Addressing misconceptions about climate change in the Himalayas

Contrary to common misconception, accelerated glacial and snow melt owing to global warming, as well as greater anticipated precipitation in the Himalayas, actually strengthens the case for further development of Nepal's significant hydropower potential, according to a series of presentations by leading climate scientists, in a webinar organized by the World Bank on 25 March. Integrated river basin impact assessments, as well as further studies about the impact of climate change most notably on the seasonality and variability of rainfall and hydrology, as well as in terms of geohazards, are, however, required to ensure the sustainable and optimal development of this potential. By incorporating smart climate planning and climate resilience designs into existing and future projects, hydropower can generate multiple social and economic benefits for Nepal. *H&D* News Editor, Martin Burdett, who moderated discussions, reports on the key points of the webinar.

As Nepal ranks among the most vulnerable countries in the world to the effects of climate change, the country is naturally taking the subject very seriously. Climate change was to be the main theme of the country's inaugural Sagarmatha Sambaad (Mt Everest Dialogue), a biennial global multi-stakeholder summit initiated by the Ministry of Foreign Affairs of Nepal to address issues of global, regional and national significance. The forum, which was to be held in Kathmandu from 2 to 4 April, was cancelled as a result of the Covid-19 pandemic, but its planned organization underlines the Government's concern over the impact of global warming on its water resources, and its desire to ensure that the future harnessing of these resources, including most notably for hydroelectric generation, is environmentally sustainable and climate resilient and, by extension, economically viable.

For Nepal, located at the heart of the Himalayas, water is its greatest natural resource and one that needs to be utilized to ensure self-sufficiency in water, energy and food supply. By extension, hydropower, if developed sustainably, is its most bankable resource and its derived revenue is vital for the country's economic and social development. The large hydropower potential of the country is currently under-used, with just 2 per cent of its estimated technical potential developed to date. This is expected to change. The Nepalese Government has adopted a Low Carbon Energy Strategy that envisages replacing imported fossil fuel-based generation through the electrification of all sectors of society and the economy, from household energy use to transport and industry, based on full development of its hydropower potential. Government ambitions to develop some 15 000 MW of new hydropower or more over the next 10 years or so will allow Nepal to exceed domestic electricity demand, enabling surplus production to be exported to India and Bangladesh. The combination of a reliable power supply and hard currency revenues from exports of hydropower will drive economic growth and support vital investment in basic infrastructure, from hospitals to schools to water supply systems, which will in turn raise living standards. In addition it will play a critical role in the future energy transition in the wider region, helping to balance variable energy from renewable sources like solar and wind, which will replace fossil-fuel energy.

Noting that hydropower is the main source of electricity for Nepal and that climate change would have a direct impact on its future development, Arjun Karki, Nepal's Ambassador to the USA, said in an opening address: "The assessment of how climate change is impacting on water resources is crucial to the sustainability of any long-term water resources utilization project. Our country has experienced an increase in extreme events such as floods, landslides and droughts in recent years. Ice loss is accelerating with rising temperatures, and threatening water supplies for hundreds of thousands of people, as well as putting the hydropower system at risk. Changing climate and hydrological conditions have placed at great risk the future of hydropower in Nepal". Ambassador Karki added that as a result, Nepal was among the first countries in the world to enact a climate change financing framework, and has since laid out a roadmap of measures and clarified the role of key ministries for improved coordination, planning and budgeting of climate change responses. "While we are still introducing new initiatives and putting in resources to fight climate change, strong regional and global initiatives and partnerships are needed now, more than ever, to mitigate the effects of climate change. Furthermore, we need more research, studies and robust scientific findings to frame our future work," he concluded.

Subsequent presentations underscored many of the opening remarks by Ambassador Karki, including most notably that climate change will inevitably continue to have an impact on water resources in Nepal and across the Himalayas, and that while past and ongoing studies have started to confirm expected temperature rises and their likely impact on glacial and snow melt, much more research is required to understand completely the implication of global warming on Nepal's water resources, and for the large-scale hydropower potential to be exploited more fully.

Presentations by Divas Basnyat, coordinator of the Water and Climate Programme of the Nepal Development Research Institute (NDRI), Walter Immerzeel, Professor on Mountain Hydrology at the University of Utrecht, Patrick Ray, Assistant Professor of Environmental Engineering at the University of Cincinnati, Prof. John Reynolds, a global leader in glacial hazard assessment and mitigation, and Nagaraja Rao Harshadeep, a Lead Environmental Specialist at the World Bank, provided a broad overview of the expected changes in hydrological conditions in the Himalayas. They focused in particular on the impact of the projected intensification of monsoons and the accelerated retreat of glaciers as well as natural hazards on the development of hydropower in Nepal. The findings of, in particular, Profs. Immerzeel and Ray, two leading hydrologists, showed that global warming is, contrary to common misconception, likely to result in increased water flows in most of Nepal's glacier-fed rivers through to the middle of the century, at the very least in spite of the accelerated retreat of glaciers and the unpredictability of future rainfall.

Some key points emerging from the webinar discussions were as follows:

• increased streamflow, especially during high-value spring snowmelt months, though uncertainty about the variability and seasonality of rainfall will require further detailed studies and more investment in monitoring and research;
• the accelerated melting of glaciers will not have a significant impact on river flows, and thus on the viability of hydropower development;
• rising temperatures could result in a shorter dry season, as snow and glacial melt will precede the arrival of the wet season, with positive knock-on effects on the economic viability of hydropower;
• likely increased propensity for extreme weather events, which with the threat of natural hazards, such as earthquakes, landslides, rockfalls, and glacial lake flood outbursts (GLOFs), will require project developers to take the physical environment into account increasingly;
• the need for integrated river basin planning to take into account the management of water resources, sediment and geohazards, as the region's rivers cross numerous countries and the rivers are important for various types of downstream users in Nepal, India and Bangladesh;
• the need for national bodies and governments and international institutions to coordinate studies and share results; and,
• the need to use climate smart planning to design and develop climate resilient projects.

The retreat of glaciers

One of the most evident aspects of global warming, at least in high mountain areas such as the Himalayas, is the retreat of glaciers, with temperatures rising faster at higher altitudes. "High Mountain Asia glaciers are losing mass at a rate of 20-30 cm/year over their entire surface, and we clearly see that the glaciers that are losing mass are also slowing down, so it is pretty evident that a lot has been happening to the cryosphere over the past decades in Nepal and in the region in general,"" noted Prof Immerzeel. A study, which was co-authored by Prof Immerzeel on the impact of the Paris Climate Agreement on glacier ice volumes in High Mountain Asia, and published in Nature in 2017, projects that: "Even if we meet the ambitious 1.5 °C threshold that was agreed (for the rise in temperature by 2050) we would still lose 36 per cent of the total ice volume, but more realistically we will lose about 50-60 per cent of the total ice volume by the end of the century," he said. More recent work has also shown the likelihood of "quite strong decreases" in snow melt run-off in High Mountain Asia, with the most extreme scenario projecting about 42 per cent less snow melt by the end of the century. "For snow melt there is a much stronger dependence on the type of climate change scenario that we will follow than for glacier melt. For glacier melt there is a big change, but it is more or less constant and that is caused by the fact that in a more extreme scenarios, temperatures are rising more rapidly, but also there is more precipitation and so also more snow, so that compensates for the extra temperature effect," he explained.

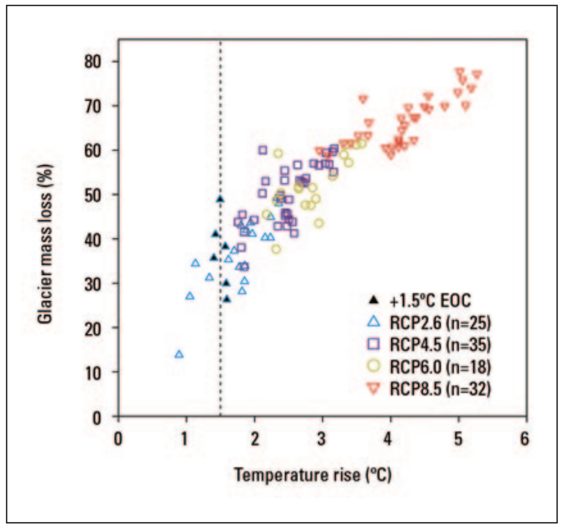


Fig. 1. Modelled glacier losses for the end of the century under various representative concentration pathways [Kraaijenbrink, 2017[4]].

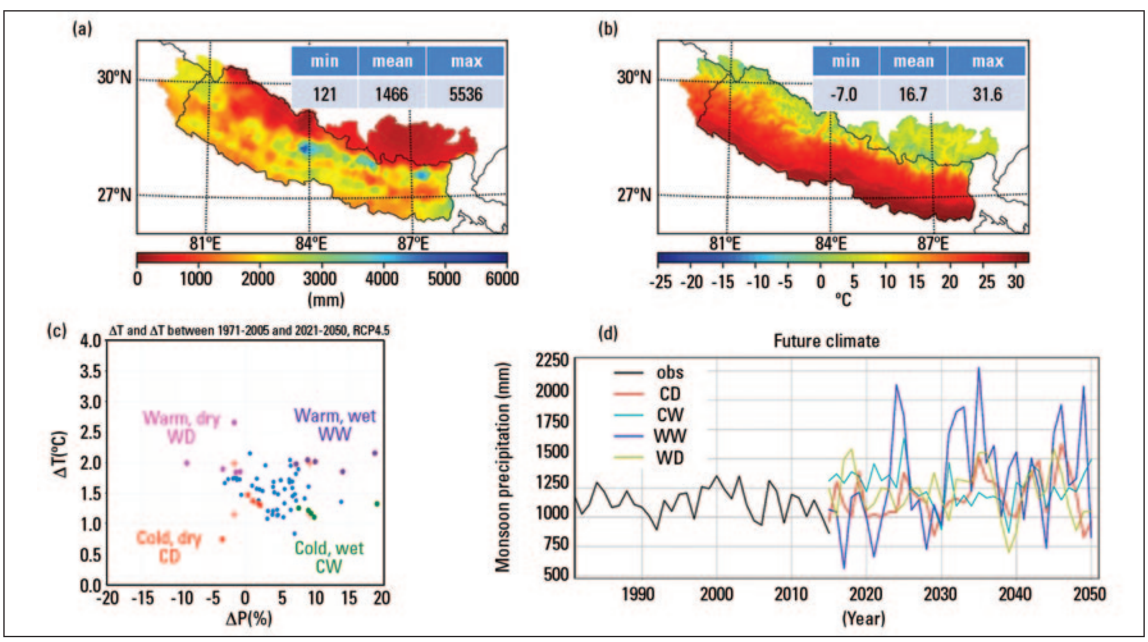


Fig. 2. Current climate for Nepal: annual precipitation and average monsoon temperatures (a and b) and future climate projections (c and d).

The webinar corrected an unintended, but misleading, generalization of the impact of the melting of glaciers on water availability in Nepal's rivers. The presentation by Divas Basnyat, and supported by his co-presenters, underlined that Nepal's rivers are actually generally reliant for most of their annual flows on rainfall. Located in the upper catchment of the Ganges river system, in the eastern Hindu-Kush-Himalaya region, the precipitation in the river basins of Nepal is largely influenced by the Indian Summer Monsoon, with about 80 per cent falling within the four wet months, which typically extend from June through to September, Basnyat noted. "At the river-basin scale, in the eastern Hindu-Kush-Himalaya (HKH) basins (Ganges and Brahmaputra Basins), glaciers play a relatively small role in annual surface runoff", he said, [Wester *et al*., 2019[1]]. "Unlike the upper Indus Basin where 40.6 per cent of the total runoff is from glacier melt, glacier melt contribution is only 11.5 per cent of the total runoff in the Upper Ganges Basin owing to a rain dominated runoff regime [Lutz *et al*., 2014[2]]. The contribution of glacier and snow melt can be important in the smaller catchments located in higher elevations near glacier and snow sources, but it reduces significantly downstream in the mid- and lowlands, where most hydropower sites are located," he said. "A closer look at the hydrograph of the river flows of Nepal reveals that glacier melt starts in May-June and continues to around November, because of the favourable warm temperature at the high elevations of the catchments. During these months, the rainfall runoff is already much higher than the glacier melt, so any future loss of glaciers will have insignificant impacts on water availability. As there is no evidence of any substantial decrease in the Indian Summer Monsoon in the future, there is no reason to worry about reduced water availability in the Nepalese rivers," he added.

"Why would we still develop hydropower when the glaciers are shrinking and snow melt is going to decrease?" asked Prof Immerzeel. He continued, "I think there are definitely a number of good reasons to do that. It is not only about glaciers and ice melt, but also about rainfall. There are different contributors to streamflows for the main river systems such as the Indus, Ganges and Brahmaputra basins. Particularly in Nepal, most large rivers averaged over the entire year are really mostly rain-fed. It is really the rain that matters, and it is about how climate change will affect the rain patterns, which is probably the key to understanding the impacts on hydropower development," he said. "Second, glaciers are shrinking, but they are also melting at a more rapid rate per unit area, so even though the total ice volume is gradually declining, the amount of meltwater that is being generated by the glaciers will rise for a few more decades to come and then slowly start declining".

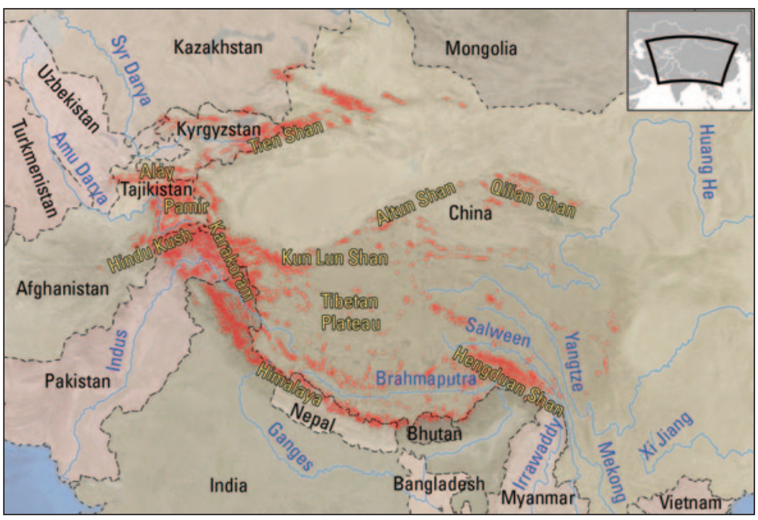
Various global and regional studies that have been undertaken, including one on the Langtang river basin in Nepal and the Baltoro in Pakistan, show that the total amount of glacial melt across the whole Himalayan region will only start to decline by the end of the century, he added, although more localized effects are expected to start sooner. "A number of larger and smaller hydrological impact studies, which we have undertaken, project a slight increase in overall water availability in various major river basins in Asia up to 2050. In some basins, a reduction in glacial melt is being compensated by an increase in rain runoff and in others there are trade-offs between snow and glacial melt and snow and rain runoff. Basically because of the trade-offs between the different components of the hydrograph, you see only a minor increase in terms of general water availability. This is good news for hydropower development in future," Immerzeel explained.

When glaciers and snow melt matters

Most of Nepal's existing and future planned hydropower plants are peaking run-of-river facilities located at lower altitudes with minimal or no storage capacity. As a result, there is substantially more generation during the wet season, which typically extends from June to September. As previously mentioned, at present the precipitation in the river basins of Nepal is largely influenced by the Indian Summer Monsoon, with about 80 per cent of the precipitation falling in the four wet months. Glacier melt, meanwhile, typically enters rivers from May or June to around November, which currently has no impact on hydropower production, as the facilities have more than enough water flow at this time of the year. Lower production in the dry season is, meanwhile, largely dependent on snow melt and groundwater base flow. According to Basnyat, the ratio of dry season and wet season production varies from a little less than 20 per cent to 70 per cent for run-of-river projects, depending on the dependability (exceedance probability) of the design discharge, and from 20 per cent to almost 100 per cent for storage projects, depending on the live storage capacity. However, should glacial and snow melt occur earlier in the year, preceding the arrival of the wet season, as a result of rising temperatures, the impact on the economic viability of hydropower production would be significant, according to the climate experts.

The findings of studies being carried out to evaluate five capacities, from 335 MW up to 2000 MW, for the Upper Arun project in northeastern Nepal by Prof. Patrick Ray with colleagues from the University of Massachusetts, Cornell, and the University of Cincinnati, on behalf of the World Bank, support this scenario. For Ray, the key factor for Nepal is how glacier and snow melt are going to impact the seasonality and long-term sustainability of stream flows in river basins, and as a consequence hydropower production. The studies have involved an analysis of 20 years of streamflow in the Arun river basin (from 1985 to 2005), which

Fig. 3. The area of focus, the Himalayas.



is convertible to hydropower potential in GWh/year, following steps laid out in the Climate Change Decision Tree, which Ray helped develop for the World Bank in 2015. Development of their own statistical models for climate change or 'weather generators', allowed the team to control the experiment, resampling and reinterpreting historical climate data to make "a fairly systematic structured evaluation of climate change risks and then assign likelihoods to those risks based on the bulk of climate science from the most recent Intergovernmental Panel on Climate Change GCM models". On the basis of their climate scenarios, the researchers then carried out a climate risk assessment on water infrastructure, including hydropower, and ran it through a hydrological model they had developed to include a glacier component. Finally, the data were put through "a very simple run-of-river conversion with hardly any storage, converting that stream flow to hydropower potential" to generate a climate response surface, and make it possible to determine the climate change scenarios that are acceptable and not acceptable for the project. The hydrological model with a glacial component is a really important part of what the research results mean, Ray explained, because these results shows when the glacier might melt down and when it might run out, and how the seasonality of glacier and snow melt impacts the viability of hydropower production from this basin. "The result is that we are projecting a lot of the snow and glacier melt happening in April and May, then a bit in June and in March," he said, though adding that it is hard to partition snow from glacier melt from precipitation stream flow and groundwater-fed base flow.

"Because we don't measure the source contributions directly (which would typically require in situ dye tests or isotope trails), it is difficult to know how much of the non-precipitation-fed streamflow comes each month from each of the other sources: glacier, snow, or groundwater. Snow and glacier melt become a significant contribution to streamflow when the surface temperature at the location of the snow and glacier increases above 0°C. Let us assume that has historically happened at the location of the glacier feeding the Upper Arun river every year in about April or May (and then stayed above 0 °C through the summer and into the autumn). If this happens earlier in the year than it has in the past, then it will really impact the profitability of hydropower. Hydropower produced in March is worth nearly double per unit the selling price of hydropower produced in April. Power purchase agreements (how much the Nepal Electricity Authority, the country's state utility, is willing to pay to purchase electricity from its suppliers) prioritize dry season hydropower and that has a huge impact on the economic and financial consequences of hydropower production in this basin," Ray said.

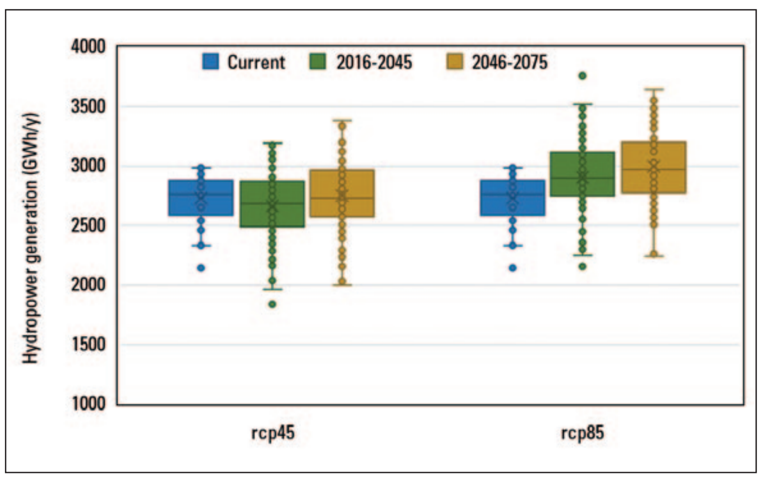
Ray, who had previously studied a 335 MW project for Upper Arun in 2015-16, added that the seasonality of river flow is also important for the capacity of the project. "The larger the installed capacity, the smaller the fraction of the year you are producing at capacity, so there is a trade-off between the amount of hydropower you could produce in the summer (when maybe you do not need it so much because every other hydropower facility in Nepal is also producing at full capacity in the summer) versus how efficiently you can use your capacity in the winter dry season," he said. "The larger the installed capacity, the greater the potential to produce large amounts of hydroelectricity in months when there is sufficient streamflow. But larger capital investments are required to develop that larger production capacity, so the key question is what is your ability to maximize your revenues during high-value dry season flow months to justify what would be larger capital investments? The question becomes very interesting if the flow is increasing (because of earlier snow melt, monsoon shifts, or any other reason) in those months that were historically labelled 'dry season'. The results of our analysis caused us to think that maybe we do not want to be at the extreme at either end (very large capacity or very small capacity) and that the 'sweet spot' is maybe a design size of around 1000 MW," he added.

Rising temperatures and higher profitability

While climate experts expect, with varying degrees of certainty, slightly higher precipitation on average in the future, general circulation models (GCMs) from the most recent Intergovernmental Panel on Climate Change (IPCC) ensemble and others project temperatures to rise somewhere between 1 and 3°C over the next 20 years or so. This will, according to Ray, have a positive impact on the profitability of hydropower. From the studies carried out in 2015-16, and employing a baseline historical climate with 100 per cent precipitation (one times the historical baseline precipitation with zero change in temperature) the original planned project of 335 MW in Upper Arun could be expected to generate a profitability of around US$ 500 million over its lifetime, which is in line with what was projected by the project designers, said Ray. The project, however, becomes more profitable in the scenario where temperature rises, but precipitation remains unchanged, he added. He explained "We are projecting only to the middle of this century, but as temperatures increase we will have more melt during high-value spring months, and so much more melt that it overcomes the increase of evapotranspiration. That additional melt from the glacier, as long as the glacier remains viable, means more stream flow and thus greater ability to make more profit from selling hydropower".

But what about other kinds of uncertainties? "All these uncertainties (climate change and precipitation; change of temperature; economic lifetime, plant load factor, capital cost, selling price, discount rate, and so

Fig. 4. Assessment of hydropower potential.



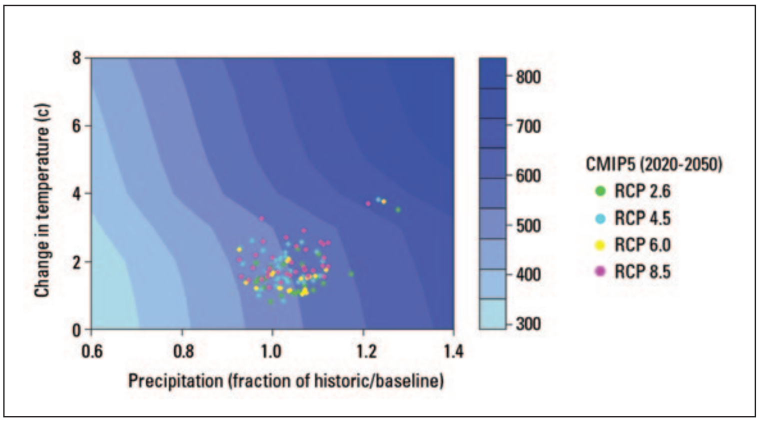


Fig. 5. Net present value (millions of US$) for a 335 MW capacity design [Ray et al., 2018[6]]

on) go into the net present value. Just selecting all climate change uncertainties but holding everything else at baseline values we project an uncertainty of something like US$ 300-800 million, which is exactly the same uncertainty of potential profitability", (see Fig. 5).

"What are the uncertainties that really impact the performance of this project and put us in a risky situation? We can evaluate, for example, changing the economic lifetime. For instance, what happens if there is an earthquake and it destroys the infrastructure and that the plant will not have its design lifetime. It does not really have an impact on the net present value uncertainty, because it has a discount rate, and discounting future values anyway and the way we evaluate the net present value does not have a huge sensitivity to how long the project lives, as long as it lives for 15-20 years. Capital costs, such as construction costs, are hugely uncertain. The uncertainty of the selling price also has a huge impact on the uncertainty of the profitability of the project, which tells us that we should make sure not to over-focus on the climate change question, and look also at these other uncertainties, which are really driving uncertainties for this project. Most recently we have been evaluating the possibility of building a 1000 MW project instead of a 335 MW one, as there seems to be real opportunities to profit from additional stream flows over the next 20-30 years. This is a preliminary indication of the hydropower that could be produced by a larger facility. The larger facility faces different kinds of risk, but the hydropower potential is good, especially taking into account seasonality questions," he said.

Inter- and intra-annual variability and seasonality

"The next step we have to be careful about is the thermodynamic question of how climate change could change inter- and intra-annual variability and seasonality. Clausius Clayeron Scaling could increase the flood risk, meaning that the atmosphere of moisture holding capacity could result in larger floods in the basin, which could damage the structure, and it certainly could impact glacial lake outburst floods (GLOFs)," Ray said. "Potential changes to inter-annual variability and drought may be related to ENSO (El Niño Southern Oscillation) behaviour, and this could impact drought periods when there is low hydropower production for a period of, say, five consecutive years. This would be a major problem and is something we have got to concern ourselves with. In conclusion, climate change speeds up the hydrological cycle, leading to changes in variability and long-term rainfall means. We have a pretty good handle on the questions of sustainability and long-term (rainfall) means, but a less confident handle on the variability question. This is what we are really prioritizing now: the questions of variability, seasonality, floods and droughts and how changes to inter- and intra-annual variability would impact on the viability of this project both in terms of its profitability, and its role in supporting a whole sector of electricity generation in Nepal".

Geohazards should not be overlooked

The uncertainties about variability, seasonality and geohazards were also raised by the other presenters. On the subject of natural disasters, Prof. John Reynolds called on hydropower developers to consider the scale and complexity of natural hazards, many of which occur in Nepal and the wider Himalayan-Hindu Kush-Karakorum region, with devastating impacts. "When we talk about managing risk, we have to come back to the geological and hydrological aspects, and then think

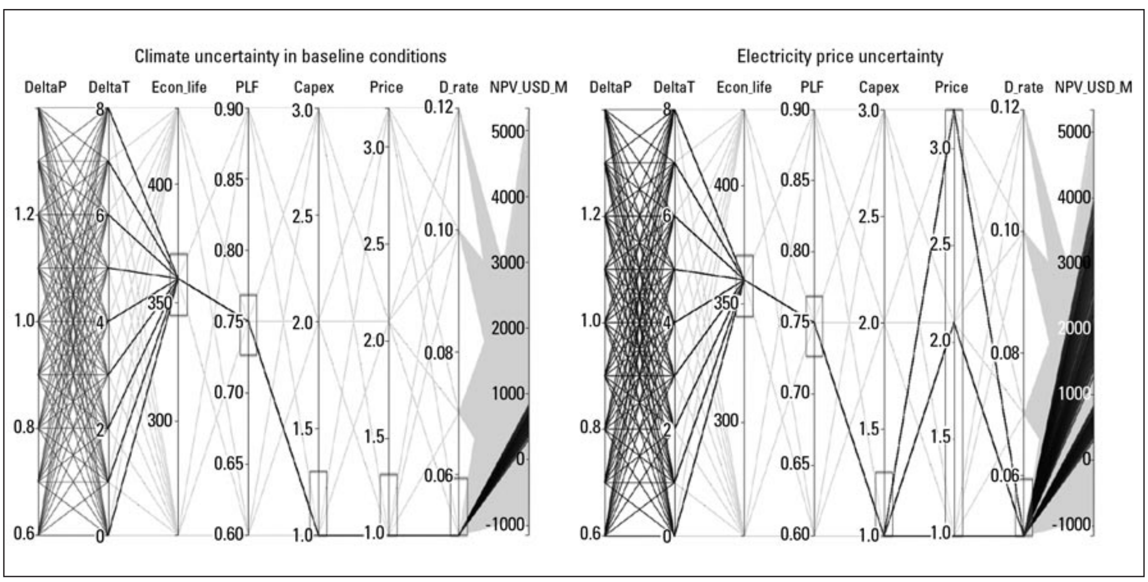


Fig. 6. Model output of climate and price uncertainties [Ray et al., 2018[6]]

about how these all relate in varying degrees to generating possible disasters," he said. "The difficulty is that so often in the hydropower sector, people tend to look at what is an earthquake, a landslide, a GLOF, a cloudburst, without recognizing that the causality of the devastation is often a complicated compound cascade of multiple processes that are both hydrological and geological."

To address these deficiencies and assess risk, Reynolds has, with the World Bank, developed an Integrated Geohazard Assessment protocol, which builds on existing studies that are typically undertaken for hydropower projects, such as seismic risk analysis, due technical baseline reports, GLOF assessments and hydrological risk analysis. He described this as "a mechanism by which we can improve our risk registers and develop a disaster risk management action plan". Reynolds continued: "One of the other benefits is that a hydropower company that does this kind of integrated geohazard assessment is likely to be able to obtain a substantial discount to its annual insurance premium if it is shown to be able to identify the hazards and what their action plan is for those hazards".

Reynolds also sought to set straight misconceptions about glacial lakes and the risks of GLOFs: "The first thing I want to stress is that glacial lakes and moraine dams are generally stable and have been around for many years, and they have survived many earthquakes," he said. "Second, earthquakes do not generally trigger GLOFs. There is no correlation between earthquake activity and GLOF occurrence. The other thing is that the rapid growth area of glacial lakes is not a contributory factor in the triggering of GLOFs". Reynolds continued: "As glaciers become thin and retreat, glacial lakes grow, storing much of the glacier melt so that only the excess over a lake's storage capacity enters the river system. Increased glacier shrinkage will result in the formation of more glacial lakes and more lake storage, as existing and future lakes grow, by filing the space vacated by the retreating glaciers. For decades in Peru, for example, such natural reservoirs have also been used to augment artificial water supply systems for irrigation and hydropower. There is no real reason why the same approach could not be adopted in Nepal, particularly to augment dry season flows, and there are already a couple of glacial lakes in Nepal where this is being considered".

In conclusion, Prof. Reynolds stressed the need for an integrated and coordinated cross-border approach to the management of geohazards, sediment and water resources, as the major rivers in the region originate in Tibet in China, before crossing the Himalayan mountains and Nepal. As an example, he explained how the destruction of the Upper Bhote Khosi headworks and powerhouse, in June 2016, had originated from a cloudburst in the southern part of Tibet and the autonomous region of China, and north of Nepal. "The challenge to the Upper Arun hydropower project is the management of the entire river system from the headwaters in Tibet in the Pum Qu, through Nepal, and then downstream through northern India into Bangladesh and ultimately into the Bay of Bengal," he said. This includes not only the water flow but also sediment and geohazards.

Prof. Immerzeel commented: "The big challenge is not only to look at the average water availability in the future but also to look at how natural hazards will increase and how they could potentially impact hydropower and dams and how seasonality is going to change because while average annual water supply may remain constant, how that is distributed over the year may change significantly," said Immerzeel, noting the shifts in water supply over decadal, yearly and daily time scales as presented in a special report on oceans and cryospheres published by the IPCC last year (see Fig. 7). "As glaciers and snow retreat, the hydrological system will be "faster" that is to say a drop of rain will end up in the river quicker. Therefore the system becomes more susceptible to extreme precipitation events with the likelihood of higher peak flow in particular, and this is likely to see increased sedimentation and erosion rates," he added.

Three-pronged approach

"Current climate and hydrological variability, spatially and temporally within the year and from one year to another, is always a major challenge for the development of hydropower in Nepal," said Basnyat. "Hydropower projects are traditionally designed based on historical hydrological data (streamflow in the river), ideally of 30 or more years. However, due to climate and other land-use changes, future hydrology will be different. Hence, it is important to know what the future hydrology will be like and to design hydropower projects based on the new hydrological condition," he added.

"Such climate and hydrological uncertainty does not mean that future hydropower development is not economic or safe. What it means is that their design needs to recognize the uncertainty of changes in the climate and hydrology in the future. There is thus a need for a three-pronged approach to mitigate climate change risks: first, to design and retrofit current projects with low-regret measures that address current variability and provide resilience for the future; second, to start

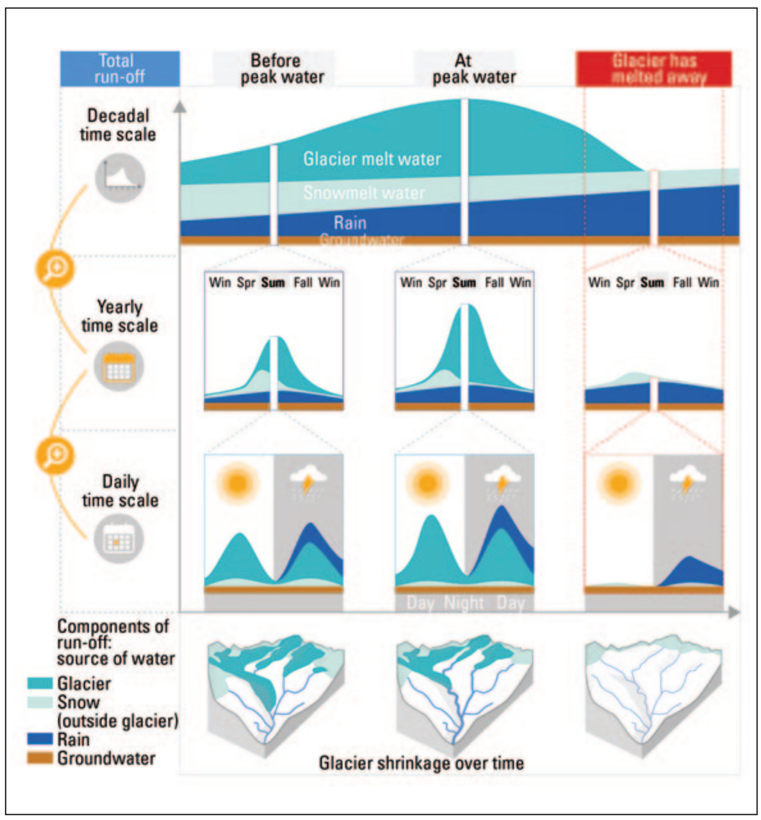


Fig. 7. Temporal changes in runoff [IPCC, 2019[5]].

climate smart planning into plants to be built in the next ten years; and, third, to start planning for future risks by investing in monitoring and research, and learning to help decision-making," Basnyat concluded. [NDRI, PAC and GCEP, 2016[3]]. ◊

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Webinar speakers

Divas B. Basnyat coordinates the Water and Climate Programme of the Nepal Development Research Institute (NDRI), a policy research think tank in Nepal. He is a member of the team preparing the river basin plans and the hydropower master plan of Nepal, funded by the World Bank. His recent research and consulting work has focused on climate resilience of the hydropower and water resources sectors in several countries in Asia and Africa, covering various climate regimes. He has carried out climate risk assessment and impact studies using both the conventional top-down approach based on global climate data as well as the bottom-up decision scaling approach. From August 2018 to 2019, he was an International Climate Change Specialist for Lahmeyer International, contributing to 'Preparation of River Basin Plans and Hydropower Development Master Plans', a World Bank-funded project.

Patrick Ray is an Assistant Professor of Environmental Engineering at the University of Cincinnati, USA. He is a specialist in the development and application of numerical models of the integrated hydro-economic system for risk management under the uncertainty of climate (and other) change. He was lead author of the World Bank's 2015 'Decision Tree for Confronting Climate Uncertainty in Water Resources Planning and Project Design', and a primary scientific contributor to the IHA's 2019 'Climate Resilience Guide', the California Department of Water Resources' 2019 'Climate Change Vulnerability Assessment', and UNESCO's 2018 'Collaborative Risk Informed Decision Analysis'. He is a past chair of the Environmental and Water Resources Systems Committee of the American Society of Civil Engineers, and was recognized in 2018 as the A. Ivan Johnson Outstanding Young Professional of the American Water Resources Association.

John Reynolds is the Managing Director of Reynolds International Ltd and is recognized as a global leader in glacial hazard assessment and mitigation, with experience over the last 34 years from South America (Peru and Chile), Scandinavia, Himalayas (Nepal, Bhutan, Tibet/China), Hindu Kush Karakoram (Pakistan), and the Tien Shan Mountains (Kyrgyzstan). He has been responsible for successful mitigation works in Peru and pioneered engineering remediation of a major glacial lake in Nepal, a world first.

Walter Immerzeel has 20 years' experience in geo-informatics, water resource management and climate change, and is skilled in hydro-meteorological monitoring, the use of remote sensing, simulation models and spatial analysis. He has been doing research on Himalayan hydrology since 2002. He holds a PhD in physical geography from Utrecht University, The Netherlands, and he is a leading scientist on the interface of mountain hydrology, climate change and agriculture, with a particular focus on the Himalayas. He currently works as Professor of Mountain Hydrology at Utrecht University where he is leading a number of projects on the cutting edge of climate change, glaciology and hydrology.

Nagaraja Rao Harshadeep is a Lead Environmental Specialist in the Environment and Natural Resources Global Practice of the World Bank, and is leading efforts to promote sustainable multi-sectoral development approaches in a spatial context. During more than 19 years at the Bank, he has led, or been part of, a range of environmental, water, and other natural resources projects and studies, primarily in Africa, South, Central and East Asia. This has included work on integrated watershed and basin approaches, climate resilience, international waters (including the Aral Sea, Nile, Ganges and Brahmaputra), pollution, water and environment institutions, irrigation systems, biodiversity and environmental assessments. He also leads several activities at the Bank related to the use of innovative analytical tools (GIS, modelling, decision support systems), modern hydromet services, and mobile Apps (for example, 'Spatial Agent' to promote public domain open data access).