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Editorial overview: Introduction to the special issue: Hydropower and sustainability in the Anthropocene

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As humanity navigates through the Anthropocene, persisting challenges and implications of the human footprint on earth's systems pose important research and policy questions for local and global futures. The Anthropocene is an emerging concept proposed by scientists to denote an epoch of significant human impact on earth's geology, atmosphere and social-ecological systems [1]. Along with this human-induced unprecedented process of environmental change, societies have also been changing at a fast pace. Population growth, growing consumption, and transformations in education, technology, communications, and the globalized economy are creating a growing complexity that is difficult to model, manage and predict. A critical challenge for researchers and policy-makers is to address the complex nexuses and trade-offs between natural resource use, economic development and socio-environmental well-being [2].

One of the most important topics that needs to be addressed is how to reconcile energy production, water sustainability, food security, and societal well-being in countries under a changing climate, knowing that water is rapidly becoming a scarce resource, food security is an ever-present challenge for many people worldwide, and that we are growing ever more dependent on reliable energy to carry on our daily lives—thereby creating competing interests and conflicts over their use and ownership [2,3]. A solution that a growing number of countries have run to adopt to address these three challenges is to build hydroelectric dams as a way to produce abundant and reliable energy including building reservoirs that can be used for water storage, irrigation and urban uses [4,5]. On first look, hydropower seems to be an option to address these challenges, but they also have been criticized for having unacceptable social and environmental costs [6–9]. A current debate, which this special issue addresses, is whether hydroelectric dams should continue to be constructed, despite the risks and uncertainties related to climate change, the unequal distribution of their costs and benefits, and the significant social and ecological negative impacts of hydroelectric dams on river systems, biodiversity and the people affected by these projects.

An estimated 3700 large dams are either planned or under construction worldwide right now (defined as producing 30 MW or more) [10]. It is easy to understand why: hydropower represents the largest renewable source of electricity (15% of global production) and it is estimated that two-thirds of the global potential remains unexploited [11]. Substantially increasing the share of renewable energy in the global energy mix by 2030 is among the U.N.'s Sustainable Development Goals and helps to meet the Paris Climate Agreement [12]. Hydropower development is global in its significance and reach. It is

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transforming the most important river basins in the world, such as the Amazon, the Congo and the Mekong, with substantial existing and potential damages to livelihoods, river systems and biodiversity in those regions [13,14]. The hydrologic consequences of large-scale dams and reservoirs are extensive. Sharp declines in available freshwater, because of dam construction, drive changes in seasonal river sediment load, discharge and flow [14,15], downstream freshwater habitat [16], loss of floodplains and riparian vegetation [17,18], breaks in connectivity [19,20], and even coastal erosion and salinity changes [14]. The negative consequences for ecosystem structure and composition (e.g. habitat fragmentation, loss of aquatic faunal diversity), and function (e.g. nutrient flows, primary production) are at times severe. Reservoirs can also be significant sources of greenhouse gases, especially methane [21,22], and reductions in river flow can increase pollutant concentration, especially when the impacts of diverse dams and/or extractive activities are combined [23,24].

Most of the literature, and this special issue, focuses on large hydropower dams and their impacts on people and the environment. That is because their impacts are indeed very large, and they are more visible. In all countries, large dam developers are required to produce Environmental and Social Impact Assessments (ESIAs) that even when they are poorly done, provide an empirical foundation for evaluating the impacts before and after their construction, as well as set up the basis for mitigation and compensation plans—and thus critiques tend to have more to work with.

However, we cannot forget that there are far more small hydropower dams than large ones, and because they are smaller, they are not held to the same standards. A recent survey estimated 82 891 small hydropower plants operating in 150 countries [25]. Small dams' definitions can be fairly arbitrary and variable from country to country [26]. Most international agencies define SHPs as those producing up to 10 MW of generating capacity. Policies regulating small dams are less strict and more flexible in comparison to those of large dams, and thus many countries build them with abandon and without enough consideration for their social and environmental impacts, as well as cumulative impacts when they are built in cascade [26]. Concerns are dismissed that the impact is small. Some scientists that have examined small hydropower in China and Europe have concluded that the environmental impacts can surpass those of large dams by KW of energy produced [27–29]. Since governments tend to build many small dams in the same subwatershed, their cumulative impact on a given river may be the same or even larger than one large dam [26]. More attention should be given to small dams and their impacts, especially now that wind power has proven to be capable of producing electricity at a lower price per KW than small dams.

The human costs of large dams are no less important. The social, cultural, economic and political disruptions resulting from the violation of human rights, displaced populations and transformed livelihoods bear costs that are routinely underestimated. The World Commission on Dams (WCD) has documented the socio-economic problems observed in dam development projects in the past: 40–80 million people have been resettled, and it has proven challenging to resettle them properly [30]. In addition, the living conditions and food security and sovereignty of communities affected by these projects are often placed in peril [31–33]. Many cases of non-existent or poorly conducted free, prior and informed consultation (FPIC) processes involving indigenous peoples and traditional communities directly affected by large dams have also been documented in different countries [34–36]. Hydropower is on face value an attractive renewable source of energy in a world that wants to decarbonize the economy and reduce fossil fuel emissions. A debate has been going on for some time as to the extent that it offers a desirable pathway for the future. This special issue tackles many of these issues and brings up to date the on-going debates in diverse settings and countries.

Large-scale hydropower stopped being an acceptable option in the 1970s in Europe and North America because the energy benefits were deemed not to justify the social and environmental costs [37]. Since then, however, large-scale hydropower has returned as an option for the global South. What are the social, ecological and economic trade-offs and implications of this new boom? What's new, in terms of policies, research priorities, management and technology? Why have financial institutions coupled with national governments invested in this pathway knowing well why it was abandoned in the North? Have the issues that led to abandonment of large hydropower been addressed in developing countries? Are the issues the same or different in developed and developing countries? The issue of whether hydropower is a sustainable undertaking in the 21st century is discussed in a recent article in the Proceedings of the U.S. National Academy of Sciences [38].

This special issue will provide a global synthesis of the important social, ecological and economic issues related to the new boom of hydropower expansion in the global South, and implications for sustainable development in the Anthropocene. The set of papers includes examination of current social-ecological processes documented for major rivers of the global South with examples from the Amazon and Mekong watersheds, as well as illustrative cases from Europe and North America.

The special issue leads off with a paper on the Amazon Basin, an area with rapid hydropower development. The Amazon Basin—an area of 6 million square kilometers—is the location of 147 planned dams, 65 of which are in Brazil [39]. Brazil is also investing in developing hydropower resources in Bolivia and Peru with a view to buying their energy—estimated at 180 GW in Peru, and 20 GW in Bolivia. The scale is multinational and will affect very high biodiversity ecosystems, along with a rich diversity of ethnic and cultural groups, and the wellbeing of millions. Brazil has amongst the largest hydroelectric potential in the world, estimated at 260 GW (41% of this lies in the Amazon Basin). In the article by Athayde et al., the authors present a literature review of academic publications focusing on hydropower development in the Brazilian Amazon published in the past five years (2014–2019). The authors present results of a co-occurrence network analysis of these publications, highlighting bridging fields, disconnections, and opportunities for interdisciplinary research. The analyses also showed the leadership role that Brazilian scientists, universities and academic institutions play in regards to this field of study, as well as the importance of Brazilian government investments in science and technology, especially through the research agencies National Council for Scientific and Technological Development (CNPq) and Coordination for the Improvement of Higher Education Personnel (CAPES). Recent research advances in the fields of biophysical and social ecological systems, energy and infrastructure and governance, development and the social impacts of dams are presented and discussed. The authors conclude by identifying knowledge gaps and future research directions, highlighting opportunities for improved communication among scientists, practitioners, decision-makers, indigenous peoples and local communities.

The second paper by Arantes et al. provides a synthetic analysis of the impact of dams on tropical fishes and fisheries, through the lens of fish functional traits. The paper is an important contribution to ecosystem-based approaches to the study and management of social-ecological systems affected by river impoundment in the tropics. On the basis of a literature review, the authors define functional traits as any feature of an organism that affects performance or fitness, including those related to food acquisition, mobility and habitat use, reproduction and defense tactics, among others. The authors propose that functional approaches might improve the ability to predict fish and fisheries responses to river impoundment by hydroelectric dams across scales. In addition, it suggests that a functional approach might support biodiversity conservation and fisheries management by improving the ability to associate changes in species' relative abundance or biomass with particular traits that in turn affect ecosystem services provided by fishes.

The paper by Siciliano et al. addresses the growing role of Chinese investments in large hydropower dams which have rapidly increased in the global South in the last 20 years. Some of these projects have been contested both from a technological and political point of view due to the ways in which decisions have been made, as well as in relation to the resulting social-ecological change and ecological distributional aspects. From an Environmental Justice perspective, authors analyze the main drivers and contested aspects of Chinese hydropower investments in the global South. The paper builds on Chinese projects located in different regions of the world, by combining information from the literature and the Global Atlas of Environmental Justice—EJAtlas dataset. On the basis of the analysis of Chinese hydropower projects and environmental justice concerns, this paper sheds light on the current literature on drivers and multidimensional conflictive outcomes of these large hydropower investments.

One area where Chinese investments have been particularly focused has been in the Mekong. Two papers in this special issue focus on the Mekong. The paper by Arias et al. addresses the physical changes taking place as a product of hydropower development. The Mekong River harbors immense natural resources that are the basis of local economies. Research on how dams and climate change could alter river systems has heightened in recent years, but while this research has led to important scientific concepts and increased discussion of sustainable development, it has done little to prevent the rapid environmental change in the Mekong floodplains of Cambodia and Vietnam. This is in part because localized drivers of floodplain change (i.e. overfishing, deforestation, and water infrastructure development) have arguably decreased environmental sustainability faster and more directly than regional factors such as hydropower and climate change.

The paper by Geheb et al. addresses the rapid hydropower development in the Mekong River Basin, pitting a variety of stakeholder groups against each other at both intra-national and inter-national scale, and affecting state relations across scales. In this paper, the authors explore the narratives surrounding hydropower development in this basin, while referring to the concept of hydro-social cycles as a central analytical tool. This tool looks at the processes of socio-political construction of nature, viewing water as a medium that conveys power, and thus sources of both collaboration and conflict. The authors conclude that while the Mekong hydropower narratives do, indeed, attempt to conflate the massive regulation of hydrological systems with large-scale social and economic ambitions, they are also intended to obscure a widespread and systemic effort to control and alienate the region's waters via engineering at multiple scales.

Dam removal, rather than construction, has become the norm in North America and Europe because many that were built before 1950 are at the end of their useful lives, they would be too costly to repair, many no longer serve their initial purpose, and their social and environmental negative externalities became unacceptable. European countries with favorable topography and rain patterns, such as France and Switzerland, continue to have hydropower as an important part of their energy mix through continued development of small hydropower and technological innovations at existing dams. In contrast, 3450 dams have been removed to date in Sweden, Spain, Portugal, the U.K., Switzerland, and France. Hundreds of dams were removed in the U.S. (546 from 2006 to 2014) and Europe at enormous financial cost. This situation contrasts with what is happening in developing countries, as we can see in the articles in this special issue.

The last two papers in this Special Issue present experiences and reflections on dammed systems in the global North, focusing on US and Europe. The paper by Wagner et al. present a summary of hydropower development in Europe, providing key statistics, reviewing recent technological developments, and summarizing current and future sustainability challenges regarding both existing and new hydropower projects in Europe's watersheds. Given the fact that more than half of the total hydropower potential in Europe has been already exploited, there is increased environmental concerns regarding the use of remaining suitable river sections. The authors explain that, as a result, many European countries are focusing efforts on extending and upgrading existing facilities through technological advances, which could provide important insights for enhancing the efficiency of existing hydropower projects in developing countries. In addition to technological developments and climate-resilient hydropower technologies, the authors highlight the importance of integrated management approaches involving river basin scales.

The article by Bair et al. on hydropower in the Colorado River Basin provides further cautionary tales about hydropower development as a continuing challenge where it has been built. The Colorado river is an important lifeline to populations near and far in what are largely semi-arid to arid zones. While there is hydropower produced, in one of the largest US hydropower dams, the lake that supplies the water for it has been declining over the years due to demand by urban populations, agriculture, and the decreased precipitation brought on by climate change. This has only exacerbated the conflicts over the remaining water, the recreational fisheries that grew up around the lakes and reservoirs, and the rights of indigenous people to the Basin. The paper offers useful insights on how to develop adaptive management of water and social-ecological systems in the Basin.

This Special Issue has aimed to shed insight for improved planning and decision-making, implementation, and monitoring of hydroelectric dams. The contributions in this collection highlight the enormous environmental and social costs of building large dams illustrated by experiences from the Amazon and Mekong basins. Articles focusing on both the Global North and South show the importance of integrated basin-wide approaches to managing river systems, including technological innovations and adaptive management initiatives.

Dependence on large dams for generating hydropower can be questioned as a reliable strategy for power generation under existing climate change scenarios. Moran et al., found that the best future scenarios need to include rapid development of wind, biomass, and solar to complement the existing installed hydropower, in addition to the implementation of innovative approached to managing existing hydroelectric plants, and investments in energy efficiency. The latter is not expected to meet the demands of the future, which will be more reliably provided by a complement from solar, biomass, and wind power generation with existing hydropower providing stability to the grid. The use of floating photovoltaics on existing reservoirs is a growing trend across the world that offers a way to offset the lower capacity of existing hydropower dams to reach installed capacity [40]. This hybrid approach promises a more reliable way to meet global energy needs in the Anthropocene than the over-reliance on hydropower that some countries seem to be pursuing.

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