The legacy of large dams and their effects on the water-land nexus

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Large dams trigger controversial effects

Man-made river dams and reservoirs have increasingly been constructed to modify free-flowing rivers to benefit society through hydropower generation, irrigation, and other water supplies, navigation, and flood prevention. However, this ongoing global boom (Zarfl et al. 2015) also triggers harmful outcomes to local, directly affected stakeholder groups, and the environment. Particularly, profound social impacts of involuntary resettlement need alleviating measures and room for remembrance. Restoring vital characteristics of aquatic ecosystems after artificial reservoir establishment, to any possible degree, may contribute to higher welfare and sustainability.

Large reservoirs cause both particularly large positive and negative effects on society, the economy, and the environment. In Brazil, reservoirs were initially constructed for the primary purpose of hydroelectricity generation, to prevent flooding, and to provide irrigation capacities in the dryer parts of the country. However, an increasing number of users and

usages have increased the pressure on stored and flowing water. Their requirements differ in terms of river discharge, water quality, and reservoir levels, most often reducing the options of the water users downstream. The resolution of conflicts over water allocation and management has been legally supported by the Brazilian Water Act since 1997, which introduced the paradigm of multiple and equally important water uses.

Several of these water uses are closely linked to land-use practices, particularly irrigated agriculture. By law, domestic supply for the river basin's residents sets a priority for water consumption during pronounced water scarcity. In terms of accessibility and water quality, water abstraction for domestic supply is being affected by water levels. Domestic water supply is also directly linked to water pollution through dilution of untreated wastewater in the river or reservoir. The intertwined and often divergent necessities and externalities of water and land use call for a coordinated management and governance approach to mitigate conflicts. Yet many of

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the natural and societal processes underlying these conflicts have not been sufficiently understood.

Climate change causes additional burdens on river basins. While a general rainfall reduction has not been confirmed by climate simulations in the semi-arid regions of Brazil (increasing as well as decreasing climate model simulations have been proposed), rising temperature projections are more certain. These conditions will impact the growth of cultivated crops and natural vegetation, as well as increase heat stress on domestic and wild animals. The subsequent change of habitats will ultimately affect the provision of ecosystem services.

The INNOVATE project (Interplay among multiple uses of water reservoirs via innovative coupling of aquatic and terrestrial ecosystems) had been set up in the São Francisco River Basin to contribute to a more profound understanding of an exemplary case of a land and water nexus—as a prerequisite toward more sustainable land and water management of large dams and reservoirs. The major topics of the relevant Brazilian-German project consortium were land use and its impacts on the water body, the conservation and development of ecosystem services toward increased sustainability, the interplay between multiple uses of reservoirs, their positive and negative externalities, the recycling of scarce resources (i.e., nutrients and water) between different sectors, and participatory governance of natural resources.

The project aimed at generating and bringing together knowledge on the dynamics of the aquatic and terrestrial ecosystems, as well as adequate management options. We focused on innovative land management strategies, which effectively contribute to sustainable practices, fair governance, and adaptation to climate change in the chosen river basin. This Special Issue presents research results from the INNOVATE project. It also reports on the implementation of the project's achievements by focusing on land and water management insights and recommendations. A large part of the research was undertaken in collaboration with relevant stakeholders. The major results are summarized in a guidance manual for stakeholders at different levels who are involved in land and water management in semi-arid dam-reservoir regions (Siegmund-Schultze 2017a, b), as well as in a book that integrates findings of various collaborative projects of the same funding scheme (Liniger et al. 2017).

The comprehensive research project INNOVATE and its study region

The greater study region comprises a very large river basin, located entirely in Brazil: the São Francisco River Basin (Fig. 1, left). It spans an approximate 640,000 km² and houses more than 16 million people, which is roughly equal to the population of Ecuador and more than twice the area of Ecuador. The river basin consists of four administrative

regions (Upper, Middle, Sub-Middle, and Lower São Francisco, Fig. 1, left). The Upper administrative region has the highest precipitation and runoff contribution as well as the largest population. The Middle also has substantial precipitation, important agricultural production which is partly achieved through irrigation, and has a lower population density. The Sub-Middle is characterized by very low precipitation despite its substantial water demand for irrigation and hydropower generation. The Lower again shows more significant precipitation while the mouth of the river is threatened by increasing saltwater intrusion. The project had a local focus within the third semi-arid Sub-Middle region, covering the Itaparica Reservoir and adjacent municipalities of Pernambuco state, which is home to the unique, native, seasonally dry tropical Caatinga forest (Fig. 1, right). A more detailed description of INNOVATE's study region can be found in Siegmund-Schultze et al. (2015), while the papers in the Special Issue provide information on specific environmental, social, and technical characteristics.

INNOVATE was a large consortium of scientists from Brazil and Germany. The collaborative project spanned five core years—from January 2012 to December 2016. Members of the project sampled, surveyed, and modeled the aquatic and terrestrial management systems, along with their ecosystem functions and services. Innovative approaches such as modified fishery systems, biochar, and other approaches for soil improvement, as well as adaptations of the existing smallholder grazing regime have been explored empirically to improve farming practices and socio-economic perspectives. The biodiversity along functions and patterns of the predominant Caatinga ecosystem, the crop systems, and the reservoir were assessed. Global climate scenarios were down-scaled, a cascade of land and hydrological models was set up, and different sets of simulations were evaluated. Furthermore, the water basin's multi-level governance system was scrutinized. The stakeholder arena involved federal, state, and municipal departments and agencies; local land users; civil society actors; and mixed organizations such as the river basin committee. The specific methods of the papers compiled in this issue are described in detail in the individual contributions.

Of paramount importance was to advance both disciplinary and interdisciplinary research, while also working with relevant stakeholders from the local to national scale. Carrying out inter- and transdisciplinary research was the particular interest of the Sustainable Land Management program of the Federal Ministry of Education and Research on the German side (Eppink et al. 2012; Václavík et al. 2016). As a primer, scientists were invited to interdisciplinary workshops, as well as to bigger transdisciplinary workshops applying constellation analysis, inter alia. Constellation analysis involves a joint process of systematically identifying and arranging actors, rules

Fig. 1 The INNOVATE study sites. The São Francisco River Basin with four administrative regions (left) and the Itaparica Reservoir region (right) (source: Siegmund-Schultze et al. 2015)

and regulations, technical artifacts, and natural components (compare Schäfer and Kröger 2016). It served as a bridging approach to foster a joint understanding of the intertwined study subjects, including potential opportunities and barriers to change.

Further mutual understanding, exchange, and collaboration among scientists of all disciplines were fostered through thematic workshops. Topics of workshops were, for instance, models and scenarios, ecosystem services, water quality, and sustainable land use and conservation. In addition, series of stakeholder workshops were conducted in Brazil, addressing stakeholders at various levels and locations. Workshop scales ranged from the entire consortium (e.g., kick-off meeting, status conference), to national meetings (annual meetings on location, thematic meetings, a seminar series), to thematic subgroup meetings, and stakeholder workshops. The scientific coordination group boosted interdisciplinary cooperation by connecting people around common aspects. Young researchers interacted with local residents to make research activities tangible and to discuss the relevance of initial results. Electronic interaction completed the set of communication tools developed by the project, which also included a website (innovate.tu-berlin.de) and social media ([facebook.com/innovate2012](https://www.facebook.com/innovate2012)). The recent drafting of a new ten-year river basin management plan for the São Francisco River further promoted cooperation and integration. INNOVATE contributed information and communicated with the responsible agency, thus serving the river basin committee.

The multi-faceted impacts of damming on land and water resources, and possible management adaptations

The reservoir's habitats, operation, and water allocation

The construction of a reservoir leads to the creation of new ecosystems at the expense of previously existing ones. This also holds true for social systems that are often tremendously disrupted due to damming. These disruptions require efforts from a diverse array of stakeholders to create new social structures that correspond with people's needs and expectations. Nogueira da Silva et al. (2018) demonstrated that net-cage aquaculture, which increasingly uses the calm waters of the Itaparica Reservoir at a commercial scale, and introduces exotic fish species, substantially affects artisanal fisheries, i.e., local fishermen. Unresolved conflicts within the reservoir arise from the reduction of endemic fish species diversity and abundance, while spatial conflicts exist regarding the use of and access to the reservoir's lakeshore.

Tropical reservoirs in humid regions are often blamed for their huge greenhouse gas (GHG) emissions: but does this also apply to a semi-arid reservoir? Rodriguez and Casper (2018) confirm that the semi-arid tropical Itaparica Reservoir is in fact a source of GHG emissions. They emphasize, however, the spatial and temporal variability in the magnitude of the emissions. Shallow areas turned out to be emission hotspots in the reservoir. Long-term monitoring is needed to

reveal the significance of the seasonal variations of the GHG emissions. Uncertainties or differences in emissions are due to the length of the period used for the estimations (i.e., 20 or 100 years) and whether measurements were undertaken shortly after damming or decades later; the weather patterns during measurements (precipitation, temperature, and wind); the magnitude of the related electricity production; and the inclusion or non-inclusion of the whole life cycle emissions of the tested infrastructure.

Reservoir operations induce artificial water level changes whose effects are multifaceted and become evident at different levels. Gunkel et al. (2018) synthesized a number of studies that were conducted to better understand the nutrient dynamics of the Itaparica Reservoir affected by its operation and use. Their particular interest lay in water exchange processes between the main river flow and an isolated bay. The rewetting of formerly desiccated littoral zones is an important driver for nutrient release, mediated by the macrophyte *Egeria densa*, which proliferates (too) well under warm conditions. Further, intensive fish aquaculture elevated the phosphorus level of the reservoir to a critical concentration. Measures to limit the nutrient content, and therefore oligotrophication, include the regular harvesting of macrophyte stands, restricting the establishment of net-cages in the reservoir, and favoring land-based aquaculture as an economic alternative along with the reduction of irregular water level changes through refraining from prioritizing hydropower generation in the reservoir's operation.

The continuous competition, worldwide, between productive water uses and conservation purposes has triggered the development of the environmental flow concept. The latter, however, has been little accounted for in the generally hydropower-oriented current operation practice. Koch et al. (2018) propose a win-win approach that attends to both the environmental flow and the electricity generation, minimizing the use of thermal power plants and electricity imports. The integration of hydro- and wind power was considered crucial for a novel operation system both allowing for environmentally sounder, yet energetically viable, scenarios. High wind speeds in large parts of the São Francisco River Basin are complementary in season to precipitation's and river discharge's seasonality. However, the environmental and social impacts of upscaling wind energy need to be monitored and adjusted where necessary.

To explore who should get the scarce water in the future, Alcoforado de Moraes et al. (2018) integrated a global agro-economic land and water use model with a local economic model to test the impact of global changes on the economic value of water in two clusters of public irrigation schemes. Global demand and trade structures do influence their crop choice, while climate change affects average yields, which ultimately impacts water values. The water prices for major irrigation users in particular are currently very low and do not

reflect the scarcity of the water in the region. Demand curves were derived and then used in the hydro-economic allocation model by Souza da Silva and Alcoforado de Moraes (2018), replacing the concept of a fixed water "requirement" with one that captures user behavior and the economic meaning of scarcity costs of water. From an economic point of view, the scarcer a good is, the higher the value of a good. Securing a fixed supply of water will increase the scarcity costs for irrigated agriculture. New users, such as the upcoming water transfer project, will further increase the scarcity costs of water for the other users. The economic optimal water allocation addresses highest economic benefits from using the scarce water: that means the less efficient users would get less water, while the sufficient supply of domestic water was introduced as a constraint into the model. The model quantifies the interrelationships among the water uses and helps to identify trade-offs among different uses and users, meant to inform policy and decision-making. Attaching a more realistic price to irrigation water—as a means of water allocation policies—may be an important step toward a more sustainable use of natural resources.

Near the water, but suffering from diverse scarcities: the surrounding land

The non-irrigated land adjacent to the reservoir is widely used for grazing which may impact forest cover and aboveground carbon stocks. Schulz et al. (2018) therefore studied how grazing affects forest density and carbon storage of the native Caatinga vegetation. Trees and shrubs were found to account for 89% of aboveground carbon stocks. Heavy grazing, mainly by goats, primarily reduced carbon stocks of the herb layer but not of the tree layer. In contrast, carbon storage in trees and shrubs was higher with increasing altitude, which is representative of limitations in water availability and a lower anthropogenic impact. The three most common tree species showed abundant recruitment, irrespective of grazing, whereas the recruitment of less frequent woody species was negatively affected by grazing. An adapted grazing management should limit grazing impacts by promoting feed reserves to overcome times of fodder shortage, and avoiding the uncoordinated free-roaming of livestock. Although carbon stocks of aboveground Caatinga vegetation per hectare were relatively low compared to other tropical forests, the spatial extent of the entire Caatinga area makes it an important global carbon sink.

In order to test the implementation probabilities of innovative land-use interventions, Rodorff et al. (2018) developed a decision support tool by creating a Bayesian network (BN). The BN model—derived from a constellation analysis—shed light on systematically cultivating a significant local Caatinga tree that is well adapted to the harsh climate, and whose fruits can boost income generation. Relevant key factors for a substantial implementation probability were identified, such as

specific tree planting material and policy interventions such as financial incentives.

Aside from water scarcity, the low soil nutrient content limits crop yields in the semi-arid study area. At the same time, nutrients are abundant in sediments, where they are considered a pollutant. Making use of such substrates, instead of disposing of them in an uncontrolled manner, is the essence of the recycling or reuse concept. In an experimental approach, Silva et al. (2018) tested sludge stemming from land-based fish fingerling production as a readily available fertilizer for local vegetable production. They determined the best mixing proportion with local soil for lettuce production. Studies on local feasibility, economic efficiency, and farmer acceptance under real-world conditions remain to be prepared before upscaling might become an issue.

Sustainable land management insights

A dialog between stakeholders of different sectors and governance levels is crucial in handling the water and land nexus. This Special Issue gives an insight into studies on the practical context of the research project. Blended with additional studies from the INNOVATE project, Siegmund-Schultze et al. (2018) concluded that sustainable land management in semi-arid watershed regions needs to account for:

1. A proactive management of the increasingly variable water availability;
2. The timely establishment of adequate communication and monitoring of upcoming megaprojects (such as the water diversion project in the studied case that will further stress water availability);
3. The informed management of water quality under consideration of water quantity-quality linkages;
4. The adaptation of reservoir releases that mimic at most the natural seasonal differences in water level fluctuation;
5. The promotion of the cycling of scarce nutrients between productive sectors;
6. Sustaining and reinforcing the chemical and physical soil characteristics;
7. Safeguarding the beneficial interplay between biodiversity and crop production;
8. Preserving the diversity of water and land uses along with the diversity of biological resources, including the reconsideration of native species with superior adaptation abilities; and
9. Engaging in the dynamic governance process to make the transition toward sustainable land and water management happen in a transparent and fair way.

A scientific project is a temporary endeavor. Further implications of the research results will depend on the enduring

commitment of local actors and institutions. Further adaptations, reviews, and supplements to the suggested pathways may be necessary to ultimately advance toward a more sustainable management of natural resources, particularly in the aftermath of major interventions like river dams and reservoirs. A fruitful cooperation can be envisaged in this process with research itself becoming more accountable and sustainable through mutual dialog with society.

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