

The Role of Glaciers in Hydropower Production in Nepal

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Abstract

Nepal is a mountainous country rich in water resources, with huge potential for hydropower generation. The Department of Electricity Development (DoED), which sits within the Nepalese Ministry of Energy, has published *Guidelines for Study of Hydropower Projects* to set out the official standards for the detailed study of hydropower projects in Nepal. The guide is regularly revised, with the latest revision having taken place in 2018, in order to ensure the long-term sustainability of the projects. Among the key issues considered are the linkages between glaciers and hydropower projects in Nepal under a changing environment. The formation of new glacial lakes and the potential for glacial lake outburst floods (GLOFs) are recent challenges in the Himalayan region. As such, any change impacting these processes may have serious consequences on hydropower projects or cause severe damage to these projects across the country, whether they are in the planning phase, under construction, or completed. This paper aims to make the connection between the status of hydropower projects in Nepal and the state of glaciers in the Himalayas, and suggests that advanced studies on glacial lakes and GLOFs are needed to ensure the long-term sustainability of hydropower projects under changing climate.

Keywords: glaciers, hydropower, sustainable hydropower development, glacial lake outburst flood (GLOF), Nepal

1. INTRODUCTION

Nepal is approximately 80% mountainous, with altitudes ranging from a few hundred meters to over 8000 meters above sea level (m asl), and a climate that varies with topography and altitude. The high mountains on the northern edge of the country are covered with snow and glaciers, while its southernmost part, known as the Terai belt, is flat; the rise in elevation between the two

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is scattered with valleys between mountain ranges rising to the north (Figure 1). Within such a complex geography, over 6000 rivers and streams (including rivulets and tributaries), with a total drainage area of 194,471 km², flow mostly north to south and at generally high velocities due to the high slopes. The cumulative length of all the rivers of Nepal is around 45,000 km. According to estimates, the country counts 1000 rivers longer than 10 km, with about 24 of them over 100 km long, and 33 rivers with drainage areas exceeding 1000 km² [1]. Nepal is thus believed to be one of the richest countries in water resources worldwide.

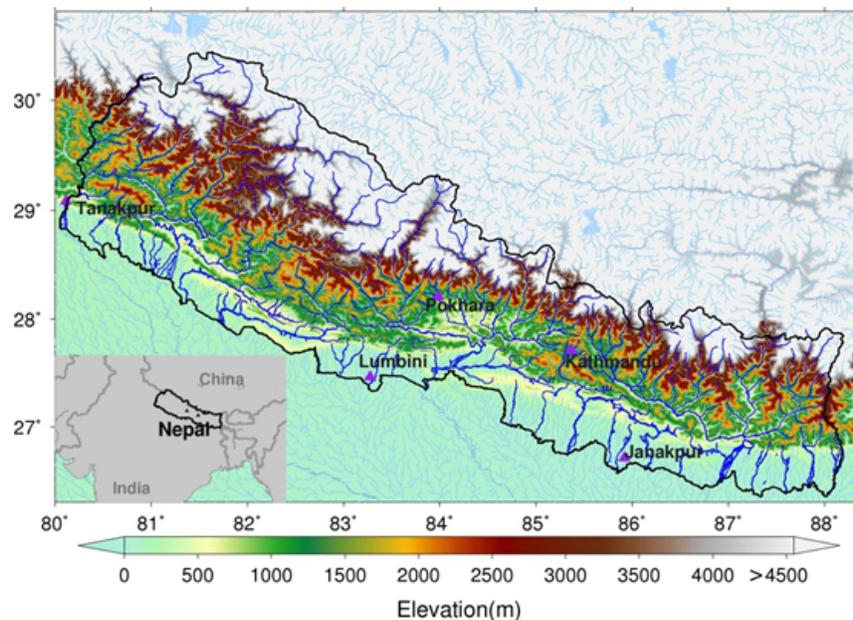


Figure 1: Major river networks (dark blue) in Nepal. The light blue lines on the map represent the minor river networks.

Most perennial rivers in Nepal are glacier-fed and provide sufficiently sustained flows to fulfil the water requirements of hydropower plants, irrigation canals, and water supply schemes downstream, even during the dry season. The country's rivers can be classified into three broad groups on the basis of their origin. In the first group, snow-fed rivers have their origins in the snow and glaciated regions of the Himalayas, and ultimately become major tributaries of the Ganges River in northern India. They include the major river systems (Figure 1) of the Koshi River, Gandaki River, and Karnali River. Rivers in the second group originate from the middle, hilly regions of Nepal. Their flow regimes are affected by groundwater and precipitation levels during the monsoon. Groundwater contribution to these rivers maintains their minimum flow level and prevents their drying outside the monsoon season. The Bagmati, Kamala, Rapti, Mechi, Kankai, and Babai rivers all belong to this second group. Rivers in the third group have their origins in the Siwalik zone. Tinau, Banganga, Tilawe, Sirsia, Manusmara, Hardinath, Sunsari, and other smaller rivers are all examples of rivers falling in this last group. Their flow is mostly dictated by precipitation levels during the monsoon, and could be significantly reduced out of the monsoon season. Approximately 60–85% of the annual river discharge from all river systems in Nepal occurs during the three months of the summer monsoon (July to September), which makes it a season of particular importance. However, some rivers are reliable for their consistent discharge through the year, and as such provide potential opportunities for different sectors. The Himalayan glaciers are the main source of water that ensure the consistency of river runoff is maintained.

There are about 3,252 glaciers in Nepal, covering a total area of 5,323 km². Attached to these are 2,323 glacial lakes, with a total area of 75.70 km², for the most part located in the steep slopes of the Nepalese Himalaya [2].

One of the important possible benefits of the mountainous rivers of Nepal is their potential for hydropower generation. Hydropower is the power derived from the energy of falling or fast-flowing water, one of the most widely used clean and renewable energy sources. According to the Nepal Electricity Authority (NEA), around 90% of the total electricity used in Nepal is generated from hydropower plants, with only about 10% generated from thermal plants. The huge potential of water resources makes the production of electricity from hydropower one of the most important sectors for the present and future economic development of Nepal. The facts and figures of hydropower development in Nepal have been the subject of many studies [1,3,4], and several public and private hydropower development projects have started over the past decade. Nepal is believed to have the potential to generate 83,000 MW of electricity from hydropower, which amounts to almost 3% of the world's capacity [1]. The national production of hydropower has increased in recent decades [1], however, although the potential for hydroelectricity generation from Nepalese rivers is now well-known, the realisation of this potential is not happening in practice, due to many factors including the lack of financial, planning, human, and time resources, as well as the issue of transportation of construction materials [3]. It should be highlighted here that most of the proposed hydroelectricity operations are run-of-the-river (ROR) hydroelectric generation plants. Therefore, river discharge and the sources of upstream runoff are important considerations to ensure a river can produce hydropower energy consistently. Any fluctuation in runoff may cause remarkable changes in hydropower production.

Natural hazards such as earthquakes, floods, and landslides are common in Nepal. They have many causes, including changeable hydroclimatic conditions, young geological features, unplanned human settlements, deforestation, environmental degradation, and a growing population [5]. Disasters resulting from natural hazards cost lives, destroy infrastructure, and are an unparalleled threat to sustainable development. Since natural disasters are extremely sensitive to climate change, Nepal is one of the highest risk countries in the world. One of the important issues is the possible risk arising from natural disasters for hydropower projects. For example, landslides, extreme floods, glacial lake outburst floods (GLOFs) and landslide-dam outburst floods can have a direct impact on hydropower projects in many ways. On the other hand, the impact of climate change on water resources, causing the shrinkage of glaciers, the expansion of glacial lakes, and fluctuations in runoff is a serious concern, especially in mountainous regions [6–8].

Nepal intends to grow its grossly under-developed hydropower sector, both for internal consumption and exports, and has an ambitious pipeline of projects. However, over the last few years, many hydropower installations throughout the country have been badly affected by natural disasters, resulting in significant economic losses. It is widely agreed that Nepal is not well prepared yet to manage such disasters. As recently as 5 July 2016, the Bhotekoshi River in Sindhupalchowk District swept away 20 concrete houses, and put 200 more houses at high risk [9]. At Kodari along the Araniko highway, the river eroded 50 meters of road; the flood swept away half of the dam of the Upper Bhotekoshi Hydropower Project (Figure 2). The severe flash floods in the Bhotekoshi River reportedly occurred after a glacial lake burst through its dam near the head of the river, in the upper Himalaya. As glaciers retreat at alarming rates due to global warming and climate change, glacial lakes are rapidly expanding [7]. At least 20 glacial lakes have been identified as potentially dangerous in Nepal, posing imminent risk to downstream households, livelihoods, and infrastructure, including hydropower projects. This study explores the relationship between glaciers and hydropower development, and discusses the challenges with and sustainability of hydropower projects in Nepal.



Figure 2: Damaged dam of the Upper Bhotekoshi Hydropower Project after flooding on 5 July 2016 on the Bhotekoshi River in Sindhupalchowk district, Nepal [18].

2. DEVELOPMENT OF HYDROPOWER PROJECTS

The history of hydropower development in Nepal spans over 100 years, and started with the construction of the Pharping Hydroelectric Plant (500 KW) in 1911. According to the NEA, Nepal's total installed electric capacity (as of June 2016) is 765 MW, which is nominal compared to its hydropower potential. The annual peak power demand from the Integrated Nepal Power System (INPS) was 946.10 MW in 2011, and the electricity demand in Nepal is increasing by about 7–9% (approximately 80 MW) every year. Although the country boasts tremendous hydropower potential, only about 40% of Nepal's population has access to electricity, via both the grid and off-grid systems.

As mentioned earlier, most hydroelectricity in Nepal is produced in ROR power plants. Figure 3 shows a schematic diagram of how power is generated from a river in a typical ROR process used in Nepal. Water is made to drop elevation through a canal or large tube called a penstock. When the water reaches the end of the penstock, it turns a water wheel, or turbine, connected to an electrical generator, which in turn generates electricity. In general, the maximum electricity can be produced from river water levels during the monsoon season; however, during the dry season, only a minimal amount of power can be derived from the river system. This is particularly true in the case of rivers that are not snow-fed. To guide the development of hydropower projects in Nepal, the Department of Electricity Development (DoED) of the Ministry of Energy published the *Guidelines for Study of Hydropower Projects* in 2003. These provide guidelines to carry out pre-feasibility and feasibility studies, as well as related information useful throughout the construction of hydropower projects.

As mentioned above, several hydropower development projects are in the planning phase, while a few are already operational, or at the site survey or construction stages. There are currently 250 hydropower projects proposed across Nepal. Figure 4 presents the location of each of these hydropower projects, and clearly highlights that they nearly all are or would be installed across rivers that are ultimately connected to glaciers located in the northern half of Nepal. The density of projects seems much higher to the east, while there are almost none in the Terai belt to the south.

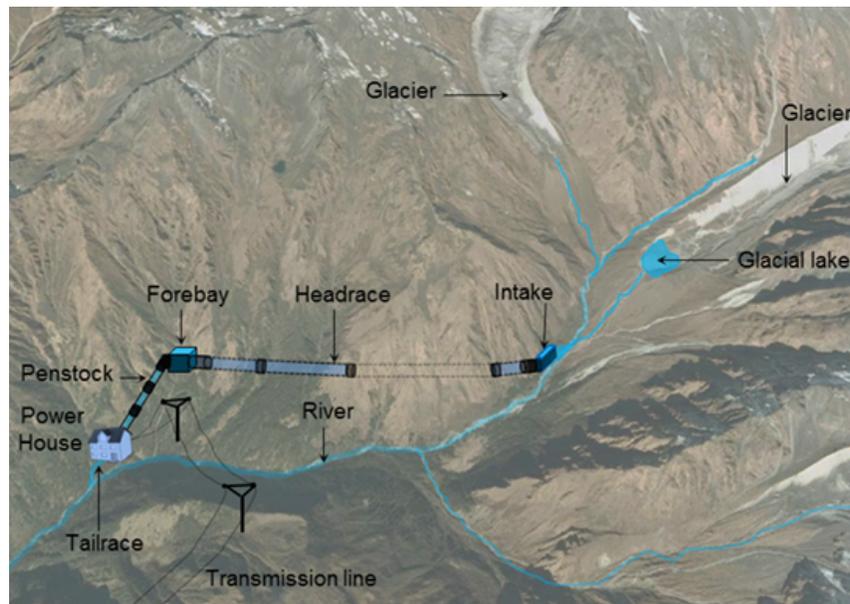


Figure 3: Schematic diagram of a run-of-the-river hydroelectric project.

3. THE LINK BETWEEN GLACIERS AND HYDROPOWER

Hydropower is highly dependent on the volumes of water available in rivers. A regular river flow is as important and depends on the river basin's characteristics, as well as various other factors which may affect the water level. Any change in the corresponding river basin can therefore directly affect a hydropower project. Glaciers are a key source of water for mountainous rivers, and can release water steadily for a long time. Therefore, understanding the relationship between glaciers and hydropower can play a crucial role in sustaining power production throughout the year.

Most glaciers in Nepal are located in the northern part of the country (Figure 4), generally over 2500 m asl. Their area, length, and depth vary from a few square kilometres to over 50 km², 200 m to more than 4 km, and a few to several meters, respectively [2,7]. All of them play an important role in supplying water to rivers throughout the year. Hydropower projects (proposed, planned, and under construction) are mostly located in the lower to middle mountain range, while glaciers are located in the upper mountains (Figure 5-7). Releasing water from glaciers is therefore a sensible factor for power production, and any change in glacial mass can directly affect hydropower production.

If glaciers gain more mass than they lose, they will have a positive mass balance. Glaciers lose mass through ablation processes. In general, the gain and loss in a glacier mass balance can be variable across a season, but a glacier should neither advance nor retreat over the year. However, studies across various glaciers worldwide agree that most glaciers are retreating due to global warming [7], which is problematic for water availability and supply for hydropower generation, in particular in countries like Nepal, where hydropower is mostly ROR based. Additionally, some studies have attempted to simulate and predict the extent of glacier retreat and its impact in terms of water runoff amounts and timings, and have as a result questioned the sustainability of hydropower generation over the longer term. The next subsection discusses the challenges faced by hydropower projects in more detail.

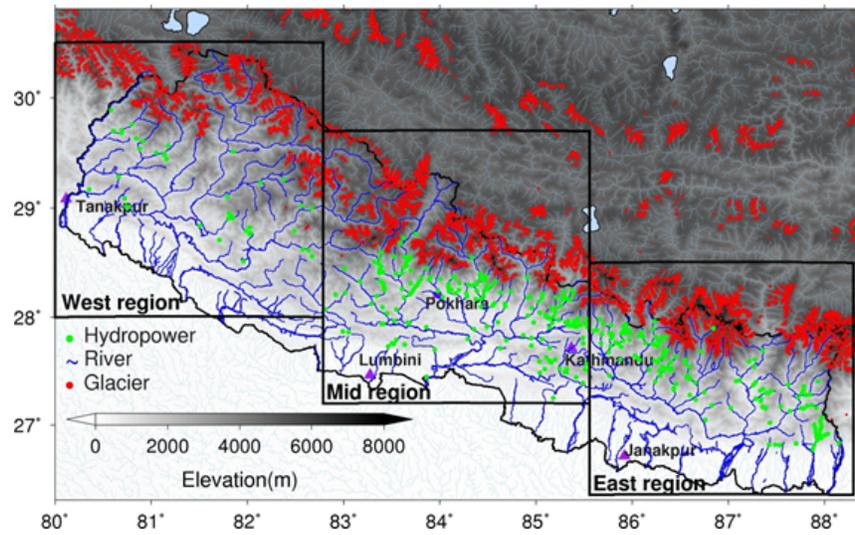


Figure 4: Distribution of glaciers (red points) and location of hydropower projects (green) in different regions of Nepal. All types of license issued hydropower projects, under construction and in operation, are showed.

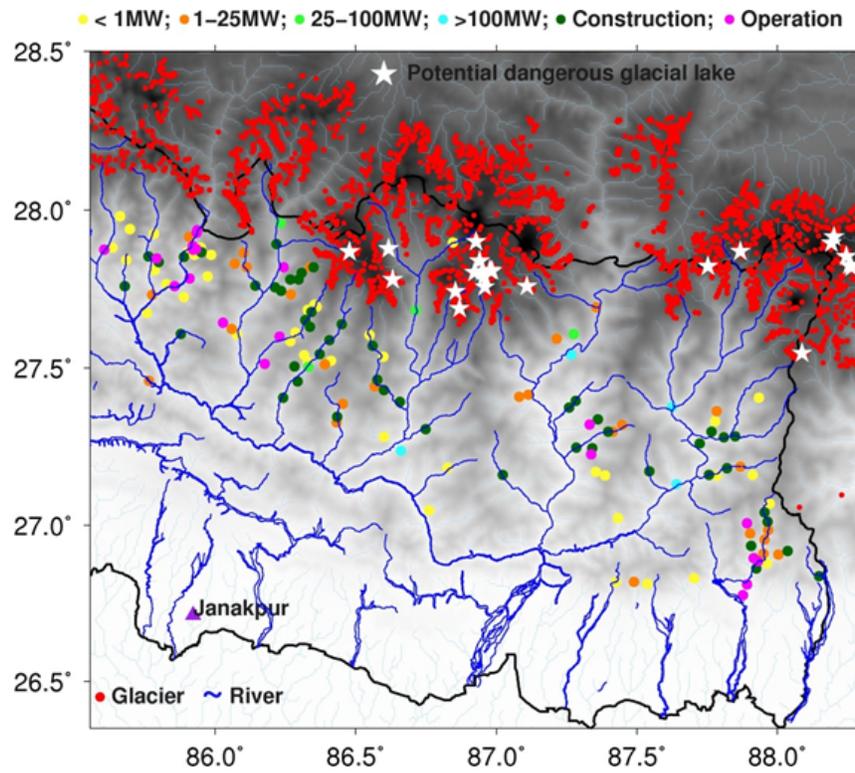


Figure 5: Location of hydropower projects in the eastern region of Nepal. White stars represent potentially dangerous glacial lakes.

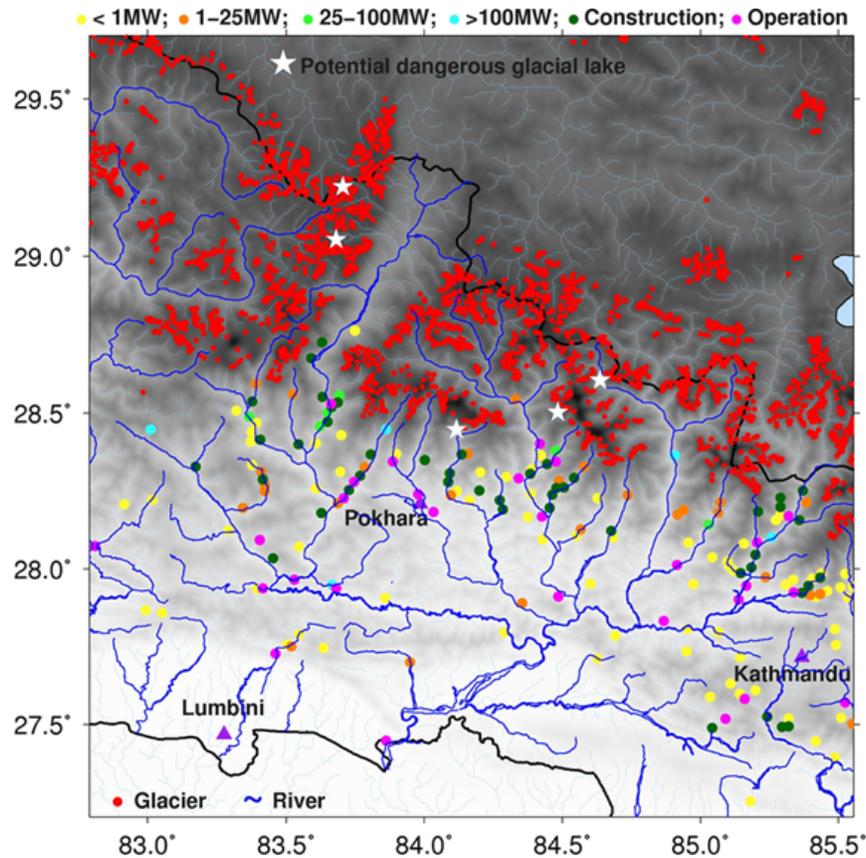


Figure 6: Location of hydropower projects in the middle region of Nepal.

4. CHALLENGES FOR HYDROPOWER PROJECTS

The policy, political, social, and market issues before and/or after the development of hydropower projects are the subject of many studies [3,4,10,11]. All of these can be resolved after a serious analysis and thoughtful discussion. By contrast, other challenges not under our control include water-related hazards, which can potentially play a noteworthy role in the development, protection, and maintenance of hydropower projects. This paper considers such challenges for hydropower projects in Nepal, and more specifically disasters resulting from GLOFs, which have already damaged several hydropower plants across the country. Here we briefly and comprehensively discuss such challenges as they closely relate to Glaciers.

4.1. Climate Change

Nepal's vulnerability to climate-related disasters is likely to be exacerbated by the increase in the intensity and frequency of weather hazards induced by anthropogenic climate change [7]. Research has shown that the country's maximum mean temperature [12] is on a steady rise over the past decades [13]. The trend of increasing temperatures in Nepal suggests that the retreat of glaciers as well as a significant increase in the area of several glacial lakes should also have been documented over recent decades. Hence, there could be a chance of disappearing glaciers in the Himalaya if such a steady increase in temperature exists. If so, runoff in rivers will not

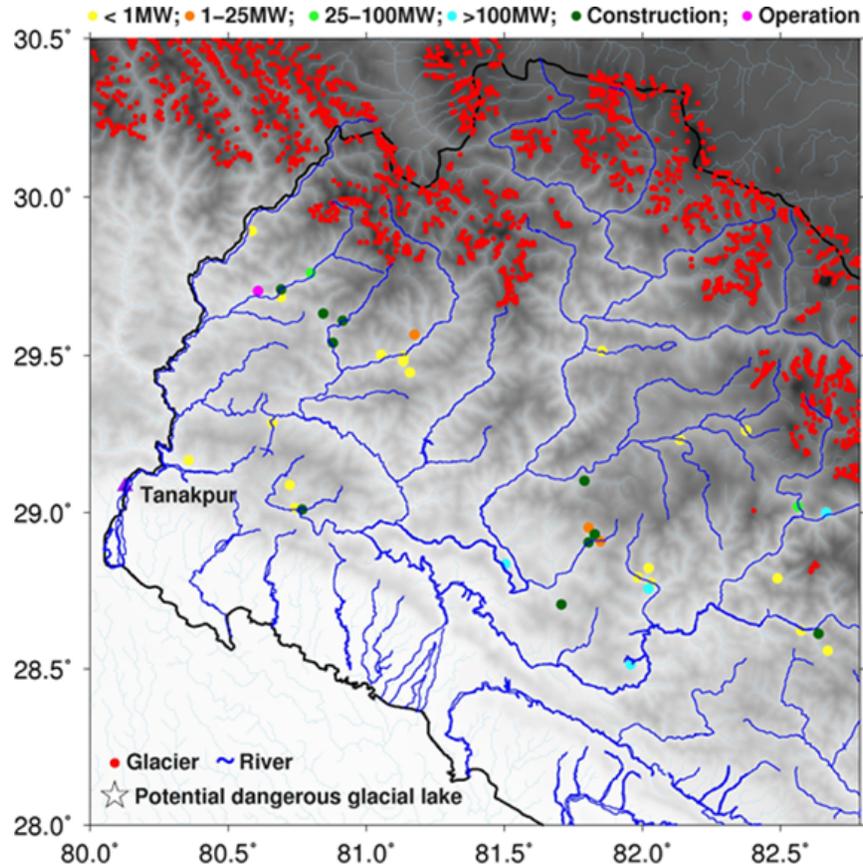


Figure 7: Location of hydropower projects in the western region of Nepal.

be sufficient to supply hydropower projects in the long term. In Nepal, the most critical impacts of climate change on the country's water resources and hydropower generation potential stem from glacier retreat, the expansion of glacial lakes, and changes in the seasonality and intensity of precipitations. The analysis of long-term hydrometeorological data can show the impact of climate in any region, but long-term hydrometeorological data is rarely available in Nepal, in particular across mountain topography. Feasibility studies for hydropower projects are thus limited to the use of short-term hydrometeorological data from very limited stations, from which less impacts are likely to be detected. Addressing these issues using alternative methods is needed in the future.

4.2. River Discharge

During the monsoon season, the level of runoff into the rivers of Nepal is generally high. Out of the monsoon season, river flow is mainly dependent on groundwater recharge and glaciers. Consequently, changing glacier systems will directly affect river discharge. Two additional factors may contribute to the increased variability in river discharge: glaciers retreating and changes in the timing and intensity of precipitation. Runoff in rivers initially increases as glaciers melt, then decreases as glaciers disappear. Many of Nepal's rivers are fed by runoff from over three thousand glaciers scattered throughout the country. The most severe projections for Nepal show that runoff

could be reduced by 14%. This would reduce the electricity generation of existing plants, and impact the expansion of hydropower projects in the future. However, even when considering only the limited potential realised and currently developed hydropower projects, the installed capacity is designed based on a 65% dependable flow. This is modelled using past records of a few years of data, but some mountainous rivers show a trend towards a seasonal reduction in dependable flows going forward, with potentially significant declines in the dependability of dry season flows. For example, a study of the Bagmati River Basin in Nepal shows that the trend for its discharge has been to increase in the pre-monsoon season, but to decrease post-monsoon [14]. This can have critical consequences for both water supply and energy generation, and the unpredictability of scenarios makes the task more complex for hydropower planners and engineers to maintain the generation of electricity throughout the year.

4.3. GLOF

Glacial lake outburst floods (GLOFs) are one of the most serious challenges for hydropower projects in the country. When a glacier retreats and a lake forms at its lower tail, the moraine holds the water back. A GLOF can occur when a lake forms beneath or on a glacier. Many glacial lakes drain periodically when the water reaches a certain level. This can start with a hole in the ice-cored dam, which increasingly widens until the drainage suddenly accelerates to become a flood. In some locations, this process is regulated by the seasons, and some lakes will drain by themselves once or several times each summer. When a GLOF occurs from moraine-dammed lakes, too much of the moraine material are washed away and the lake is unlikely to reform. A number of reports have documented significant GLOFs and recorded the extent of damages caused over the years. For example, the Dudh Koshi River flooded in 1977 after a GLOF, leading to several casualties, destroying a number of bridges 35 km downstream, and triggering many debris flows. In 1984, the Dig Tsho glacial lake was breached when a large avalanche slid into it. Two hours later, the flood reached a peak discharge, which transported four million cubic meters of sediment down the Dud Koshi River. It destroyed a hydroelectricity project, bridges, houses, and farmland along the river. Three years earlier, the breach of Zhangzangbo Lake killed four people and damaged the China-Nepal Friendship Bridge on the northern border as well as seven other bridges, a hydropower plant, the Arniko Highway, and several houses. In 1985, another large avalanche triggered a GLOF at Dig Tsho, and a 10 to 15-meter-high surge of water and debris flooded down the Bhote Koshi and Dudh Koshi Rivers for 90 kilometers. At its peak, 2,000 m³/sec discharged, equivalent to two to four times the magnitude of the maximum monsoon flood levels. It destroyed the Namche Small Hydel Project, which was almost completed at the time. The devastating impacts of a GLOF were also suffered at Tam Pokhari in 1998. Many other potential GLOFs are still likely in the Nepalese Himalaya, threatening hydropower projects in the future.

5. POTENTIAL DANGEROUS GLACIAL LAKES

Glaciers are scattered across the Nepalese Himalaya, but most active glaciers can be found in the eastern region (Figure 4). Licensed hydropower projects (colour points of Figures 5 and 6) are also mostly located in the middle mountain regions to the east of the country, with comparatively less project density in the west (Figure 7), clearly highlighting a direct correlation between the location of glaciers and hydropower projects.

We discussed how any physical changes in glaciers could affect projects located on corresponding rivers downstream, and several studies have highlighted that retreating glaciers and the

formation of glacial lakes are also common in the Himalayan region [7,10,13,15]. Recent research carried out by the International Centre for Integrated Mountain Development (ICIMOD) shows about 20 GLOFs as potentially dangerous (Figures 5–7), with most of them on the eastern side of the country, and almost no risk of a GLOF to the west. The concentration of potential GLOFs in the east increases the likelihood of severe impact on hydropower projects in the future.

Hydropower projects are not only useful for generating energy for production sectors but also a powerful medium of facilitating the socio-economic transformation and development of rural areas. Indeed, a hydropower project leads to development activities in villages, mostly brought at the time of the construction of the power plant. It is expected that the number of hydropower projects in Nepal will increase in the coming years.

According to the *Guidelines for Study of Hydropower Projects in Nepal* [11], in the detailed study requirements, GLOFs are listed as a major risk factor for many hydropower projects in Nepal. Therefore, it is recommended that the status of existing glacier lakes in a river basin, the condition of marine dams, and the volume of glacier lakes should be determined, with even more detailed investigations on glaciers and GLOFs required in the case of larger capacity hydropower projects. This information is also needed for both hydrologic and sedimentological studies, also directly required within the scope of pre-feasibility studies for hydropower projects. It should be noted that the availability of resources for a regular monitoring of glacial lakes and their conditions is very limited, especially for the Himalayan region, even though they are considered a risk for hydropower projects.

6. SUSTAINABILITY OF HYDROPOWER PROJECTS

The sustainability of a project refers to its ability to maintain operations, targeted services, and benefits during its projected lifetime. Therefore, identification and analysis of risk factors likely to impact any project is necessary. The social, environmental, and economic aspects of new and existing hydropower projects are also important. Running hydropower projects over a long time while minimizing risk is an expectation anywhere in the world. In order to do so, recent guidelines for hydropower projects were issued by the DoED in 2018. These guidelines recommend several approaches to ensure the sustainability of projects and the mitigation of possible risks. A number of adaptation strategies are described to cope with glaciers, glacier lakes, GLOF, and associated risks as well as streamflow variability. However, the analysis of scenarios is still quite difficult in practice due to the unavailability of sufficient data.

One of the main challenges in addressing the risks associated with GLOFs for hydropower projects is the spatial mapping of glacial lakes, showing their expansion and formation process. This is in part due to the distance between glaciers and hydropower projects, and the fact that glaciers are located in high, remote areas. There is thus no straightforward method to consider them in the feasibility study. A basic analysis is generally performed based on available data and information to identify any potential glacier-related risks for the hydropower project considered. More advanced analyses should be undertaken to determine the vulnerability of areas located downstream of hazardous glacial lakes considering climate change scenarios. It is likely that the levels of risk may be greater if the status of glaciers in the Himalayan region under a rapidly changing climate were to be carefully studied and considered.

There is no doubt that a number of other factors are also very important. Environmental and economic aspects for instance, are vital aspects of the sustainability of hydropower projects. Environmental considerations should include all the environmental impacts of hydropower projects, which may arise through its lifetime. These should then be mitigated through appropriate management of the projects. The public and private sectors of Nepal, including foreign aid and

investment, have direct and indirect interests in this sector [16] and bilateral and multilateral funding has been funnelled towards hydropower projects (Figures 5–7). Nepalese companies are actively investing in hydropower projects as they resonate with the national socio-economic culture and cost relatively little overall. Nepal's hydropower policy has seen many improvements, nevertheless advanced studies on hydropower are still limited. If such work was performed during the prefeasibility/feasibility studies for hydropower projects, their long-term sustainability would ensure that they remain beneficial and cost effective.

Since runoff in most of the rivers in Nepal is still steady to this day, it is not yet a problem and all the plants currently in operation are still capable of releasing the minimum requirements downstream. Hence, Nepal has no problems yet in allowing and enforcing the natural flow of rivers downstream, with no issue for hydropower production. But it is quite clear that the changing environment may likely affect its hydropower projects in a number of ways. With many projects already launched, under construction, and in preparation, it would be logical that existing guidelines, plans, and policies should be revised, prioritizing the connected role of glaciers for hydropower production.

7. CONCLUSION

Rivers are natural assets, and using such natural systems correctly can be beneficial for several sectors of activity. In this paper, we discussed the role of glacier systems for hydropower production in Nepal. Most hydropower plants in Nepal have been installed on rivers in the complex mountainous regions of the country. Sudden river flooding has the potential to easily destroy not only the river system, but also hydropower plants and infrastructure. On the other hand, hydropower projects cannot run if there is not enough flow in the river, and it is true that natural disasters are not completely unavoidable under our changing environment. However, proper management or understanding of the physical processes of river systems could be beneficial for the long-term running of hydropower projects in any river basin. Moreover, understanding the glacier system at the head of a river is also essential for the sustainability of hydropower projects in Nepal. Therefore, proper data and documentation of observed facts are important.

Nowadays, various research studies indicate that the effect of climate change can be experienced in the snow-fed river system of Nepal. Possible causes may be the increase of runoff in the rivers, sudden flash floods, melting glaciers, and the formation of glacier lakes. The formation of such lakes is dangerous for human life and infrastructure downstream along those rivers. Hydropower production has already faced problems in several places to cope with streamflow fluctuations. The current design for small hydropower plants assumes an average project lifespan of 50 years, with most investors expecting a return on their investment within 7–26 years. However, most of them do not take into consideration the sudden damage caused by potential natural disasters or change in river runoff over that period, even though they are major issues that hydropower projects face.

Hydropower projects in Nepal are conceived taking into consideration short-term hydro-meteorological data only. However, the real impacts of climate change on hydropower projects may not be made sufficiently clear through the analysis of short-term data only. Recent studies have pointed to an increase in temperatures over the years, with remarkable warming at high altitudes. The Himalayan region of Nepal has witnessed an increase of 0.15 to 0.6 °C per decade in the past 30 years. These changes have seemingly been accompanied by a significant change in precipitation (volume and pattern). Even though the spatial distribution of quantitative precipitation estimations in Nepal has been lacking in the absence of advanced techniques to estimate precipitation [17], the data observed at certain stations shows a decreasing trend for most of the areas in southern and western Nepal. In contrast, observation records indicate that the hilly and mountainous regions of

western and north-eastern Nepal are experiencing an increase in precipitation. Climate change affects different aspects of local hydrology, such as water quality and the magnitude and pattern of water availability in rivers, which ultimately affect the operation of reservoirs and hydropower production. A more precise assessment of how climate change is likely to impact water resources would, therefore, be crucial to evaluate the long-term sustainability of any project dependent on water resources. The level of knowledge on the impacts of climate change on water resources in the hills and mountains of Nepal is unfortunately limited. To allow for efficient planning of hydropower production and the development and management of the hydropower sector over the long-term, it is important to understand the different climate change scenarios and their consequences in terms of changes in temperature, precipitation, and river flow, and their impacts on glacier systems.

In conclusion, climate change-induced glacial retreat has wide-ranging and predominantly negative impacts on ecosystems. Based on long-term global data, a rising average annual global temperature will continue to pose challenges for vulnerable communities and physical landscapes. In particular, we sought to highlight the complex nature of the impacts of glacial retreat on water quality, outburst floods, and hydropower production. The impacts of climate change on glacier systems may increase the number of glacial lakes and GLOF, which can affect the potential energy produced by hydropower projects to varying degrees over the short- and long-term. These issues should therefore be assessed in advance, which requires more research in the future.

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