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Cradle-to-grave greenhouse gas emissions from dams in the United States of America

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ABSTRACT

Hydropower is traditionally considered to be one type of “clean” energy, and has been heavily developed in many regions of the world. Nevertheless, this assumption is increasingly being challenged by recent findings that a large amount of methane and other greenhouse gases (GHGs) are emitted during reservoir creation, turbine operation, and dam decommissioning. Via a critical review of existing hydropower life cycle assessments and reservoir emission studies, we compared the GHG emissions of various types of dams based on their structural type, size, primary function, and geographical location during their construction, operation, and decommissioning phases. Means to improve dam performance and reduce related GHG emissions were identified. It was found that dams with reservoirs usually have much higher GHG emission rates than diversion dams. GHG emissions are mainly generated at the construction and maintenance stages for small-scale run-of-river dams, whereas decomposition of flooded biomass and organic matter in the sediment has the highest GHG emission contribution to large-scale reservoir-based dams. Generally, reservoir-based dams located in boreal and temperate regions have much lower reservoir emissions (3–70 g CO_2 eq./kW h) compared with dams located in tropical regions (8–6647 g CO_2 eq./kW h). Our analysis shows that although most hydroelectric dams have comparable GHG emissions to other types of renewable energy (e.g., solar, wind energy), electricity produced from tropical reservoir-based dams could potentially have a higher emission rate than fossil-based electricity.

1. Introduction

The United States of America (USA) has one of the most heavily dammed river systems in the world [1–3]. More than 90,000 existing “large” dams are documented in the latest National Inventory of Dams (NID) maintained by the Army Corps of Engineers [4]. This does not include an estimated 2,000,000 or more smaller dams that do not meet the NID criteria for inclusion in the inventory (high or significant hazard classification; 7.6 m in height and exceed 18,500 m^3 in storage; or, 61,700 m^3 storage and exceed 1.8 m in height). The USA also has a long history of building dams. Some of the oldest dams listed in the NID were built in the mid-1600s. The construction of dams continued to grow exponentially thereafter and did not slow down until it peaked in the 1960s (Fig. 1). In fact, more than one-third of all dams in the NID were built between 1961 and 1980. Dams are constructed for a myriad of primary functions. The primary functions of NID-listed dams are recreation (28.0% of the total number of dams), flood control (17.9%), fishing and fire protection (17.3%), water supply and irrigation (14.7%), power generation (2.3%), erosion control (1.6%), and mine tailings storage (1.3%) [4]. These primary functions have changed substantially over the years. Most of the dams constructed before the 1900s primarily serve recreational functions currently, although most likely served alternate purposes at the time of their construction. The need for dams for water supply and irrigation became prominent in the late 1800s and the first half of the 1900s, while most dams constructed in the past 50 years are primarily for flood control, fishing, and fire protection. Most of the existing hydroelectric dams (dams capable of generating hydropower) were built between 1800 and 1960; however, hydropower has consistently comprised a small percentage of primary dam functions.

Although the USA has benefited from the multiple functions provided by dams, their adverse environmental and social impacts and safety risks are increasingly being recognized and debated. For instance, dams have been criticized for altering natural flow regimes, blocking fish passage, affecting sediment transport, and changing watershed characteristics, which collectively contribute to the degradation

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Abbreviations: EIO, economic input-output; GHG(s), greenhouse gas(es); GWP, global warming potential; HPs, hydropower projects; LCA, life cycle assessment; NID, National Inventory of Dams; O&M, operation and maintenance; PV, photovoltaic

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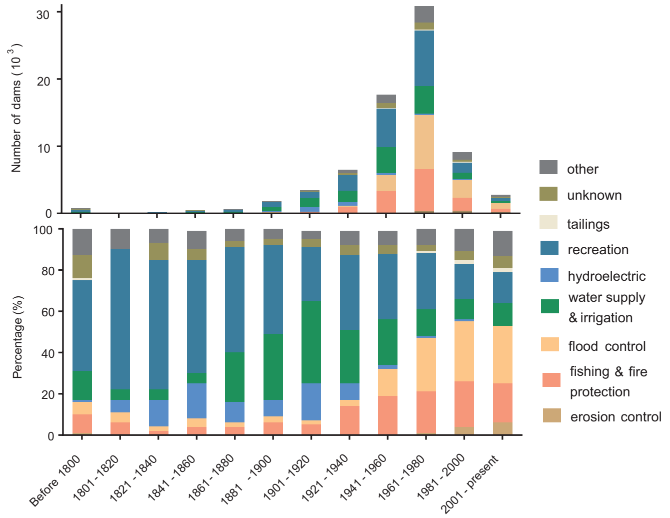

Fig. 1. The current primary functions of dams constructed in the USA history based on the data obtained from the National Inventory of Dams [4].

of water quality, fish population, and biodiversity as well as cascading social and economic problems (e.g., revenue loss in the fishing industry) [5–9]. Furthermore, some of the older and/or larger dams are often perceived as a public-safety risk under the increasing possibility of natural and man-made threats [10,11]. These changes in knowledge have led to a subtle shift in scientific and public attitudes towards dams, and the classification of hydropower as "clean" energy has also been challenged. New dam construction is often accompanied by social opposition, and most importantly, dam removal and upgrades can be contentious, often driven by grassroots movements initiated by local communities [12,13]. Table 1 summarizes existing literature on major environmental, social, and economic impacts associated with dams as well as their potential rehabilitation methods.

In the last decade, the method of life cycle assessment (LCA) has increasingly been adopted in assessing the sustainability of products and systems [14–16]. LCA, guided by the ISO 14040 and ISO 14044 standards, is an approach for characterizing the cradle-to-grave or cradle-to-cradle impacts of a product or system, i.e. from raw material acquisition, equipment manufacturing, and use to disposal or reuse [17,18]. Hydroelectric dams, although representing only 2.3% of the total number of dams in the NID, have been the core of most dam-related LCAs [17,19]. This can be partly explained by the significance of hydropower as a type of renewable energy in the USA; hydropower accounts for 6% of the annual USA net electricity generation and 46% of the total renewable energy generation (compared with 35% wind, 2% wood and waste, 1% solar, and 0.4% geothermal) [20–22]. Hydropower continues to be developed around the world and holds a critical position in meeting future energy demand, especially in countries where the hydropower potential has not yet been fully exploited [23]. Although new construction of hydroelectric dams has been sluggish since the 1960s in the USA, new programs have been implemented to increase hydropower generation, including (1) development of hydrokinetic energy technologies to extract and convert energy obtained from oceans, rivers, and man-made canals; (2) upgrades of existing

Table 1
Potential environmental and socioeconomic impacts of dams and prospective amelioration approaches.

Potential impacts	Response	Potential rehabilitation tools	Impact assessment methods
Environmental impacts			
Alteration of natural flow regime	Dampening of large or seasonal floods, resulting in a negative impact on both habitat and organisms [38,39]	Allow spring floods; reduce daily fluctuations; create periodic high flows; widen river	Field observation and measurements [40]; ecological model [41]
Barriers to longitudinal fish migration	Fishes killed when they pass through turbine or fish ladder; reduction of fish population and biodiversity; economic losses from fishery	Remove dam; add or improve fish ladders; upgrade to low-impact hydropower generation technology	Field observation and measurements [42]; Bayesian state-space model [9,43,44]
Barriers for the drift of organisms	Degradation of water quality; reduction of biodiversity; reduction of property or recreation values	Remove dam	
Blockage of sediment transportation	Accelerated siltation processes; reduction of the vertical connection between the river and groundwater; effects on the benthic community and spawning conditions for fish; reduction of biodiversity [45,46]; greenhouse gas (GHG) emissions [47,48]	Remove dam; widen rivers; manually move sediment from reservoir to downstream	Ecological model for fish biodiversity [42,45]; LCA of sediment contribution to GHG emissions [48]; life-cycle cost analysis of sediment removal and processing system [49]
Temperature changes	Temperature stratification in the reservoir [50]; change of downstream temperature when warm or cool water is released	Remove dam; modify dam structure (e.g., change penstocks to allow withdrawal at different reservoir levels; add weirs downstream	Field observation and measurements [51]
Inundation of terrestrial habitat	GHG emissions from the degradation of inundated biomass; change of local land use patterns; loss of habitat of original inhabitants	Remove dam	Field measurements and empirical models; life-cycle assessment [27]
Socioeconomic impacts			
Involuntary resettlement for some local communities	Economic and cultural shocks and losses of resettling community; poverty and inequity problems	Avoid or minimize involuntary resettlement; improve livelihood of resettling community; encourage public participation and consensus; provide group support [52]	
Waterborne disease from water impoundment schemes	Fatality; economic losses; common in tropical and subtropical regions	Implement prevention strategies and appropriate disease diagnosis; finance medical care [53]	
Reduction of fish population and biodiversity	Reduction of a protein source in the diet; economic losses from fishery; reduction of property or recreation values	Remove dam; add or improve fish ladders; upgrade to low-impact hydropower generation technology	Bayesian state-space model [9,43,44]
High upfront capital cost	High cost for dam construction, engineering, and design causes public or private economic burdens [54]		Life-cycle cost assessment [55,56]
Risk of dam failure	Economic losses; life loss	Remove/upgrade dam; inspection and maintenance	Risk assessment [57,58]