Emergy-based accounting method for glacier ecosystem services valuation (ESV): A case of Tibetan Plateau

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Glacier ecosystems play a vital role in providing freshwater resources to humans, in regulating and stabilizing climate, runoff and offering potential for hydropower generation, and in providing unique cultural services for humans. However, few studies have systematically assessed the socio-economic contribution of glaciers, especially from a contributor perspective. To fill this knowledge gap, the aim of this study is to develop an assessment method applied to glacier ESV based on emergy theory. Emergy analysis is a measure that converts all forms of energy into the same unit of comparison, providing a common scale for measuring and comparing all forms of energy. This includes: (1) to develop an emergy-based accounting system and methods for glacier ESV from a donor-side perspective; (2) to evaluate the spatiotemporal characteristics of glacier ecosystem services (ESs) on Tibetan Plateau (TP) during the early 21st century. The results show that: (1) glacier ESs on TP increased from 1.25E+25 sej/yr in the 2000s to 1.28E+25 sej/yr in the 2010s, which is mainly due to the fast growth of provisioning services, although a slow decrease of regulating services is observed during the study period; (2) among the various services, the descending order of value is climate regulation (7.34E+24 sej/yr, 55.65%), hydropower generation (2.73E+24 sej/yr, 20.67%), and freshwater resources (2.68E+24 sej/yr, 20.31%); (3) the spatial characteristics of glacier ESs, where the glacier ESs values in the marginal TP are larger than in endorheic TP; (4) glacier ecosystems are divided in stock and flow, with stock referring to glaciers in the solid state and flow referring to glaciers in the so-called meltwater state. The glacier stock service still dominates in the early 21st century with a small downward trend in the last decade, while the glacier flow service has increased significantly from 2000s to 2010s due to the glacier recession. (5) Except climate regulation and carbon sequestration, all other services values are increasing, especially for tourism and recreation, and knowledge and education, which have shown a rapid growth with the social development. The theory and methodology used here are conducive to enhancing the understanding of material and energy flows within the cryosphere-society system and providing common scales for measuring and comparing different material, energy and monetary flows. Furthermore, this study will help to improve the glacier service assessment system, lay the theoretical and methodological foundation for the development of regional and global glacier service accounting, and provide a scientific basis for glacier resource development and management.