Ecological footprint analysis of environmental impacts by cascaded exploitation of diversion-type small hydropower: a case study in southwest China

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Abstract. Cascaded exploitation of diversion-type small hydropower (SHP) offers a source of new energy as well as socioeconomic benefits; however, it inevitably causes environmental disturbance and damage. Previous studies on the cumulative effect of cascaded diversion SHP rarely discussed using quantitative analysis method. In this paper, the ecological footprint analysis approach is proposed to assess the positive and negative impacts of cascaded diversion SHP on environment of a small-scale river in Southwest China. Positive impact is defined as ecological supply footprint (ESF), which refers to vegetation protection by replacing firewood with SHP. Negative impact is defined as ecological loss footprint (ELF), which includes fish and net primary productivity loss, vegetation destruction and soil erosion. With the raising in the number (n>4) of diversion SHP stations, the difference between ELF and ESF increase remarkably, suggesting that the adverse impacts of cascaded diversion SHP accumulate in the study area. Compared with vegetation destruction and soil erosion, the cumulative loss of fish and net productivity is the most important aspect of the adverse impacts which needs more attentions.

1. Introduction
In China, hydropower with installed capacity not more than 50 MW is officially defined as small hydropower (SHP). The investigation and evaluation result of rural hydropower resources of P. R. China in 2008 indicates that the total technically exploitable SHP potential is 128 GW, located in more than 1,700 counties [1]. By the end of 2015, China has built more than 47,000 SHP stations with total installed capacity of 73 GW and annual electricity generation of 2300 billion kWh, accounting for 25% of the national hydropower [2]. Statistical data indicates that diversion-type SHP stations account for more than 80% of these built SHP [3].
SHP is clean and renewable energy which is internationally recognized [4]. The exploitation of SHP plays an important role in improving energy supply and rural electrification in remote mountainous regions [5]. In China, SHP serves as the main power source in many rural areas [6]. This shifts the pattern of rural energy consumption from biomass-based energy source to a clean energy source. The utilization of SHP is a practical solution to prevent deforestation by reducing the consumption of firewood for cooking and heating [5, 6]. Statistical data shows that the implementation of the Project of Replacing Firewood with SHP by the Chinese government reduces the firewood consumption of 6.7 million m$^3$ and protects forest area of 930 thousand hm$^2$ [7]. This is obviously beneficial to environmental improvement. However, the development of SHP, especially diversions, is also likely to cause environmental disturbance and damage, including changes to the hydrological conditions, aquatic ecosystem structure alteration, vegetation destruction, soil erosion, etc. [8]. These impacts of diversions SHP development could lead to a certain extent loss in the ecosystem [9]. The impact of single diversion SHP on the environment is probably thought to be not severe [10]. But their impacts could possibly increase with cascaded exploitation of river basins.

For a long time, due to lack of single unified term on expressing environmental impacts, previous studies on the environmental effects of diversion SHP mainly discussed using qualitative analysis methods [11-13]. There was little study of the cumulative effect assessment of cascaded diversion SHP using a quantitative analysis method [14]. The Environmental impact assessment code hydroelectric station project for rural area (SL315-2005) formulated by the Ministry of Water Resources of China is available only for the environmental effect assessment of single SHP station, and not applicable for the cumulative effect evaluation of cascaded diversion SHP [3]. In order to evaluate and compare the extent of the positive and negative cumulative effects, it is necessary to quantify them using a single unified method [15].

The ecological footprint (EF) analysis method is a simple evaluation tool based on biological physical quantity and closely associated with the sustainable development theory [9]. The EF is expressed in global hectares. A global hectare is one hectare of biologically productive space with world average productivity. The EF can be used to measure any product, activity or impact, at all levels from self to planet. The necessary data can be easily obtained and the operational method can be conveniently operated. It is therefore possible to use the EF in environmental management and as a planning tool [16].

The first aim of the study is to assess the cumulative environmental effects of cascaded diversion SHP stations which in a small-scale river in a mountainous area of Southwest China, using the EF approach. The second objective is to compare the EF components to identify the most important aspects of the environmental impacts which need more special attentions. The EF method could become an effective analysis tool for SHP development policy design and planning.

2. Methodology

2.1. EF Accounts: Accounting Framework
Considering the main positive and negative environmental effects of diversion SHP development discussed above, the EF accounting framework in Figure 1 was proposed. In this present study, positive effect was defined as ecological supply footprint (ESF), which mainly referred to vegetation protection by replacing firewood with diversion SHP. Negative effect was defined as ecological loss footprint (ELF), which included fish and net primary productivity loss in water-reduction section, vegetation destruction and soil erosion by diversion SHP during construction and in the operation period following construction.

2.2. Conversion Factor
The EF account includes a combination of two conversion factors: equivalence factor and yield factor.
2.2.1. **Equivalence Factor.** Equivalence factor is a scaling factor that converts a specific land type (such as cropland or forest) into a universal unit of bio-productive area, a global hectare. Equivalence factor represents the world average potential productivity of a given bio-productive area relative to the world average potential productivity of all bio-productive areas. For land types (e.g. forest) with productivity higher than the average productivity of all bio-productive area on the earth, the equivalence factor is greater than 1. Different regions in a given year have the same equivalence factors, which only change slightly from year to year. The equivalence factors used in this study are 1.1 for forest and 0.2 for productive waters.

2.2.2. **Yield Factor.** Because the productive factors (e.g., climate, soil, technology, etc.) vary across regions, the yield capacities of the same land are different in different regions. The yield factor represents the differences between the local yield for one category of productive space (e.g., forests) and the global average yield for the category of productive space (e.g., forests). Each region has its own set of yield factors, one for each type of bio-productive area. In the present study, the yield factors are 0.91 for forest and 1.0 for productive waters.

![Figure 1. Indicators of ESF and ELF accounts](image)

2.3. **Evaluation Models of ESF**

2.3.1. **Evaluation Model of ESF for Single Diversion SHP.** Electricity can be converted into heat. Global average productivity of hydropower is 1000 GJ ha\(^{-1}\). The conversion relation is as follows: 1 GJ equal to 1×10\(^9\) joule (J) and 1 J equal to 2.778×10\(^{-7}\) kWh. Applying the heat conversion method (converting electricity generation of SHP for replacing firewood into heat) to evaluate the area of protecting vegetation land:

\[
EF_f = \phi \left[ \frac{Q_e}{1000 \times 10^9 \times 2.778 \times 10^{-7}} \right] r_f y_f = 3.6 \times 10^4 \phi Q_e r_f y_f \tag{1}
\]

In the above formula, \(EF_f\) is the ESF of single diversion SHP (ha); \(\phi\) is the ratio of electricity generation for replacing firewood to total electricity generation; \(Q_e\) is the average annual energy generation; \(r_f\) is the equivalence factor for forest; \(y_f\) is the yield factor for forest.
2.3.2. Evaluation Model of ESF for Cascaded Diversion SHP. The ESF of cascaded diversion SHP is the sum of that for single diversion SHP station:

\[
EF_{nsf} = \sum 3.6 \times 10^{-6} \varphi_n Q_{ne} r_3 y_5 = 3.6 \times 10^{-6} r_3 y_5 \sum \varphi_n Q_{ne} \tag{2}
\]

Where \( EF_{nsf} \) is the ESF for \( n \)-cascade of diversion SHP (ha); \( \varphi_n \) is the ratio of electricity generation for replacing firewood to total electricity generation in the No. \( n \) diversion SHP; \( Q_{ne} \) is the average annual energy generation in the No. \( n \) diversion SHP.

2.4. Evaluation Models of ELF

2.4.1. Fish and Net Primary Productivity Loss of Single Diversion SHP. The production of the unit weight of fish, consumes at least 25 times as much as the amount of phytoplankton. Thus, there is a quantitative relationship between fish and net primary productivity loss footprint in water-reduction section of diversion SHP:

\[
EF_f = EF_a + EF_p = S_r r_5 y_5 + k S_r r_5 y_5 = (1 + k) S_r r_5 y_5 \tag{3}
\]

Where \( EF_f \) is fish and net primary productivity loss footprint of single diversion SHP (ha); \( k \) is the ratio of net primary productivity to fish biomass \( (k = 25) \); \( S_r \) is the decrease of water area in water-reduction section (ha); \( r_5 \) is the equivalence factor for productive waters; \( y_5 \) is the yield factor for productive waters.

2.4.2. Fish and Net Primary Productivity Loss of Cascaded Diversion SHP. Based on theoretical analysis and field research, it was assumed that fish and net primary productivity cumulative loss for \( n \)-cascade of diversion SHP increase nonlinearly. With the increase in the number of diversion SHP stations, fish and net primary productivity loss footprint for \( n \)-cascade of diversion SHP will increases by \( \lambda^{n-1} \)-fold:

\[
EF_{nr} = EF_{(n-1)r} + (1 + k) S_{nr} r_5 y_5 \lambda^{n-1} = (1 + k) S_r r_5 y_5 \left( S_r + S_{2r} \lambda + S_{3r} \lambda^2 + \cdots + S_{nr} \lambda^{n-1} \right) \tag{4}
\]

Where \( EF_{nr} \) is the fish and net primary productivity loss footprint for \( n \)-cascade of diversion SHP (ha); \( EF_{(n-1)r} \) is the fish and net primary productivity loss footprint for (\( n-1 \))-cascade of diversion SHP (ha); \( k \) is the ratio of net primary productivity to fish biomass \( (k = 25) \); \( S_{nr} \) is the decrease of water area in water-reduction section of the No. \( n \) diversion SHP (ha); \( \lambda \) is river ecological damage degree index \( (\lambda = 1.3) \).

2.4.3. Vegetation Destruction of Single Diversion SHP. Vegetation destruction of diversion SHP is mainly caused by the construction of long-distance diversion pipe engineering. Vegetation destruction footprint of single diversion SHP can be calculated as follow model:

\[
EF_v = S_r r_5 y_5 \tag{5}
\]

Where \( EF_v \) is vegetation destruction footprint of single diversion SHP (ha); \( S_v \) is the area of vegetation destruction through the construction of long-distance diversion pipe engineering (ha).
2.4.4. Vegetation Destruction of Cascaded Diversion SHP. The vegetation destruction footprint of cascaded diversion SHP is the sum of the vegetation destruction footprint of single diversion SHP station:

\[ EF_{nv} = \sum S_n r_3 y_3 = r_3 y_3 \sum S_{nv} \]  \hspace{1cm} (6)

Where \( EF_{nv} \) is vegetation destruction footprint for \( n \)-cascade of diversion SHP (ha); \( S_n \) is the area of vegetation destruction through the construction of long-distance diversion pipe engineering in the No. \( n \) diversion SHP (ha).

2.4.5. Soil Erosion of Single Diversion SHP. Soil erosion of diversion SHP is mainly caused by the construction of long-distance diversion pipe engineering. Soil erosion footprint of single diversion SHP can be calculated as follow model:

\[ EF_e = S_e r_3 y_3 \]  \hspace{1cm} (7)

Where \( EF_e \) is soil erosion footprint of single diversion SHP (ha); \( S_e \) is the area of soil erosion due to the construction of long-distance diversion pipe engineering (ha).

2.4.6. Soil Erosion of Cascaded Diversion SHP. The soil erosion footprint of cascaded diversion SHP is the sum of the soil erosion footprint of single diversion SHP station:

\[ EF_{ne} = \sum S_{ne} r_3 y_3 = r_3 y_3 \sum S_{ne} \]  \hspace{1cm} (8)

Where \( EF_{ne} \) is soil erosion footprint for \( n \)-cascade of diversion SHP (ha); \( S_{ne} \) is the area of soil erosion due to the construction of long-distance diversion pipe engineering in the No. \( n \) diversion SHP (ha).

2.5. Judgment of Environment Effects.
The environmental effect of diversion SHP stations can be quantitatively analysed based on the comparison of the ESF and the ELF. A positive result from the numerical value of the ecological supply plus the numerical value of the ecological loss represents a beneficial effect of diversion SHP on the environment, and the greater difference between the two represents the greater positive effect. A negative result represents a negative effect of diversion SHP on the environment, and the greater difference between the two represents the greater adverse effects.

3. Study Area
The study area for the present study was in a small-scale river in Yunnan province, Southwest China. The river runs about 85 km long with a drainage area of 634 km² and the altitude of 800-1200 m. Climate in the study area belongs to the subtropical monsoon climate zone, with an annual precipitation of 1200 mm~1600 mm. This river catchment is mainly covered with dense forests and grassland, in addition to a small amount of arable land, houses, roads and water, with vegetation coverage of over 74%. Exposed rock in the basin is relatively fragmented and weathering, coupled with high mountains and steep slopes, geological disasters like landslides, collapse or mudslides occurs in case of heavy rain and flash floods, with an average erosion intensity of 1000 t/km².

From the end of last century, seven-cascade of diversion SHP stations have been built on this river, namely one to seven SHP, expressed as H₁, H₂, H₃, H₄, H₅, H₆ and H₇ respectively. For the seven diversion SHP stations, the installed capacity, annual power generation, electricity generation for replacing firewood, and the area of water-reduction section, vegetation destruction area, soil erosion area are listed in the following table (Table 1).
Table 1 The basic situation of the seven-cascade of diversion SHP stations

|                        | H1   | H2   | H3   | H4   | H5   | H6   | H7   |
|------------------------|------|------|------|------|------|------|------|
| Installed capacity (kW)| 2000 | 630  | 400  | 6300 | 7200 | 6300 | 500  |
| Total annual electricity generation (10^4 kWh)| 650 | 260  | 180  | 2100 | 2300 | 2000 | 180  |
| Ratio of electricity generation for replacing firewood to total electricity generation (%)| 50  | 45   | 50   | 40   | 45   | 45   | 50   |
| Area of water-reduction section (ha) | 0.78 | 0.56 | 0.53 | 2.33 | 2.74 | 2.59 | 0.68 |
| Area of vegetation destruction (ha) | 2.68 | 1.07 | 0.94 | 3.14 | 2.90 | 2.13 | 1.08 |
| Area of soil erosion (ha) | 2.50 | 0.90 | 0.84 | 2.70 | 2.50 | 1.50 | 0.80 |

4. Results and Discussion
The ESF and ELF of single diversion SHP are presented in Figure 2, the calculation of which was in accordance with formulae (1), (3), (5) and (7) based on data from Table 1. In this study, the values of ESF range from 3.24 ha to 37.26 ha, and that of the ELF range from 4.88 ha to 19.65 ha. For single diversion SHP of H1, H4, H5 and H6, the ESF exceeds ELF, and for H2, H3 and H7, the ESF is less than ELF (Fig. 2). From the view of single diversion SHP, most projects have positive impacts on environment; a few have slight negative impacts.

![Figure 2. Comparison of ELF and ESF for single diversion SHP](image)

The cumulative ESF and ELF of cascaded diversion SHP are presented in Figure 3, the calculation of which was in accordance with formulae (2), (4), (6) and (8) based on data from Table 1. For cascaded diversion SHP, the cumulative ESF and ELF increases notably with the increase in the number of SHP stations. The values of cumulative ESF range from 15.93 ha to 122.41 ha, and that of the cumulative ELF range from 15.00 ha to 172.47 ha. There is no remarkable difference between the cumulative ecological loss and supply for 2-, 3-, 4-cascade of diversion SHP in the study area. But the imbalance between the cumulative ecological loss and supply is obviously for 5-, 6-, 7-cascade of diversion SHP. With the raising in the number (n>4) of diversion SHP stations, the difference between ecological loss and supply increases clearly, suggesting that the adverse impacts of cascaded diversion SHP would accumulate in the study area.
For cascaded diversion SHP, the cumulative loss of fish and net productivity is the largest ecological loss, accounting for 52.3%~85.1% of the total (Figure 4). With the increase in the number of diversion SHP stations, the proportion of fish and net productivity cumulative loss is gradually increasing in the total ecological loss. The increasing cumulative loss of fish and net productivity suggests that more water-reduction sections caused by cascaded diversion SHP could lead to great adverse effects on aquatic ecosystem. Thus, fish and net productivity loss of cascaded diversion SHP development needs more attentions. The cumulative vegetation destruction (8.3%~25.0%) and soil erosion (6.8%~22.7%) are relatively small compared to those of fish and net productivity. This suggests that vegetation destruction and soil erosion are not intensive as fish and net productivity losses during cascaded diversion SHP development in the study area.

Figure 3. Comparison of ELF and ESF for cascaded diversion SHP

![Figure 3](image)

Figure 4. The components of ELF of cascaded diversion SHP

![Figure 4](image)
5. Conclusion
The EF analysis method is available to quantitatively evaluate the extent of cumulative environmental impacts by cascaded exploitation of diversion SHP. Based on the established evaluation models, the ESF and ELF of cascaded diversion SHP stations in Southwest China are calculated. The ESF and ELF show a similar variation tendency for cascaded diversion SHP in this study. For less than 4-cascade ($n \leq 4$) diversion SHP, there is no remarkable difference between the cumulative ESF and ELF. With the raising in the number ($n > 4$) of diversion SHP stations, the difference between the ELF and ESF increases clearly, suggesting that the adverse impacts of cascaded diversion SHP accumulate in the study area. Compared with vegetation destruction and soil erosion, the cumulative loss of fish and net productivity is the most important aspect of the adverse impacts by cascaded diversion SHP, which needs more attentions.

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