Journal of Cleaner Production 112 (2016) 3000–3006

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# EMergy accounting for the Three Gorges Dam project: three scenarios for the estimation of non-renewable sediment cost

Juan Yang

*School of Marine Science, China University of Geosciences, No. 29 Xueyuan Road, Haidian District, Beijing, 100083, PR China*

ARTICLE INFO

*Article history:*
Received 27 April 2015
Received in revised form
5 October 2015
Accepted 24 October 2015
Available online 10 November 2015

*Keywords:*
EMergy accounting
Sediment
Environmental sustainability index
Three Gorges Project

ABSTRACT

Dam construction conflicts are typically multidimensional, complex, and dynamic. Until recently, the environmental impact assessment of large dam projects was not fully acknowledged due to the uncertainty of the issue and the current knowledge on the accountability of ecological services. The measurement on the sustainability of the production system with a holistic view are thus of great relevance for the decision makers to implement the sustainable energy policy. In this paper, an integrated EMergy accounting was presented for assessing how the Three Gorges Dam project has performed based on the sustainability criteria. We quantified each EMergy flow component of energy, material and purchased input with available data in an assumed 100-year lifetime run. Special attention is focused on three simplified scenarios for estimating the EMergy cost of sediment. Our results showed that when the EMergy cost of sediment was counted, the Environmental Sustainability Index decreased dramatically with the increasing of the nonrenewable input. The results serve as a reminder of the necessity to apply different transformities for sediment EMergy cost in any hydro project, depending on the unique ecological service of sediment in the local river system. However, due to the high intensity of local renewable EMergy flow, the Environmental Loading Ratios and the Investment Ratios of the Three Gorges Dam system were relatively low. In spite the fluctation, the Environmental Sustainability Index remained higher than that of China in 1996, no matter the sediment EMergy cost was included or not.

## 1. Introduction

As powerful symbols of modernization, the big dam era started with the construction of the Hoover Dam on the Colorado River in the 1930s. Large dam-building projects were parallelled with improvements in engineering skills and construction technology after the World War II. By the year 2000, the world had built over 45,000 large dams (WCD, 2000). Many people believe that more dams will be needed in the future to meet the increased demands of the increasing population and water consumption. However, in recent years, the value of dams to human society has been questioned because they pose severe environmental and social risks in their life time (Bednarek, 2001; Sikder and Elahi, 2013). Intensive opposition to large dam construction has been aroused in many places. Underpinning many of these augments is the evidence of severe environmental and socioeconomic degradation after river damming (Beck et al., 2012; McCully, 1996; Pearse-Smith, 2012). In response to the dam construction conflict, WCD (World Commission on Dams) released a final report entitled *Dams and Development – a New Framework for Decision Making* in 2000, presenting its harsh criticism of large dams as well as recommendations on how to deal with the differing interests and conflicts over dam projects (Bird and Wallace, 2001). Since then, applying the WCD's framework was believed to result in better decision-making at the preliminary stage of dam planning (Bosshard, 2013; Pearse-Smith, 2014; Skinner et al., 2009).

There are real and varied benefits that human beings obtain from large dam construction. In China, the annual mean shares for hydropower has remained constant in China, 6.90% in the total energy production during 2000–2011 (Hu et al., 2014). Due to the huge gap between energy supply and demand, the Chinese government has been pressed ahead with plans to build multiple large dams in western provinces. The development of large hydro plants is expected to provide sufficient energy to meet the overall requirements, as well as a notable cutting in $CO_2$ emissions during the power generation. According to the National Development and Reform Commission of China, 366 g of coal produced 1 kWh of

*E-mail address:* yangjuan@cugb.edu.cn.

http://dx.doi.org/10.1016/j.jclepro.2015.10.110

electricity in 2006 (NDRC, 2007). The operation of Three Gorges Dam (TGD) project at full power reduces coal consumption by 31 million tons per year, which prevents 100 million tons of greenhouse gas emissions. The competitive advantages meet the national strategic demand for more economic and cleaner energy supply, in spite of the fact that the lakes created by large dams act as a source of greenhouse gas emissions. In the case of Itaipu Power Plant, the greenhouse gas emissions were estimated as $9.644 \times 10^4$t $CO_2$/yr plus $1.175 \times 10^4$ t $CH_4$/yr from Itaipu's reservoir (Ribeiro and Silva, 2010).

Except for the success in improving people's life quality, some underestimated environmental consequences of the TGD project have become visible since the reservoir started filling to the height of 135 m in 2003. According to the systematic hydrological data between 1950 and 2010, the significant deposition centre of sediment shifted from the middle and lower reaches (before 2000) to the upper Yichang following the river impoundment in 2003 (Dai and Lu, 2014). Moreover, due to a series of environmental projects and hydropower cascade development in the upper Yangtze River, the sedimentation rate (average 176 Mt per year for the 2008–2010 period) in the reservoir was much lower than expected. However the downstream riverbank erosion in the middle reaches was significantly underestimated in the early EIS (*Environmental Impact Statement for the Yangtze Three Gorges Project*) Report (Xu et al., 2013). The annual erosion rate downstream averaged 108.8 million $m^3$ from 2002 to 2010, which was greater than the average of 6.25 million $m^3$ per year in 1975–2002 (Lu et al., 2011). Riverbank collapse not only occurred in the midstream but also expanded to the downstream and estuarial zone, coinciding in the sharp decline in sediment load at Datong (the lowest gauging station of Yangtze River) since 2003 (Dai and Lu, 2014). Another underestimated environmental problem in the early EIS report was the water quality deterioration and eutrophication in the reservoir area. The frequency of algal bloom events in the reservoir area increased from three events in 2003 to 26 events in 2010, with a widening affected scope of water body (Yang et al., 2009). In addition, over 80% of the available phosphor and heavy metal pollutants are absorbed in the suspended sediments, which are partially precipitated in the reservoir. When dredging the drainage ditch behind the dam, the pollutants are released into the water. Between 2001 and 2010, the Chinese government budgeted approximately RMB 40 billion yuan for the *Water Pollution Prevention Plan for the Three Gorges Reservoir and the upper Reaches of the Yangtze River* (*Revised*), to improve the water quality and reverse eutrophication. However, the target of water quality criteria has not yet been achieved.

These severe environmental impacts are more or less linked to the sediment and nutrient retention after the impoundment. Combined with other disputes in the TGD project, these underestimated consequences urgently require reassessing for a better acknowledgement on the dam project sustainability. Relying only on energy security and $CO_2$ abatement to measure the sustainability of the TGD project is not sufficient without considering other uses of environmental services (New and Xie, 2008; Romitelli, 1997; Shen and Xie, 2004; Tilley and Comar, 2006). In the long run, dam projects may be far more destructive and threaten human well-being than the tons of $CO_2$ released (Brown and Ulgiati, 2002). The mentioned drawbacks have also reduced the green power efficiency of large-scaled hydro (i.e., more than 15 m in height or, if 5–15 m high, has a storage capacity of more than 3 million cubic metres) in comparison to small-scaled ones (Hicks, 2004; Pang et al., 2015; Kosnik, 2010).

The environment has a renewable capacity to support economic processes and human welfare. As one of the natural components of river system, sediment provide a variety of ecological services in fluvial geomorphology, biogeochemistry, and engineering, as well as land ocean interactions (Dai and Lu, 2014). The erosion and sedimentation processes are strongly linked to the change of hydrology of a river after large dam building. Globally, Syvitski et al. (2005) estimated that reservoirs hold over one billion tons of sediment, preventing sediment transport to coastal areas, reducing nutrient delivery to agricultural areas and increasing coastal erosion rates. In the environmental impact assessment of dam projects, Brown and McClanahan (1996) first identified the largest environmental impact of the Mekong River Dam as the loss of sediment delivery to downstream ecosystems.

EMergy analysis, as a feasible method to appraise the total energy embodied in any product or service, has been considerably advanced in the efficiency and sustainability evaluation as well as in the comparison of different production systems (Brown, Ulgiati, 2002; Lima et al., 2012; Pang et al., 2015; Wang et al., 2014; Wang et al., 2015). Due to the unit EMergy baseline could be different in the EMergy method, how to determine the EMergy transformity of sediment flow component in a hydro project is not fully explored yet. In some cases, the EMergy estimate on sediment is based on transformity of the organic energy contained in the sediments (Brown and McClanahan, 1996; Kang and Park, 2002), while in other practices, sediment EMergy was ignored (Pang et al., 2015; Zhang et al., 2014) or calculated as a renewable resource by summing the rainfall and geologic contributions and dividing by the annual flow of sediments (Martin, 2002). Accordingly, the purpose of this study is to quantify each EMergy flow components of the TGD project system under three scenarios with considering the potential cost of sediment. Two important questions to be addressed are how to objectively assess the environmental and ecological disadvantages of sediment after river damming and whether the TGD project yields a net public benefit with sustainability criterion within the assumed 100 years life time.

## 2. System description

The TGD project is located at Sandouping, Yichang, Hubei Province, on the upper Yangtze River. Being the longest river in Asia, the Yangtze River flows for 6418 km from the glaciers on the Tibetan Plateau in Qinghai eastward across southwest, central and eastern China before emptying into the East China Sea. The Yangtze River drains one-fifth of China's land area, and its river basin is home to one-third of China's population. The elevation decreases from above 5000 m to less than 1000 m along the river course.

After a long-term feasibility study and comprehensive design, Three Gorges Dam began construction in 1992. The dam's main structure was completed in 2006, and the first generator started working on July 10, 2003. Before the dam construction, the average discharge of the Yangtze River was 30,166 $m^3$/s. The sediment load was $5.3 \times 10^8$ t/yr at the Yichang gauge station near the dam. The Three Gorges Dam controls a drainage area of $1.0 \times 10^6$ $km^2$, which is 55% of the total catchment area of Yangtze River, with a reservoir capacity of approximately 20 $Gm^3$. Table 1 shows the main engineering features and multipurpose of the dam project (Zhang, 1998).

**Table 1**
Features of the Reservoir and Dam buildings of the TGD project.

| Engineering structures | Item | Index |
|---|---|---|
| Reservoir | Reservoir area | 1084 $km^2$ |
| | Normal storage elevation | 175 m |
| | Total storage | $393 \times 10^8$ $m^3$ |
| | Storage for flood reduction | $221.5 \times 10^8$ $m^3$ |
| | Improved navigation channel | 570–650 km |
| Dam Buildings | Maximum height of dam | 175 m |
| | Installed capacity | $2250 \times 10^4$ kW |
| | Annual electric generation | $847 \times 10^8$ kW h |