Sustainable Dam Development: Balancing Hydropower, Water Management, and Environmental Conservation in a Changing Climate

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Received: 29 January 2025 Accepted: 08 April 2025

Abstract

The development of dams plays a pivotal role in global water management, hydropower generation, and environmental conservation. However, as climate change accelerates, the traditional approaches to dam construction and operation are being challenged. This review examines the need for a sustainable approach to dam development, focusing on the balance between hydropower production, efficient water management, and environmental conservation. It explores the current challenges posed by climate change, including altered hydrological cycles, the impact on ecosystems, and the shifting energy demands. Additionally, the review highlights innovative approaches, including the integration of green technologies, environmental monitoring, and adaptive management strategies. The aim is to provide insights into how dams can be developed and operated in a way that supports sustainable development goals, particularly in the face of climate uncertainties.

Keywords: Adaptive Strategies, Dam Infrastructure, Water Resource Management, Climate Change, Predictive Modeling, Sediment Management, and Ecosystem-Based Approaches

Introduction

Dams have played a pivotal role in human development for centuries, providing essential services such as water storage, flood control, irrigation, and power generation. Hydropower, in particular, is a significant renewable energy source that contributes to meeting global electricity demand. According to the International Energy Agency (IEA), hydropower accounts for approximately 16% of global electricity production and more than 60% of the world's renewable electricity (IEA, 2020). Besides power generation, dams support water storage for agriculture, drinking water supply, and flood mitigation, thus serving rural and urban communities.

However, the increasing effects of climate change on water resources, together with increasing global energy demand, have raised critical concerns about the sustainability of traditional dam development. Climate change is expected to alter precipitation patterns, temperature regimes, and river flows, which in turn affect the performance and reliability of existing dams (Piao et al., 2017). These changes are increasingly challenging the long-term viability of hydropower as a reliable energy source, especially in regions that are already experiencing water scarcity or more frequent extreme weather events (Vörösmarty et al., 2010). This therefore calls for the reassessment of the role that dams play in meeting water and energy needs in light of these changing challenges.

Sustainable development of dams is a delicate balance between hydropower production, efficient water management, and environmental conservation. Hydropower is a renewable source of energy, though the environmental and social impacts related to the construction and operation of dams are considerable. Dams often disrupt natural river ecosystems, affecting biodiversity, sediment transport, and water quality downstream (McCully, 2019). Furthermore, large-scale dams can displace local communities and disrupt livelihoods, particularly in developing regions (Fearnside, 2016). Given these complexities, it is essential to integrate environmental and social considerations into the planning, design, and operation of dams to minimize adverse impacts while maximizing their benefits.

Given that reality, all efforts should go into ensuring that dam development becomes sustainable, guaranteeing the full realization of the benefits of hydropower and water management without compromising environmental integrity or affecting the needs of future generations. For this, adaptive management strategies are essential, considering uncertainties in climate change, the evolution of water demand, and shifting ecological conditions. Additionally, the integration of modern technologies, such as environmental monitoring systems, remote sensing, and data-driven decision-making tools, is essential for enhancing the sustainability of dam operations (Zhang et al., 2020).

This review focuses on the main issues linked to sustainable dam development concerning hydropower and water management, as well as environmental conservation, underlining the need to apply adaptive and resilient approaches against climate-induced challenges. This review also reveals several innovations in dam operations such as Somerset, environmental flow management, green infrastructure, and nature-based solutions that strike a balance between hydropower generation and ecosystem protection.

Dams serving hydropower and water management

Dams have long been the backbone of hydropower production, holding the majority share in renewable energy production globally. Hydropower is the currently most utilized renewable energy source that supplies electricity reliably; large-scale dams contribute to base-load power generation. According to the International Renewable Energy Agency (IRENA), hydropower represents about 16% of global electricity generation and more than 60% of global renewable electricity production (IRENA, 2020). Large hydropower projects, such as the Three Gorges Dam in China and the Itaipu Dam on the Brazil-Paraguay border, provide critical power to millions of people, supporting economic development and energy security in many regions (Srinivasan et al., 2016).

Besides electricity generation, dams are also very vital in water management, serving a variety of functions that have become crucial to human society. They regulate the flow of water, hence allowing the accumulation of water at wet times and a controlled release of the same during dry periods. This storage capacity of water provides a sure means of ensuring agricultural production is maintained in those areas where crop production depends solely on irrigation. The Food and Agriculture Organization estimated that more than 40% of worldwide food production depends upon irrigation, and most of this water is supplied by reservoirs created by dams (FAO, 2017). In addition, dams supply water for domestic consumption, industrial use, and maintenance of ecosystems, hence enabling access to clean water both in urban and rural settings.

Besides, dams are helpful in flood control. By streamlining the flow of streams and retaining excess water during rainfall, the possibility of flooding downstream is reduced, a factor that, when it does occur, massively destroys infrastructure and agriculture, besides communities. Thus, the cataclysmic floods in 2010 that displaced millions of people and caused unprecedented devastation in Pakistan yet again underlined the vital role of the flood control infrastructure, including dams, in mitigating these extreme weather variabilities Khan et al. (2014).

These conventional methods of water management are, however, being challenged by the increase in variable precipitation patterns, temperature regimes, and evaporation rates under the changing climate. Indeed, changing river flows-in particular, reduced snowpack, and changes in seasonal rainfall-are testing the stability of many existing dams. For example, a study by Piao et al. (2017) estimated that climate change is likely to affect hydropower production through the alteration of seasonal river flows and water availability. Besides, the increasing levels of floods and droughts resulting from climate change also create greater risks to performing well in all dam infrastructures. For instance, the 2018 drought in the Horn of Africa affected the hydroelectric generation in Ethiopia, which provides a clear indication of how changes in precipitation and water availability can impact hydropower system efficiency (Hess et al., 2019).

In general, there is increasing uncertainty in the availability of water and hydropower production, coupled with an increasing call for a more adaptive approach in dam operation and water management, including flexible management strategies that can cope with changes in river flows and water availability as a result of climate change. Techniques such as real-time data monitoring, improved weather forecasting, and adaptive water storage management can enhance the resilience of dam infrastructures in the face of changing climatic conditions (Hirabayashi et al., 2013). Additionally, incorporating climate projections into dam design and operation planning is essential to ensure the long-term viability of these critical infrastructures.

Future dam development will have to be integrated and adaptive to balance hydropower production and water management needs. It should cover environmental flows, ecosystem protection, and stakeholder involvement to ensure that the dams continue to serve their purposes with as little negative social and environmental impacts as possible. The adoption of such adaptive management practices is crucial for the sustainability of hydropower and water management systems in a changing climate.

Environmental Impacts of Dams

While serving very essential services including hydropower generation, water storage, and flood control, dams pose significant environmental challenges that may last for long periods and alter ecosystems and biodiversity. Most dam constructions are normally associated with the flooding of large areas of land, which essentially means the displacement of communities, wild animals, and flora. A report by the International Commission on Large Dams says that more than 60 million people all over the world have been displaced because of dam building, and these numbers are still increasing with every new dam (ICOLD 2016). Flooding for reservoir creation transforms natural habitats and affects both terrestrial and aquatic ecosystems. This often involves the conversion of fertile agricultural land, forests, and wetlands into the reservoir area, adding to the socio-economic impacts on affected communities in so many ways (Gleick, 2009).

Aside from these direct impacts of the dam on land use and human populations, the actual construction and operational functions of the dams disrupt the natural flow of rivers and streams, which is a serious ecological concern. One of the most immense effects is an alteration in water ecosystems, particularly due to interference in the migration courses of fish. Salmon, sturgeon, and many other species depend on unobstructed rivers to finish their life cycles: migrating upstream to spawn, and downstream toward the ocean. By blocking these migration routes, dams inhibit these species from reaching vital habitats, thus causing population decline and, in some instances, even species extinction (Peterson et al., 2015). In addition, the alteration of river flow and water temperature may further impact the survival of other aquatic species, such as invertebrates and plant life, which depend on specific environmental conditions to thrive (Dudgeon et al., 2006).

Another major environmental problem of dams involves the sedimentation process. Normally, natural river systems transport sediments that originate from upstream areas and carry them into downstream ecosystems. The natural sediment load keeps wetlands, deltas, and coasts healthy. However, when a dam is constructed, the reservoir caused by the dam blocks much of the sediment flow. This leads to significant sediment deposits in the area upstream, whereas those downstream have to deal with sediment deficiency (Poff et al., 2010). This can disrupt sediment transport, which sometimes leads to the loss of vital ecosystems that may also include wetlands; these are important habitats for wildlife and natural barriers to flooding. Moreover, a lack of sediment supply downstream can lead to deterioration in the quality of water because, over time, sediment deposition in reservoirs can stimulate the release of toxic chemicals like heavy metals and nutrients, which can lead to water pollution, hence, (Syvitski et al., 2005).

The environmental impacts of dams are further made complex by the presence of climate change. All these impacts on river ecosystems are likely to be exacerbated by further warming of the planet and altered rainfall patterns. For instance, it is generally expected that climate change will increase the frequency and magnitude of extreme weather events such as flooding and drought, which may increase stress on the dam infrastructures and downstream ecosystems. As rainfall patterns shift, the timing and quantity of river flows will change, potentially leading to more erratic and unpredictable water availability for both hydropower production and ecological functions (Pittock & Connell, 2010). Moreover, higher temperatures may mean increased rates of reservoir evaporation, therefore reducing the volumes of water that can be left downstream for other ecosystem requirements and human use. It also further deteriorates water quality by increasing levels of pollutants concentrated in stagnating waters (Kundzewicz et al., 2008).

In the face of such challenges, there has been an increasing demand for more ecologically compatible alternative dam development policies. For the lessened negative impacts and promotion of restoration of affected ecosystems, dam construction should integrate environmental conservation at the planning, design, and operation levels. One of these approaches is including fish passage facilities, such as fish ladders or fish elevators, in the design of dams to enhance the migration of aquatic species and lessen the impacts on fish populations (McKinney et al., 2017). Another important approach involves the creation of dams that work within the natural flow regimes of rivers, allowing sediment transport and downstream ecosystems to be sustained. Adaptive management strategies incorporate continuous monitoring and alterations according to the situation in real-time, which can be another way of minimizing environmental impacts and making sure the operation of the dam becomes responsive to changing conditions in both the environment and climate (Barton et al., 2019).

In addition, it has been argued in some cases that the decommissioning of old or no longer operational dams is the most effective method for restoring natural rivers and partly undoing some environmental damage created by the construction of dams. Successful dam removals, like that of the Elwha River in the United States, have shown promising results in ecosystem restoration and recovering fish populations whenever the river is returned to its natural flow (Pess et al., 2019). These efforts set precedence to include environmental restoration in the processes of dam management and decision-making.

Sustainable Dam Development Strategies

From the given challenge of maximizing the benefits of dams while minimizing the various environmental and social impacts, several sustainable development strategies have emerged. They all emphasize that approaches must be adaptive and integrated, with the understanding that water management, hydropower, environmental conservation, and climate change adaptation are closely interrelated. This section identifies some key strategies gaining momentum within the sustainable development of dams.

Integrated Water Resource Management (IWRM)

Integrated Water Resource Management is a holistic approach that seeks to manage water resources sustainably and equitably. IWRM aims to integrate all the various uses of water, such as hydropower generation, irrigation, and domestic water supply, into one management framework. The main principle of IWRM is to acknowledge that water is a finite resource, and its management must consider the needs of all relevant stakeholders, from local communities and agricultural sectors to governments and environmental groups (Global Water Partnership, 2000).

In this perspective, the approach of IWRM, on dam development, integrates environmental and social concerns in the planning and operational phases. This coordinated model in water resource management ensures equitable sharing of the resources between energy production, agricultural irrigation, and environmental conservation. It thus fosters IWRM through transparency, resolution of conflicts, and equitably distributed benefits accrued from the dams among the beneficiaries (Lebel et al., 2005).

IWRM also promotes the use of a basin-wide approach to water management, considering an entire watershed with its interlinks in water management rather than isolated projects. This shall ensure that, among other factors, the cumulative impacts of many dams, as well as other infrastructure constructions, are taken into consideration to avoid causing unintended environmental degradation to ensure that this utilization of water resources is sustainable. According to Hughes & Jackson, 2006.

Environmental Flow Management

One of the most critical aspects of sustainable dam operation is the maintenance of environmental water releases from dams that mimic natural river conditions. Environmental flow management is a practice that seeks to ensure water release from dams in a manner that sustains healthy downstream ecosystems. These releases are designed to mimic the natural variability of river flows, integral for sustaining biodiversity, protecting wetlands, and maintaining fisheries (Poff et al., 2010).

Environmental flow releases are essential in light of climate change as well, due to the projected alteration of natural flow regimes. Dams that do not accommodate these flows may disrupt the functioning of ecosystems; this is attributed to degraded water quality, habitat loss, and reduced species dependent on natural patterns of flow. King et al. (2013) also highlighted that the application of EFM typically involves scientific modeling to estimate the appropriate regimes of flow, coupled with ongoing monitoring of these flows to satisfy the environmental concerns of rivers.

In some regions, legislation has been passed that requires the release of environmental flows from dams, and the approach is receiving increased attention worldwide as an integral part of sustainable water management; Acreman & Dunbar, 2004. The Murray-Darling Basin in Australia presents one such success story in managing environmental flow where, through concerted efforts by governments, scientists, and local involvement, better ecological outcomes for river systems have been achieved; Arthington et al., 2013.

Green Infrastructure and Nature-Based Solutions

Green infrastructure and nature-based solutions can be considered in dam projects to reduce the environmental impacts of dam construction and operation. Green infrastructure is defined as a natural or semi-natural system that offers ecosystem services, which include flood regulation, water purification, and habitat creation. Examples of green infrastructure in dam projects include wetland restoration, riparian buffers, and floodplain habitat restoration (BenDor et al., 2015).

Nature-based solutions, such as recovering natural vegetation on riverbanks and artificially built wetlands that filter water, can be cost-effective and ecologically advantageous compared to hard engineering solutions using levees and concrete channels. This is evidenced in Temmerman et al. (2013). It reduces the ecological footprint of dams by increasing biodiversity, improving water quality, and making ecosystems more resilient to climate change.

Green infrastructure in dam development can also encourage EbA, which is an approach that involves the use of natural systems to decrease vulnerability to the effects of climate change. Wetland restoration, for example, could improve flood storage capacity, reduce erosion, and increase water quality, thereby increasing the resilience of human and ecological communities to climate-related hazards (Narayan et al., 2016).

Adaptive Management

Adaptive management is a non-monolithic, iterative approach to dam operation that allows for continuous monitoring and adjustment in light of changing conditions. This is especially relevant in the context of climate change where future environmental and hydrological conditions are not well known. In general, adaptive management utilizes real-time data regarding hydrological, environmental, and operational conditions to make informed decisions on the operations of the dam (Williams, 2011).

Meanwhile, the key notion of Adaptive Management is the continuous flow of new information that inherently updates decision-making and changes management strategies when conditions change. This is especially vital regarding hydropower dams, since climate change may affect water availability and river flow patterns in unpredictable ways. By regularly assessing environmental conditions, adaptive management helps ensure that dams are operated in a way that minimizes negative impacts while optimizing water use and power generation (Walters & Holling, 1990).

This adaptive management could involve modifying the timing and volume of releases in drought or reduced river flow scenarios so as not to have adverse effects on downstream ecosystems. Equally, it is feasible to design dams that integrate systems to monitor water quality and aquatic species and provide the needed information to dam operators for making decisions supportive of ecological health (Cohen et al., 2013).

Adaptive management allows the incorporation of stakeholder feedback into decision-making in such a way that the interests of affected communities, industries, and environmental groups are taken into consideration. Participation in this manner enhances resilience to climate change and long-term sustainability in dam operations. Lynam et al., 2014

Climate Change and the Future of Dam Development

The impacts of climate change on dam performance are profound and far-reaching. Already with the continued warming, dramatic changes in precipitation patterns, river flows, and temperature are occurring, affecting the hydrology of many regions; these are likely to intensify over the coming decades and pose new challenges to the continued viability and effectiveness of existing and future dam infrastructure. The integration of climate change projections during planning, design, and operation is, therefore, of particular importance to continue or assure services in water management and hydropower provisions. It will be necessary for climate-resilient infrastructure with mitigation and adaptation to become built into normal practice in the development of dams.

Climate-Resilient Infrastructure

Climate-resilient dams should be designed because of the forward-looking impacts of future climate change at the local level on hydrological systems: increased frequency and severity of flooding, seasonal water availability, shift in timing, and intensity of river flows. Such challenges require flexible dam designs that can handle higher or more variable flows and maintain infrastructure safety and stability during extreme weather conditions.

The key strategies in infrastructure development toward climate resilience are summarized below:

Flood Management: Dams should be designed with appropriate robust flood management ability to cope with the increased risk of heavy rainfall and snowmelt amongst others caused by extreme weather events, WMO 2018. This could be achieved with larger spillways, enlarged reservoir capacity, and designs for higher flood control standards to manage the expected increase in extreme events.

Variable In-Water Storage: Reservoirs have to accommodate or manage increased variability of water supply; the variation in supply due to extreme floods and droughts calls for their structure to either be able to contain an excess amount of water at high-flow levels and release when the flow is lower to maintain stable levels. Sivapalan et al. (2012).

The integration of renewable energy, such as solar/wind power in the works of a dam, further contributes to the diversification of the energy mix in decreasing its dependence on hydropower. Besides providing a secure supply of energy against the modifying hydrological condition, it provides added value for climate change mitigation through the reduction of the dependence on fossil fuels. (Duan et al., 2019).

Mitigation and Adaptation Measures

Within the context of climate change, mitigation and adaptation measures will be fundamental in allowing dams to provide services reliably into the future with minimal environmental footprint. These need to be part of the design, construction, and operation of dams and integrated within wider regional water management strategies.

Thus, the mitigation measures include a reduction in greenhouse gas emissions from the construction, operation, and decommissioning of the dams. Construction and operational activities, especially large-scale projects of dams, are associated with big emissions due to the intensity of energy involvement in such processes. Besides, reservoirs, which are created by the construction of dams, can be subject to methane emissions due to the decomposition of organic matter in submerged areas, a very potent greenhouse gas (Barros et al., 2011). This, however, can be partly offset by the use of cleaner technologies in construction, carbon offset programs, and optimization of hydropower operations. Adding renewable energy to provide the power, it uses may even further lower carbon footprints produced by dams (Meadows et al., 2015).

Adaptation Measures: With climate change, new uncertainties call for adaptation measures that could ensure that dams remain functional and resilient. Adaptation measures would include the enhancement of monitoring systems of the dams to monitor changing water flow, sedimentation, and ecological health. This would assist in operational adjustment. Water-saving technologies such as more efficient irrigation systems and water storage techniques can manage reduced water availability and improve the efficiency of general water use. UNEP 2019.

Dams in the Broader Perspective of Climate Adaptation Strategies: It is very important not to consider dams in isolation but rather as part of a greater climate adaptation strategy. Besides the supply of energy, dams could be very important in the conservation of water, flood control, and ecosystem resilience. For instance, by carefully managing reservoir levels and flow releases, dams can support the restoration of wetlands, maintain river connectivity, and protect downstream communities from extreme weather events (Lebel et al., 2017).

Climate-Proofing Dam Operations

Proactive climate-proofing is needed to ensure that the operations of dams remain effective against a changing climate. This includes adapting dam operations to current and projected climate conditions and considering changes in precipitation, temperature, and hydrological patterns. Effective climate-proofing includes:

Regular Monitoring and Data Collection: The establishment of robust monitoring systems that track the variables of climate change, such as precipitation, river flow, and temperature, is an important component in adapting dam operations to the shifting climate. This will be helpful in guiding decisions on water releases, reservoir management, and hydropower generation so that the dams can continue with their services within a shifting climate context (Poff et al., 2010).

Scenario Planning: Climate change introduces significant uncertainty, so scenario planning is an important tool for preparing for a range of potential futures. By considering various climate scenarios, including extreme droughts, floods, and shifts in river flows, dam operators can develop contingency plans to maintain dam performance during unexpected climate events (Milly et al., 2008).

Multi-Objective Dam Planning

Given the increasing severity of climate change, multi-objective dam planning is becoming an issue of growing concern. That is to say, a dam should be designed and operated for multiple usages: hydropower generation, water supply, flood control, and ecological health. Multi-objective planning can help ensure that dams are resilient to climate change while meeting the diverse needs of a variety of stakeholders. Some of the key strategies for multi-objective dam planning include:

Stakeholder Involvement: The involvement of local communities, governments, and environmental organizations during the planning process incorporates multiple perspectives in the planning, addressing trade-offs among different objectives. This is a participatory approach that promotes the long-term sustainability of the projects with minimal conflict. Hughes et al., 2010.

Integrated Decision-Making: Multiobjective planning necessitates integrated decision-making, considering interactions among various objectives and with the larger socio-ecological system. As one example, maintaining environmental flows alongside hydropower generation could help protect ecosystems while meeting energy needs (Poff et al., 2010).

Collaboration for Climate-Resilient Water Systems

In developing climate-resilient water systems with dams, collaboration between stakeholders at the local, national, and international levels is crucial. The sharing of knowledge, resources, and expertise by stakeholders will go a long way in devising more effective solutions to overcome climate-related challenges. This includes:

International cooperation will be necessary regarding water resource management in light of climate change since a majority of the river basins are shared among several countries. A shared framework in water management can enable countries to cooperate in operating dams, managing transboundary water resources, and adapting to changing climate conditions (Haas et al., 2019).

Cross-Sector Collaboration: Similarly, collaboration across the water, energy, agriculture, and environmental sectors provides critical opportunities for devising integrated options that ultimately deal with some of the complex challenges developed in climate variation. For example, integrating water storage and irrigation strategies with hydropower generation can help optimize water use and ensure that all sectors benefit from the dam (Sivapalan et al., 2012).

Conclusion and Recommendations

Conclusion

This review highlights the pivotal role of dams in balancing hydropower production, water management, and environmental conservation in a changing climate. While dams contribute significantly to renewable energy, water security, and flood mitigation, they also pose considerable environmental and social challenges. The impacts of climate change—including altered hydrological cycles, extreme weather events, and increased sedimentation—underscore the need for sustainable dam development strategies. These strategies must integrate adaptive management, environmental flow management, and nature-based solutions to ensure that dams continue to meet human and ecological needs.

Future dam development must prioritize climate resilience by incorporating innovative technologies, flexible operational frameworks, and stakeholder collaboration. This approach will enable the optimization of dam benefits while minimizing environmental and social costs. Sustainable dam infrastructure, supported by integrated water resource management (IWRM) and adaptive governance, is essential to achieving long-term water security, energy sustainability, and environmental conservation.

Recommendations

1. **Integrated Water Resource Management (IWRM)**: Implement basin-wide approaches to water management, considering the cumulative impacts of dams on ecosystems and communities. Promote transparency and stakeholder engagement to ensure equitable sharing of water resources and benefits among all users.

2. **Climate-Resilient Infrastructure**: Design dams with enhanced flood management capabilities, such as larger spillways and variable reservoir storage, to address extreme weather events. Incorporate renewable energy sources like solar and wind to diversify energy production and reduce reliance on hydropower.

3. **Environmental Flow Management**: Establish and enforce policies for maintaining environmental flows to support downstream ecosystems and biodiversity. Use scientific modeling and real-time monitoring to optimize water releases and ensure ecological health.

4. **Nature-Based Solutions and Green Infrastructure**: Integrate nature-based solutions, such as wetland restoration and riparian buffer zones, to enhance ecosystem services and mitigate environmental impacts. Employ green infrastructure to complement traditional engineering approaches, reducing the ecological footprint of dams.

5. **Adaptive Management Practices**: Develop real-time monitoring systems to track hydrological, environmental, and operational conditions. Use adaptive management to adjust dam operations based on evolving climate scenarios and stakeholder feedback.

6. **Mitigation and Adaptation Measures**: Reduce greenhouse gas emissions from dam construction and operations through cleaner technologies and carbon offset programs. Enhance water-use efficiency with advanced irrigation systems and water-saving technologies.

7. **Stakeholder Collaboration**: Foster international cooperation for managing transboundary water resources and addressing shared climate challenges. Engage local communities, governments, and environmental organizations in the planning and operation of dams to promote inclusive decision-making.

8. **Research and Innovation**: Invest in research to improve predictive modeling, sediment management, and the integration of emerging technologies like AI and blockchain. Explore the feasibility of decommissioning aging or non-operational dams to restore natural ecosystems and reduce environmental risks.

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