N/A	N/A
	Total	100	+2867.30		Total	100	+2224.31		Total	100	+1482.26

By applying the proposed methods in this study, we selected 3 hydropower projects at Daguan, Xizaikou and Tiangong in the Jiulong River (Fig. 1) to valuate hydropower's effects on watershed ecosystem. The 3 cases are comparable in the construction time (Feb. 2004, Oct. 2005 and Dec. 2004 respectively), investment scale (0.15, 0.14 and 0.13 billion Yuan) and annual electricity generating capacity (79.25, 76.20 and 70.20 million kW h). On the other hand, each case has its own characteristics in the location (upstream, midstream and downstream respectively), mean annual runoff (0.25, 46.40 and 76.32 billion m^3), station type (diversion, run-of-river and run-of-river), regulating frequency (seasonal, daily, and daily), normal reservoir storage capacity (14.70, 12.20 and 8.05 million m^3) and surrounding sensitive objects (the dam of Daguan is in the experimental zone of Meihua Mountain National Nature Reserve, Xizaikou is 500 m downstream to the intake of the Zhangping Municipal Water Plant and Tiangong is a background reference case without sensitive object); those differences make the 3 cases representative and provide the possibility for further analysis.

2.3. Data sources

The geographical survey and environmental monitoring were independently implemented during the environmental impact assessment process for the 3 hydropower plants, and the data in this study were cited from the environmental impact assessment reports. Some data were supplemented or updated according to the information collected by field study and from the yearbooks of local governments.

Contingent valuation method was applied to valuate the impacts on watershed biodiversity (Table 1). To determine the stakeholders' average willingness-to-pay for the biodiversity conservation in target watershed, a questionnaires survey with 400 participants was conducted in July 2007 in 40 villages of all over the Jiulong River Watershed.

3. Results and discussions

Valuation results of the effects on Jiulong River Watershed ecosystem services caused by the 3 hydropower projects in the monetary term are listed in Table 2 (positive benefits) and Table 3 (negative impacts) respectively.

The valuation results of negative impacts must be less than the real loss because of the data gaps and the conservative models we employed; for example, the model developed for "water flow break up" and the one for "regulation of local micro-climate" (Table 1) are both not applicable in this study because of the data gaps; and the effect on "nutrient cycle" is not valuated because of the absence of its valuation model. The above factors bring uncertainties on the results; as the fact of that the value of negative impacts was lessened, the conclusions are strengthened instead of being weakened.

From the results of Tables 2 and 3, it is found that:

(1) Although the total value of its positive benefits differs from 2867.30, 2224.31 to 1482.26 (10^4 Yuan) respectively in the cases of Daguan, Xizaikou and Tiangong, hydroelectricity provisioning is the greatest benefit of hydropower development. The benefit of hydroelectricity provisioning service accounts for about 95% in each case; effects on irrigation, flood control, and aquaculture, etc., contribute to other small part of its positive benefits.

(2) The total value of its negative impacts varies from 1837.77, 1467.41 to 1351.46 (10^4 Yuan) in each case, and the greatest three indicators contribute to the majority (92.74%, 96.89% and 98.17%) even though over ten indicators have been identified in

Table 3

The negative impacts of hydropower development on watershed ecosystem services (10^4 Yuan). Remark: (1) all results are the net present values in 2007. (2) "0" means that this indicator is NOT affected in this case; "N/A" means that this indicator cannot be valuated because of model absence or data gap.

Case1: Daguan hydropower				Case 2: Xizaikou hydropower				Case 3: Tiangong hydropower			
Rank	Indicator	Percentage	Result	Rank	Indicator	Percentage	Result	Rank	Indicator	Percentage	Result
1	Biodiversity	63.12	−1160.00	1	River water quality	67.47	−990.00	1	River water quality	46.99	−635.00
2	River water quality	19.32	−355.00	2	Biodiversity	26.81	−393.45	2	Soil erosion	34.86	−471.17
3	Education & scientific research	10.3	−189.23	3	Soil erosion	2.61	−38.30	3	Biodiversity	16.32	−220.57
	Recreation & entertainment			4	Foodstuff supply	1.42	−20.83	4	Reservoir sedimentation	0.70	−9.53
4	Forestry production	3.97	−72.99	5	CO_2 sequestration & O_2 release	0.51	−7.41	5	Forestry production	0.43	−5.79
5	Soil erosion	2.15	−39.49	6	Organic matter production	0.47	−6.87	6	Land formation by sedimentation	0.25	−3.34
6	CO_2 sequestration & O_2 release	0.49	−8.97	7	Forestry production	0.45	−6.53	7	Foodstuff supply	0.22	−2.97
7	Organic matter production	0.45	−8.31	8	Reservoir sedimentation	0.25	−3.68	8	CO_2 sequestration & O_2 release	0.12	−1.61
8	Foodstuff supply	0.11	−1.96	9	Land formation by sedimentation	0.02	−0.34	9	Organic matter production	0.11	−1.49
9	Land formation by sedimentation	0.09	−1.58	10	Geological hazard	0	0	10	Geological hazard	0	0
10	Reservoir sedimentation	0.01	−0.24	11	Recreation & entertainment	0	0	11	Recreation & entertainment	0	0
11	Geological hazard	0	0	12	Education & scientific research	0	0	12	Education & scientific research	0	0
12	Nutrients	N/A	N/A	13	Nutrients	N/A	N/A	13	Nutrients	N/A	N/A
13	Water flow break up	N/A	N/A	14	Water flow break up	N/A	N/A	14	Water flow break up	N/A	N/A
	Total	100	−1837.77		Total	100	−1467.41		Total	100	−1351.46

this study. In each case, both negative impacts of biodiversity loss and water quality degradation are among the greatest three indicators, indicating these two are the major damages on watershed ecosystem services caused by hydropower projects.

(3) The value ratio of negative impacts to positive benefits in each case varies from 64.09%, 65.97% to 91.18% (Table 3), up to 73.75% on average. Thus, the negative impacts on watershed ecosystem services due to hydropower should not be neglected.

(4) Dividing total negative value by its hydroelectricity generating capacity, we calculated the average value of negative impacts in each case as 0.232, 0.193, and 0.193 Yuan/kW h. It's considerable for every case compared with its on-grid power tariff, i.e. 0.344, 0.28 and 0.20 Yuan/kW h. The on-grid power tariff is usually determined by its construction and operation cost whereas without considering the environmental cost in China. In this study, the environmental cost reaches 0.206 Yuan/kW h on average, which accounts for about three quarter of the average on-grid power tariff. This result further indicates that environmental cost of hydropower development cannot be ignored and if we internalize the environmental cost, many hydropower projects might be unprofitable in the current pricing system.

(5) All water users in China are charged water resource fee now. The average charge of the three hydropower projects is about 0.6 million Yuan/year, which accounts for only about 4% of the value of its negative impacts on watershed ecosystem services. Apparently the existing water resource fee is significantly insufficient to cover the negative impacts on watershed ecosystem services.

From the above results and discussions, it can be concluded that negative impacts of hydropower development must be considered seriously in its approval process before construction and administration afterwards; and it is significantly undercharged in current water resource fee system without considering the environmental cost of hydropower development, a new compensatory method such as payment for ecosystem services scheme is necessary for sustainable hydropower development, where findings of this study provide a basis for the payment criteria.

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