Biophysical, socioeconomic and geopolitical impacts assessments of large dams: an overview

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Introduction: the large dams controversy

More than 45,000 large dams have been built globally, producing 19% of the World's electricity, and watering 30-40% of its irrigated areas [2]. Collectively, they retain so much water that they have lowered the global mean sea level by several centimetres [3], and altered the shape of the Earth and its rotation [4, 5]. This illustrates the scale of impacts, positive and negative, large dams can have on people and their environment, and explains why these projects are always highly controversial.

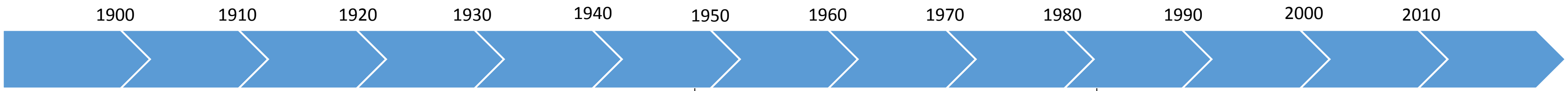
A brief chronology of the large dams controversy is given in Figure 1. Water dams have been built for more than 5,000 years, but the first large ones appeared in the 19th century in Europe and Northern America. Their construction gradually increased throughout the 20th century, first in developed countries (e.g. during the "large dams era" in the United States of America) where most suitable sites had been exploited by the 1980s, and later in developing countries, where most of the large dams are currently built [2].

Public authorities and international development institutions, often the main decision-makers for large dams, justify new projects by population growth, economic and social development (to provide water, food, energy and transport) and climatic hazards (to regulate water supplies, avoid flood and droughts), but also as means to show power and "build nations" (e.g. the Aswan dam in Egypt, or Nehru calling dams "the new temples of India") [6]. From the 1970s onwards, awareness that such large projects also have significant negative environmental and social impacts gradually increased: e.g. following the American National Environmental Policy Act (NEPA, introducing environmental impacts assessments) in 1970, and the 1972 United Nations Conference on Human Environment in Stockholm [2, 6]. In the 1980s, the debate between large dams advocates and opponents became increasingly confrontational. The controversy peaked in the 1990s, with numerous non-governmental organisations (NGOs) organising sophisticated international anti-dam campaigns (e.g. around the Sardar Sarovar project in India), driving the World Bank (the main dams financier at the time) to organise internal reviews of its dams projects, showing their negative aspects alongside the positive ones [7-9]. In the United States of America, some large dams were even recently decommissioned or removed to restore river flows [2, 10].

> **Large dams** are defined as dams "above 15 meters in height, or dams between 10 and 15 meters meeting one of the following conditions: the length of crest is not less than 500 meters; the capacity of the reservoir formed by the dam is not less than one million cubic meters; the maximum flood discharge dealt with is not less than 2,000 cubic meters per second; the dam had specially difficult foundation problems; the dam is of unusual design" [1].

In the past two decades, the large dams debate continued to rage, with numerous competing initiatives and publications. The most famous is the report from the World Commission on Dams (WCD) [2, 11], involving numerous stakeholders and aimed at reaching a consensus between dams advocates and opponents. This report was also criticised and led to several organisations making their own analysis of the large dam issue, including the World Bank [12, 13], the hydropower industry [14] and the International Energy Agency [15]. In parallel, research on large dams and their impacts also accelerated, leading to numerous conferences [16-18] and publications [6, 19-25].

The following pages aim to give a broad and contemporary overview of the debate on large dams and their impacts. First, general principles that need to be taken into account when assessing these impacts are presented. Then, the typical biophysical, socioeconomic and geopolitical impacts of large dams are listed and briefly described. Finally, various competing international initiatives developed around the impacts of large dams are discussed.



19th century
The first large dams are built

Beginning of the 20th century
About 700 large dams in North America and Western Europe

Mid-1930s to mid-1960s
"Large dam era" in the USA

1949
About 5,000 large dams, 75% of which are in developed countries

1950s-60s
Large dams construction booms all over the World

1970s
- Global peak of large dam construction
- NEPA is passed in the USA
- First UN mega-conference on Human Environment

1980s
- Large dam construction gradually decreases in developed countries, but continues in developing countries
- The large dam debate becomes increasingly emotional, dogmatic and confrontational

1990s
- NGOs start to develop sophisticated local and global anti-dam campaigns
- First large dam removal in the USA
- Series of global reviews on large dams, leading to the WCD.

2000s
The large dam debate continues, with numerous competing initiatives on assessing and mitigating their impacts

Acronyms:
- *NEPA*: National Environmental Policy Act
- NGOs: non-governmental organisations
- *UN*: United Nations
- *USA*: United States of America
- *WCD*: World Commission on Dams

Figure 1: Brief chronology of the large dam controversy.

Impacts assessments of large dams: general principles and dimensions

The stakeholders dimension

Large dam projects involve a wide variety of stakeholders having different needs, objectives and interests. These are typically divided in two groups confronting each other, sometimes asymmetrically: dams advocates, and dams opponents (Figure 2) [26, 27]. This division is however simplistic as some stakeholders may not easily be classified either as pro- or anti-dam (e.g. organisations demanding more transparency and consultations). Natural components of the environment (e.g. rivers, forests, ecosystems) also are stakeholders, with their own needs, which interact with others [28]. Impacts assessments (IA) of large dams should integrate the points of view and needs of all these stakeholders, and consider all the impacts large dams can have on them, including current and future, direct or indirect, individual and cumulative and positive and negative ones [29].

Temporal dimension and scales

Large dams have short, medium and long-term impacts. These can occur at various moments of the project, from before the dam construction (e.g. people and public authorities often stop investing in the area likely to be flooded [6, 22]) to long after (e.g. greenhouse gases emissions resulting from dams can continue for decades or centuries after construction [30] and will impact climate in the very long term). Dams are usually managed to fit short- or medium-term human objectives (e.g. cyclic release of water to produce electricity or food), while the ecosystems they impact might take decades or more to adapt [24, 31]. In contrast, institutions managing dams and water might be structured rigidly, making it difficult to react to rapid environmental changes like large floods [31]. Large dams become projects well before they are built and operated. Their impacts should therefore be assessed throughout their whole project cycle [2, 10]. Figure 3 describes the ideal large dam project cycle and how IA can support decision-making at each step. Life-cycle assessment methodologies can also facilitate the comparison of large dams with other development options [32, 33].

Spatial dimension and scales

Dams can have very different impacts depending on their location [19], including punctual impacts in and around the reservoir (e.g. displacement, deforestation), longitudinal and lateral impacts along the river (upstream, downstream, around the river bed and in its floodplain, e.g. changes in water quality, habitats and species composition) [34], as well as collateral impacts (e.g. deforestation) around associated infrastructure (e.g. quarries, power transmission lines, resettlement towns) [19] (Figure 2). When several dams are built on the same river, their impacts can accumulate and should be studied simultaneously [35-37], considerably enlarging the spatial extent of the IA. The most logical natural scale to study environmental impacts is often said to be the watershed, but small impacts can occur at finer natural scales (e.g. sub-basin, habitat). Human scales should also be considered, e.g. administrative boundaries at which decisions are made, from local (e.g. field, community) to regional (e.g. district, province) and national (e.g. ministry of the environment) [31]. The direct outputs of dams (e.g. irrigation, power, navigation) can also have impacts in other areas that should be considered in the IA (e.g. powershed and tradeshed) [24]. In some cases, the international scale also has to be considered, e.g. dams built on large transboundary rivers, having significant greenhouse gases emissions, or involving transnational organisations (NGOs, companies or donors) [26, 30, 38].

The disciplinary dimension, and interdisciplinarity

From a human point of view, dams can have social, cultural, sanitary, societal, economic, financial, institutional, legal and political impacts. From a natural one, the range of impacts include hydrological, chemical, geomorphological, ecological, atmospheric, climatic and seismic. All these impacts can be studied individually through specific disciplines. However, the IA of large dams should target, through interdisciplinary approaches, an integrated understanding of the whole socioecological system and its modifications [31].

Classification of impacts

Impacts of large dams can be classified in various ways, centred on one or several of the above dimensions. Some classifications focus on the affected stakeholders (e.g. ecosystems [39], displaced populations [22]), others focus on the impacted locations and/or the timing of impacts [19, 25, 34, 39]. For an holistic approach, it is often preferred to classify impacts through disciplinary themes (e.g. environmental, social, economic impacts), that are then integrated. The following pages are based on a classification of impacts around three themes: biophysical, socioeconomic and geopolitical [24].

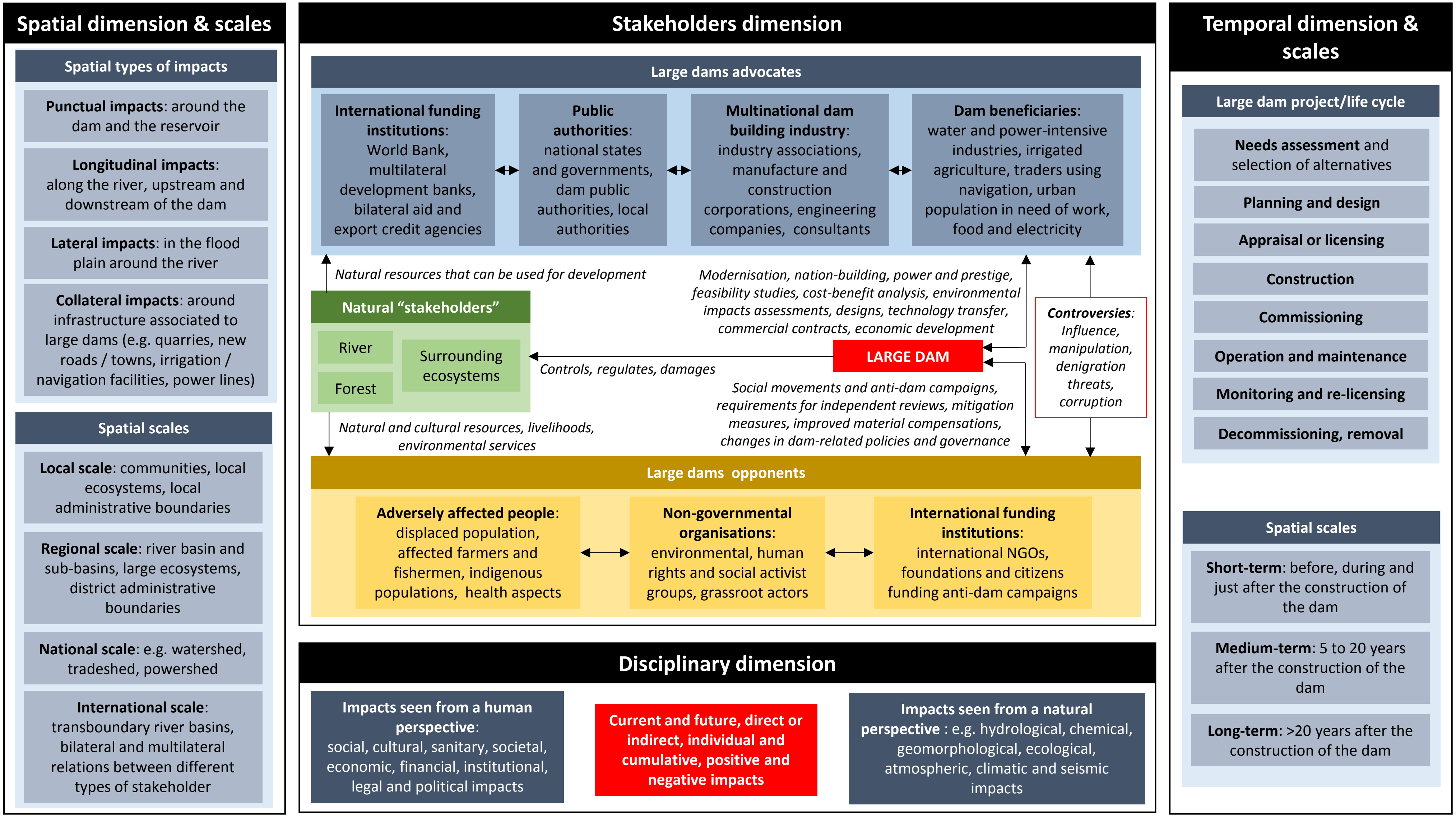


Figure 2: The spatial, stakeholder, temporal and disciplinary dimensions to be taken into account when assessing the impacts of large dams.

Ideal project cycle of a large dam	Description of each step	Impact assessment (IA) support during each step
Needs assessment & selection of alternatives	**Exploration of the needs to be satisfied** (e.g. irrigation, energy production) and **exploration of the various alternative options available to satisfy these**, including large dams but also other technologies (e.g. groundwater extraction, solar power) or policies (e.g. demand management). Selection of the preferred option, according to their respective feasibility, financial, social and environmental costs.	**Preliminary IA enables the comparison of the various feasible alternatives and their respective impacts**, and serves as a decision support tool.
Planning & design	**When a large dam emerges as the preferred option, the project can to be planned and designed** in detail.	**Baseline studies** should be conducted as early as possible, to account for impacts occurring later (before or after construction). **While finalising the design of the dam, a full IA is usually required** to assess impacts and reduce them, and plan for future mitigation actions.
Appraisal & licensing	**The final design usually has to be approved by national authorities** in charge of dams, to confirm the large dam complies with national regulations. Depending on the national legislation, **licenses are sometimes given** by the public authorities in charge of large dams to the other public or private organisations responsible for planning, designing, building, operating and maintaining them. The licensing of large dams is not required everywhere and for all types of dams. **License can be granted for the whole project or just for a specific step of the project cycle** (detailed design, construction, commissioning and operation). Licensing systems are common for private operators and hydropower dams, while other types of dams (e.g. irrigation) and government operators are often exempt. Licenses usually are granted for several decades, e.g. 30 to 70 years. **At the end of a license the dam needs to be reviewed. A new license can be granted or not, and modifications (e.g. design or operation) or decommissioning can be requested or not**. This enables dams to be monitored and re-assessed regularly against their initial objectives, impacts and risks, and re-adapted to their changing environmental, societal, economic and political contexts.	Once the final design is known, **the IA should also be finalised and approved by national authorities** before construction goes ahead. **Consultation with affected people is part of international IA standards**. The IA should always include a study of what would happen / change without the dam ("zero alternative").
Construction	Following the detailed design and planning, and its appraisal or licensing if required, **the actual construction of the dam can start**.	During construction the **IA guides all the stakeholders on their respective rights and responsibilities**
Commissioning	The commissioning phase corresponds to the period during which **the reservoir starts to be filled and the dam operated**. This phase can last several years until the dam is fully operational.	Before commissioning, **compliance with the final IA should be checked**.
Operation & maintenance	This phase reflects the "normal life" of a large dam, when it is **operated at its full capacity, with regular checks (see monitoring) and maintenance**.	IA can influence operation and maintenance by **identifying operating rules optimising the balance between positive and negative impacts**. Additional IA might be required before significant maintenance or refurbishing operations.
Monitoring & re-licensing	**Large dams have to be monitored regularly** (periods depend on national legislation and agreements for specific dams) to check their safety and actual impacts. Under a licensing system, after the period for which the initial license was granted to the dam is over, a new one can be granted, or not, after a full review (see licensing above).	**Impacts should be monitored regularly and the IA updated** during the life-time of the dam, and possibly beyond (for potential very long term impacts).
Decommissioning & removal	If a dam fails to comply with national regulation (e.g. safety, concerns about social and environmental impacts), or stops being profitable, it might be **decommissioned** (e.g. open the gates to restore the natural flow and allow fish passage) or even **physically removed**.	**Decommissioning or removal of large dams can also result in significant impacts**, both positive and negative. These should be assessed through a **new IA**.

Figure 3: The ideal project cycle of a large dam, detailing the steps involved and the use of impact assessment.

Biophysical impacts of large dams

Modification of the flow regime and water cycle

Dams are primarily designed to block rivers and retain their water for specific purposes. They therefore significantly modify the river flow and the surrounding water cycle. Upstream hydrological impacts mostly occur near the dam. The reservoir floods an area, and slows the flow approaching it [35]. Evaporation from the reservoir, as well as water withdrawals or planned releases (e.g. irrigation, and hydropower) significantly modify the magnitude and timing (day, month, season) of the downstream flow [40]. This also impacts groundwater levels, getting higher around the reservoir and sometimes lower downstream [39]. Large reservoirs can modify the local climate and increase precipitation extremes, especially in arid areas [41]. Finally, large dams rely on upstream flow for their filling, although difficult to quantify, these flows might be sensitive to climate change.

Land cover, land use and deforestation

Large dams result in significant land cover and land use changes. They flood a large area of land, which was previously used by human and natural systems. Other changes might result from infrastructure associated with large dams: quarries, access roads, power transmission lines, canals, irrigation and navigation facilities, and resettlement towns [19]. These direct changes might facilitate indirect ones, such as deforestation, urban expansion, and agricultural and industrial developments around new roads, infrastructure and cities [19].

Erosion and sedimentation

Land cover and land use changes, especially deforestation and agriculture, lead to increased run-off and land erosion [42]. Upstream of the dam, increased sediment loads and slower flows often increase sedimentation upstream or inside the reservoir. This sometimes lead to reservoir siltation, reducing its storage capacity and useful life [43]. Less sediments flowing downstream, in a modified flow regime, lead to significant geomorphological changes in the river bed and its flood plain through erosion, aggradation and accretion, sometimes down to the river estuary or delta [42-46].

Physical and chemical water quality

Natural processes and human activities around dams can lead to water pollution upstream, in and downstream of the reservoir, such as agricultural inputs (e.g. fertilisers and pesticides), wastewater from human settlements or industries, heavy metals like mercury from natural (e.g. soils) or human (e.g. mining) origins [34, 35], or defoliants against vegetal growth in the reservoir or along power transmission line corridors [37]. Altered sediment transport result in modifications to water turbidity and concentration of pollutants in sediments [35, 39]. Evaporation and water withdrawals from reservoirs concentrate pollutants and increase salinity, with consequences on water quality downstream [39]. The concentration of nutrients in the reservoir also causes eutrophication and thermal stratification [34, 35, 39]. Large dams usually modify the thermal regime of the river downstream [34].

Modification of natural habitats, primary production, vegetation and wildlife

Flooding of the reservoir area, deforestation and other land use and land cover changes resulting directly or indirectly from the dam lead to losses of aquatic and terrestrial habitats and biodiversity, although they can also provide habitats to new species (e.g. migratory birds and fish). In the reservoir, eutrophication can lead to the proliferation of aquatic vegetation, while poor water quality affects molluscs, fish and other aquatic species and can result in the bioaccumulation of pollutants (e.g. mercury) along food webs [34, 35, 39, 47]. Erosion and changes of channel geomorphology have a large impact on sediment and nutrient transport, which affects downstream riparian vegetation and habitats [44]. Dams also result in river fragmentation [48] and prevent up- and down-stream migration of fish, other aquatic species and seeds. Existing mitigation measures (e.g. fish ladders) rarely are effective [34, 35, 39, 47].

Greenhouse gases emissions

By flooding vegetation or leading to deforestation, large dams and reservoirs reduce the natural absorption and fixation of atmospheric carbon dioxide (CO_2). Moreover, the flooded vegetation, and organic sediments brought to the reservoir, decompose and emit greenhouse gases (GHG), mostly CO_2 and methane (CH_4), for several decades or even centuries [30, 49]. Although less studied, dams and reservoirs can also emit nitrous oxide (N_2O), a powerful GHG [50-52]. The growth of aquatic vegetation in the reservoir, through photosynthesis, only partially offsets these emissions [3]. Impact assessment should estimate the net GHG emissions of a dam and its reservoir (i.e. emissions after its construction minus emissions before), however, this rarely occurs as few GHG emission studies are implemented before dams are built [30, 50]. Emissions of CO_2 and CH_4 of boreal and tropical dams have been estimated and show that tropical dams and reservoirs emit much more GHG [30, 53, 54]. There are however major disagreements on how GHG emissions should be estimated [55, 56]. The debate has technical, financial and political implications. Although usually considered as sources of "clean" energy, large hydroelectric dams sometimes emit more GHG than equivalent thermal power plants, and their emissions might have a greater effect on climate change [57, 58]. Although significant, their emissions are not included in national GHG emissions inventories, and dams are often partially funded through carbon credits [49].

Disasters: floods, landslides and earthquakes

Large dams and their reservoirs are extremely heavy and, when built relatively close to existing faults and filled or emptied rapidly, can trigger earthquakes of a magnitude higher than 6 on the Richter scale [59]. Sudden large releases of water from dams can also create downstream floods [38]. Through earthquakes or extreme precipitation, instability of the reservoir's banks can lead to landslides [60], which decrease reservoir capacity and can create water waves that can damage the dam itself. Dams can also fail or collapse following earthquakes, landslides, floods, high winds and erosion [61].

Socioeconomic impacts of large dams

Population and public infrastructure displacement

Dams displaced more than 40 million people in the 20th century [2]. Some settlements have even been displaced several times [36]. Displacement is always a highly controversial issue. Relocation processes and compensations (e.g. land, homes and cash), often implemented with limited prior consultation, are not always fair or effective [22, 62-64]. Resettlers are often promised to be provided with better public infrastructure (e.g. schools and water and power services) after relocation, which is not always the case [22, 65, 66]. Dam construction also attracts numerous workers and people looking for new land or opportunities, further extending human settlements and infrastructure around large dams [2]. Displaced and attracted people often settle in areas where other people are already living. The needs of both displaced and host communities need to be considered to avoid tension and conflict [67].

Economics impacts: livelihoods, compensation and employment

The widely accepted idea that resettlers should be better off after relocation than before is often utopic [2]. Displaced people might lose material wealth (e.g. houses, farms or grazing lands), embodied wealth (e.g. skills) or relational wealth (transport/access, healthcare and education facilities) [68], which are often only partially compensated [22, 62-64]. Unclear land ownership or tenure often complicate the compensation of lost land, especially in developing countries. Although less studied, large dams also have significant impacts on the livelihoods of downstream population (e.g. fishing and agriculture), sometimes up to several hundreds of kilometres downriver [38, 69]. On the positive side, large dams can also provide direct and indirect employment, temporary or permanent, on the project site and around it, e.g. new irrigation, ranching, navigation and trade, fishing and industrial development [2]. Economic impacts of dams should be studied at various scales (local, national, regional and sometimes transboundary), as the winners are often in different regions than the losers [38, 70].

Health impacts

Displacement and incertitude around large dam projects cause stress, depression and social disruption [71, 72]. Depending on their design and operation, dams can modify (increase or decrease) the presence and prevalence of water-related diseases (parasitic and communicable), their vectors (e.g. mosquitoes, snails), as well as predators (for human and cattle, which also have livelihood and food security implications) [65, 73]. Malaria [74, 75] and schistosomiasis [76] are commonly associated with large dams, among other diseases [65, 73]. Because of modifications (positive and negative) to agriculture, ranching and fishing opportunities, large dams can affect food security, nutrition and food safety, with significant health implications [65, 73, 77]. Other potential health effects of large dams include difficulties and opportunities regarding transportation and access to health facilities; deaths and injuries resulting from floods, failures and reservoir induced seismicity; accidents and occupational health; AIDS and sexually transmitted diseases (prostitution is common on construction sites); macro-economic impacts on national health and economic systems [65]. The World Health Organisation has developed health impact assessment tools for water projects, including dams

[78]. Dam projects do not, however, systematically study and address health issues, especially in developing countries [79].

Cultural impacts

Flooding (reservoir and downstream) and deforestation can destroy archaeological, religious and cultural assets (e.g. sacred forests) [2]. Although large dams also provide opportunities for archaeological excavations and salvage [80], these can themselves lead to tensions with local population, for whom present needs and compensations should receive more attention than remains from the past [81, 82]. Dams can also create recreational and tourism opportunities [2].

Specifically impacted population

Poor and voiceless populations are often marginalised in the decision-making processes linked to large dams [2]. This often includes indigenous people, who can lose land, livelihoods and cultural assets, and whose protestations are sometimes strongly repressed by private or public stakeholders [62]. Women are often more affected by dams than men, as they have even less influence on decisions and often have less livelihood and employment opportunities [83-86].

Geopolitical impacts of large dams

Political and institutional aspects

Large dam projects are usually managed by national public authorities, but involve numerous other stakeholders, institutions (e.g. public, private, non-governmental organisations and communities) and alliances (local and global) [26, 27]. These stakeholders have different interests, objectives and responsibilities, which should ideally all be considered honestly and transparently during decision-making processes [2]. In practice, decision-making is often asymmetric. Advocates use power, money [2, 6, 37] and sometimes violence [62, 87, 88], while opponents use activism and public opinion [6, 27]. Both sides sometimes manipulate information [6, 27]. The political and institutional aspects of large dam projects should be considered at different geographic scales [28, 31]. Negotiations on impacts assessment and mitigation are especially complex for dams on transboundary rivers [28, 38].

Legal and regulatory aspects

Dam projects should consider national legislation (e.g. environmental impacts assessments, land tenure), customary and indigenous laws [2]. Depending on the location of the project, the nature and willingness of national authorities, financiers and contractors, various international regulatory standards and guidelines can also apply, such as from the World Bank [12, 13], the World Commission on Dams [2], the Hydropower Sustainability Assessment Protocol [14] or the Implementing Agreement for Hydropower Technologies and Programmes [15]. Disagreements and conflicts around large dam projects can be handled by national courts or, in specific cases, through the International Court of Justice [89, 90], international water tribunals [91] or regional ones (e.g. from Latin America [92]).

Technical and financial aspects

Large dams are technologically sophisticated and capitally intensive projects. Most new dams are now built in developing countries, which often need external technical expertise (e.g. for IA, design, planning, equipment and construction) and financial assistance (e.g. loans or gifts) [26, 27]. Although national governments theoretically lead the decision-making process, this gives significant power to foreign stakeholders, especially the ones holding funds without which such projects cannot materialise. Following heavy criticisms [20, 93], multilateral organisations like the World Bank or regional development banks have gradually improved their environmental and social standards on large dam projects [94, 95]. Bilateral funding organisations (e.g. export and credit agencies from countries members of the Organisation for Economic Co-operation and Development) made less progress [94, 96]. China, which is increasingly involved in international large dam projects, both technically and financially, is also criticized for its environmental and social records, although improvements are being observed [97].

Public participation, opposition and transparency

Officially, all stakeholders agree that dam related decision-making processes should include consultations or participation and transparency. In practice, this is often not the case [2]. Opposition to large dams and related decisions remains high, both locally through communities and local NGOs, and globally through international NGOs and donors [88, 98-101]. The best mean to mediate disagreements and conflicts is an inclusive and transparent IA process [102], with meaningful participation of all parties in the decision-making process [103].

Biophysical impacts

Modification of the flow regime and the water cycle
- Flooding of an area upstream of the dam
- The river flow slows upstream of the reservoir
- Evaporation, water withdrawal in the reservoir and planned releases change the flow downstream of the reservoir
- Changes in the groundwater levels, around and downstream of the reservoir
- Modification of local climate (temperature and precipitations)

Land use and land cover changes, including deforestation
- Terrestrial area changed into aquatic area
- Other direct changes around the dam, reservoir and associated infrastructure
- Other indirect changes due to deforestation, agricultural and industrial developments, urbanisation

Erosion, sedimentation and geomorphological impacts
- Increased run-off and land erosion
- Increased sediment loads upstream and inside the reservoir; sometimes siltation of the reservoir
- Decreased sediment loads and geomorphological changes in and around the river downstream

Physical and chemical water quality
- Water pollution upstream, in the reservoir and downstream (agricultural, industrial and human waste)
- Concentration of pollutants and nutrients in the reservoir, leading to eutrophication
- Increased salinity in and downstream of the reservoir
- Modification of the thermal regime in and downstream of the reservoir

Modification of primary production, vegetation, natural habitats and wildlife
- Loss of terrestrial and aquatic habitats and biodiversity; creation of new aquatic habitats
- Proliferation of aquatic vegetation
- Poor water quality affects aquatic species; bioaccumulation of pollutants along food webs
- Geomorphological changes downstream affect riparian vegetation and habitats
- River fragmentation; prevention of fish, aquatic species and seeds migrations

Greenhouse gases emissions
- Loss of forests absorbing carbon
- Decomposition of vegetation and nutrients in flooded areas; release of carbon dioxide, methane, nitrous oxide

Large dams and natural and triggered hazards risks
- Large dams can trigger earthquakes and landslides and cause downstream floods
- earthquakes, landslides, floods, high winds and erosion can lead to the failure of the dam

Socioeconomic impacts

Population and public infrastructure displacement
- People and infrastructure located in areas to be flooded or used by the dams have to be displaced
- Their compensation (homes, public services, work opportunities) are not always fair nor effective
- Large dams attract numerous migrants looking for work, land and other opportunities
- This increased population often affects the host communities

Economic impacts: livelihoods, compensations and employment
- Dams affect the livelihoods of displaced populations
- Dams also affect the livelihoods of downstream populations, e.g. fisheries, irrigation, floods
- Dams give new opportunities on the project site and around, e.g. work, irrigation, fishing, trade
- The people benefitting from large dams are often different, and living in distinct regions, than those affected by them

Health impacts and risks
- Displacement and incertitude cause stress and depression
- Dams increase the presence/prevalence of vectors and diseases, as well as predators
- Dams can impact agricultural and fishing yields, hence food security, nutrition and food safety
- Large dams can also modify access to health facilities; cause deaths and injuries through accidents, floods, failures, reservoir induced seismicity; lead to increased prevalence of sexually transmitted diseases; and have macro-economic impacts on national health systems

Cultural impacts and risks
- Flooding can destroy archaeological and cultural (e.g. religious) assets
- Dams can also create new recreational and touristic sites

Specifically impacted populations
- Poor and voiceless populations are more vulnerable, especially indigenous people
- Women are also more likely to be affected than men

Geopolitical impacts

Political and institutional aspects
- Large dams often involve international stakeholders like funding organisations, private transnational companies, international NGOs
- Dams on transboundary rivers usually have impacts in several countries

Legal and regulatory aspects
- National legislation and customary and indigenous laws have to be considered
- Various international standards might apply, e.g. World Bank, other financiers
- Conflicts can be taken to national and international courts

Technical and financial aspects
- Large dams need sophisticated technologies and require funds, which often come from abroad, giving significant power and responsibility (including environmental and social) to international stakeholders

Public participation, opposition and transparency
- Diffferent stakeholders have different understanding of the needs for public information, participation, consultation and consent, which can lead to conflicts

Figure 4: Summary of the main impacts of large dams

Case studies

China: the Nu river cascading dams and the Integrative Dam Assessment Model

Much has been written on large dams and their impacts, with many case studies available in the literature, but few cover biophysical, socioeconomic and geopolitical themes simultaneously. The only case study covering them all concerns cascading hydroelectric dams on the Nu river in China [104]. Its central concept is to study different types of vulnerabilities resulting from those dams, from the environmental, human and hydro-political points of view. One of the main findings is that vulnerabilities of households, communities, ecosystems and institutions are somehow correlated to geographic isolation. This case study was partly based on the Integrative Dam Assessment Modelling (IDAM), a recently developed tool, based on the three themes, to analyse the costs and benefits of large dam projects [105]. The IDAM tool uses 27 impact indicators (nine for each theme) than can be evaluated both objectively (e.g. through quantitative estimations) and subjectively (e.g. by different stakeholders or groups of stakeholders). The results can be summarised and visualised through tables and graphs. Although such "standard" IA tools always have to be used carefully and possibly adapted to specific projects, IDAM is interesting for both its multidisciplinary and multi-stakeholders approaches.

Brazil: the Tucuruí dam

Although not explicitly studied through the lens of the three themes mentioned above, the Tucuruí dam (Brazil) is another interesting case study. Environmental impacts [37] included the loss of tropical rainforest and related natural ecosystems, and the alteration of aquatic ecosystems, e.g. through the deterioration of water quality (anoxic conditions, mercury pollution and defoliants) and the blockage of fish migration. The decay of flooded vegetation led to significant emissions of GHG. These might be less than fossil fuel alternatives, but might actually have a greater impact on global warming, as they are emitted much earlier [57, 106]. Against the benefits of power generation and employment were social impacts [36] including the displacement of 4,000 families, some of which had to be relocated twice and most of which were compensated with cash only. Indigenous lands were flooded and also mostly compensated with cash payments. Although fish catches increased in the reservoir area, they decreased significantly downstream of the dam, affecting people whose main source of income and protein was fishing [37, 107]. Health impacts included malaria and other water-based diseases, but also mercury poisoning through the consumption of contaminated plants and fish [36, 108-110]. Social and environmental studies and research had virtually no influence on the dam construction decision-making process, which was largely influenced by construction firms, national military and foreign financial interests [37].

Vietnam: the Yali Falls dam

The Yali falls hydroelectric dam, although less studied, offers a different and interesting perspective as it was built on a transboundary river in Vietnam, 70 km away from Cambodia. Few independent studies are available on its impact in Vietnam [111], but several were made on its impacts on downstream communities in Cambodia [38, 112-114]. Cambodian indigenous communities seem to be the most affected. The river flow downstream of the dam was significantly modified. Unpredictable and severe floods drowned people and livestock, washed away fishing boats and nets and destroyed crops. Increased dry season flows improved river travel, but hindered river bank agriculture, shellfish collection and harvesting of wild vegetables, with negative impacts on livelihoods, nutrition and health. Deteriorated water quality in the river, used for bathing and sometimes drinking, caused health problems [38]. As a result of the dam, the modified downstream flow and the increased erosion affected the downstream aquatic habitats, food webs (for aquatic plants and fish) and fish migration, making numerous fish species decline drastically and impacting a population whose protein and livelihoods mostly come from the river [38, 112, 113]. The resulting loss of income led many downstream households to borrow cash regularly (at high interest rates) from local money lenders, gradually leading to unsustainable debt [38]. Cooperation between Vietnam (politically and economically more powerful) and Cambodia (with a lower technical and financial capacity) was weak and asymmetric, and Vietnam seems to have imposed its national interests on Cambodia. Vietnam did not include downstream impacts in Cambodia in its IA, did not consult Cambodian authorities on the project, and do not inform them on the dam operation (e.g. planned water releases) [38].

International standards on large dams and their impacts assessments

The World Commission on Dams report

The World Commission on Dams (WCD) was established in the hope to give a voice to all sides of the debate on large dams and reach a consensus on these projects, their impacts (positive and negative) and their assessments. The resulting report [2] was praised by some [21, 115], but criticised by others as being sometimes incoherent, unrealistic and inapplicable [116-119]. The WCD report includes a global review of large dams, then gives recommendations and guidelines based on a "rights and risks" approach, and is structured around seven strategic priorities: gaining public acceptance, comprehensive options assessment, addressing existing dams, sustaining rivers and livelihoods, recognising entitlements and sharing benefits, ensuring compliance, sharing rivers for peace, and development and security [2].

World Bank: water resources strategy and environmental and social standards

For a long time the main financier of large dams throughout the World was the World Bank. It was heavily criticised for not giving enough consideration to social and environmental impacts and gradually reduced its funding of such projects in the 1990s [6, 20]. Although it initiated the global review of the WCD [11], the World Bank argued later that the Commission was not impartial and refused to endorse the WCD report [8]. Instead, it issued its own guidelines that were not specific to large dams, but general for the water resources sector [13]. While the WCD advocates for the "free prior and informed *consent*" of affected populations, the World Bank opted for their "free prior and informed *consultation*" [8]. The International Finance Corporation (IFC), from the World Bank group, has also issued performance standards on environmental and social sustainability for World Bank projects, including for large dams. These include standards on assessment and management of environmental and social risks and impacts; labour and working conditions; resource efficiency and pollution prevention; community health, safety, and security; land acquisition and involuntary resettlement; biodiversity conservation and sustainable management of living natural resources; indigenous peoples; and cultural heritage [12]. These IFC standards have been compared to the WCD ones [120].

It should be noted that regional development banks (i.e. African, Asian and Inter-American) are all independent from the World Bank and therefore have their own policies on water resources and dams, which are considered less stringent than those of the World Bank [94].

International Hydropower Association: Hydropower Sustainability Assessment Protocol

The dam industry generally, and the hydropower industry in particular, globally rejected the WCD report as being unrealistic and giving too many constraints (e.g. for consultation, impacts assessments and mitigations) [121, 122]. After consultations with governments and NGOs, the International Hydropower Association developed its own standards and guidelines on large dams: the Hydropower Sustainability Assessment Protocol (HSAP) [14]. Unlike the WCD report, the HSAP does not fully recognise the rights of dam-affected communities to participate in the decision-making process [121]. However, the HSAP takes many of the WCD recommendations into account and is an opportunity for the hydropower sector to improve its sustainability [122]. The HSAP has been compared to the WCD report and the IFC standards [120].

International Energy Agency: the Implementing Agreement for Hydropower Technologies and Programmes

Almost at the same time as the WCD process, the International Energy Agency (IEA) launched a competing initiative on large hydropower dams. The resulting guidelines [15], published slightly before the WCD report, did not attract as much controversy. Although extensive consultations were carried out prior to and during its development, this agreement was developed by a much more homogenous group of specialists, mostly from industrial nations and largely in favour of large dams. One of the key differences with the WCD report, which gives a significant role to affected populations and international organisations in the decision-making process, the IEA report considers national governments should have the final word on decisions related to large hydropower projects [118]. Moreover, while the WCD report considers the main alternatives to large hydropower dams are other types of renewable energy (e.g. wind and solar), the EIA report considers the main alternative to hydropower is coal-based power generation [118].

Conclusion

Large dams have always been controversial. Their positive impacts on economic and human development have been recognised for a long time and are often brought forward, while their negative environmental, social and political impacts have often been forgotten [2]. Awareness of these however gradually increased, and the debate between large dams advocates and opponents became very emotional and confrontational [6]. It is, and will always be, difficult to assess whether the overall impacts of a specific dam are positive or negative, and how these compare with alternative development options. Dams might support the achievement of certain development goals (e.g. energy), but can hinder progress on others (e.g. water, environment and agriculture). It is impossible to design a perfect dam, with only positive impacts for all the stakeholders involved. If a large dam really proves to be the best development alternative, which needs to be proven first, negative impacts should be properly and transparently assessed and addressed and communicated. Positive and negative impacts of large dams should therefore be studied in an integrated manner, taking into account, at various spatial and temporal scales, the diverging interests and objectives of the numerous stakeholders involved. Only truly multidisciplinary impact assessments, involving the participation of all the stakeholders and studying in detail the biophysical, socioeconomic and geopolitical conditions and the multiple and diverse consequences of decisions, can properly inform the decision-making process of such large infrastructure projects. The final decisions are usually political, but they should be made transparently and democratically.

Multiple international initiatives have been launched since the 1990s to try and appease the debate on large dams and propose solutions, methodologies and guidelines that would suit all the stakeholders involved. None of these initiatives have actually achieved the targeted consensus, and all have been praised by some and criticized by others. If all recognise that large dams have both positive and negative impacts, the debate still rages on which outweighs the others. Numerous disagreements still exist on how these impacts should be estimated, measured, mitigated and monitored. A typical example comes from the debate on how much GHG large dams emit [55, 56]. This technical debate has highly political and financial implications, e.g. to determine whether large dams are cleaner (in relation to GHG emissions) than thermal power plants alternatives [57, 58, 106], and whether they should be eligible to receive carbon credits [49].

Beyond technical issues, the main point of disagreement between the various stakeholders and recent initiatives is more political, and linked to how the governance systems and decision-making processes around large dams should look. In particular the debate rages on how much affected people should be informed and consulted, whether their consent to the project should be sought or not, and whether national governments and international organisations can make final decisions on their behalf. Since large dams will always have adverse effects on some people, who are likely to systematically disagree to such projects, there is no straight answer to these matters. In democratic states, however, decisions should be backed by rational evidence, should be made transparently, and should be opposable. Both the evidence and the decision-making process should be accessible publically. If democratically elected national governments and independent courts are likely (and legitimate) to be the final decision makers, citizens should be informed transparently, and their opinion properly listened to and addressed. Misinformation, corruption and violence should never be acceptable, from dams advocates or from dams opponents. These basic principles of good governance are unfortunately not always respected or achieved.

With current population and economic growth trends, global demands for water, food and electricity will continue to increase in the coming decades. With the predicted consequences of climate change, the threats of floods and droughts should increase as well. Large dams are not the only available options to solve such major challenges, but are likely to be part of the solutions chosen, especially in developing countries where numerous suitable sites are still available. Developing countries often have less stable and transparent governance mechanisms, and less technical, financial and institutional capacities to minimise and mitigate negative biophysical, socioeconomic and geopolitical impacts of large dams. Their population, often affected by high inequalities and whose cultures and livelihoods often depend on the environment they live in, are also more vulnerable to such projects. It is therefore vital that their needs, views and concerns are heard and taken into account from the first to the final stages of large dams projects.

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