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ADVANCED REVIEW

Climate change and the hydropower sector: A global review

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Abstract

Renewable sources of electricity, such as solar and wind, need to be paired with sources of reliable baseload. Hydropower is a renewable, low-emission source of electricity baseload available throughout much of the world as an alternative to electricity conventionally provided by thermal combustion of fossil fuels; however, the global hydropower sector as it stands relies upon surface water flows of substantial and predictable volume. This makes it vulnerable to climate change. The impact of climate change on the hydropower sector is difficult to predict, and not globally uniform. It might be positive, negative, or inconsequential depending upon the local timing and magnitude of changes, reservoir size, allocation priority, and the energy market. The secondary effects of climate change on glacier lake outbursts floods, landslides, and sediment load are poorly understood. In addition, when planning hydropower projects for the future, attention must be given to the greenhouse gas contribution of the impounded waters behind storage dams, and the impact of dams on water temperature. In the past decade, sovereign nations and international development agencies worldwide have evaluated the potential of hydropower as a cost-effective, clean, sustainable option for baseload electricity supply. There is therefore a crucial need to assess the opportunities and risks hydropower poses across a wide range of potential future climate conditions. This review paper conducts a global survey of the literature on the effect of climate change on hydropower and identifies room for improvement in current approaches to evaluation of the net benefits of hydropower projects under climate change.

This article is categorized under:

- Vulnerability and Adaptation to Climate Change > Learning from Cases and Analogies
- Assessing Impacts of Climate Change > Evaluating Future Impacts of Climate Change

KEYWORDS

climate change, future uncertainty, hydropower, international practice, review

1 | INTRODUCTION

1.1 | The global role of hydropower

Hydropower is the world's largest source of renewable energy, supplying nearly 16% of global electricity demand (IHA, 2019a). Hydropower meets at least half of the national electricity demand in over 35 countries and contributes to more than 90% of electricity generation in Bhutan, the Democratic Republic of the Congo, Ethiopia, Lesotho, Mozambique, Nepal, Norway, Paraguay, Zambia, and the Canadian province of Quebec (World Bank, 2015). Global hydropower capacity is increasing on average at the rate of 2.1% per year since 2015 (IHA, 2020a). The International Hydropower Association (IHA, 2020a) estimates that had the energy generated by hydropower in 2019 been generated by coal combustion instead, an additional 80–100 million metric tons of carbon would have been emitted. The International Renewable Energy Agency (IRENA, 2020a) suggests that 850 GW of new hydropower capacity will be needed by 2050 to limit global temperature increase above preindustrial levels to below 2°C. Figure 1 presents the location of existing hydropower projects (Global Energy Observatory, 2018), the location of planned hydropower dams (Zarfl et al., 2015), and the contribution of hydropower to the energy mix in each country (World Bank (2015), updated with data from IHA (2020b) for Asia and Latin America.

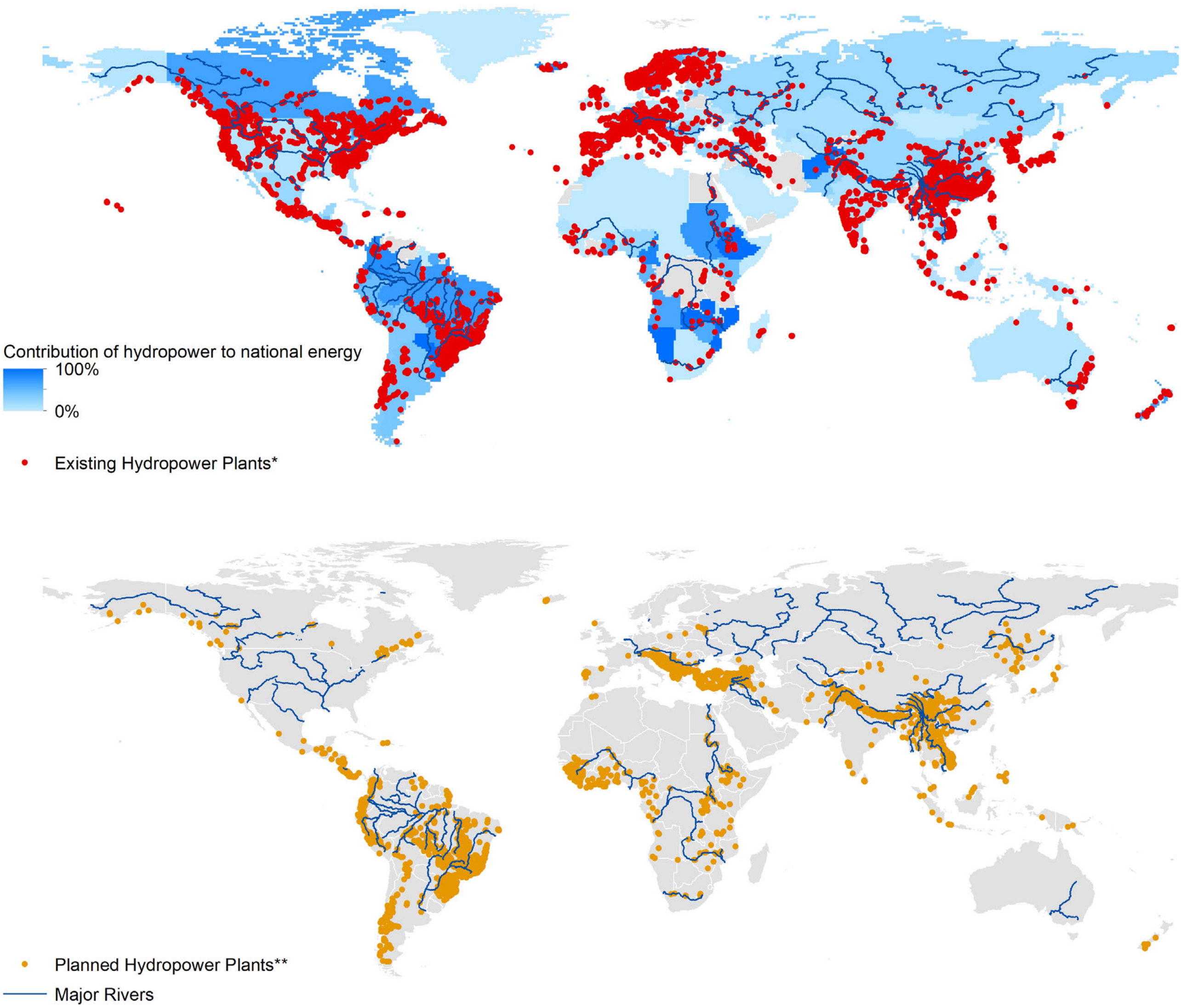

FIGURE 1 Contribution of hydropower to the national energy mix (World Bank (2015), updated with data from IHA (2020b) for Asia and Latin America. Locations of existing hydropower plants are shown as red dots (Global Energy Observatory, 2018). Locations of hydropower plants planned for completion by 2030 are shown as orange dots (Zarfl et al., 2015)

1.2 | Hydropower as an option in a diverse energy portfolio

Levelized Cost of Energy (LCOE), a measure of the unit revenue that must be recovered over the economic life of a facility to offset its costs, is lower globally for hydropower facilities than for fossil-fuel-fired thermal combustion facilities (IRENA, 2020b). Estimates of LCOE tend to be uncertain (see Braeckman et al., 2020), and they depend on many factors (e.g., size of the hydropower project). In 2018, the LCOE of hydropower was US$0.047 per kWh, making it the lowest-cost source of electricity in many markets (IRENA, 2019). Though relatively less expensive than thermal power plant options, concerns regarding hydropower investments include the possibility of large capital expenditures, the displacement of people and wildlife (Baxter, 1977; Cushman, 1985; Richter et al., 2010), interference in natural flow regimes (Kuriqi et al., 2021; Ward & Stanford, 1995), and ongoing investments in sediment management throughout the lifetime of the project (Gabbud & Lane, 2016; Kondolf et al., 2014).

As the world transitions to a cleaner energy future, electricity contributions from sources of renewable energy other than hydropower are increasing. Currently, hydropower produces 60% of global renewable energy. The relative contributions of wind and solar to the total of all renewables reached 9% in 2020, doubling in value from 2015, with biomass and other renewables contributing the remaining 31% (IEA, 2020a). With strategic reservoir operation, hydropower provides a stable baseload of energy supply, which complements the intermittency of solar and wind (Jurasz et al., 2018; Wang et al., 2019). Opportunities to efficiently combine hydropower with other sources of renewable energy are abundant. For example, floating solar panels on multipurpose or hydropower-specific reservoirs (Ferrer-Gisbert et al., 2013; Sahu et al., 2016) can maximize energy harvest at a local scale. Wind and solar generation can be operated in concert with patterns of hydropower production to optimize system-wide electricity transmission at a regional scale (Dujardin et al., 2017; Kies et al., 2016).

1.3 | The contribution of the hydropower sector to climate change

From the perspective of life cycle analysis, there is no greenhouse gas (GHG)-free option for electricity generation. In the case of the hydropower sector, more than 80% of GHG emissions are associated with construction, for example, the production and transport of materials (especially concrete), and energy usage during the construction process (Pehl et al., 2017). For projects not involving the establishment of a large reservoir, postconstruction emissions are minimal. For large reservoir-based projects, the impounded water may release carbon dioxide (CO_2) and methane (CH_4) into the atmosphere by aerobic and anaerobic decomposition of organic matter. The factors governing the rate of decomposition are site-specific and depend on nutrient content, water quality, air temperature, wind speed, incoming light/radiation, the degree of thermal stratification along the depth of the impoundment (thermocline depth), and the shape of the reservoir. Tropical reservoirs with high levels of organic material for decay, warmer water, and naturally productive carbon cycles are conducive to higher GHG emissions (Mäkinen & Khan, 2010), which would also occur in unaltered water bodies such as natural lakes. The emissions from reservoirs in tropical locations (e.g., Almeida et al., 2019; Räsänen et al., 2018) are larger due to warmer temperatures, and larger availability of easily degradable organic matter, than the emissions from reservoirs in temperate regions. In order to put GHG releases from various surface water bodies in perspective, Kumar et al. (2019) studied the emissions from a variety of Chinese fresh-water bodies and found CO_2 releases from rivers to be twice that of lakes, and four times that of hydropower reservoirs. Net emissions from the hydropower sector (as opposed to gross emissions) consider the pre-impoundment emission from the natural water body as well as any other sources of GHG emissions that were displaced with the construction of the reservoirs (Prairie et al., 2018). The median life-cycle emission from hydropower is between 18 and 24 g CO_2-eq/kWh, which is less than emissions from gas, coal, biomass, or geothermal (IHA, 2018b).

1.4 | The current dependency of the hydropower sector on rivers

At present nearly all of the world's hydropower is river-based. To generate hydropower from a river, either the river is fully dammed (storing seasonal or annual water supply) or used with minimal obstruction in the flow of the river, an approach referred to as run-of-river (RoR) hydropower. Generally, for RoR projects the design discharge is chosen by studying the flow duration curve of the river and optimizing either the generated energy or the return on the financial investment (e.g., Anagnostopoulos & Papantonis, 2007; Basso & Botter, 2012). Sometimes, RoR projects may include relatively small impounded ponds to serve demands at hours of peak electricity demand within a day.

There are alternative methods for hydropower production not directly relying on river flow. Pumped storage hydropower and coastal hydropower are two examples. In pumped storage hydropower water is pumped from a lower reservoir to an upper reservoir when demand (and/or electricity price) is low, and the energy stored in the upper reservoir is used to meet the peaking demand. When pumping is accomplished using solar or wind power, pumped-storage hydropower projects present opportunities for effectively harnessing renewable energy. Though ambitious new investments are planned, currently only 158 GW (12%) of the world's hydropower uses pumped storage (IHA, 2020a). In addition although hydrokinetic electricity generation technologies based on harnessing the energy of tidal waves are promising (Astariz & Iglesias, 2015; Laws & Epps, 2016), their current contribution to global energy is limited.

1.5 | The organization of this review

Previous review papers have studied the impact of climate change and variability on global energy production, generally (e.g., Cronin et al., 2018; Emodi et al., 2019); renewable energy production, specifically (Berga, 2016; Engeland et al., 2017; Solaun & Cerda, 2019); and energy systems in Europe (Stanton et al., 2016) and the United States (Craig et al., 2018). This review paper is structured similarly to previous global reviews (e.g., Cronin et al., 2018; Emodi et al., 2019), which organize findings according to region. While these previous two global energy sector reviews provided higher-level insights of relevance to the hydropower sector, this paper provides a targeted, detailed examination of the impacts of climate change on the hydropower sector, specifically.

Other studies have reviewed the effect of climate change on hydrology and hydropower at a regional/local scale (e.g., Falchetta et al., 2019; Sample et al., 2015; Schaefli, 2015; Wang et al., 2014), or assessed the change in gross hydropower potential under climate change (e.g., Hamududu & Killingtveit, 2012; van Vliet et al., 2016).

None of these previous studies has provided a global overview of the reported (observed) impacts on the hydropower sector from climate change to date, or a synthesis of the projected (simulated or otherwise anticipated) future impacts on existing and planned hydropower facilities. In this paper, we: (1) conduct a global survey of risks to the hydropower sector from hydrologic changes of various kinds under climate change and organize findings by region; (2) describe the primary mechanisms by which the hydropower sector is impacted; (3) discuss the room for improvement in existing approaches to the quantification of climate change risk to hydropower projects (or hydropower cascades); and (4) identify the need for further research.

1.6 | Literature review method

Following a semi-systematic review approach (e.g., Cronin et al., 2018), we began by reviewing references cited within previous global and regional subject-relevant reviews. Individual case studies were then sought with the combination of the keywords, "Hydropower" (hydroelectricity/dam/reservoir/energy), "Climate Change" (climate variability/future/warming/climate projection), and "Hydrology" (streamflow/snow/glacier/climate/ice) in "Web of Science" and "Google Scholar," with emphasis on articles published in the last decade (post-2010). The search results were then filtered to the locations of existing and planned hydropower projects (Figure 1), with emphasis placed on headwater basins. For comprehensiveness, reports, white papers, and websites of hydropower-sector organizations (e.g., IRENA, IHA) were also included. To prevent bias toward a particular climate model, only those articles whose results were based on more than one climate model, and multiple emission scenarios, were included.

2 | A GLOBAL SURVEY OF THE IMPACT OF CLIMATE CHANGE ON THE HYDROPOWER SECTOR

In this section, we present a global survey of the impact of climate change on existing and planned hydropower projects, sorted first by continent, and further by subcontinental similarity in hydro-climate or hydro-politics (Figure 2).

For each region, we first summarize the historical observations and then present projected near-future impacts (by approximately mid-century). Quantification of the impact of possible future climate change on any given

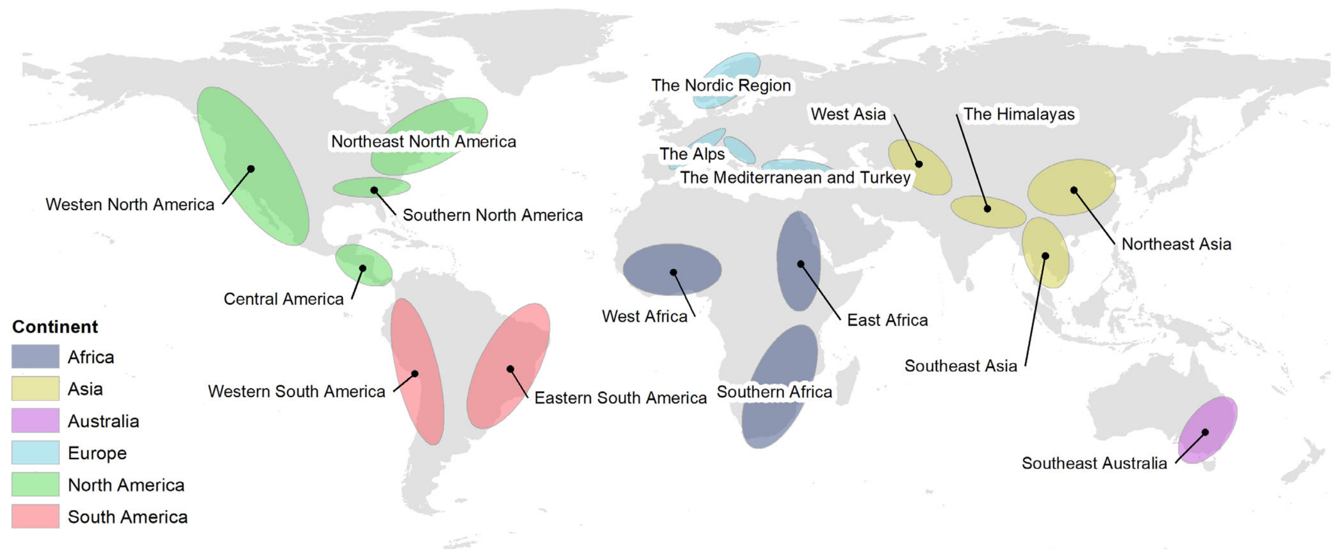

FIGURE 2 Regions of the world as relevant to the discussion of risks to hydropower from climate change

TABLE 1 Summary of the number of papers surveyed and the effect of climate change by region

S/No	Climate Change Effect	Africa	Asia	Europe	North America	Latin America	Australia	Total
1	Glacier Melt		9	3		3		15
2	GLOFs		2					2
3	Earlier Snowmelt		3	6	3			12
4	Extreme Precipitation		1		2			3
5	Increased Precipitation	3	1	2	2	2		10
6	Increased Streamflow	1	3	2	1			7
7	Floods	2	2		2			6
8	Increased Variability	6	6		1	1		14
9	Decreased Precipitation			1	1	2		4
10	Decreased Streamflow	1			3		1	5
11	Droughts	1	2	4	3	2	3	15
12	Inconclusive	2	8	1	1	1		13
	Total	16	37	19	19	11	4	106

hydropower project is subject to a cascade of uncertainty (discussed in Section 4) that includes estimates (models) of climate, hydrology, river allocation priority, energy markets, and governmental factors such as transboundary politics. For instance, in the event of a drought, one of the following could result for the hydropower facility equipped with storage capacity: (a) perhaps hydropower generation decreases only as a function of streamflow, and ceases entirely when reservoir levels fall below intake structures; (b) perhaps hydropower generation decreases nonlinearly due to priority municipal and agricultural demands; or (c) perhaps hydropower generation does not decrease at all because it holds allocation priority, and deficits are distributed to other sectors. These nonobvious outcomes are dependent on allocation policy at a local level, the detailed discussion of which is beyond the scope of this paper. Summarizing the global survey, four key mechanisms of climate change that affect the global hydropower sector are presented in Section 3.

The global survey is presented in the following sequence: Asia, Africa, North America, Latin America, Europe, and Australia. Of the 284 references in this paper, 106 provide evidence of climate change effects (observed or projected) relevant to the hydropower sector. A summary of the number of papers surveyed and the effect of climate change by each region is presented in Table 1. In Figure 3, the dominant effects of climate change on hydropower generation in each region are illustrated with symbols, arrows (up for increasing, down for decreasing), based on the frequency of

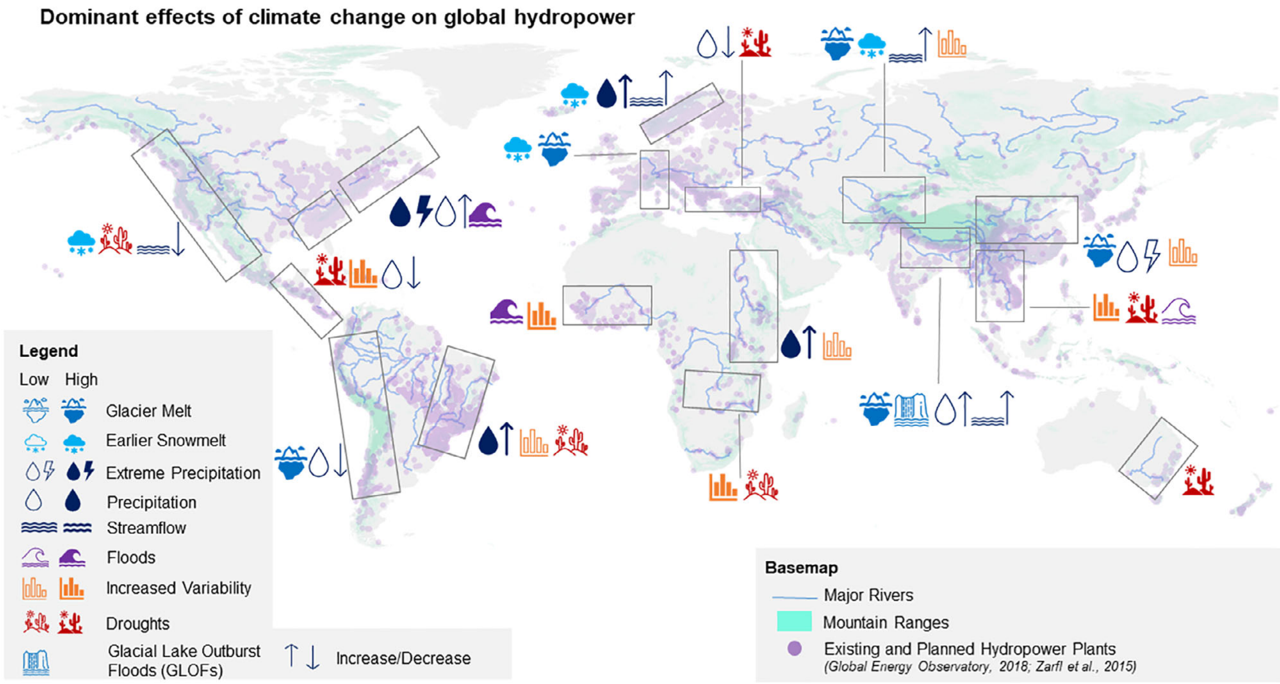

FIGURE 3 The effect of climate change on global hydropower generation, based on observed trends and near-future projections. The effects are indicated by two levels of symbols: high and low. Generally, if a climate change effect is discussed in more than 50% of the review papers for the region, a "high" symbol (filled in) is adopted. Also shown are the major rivers (blue lines), mountain ranges (cyan hue), and the location of existing and planned hydropower plants (purple dots) (Global Energy Observatory, 2018; Zarfl et al., 2015)

reference and magnitude of impact in the cited literature. Generally, if a climate change effect is discussed in more than 50% of the papers reviewed for the region, a solid symbol (high confidence) is adopted, and if it appears in less than 50% of the cited literature, a hollow symbol (low confidence) is adopted.

2.1 | Asia

Many of the river systems in Asia originate from high-altitude mountains rich in snow and glacier. Although estimates of the relative contribution to runoff vary slightly in the high Asian basins (Armstrong et al., 2019; Lutz et al., 2019; Siderius et al., 2013), glacier ice melt is a more significant source of water in Western High Asia (the Syr Darya, Amu Darya, and Indus basins) than in the central and the eastern Himalayas (the Ganges and Brahmaputra basins), where streamflow is dominated by the Indian Monsoon (Wijngaard et al., 2017). The East Asian River basins (the Mekong-Irrawaddy and Yangtze) receive moisture from both the Indian Monsoon and the East Asian Monsoon (Chen et al., 2014; Delgado et al., 2012).

2.1.1 | West Asia

The Tien Shan-Pamir-Karakorum and the headwaters of the Indus River form Western High Asia. Over the past few decades, catchments in this region with a higher fraction of glacierized area show increased summer (Unger-Shayesteh et al., 2013) and winter (e.g., Khattak et al., 2011; Sharif et al., 2013) runoff, while catchments with a lower fraction of glacierized area show increased interannual variation in streamflow (Deng et al., 2019). In the future, an increase in streamflow is projected with continued glacier melt and potentially increased precipitation; however, choices of GCM, climate change scenario and glacial melt model (Luo et al., 2018) heavily influence the magnitude of the projected increase. Some studies indicate that accelerated glacier melt may substantially augment streamflow through mid-century (e.g., Lutz et al., 2019; Soncini et al., 2015), whereas other studies suggest a net decrease in streamflow much earlier than midcentury (e.g., Duethmann et al., 2016; Sorg et al., 2014). Hydropower projects in the Amu Darya and the Syr Darya River basins are likely to face magnified flood risks with rapid snowmelt during summers (Kochnakyan et al., 2013), and worsening conflict between agriculture and hydropower water demands (Reyer et al., 2017). In the Indus River basin, hydropower production is likely to decrease in early summer (May–June) with declining snow cover and snow depth (Ali et al., 2018). This is summarized in Figure 3 as: glacier melt (solid icon for high confidence); earlier snowmelt (solid icon for high confidence); streamflow increase (hollow icon for low confidence); and increased variability (hollow icon for low confidence).

2.1.2 | The Himalayas

The hydrologic regime of the central and eastern Himalayas is characterized by wet summers with heavy monsoon precipitation and dry winters. In the Brahmaputra River basin, which originates on the north side of the Himalayan ridge, an increasing trend has been observed in streamflow coincident with increasing glacier melt (Liu et al., 2007) in the upper subbasins. In the Ganges River basin, which mostly originates on the south side of the Himalayan ridge, no significant trends have been observed in streamflow (1965–1995) in the upper subbasins (Gautam & Acharya, 2012). Significant changes in precipitation in the region have so far not been observed (Mirza et al., 1998; Mondal et al., 2015; Shrestha et al., 2017).

As of the Fifth Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC), GCM models had not demonstrated skill in the reproduction of Indian Monsoon processes (Roxy et al., 2015; Sabeerali et al., 2015; Saha et al., 2014). The monsoon precipitation in the Brahmaputra basin is projected to change between −20% and +50% by the end of the century (Ray et al., 2015) with a majority of the models projecting a strengthened monsoon (Kitoh et al., 2013) resulting in an overall annual increase in runoff (e.g., Ali et al., 2018; Lutz et al., 2019). These studies have not been updated with GCM output from the IPCC's Sixth Coupled Model Intercomparison Project (CMIP6).

Additionally, Himalayan hydropower projects face risks due to Glacial Lake Outburst Floods (GLOFs), potentially destructive dam-break floods that can occur by a sudden release of melted glacier water that has accumulated over time and is held precariously by terminal moraines or debris at the ends of glaciers (Richardson & Reynolds, 2000). With increased glacier melt since 1990, hundreds of new glacial lakes have formed in the Himalayas (Nie et al., 2017), though there does not appear to have been a significant increase in the number of GLOF events in the region between 1980 and 2017 (Veh et al., 2019). As newer hydropower projects are planned closer to the headwaters, the risks of GLOFs are projected to increase two to three times in the future (Schwanghart et al., 2016; Zheng et al., 2021). This is summarized in Figure 3 as: glacier melt (solid icon for high confidence); GLOFs (hollow icon for low confidence); increased precipitation (hollow icon for low confidence); increased variability (hollow icon for low confidence).

2.1.3 | Northeast Asia

The hydropower projects of Northeast Asia are concentrated on the Yellow River and the Yangtze River (see Figure 1), which are dense population centers in China. New megaprojects (total capacity of over 3000 MW) are planned on the tributaries of the Yangtze River: the Jinsha River and the Yalong River (IHA, 2020a).

The glaciated headwaters of both the Yangtze River and the Yellow River have experienced significant melting with increased temperatures in the past 30 years (Yang et al., 2003; Zhang et al., 2008). However, no significant trend has been observed in streamflow in the lower Yangtze, 1955–2011 (Chen et al., 2014), where the headwater effects are dampened by competing hydro-climatic processes. While temperature is projected to increase, the direction of change in the future precipitation is unclear (Li et al., 2008; Zhang et al., 2015), though extreme precipitation is projected to increase up to 34% by mid-century (Yuan et al., 2018). Analysis of existing hydropower projects on the Yalong River suggested that the projected increase in runoff variability in the future could be managed with modified reservoir operation (Zhao et al., 2021). Analysis of the changes in seasonality and reduction in streamflow volume along the Yellow River (1965–2017) shows that climate change accounts for less than 35% of the reduction in volume, with human activities (e.g., land-use changes, dam construction) accounting for over 65% (Zhong et al., 2021). This is summarized in Figure 3 as: glacier melt (solid icon for high confidence); extreme precipitation (hollow icon for low confidence); increased variability (hollow icon for low confidence).

2.1.4 | Southeast Asia

The river basins of the Salween, Red River, Chao Phraya, Mekong, and Irrawaddy are punctuated with many multipurpose storage reservoirs, with further plans for development (see Figure 1). The hydrological regime in the region is governed by monsoon precipitation that is influenced by the El Niño Southern Oscillation (ENSO), and GCMs are inconclusive on the direction of the projected change in precipitation in the future (Khaing, 2015; Thompson et al., 2014). The compound impact of future climate change, expansion of irrigation projects, and new hydropower development planned for construction by 2050 have the potential to modify the seasonality of the flow in the Mekong River (Hoang et al., 2019), and droughts are expected to increase in the future (Mekong River Commission, 2018). A study of the existing dams in the Red River indicated that both flood damages and water supply deficit are projected to worsen under climate change (Giuliani et al., 2016). Droughts in the region would reduce hydropower availability and increase reliance on thermoelectric resources, increasing GHG emissions (Chowdhury et al., 2021), which motivates investment in alternative options for sustainable energy generation such as solar power (Siala et al., 2021). This is summarized in Figure 3 as: increased variability (solid icon for high confidence); droughts (solid icon for high confidence); floods (hollow icon for low confidence).

In sum, for the short-term (through approximately mid-century) increased winter flow (observed in the western Himalayas) is positive for hydropower generation. In basins dominated by the summer monsoon (eastern and central Himalayas), an increase in glacier melt does not contribute to the hydropower generation and could potentially increase flood damages when coincident with extreme monsoon precipitation events. Earlier snowmelt increases the premonsoon flow, which is valuable to hydropower generation. The risk of GLOF events with the increased melting of glaciers (though not yet clearly observed) must be monitored. Increased variability in the monsoon system is likely to negatively impact hydropower production.

2.2 | Africa

Africa's hydropower is primarily based in the Nile, Congo, and Zambezi River basins, and smaller basins in sub-Saharan West Africa. The natural variability in West Africa is so high that the climate change signal may not be distinguishable from natural variability until after 2050 (Footitt et al., 2007), and is usually not accounted for in development projects with planning horizons of 25–30 years (Lumbroso et al., 2015).

2.2.1 | East Africa

The White Nile and Blue Nile Rivers drain the majority of East Africa. The White Nile originates from Lake Victoria, which has exhibited large fluctuations in water level, including a severe drop in the 1960s (Nicholson et al., 2000). Despite disagreements between GCMs, downscaling techniques, and the choice of climate forcing scenarios, the magnitude of wet season precipitation over Lake Victoria is expected to increase in the future (Akurut et al., 2014; Onyutha et al., 2016). The Blue Nile originates from Lake Tana, which is smaller than Lake Victoria and has maintained a more or less stable water level throughout the last 50 years (Kebede et al., 2006). Floods and droughts in the Blue Nile are attributed to rainfall variability downstream of Lake Tana associated with the changes in the Southern Oscillation Index (Conway, 2000). In the Blue Nile basin, despite high uncertainty in precipitation projections, increases in both the frequency and severity of floods and droughts are expected in the future (Tariku et al., 2021). The Grand Ethiopian Renaissance Dam currently under construction on the Blue Nile in Ethiopia will be the largest dam in Africa upon completion. With a surface area of 1874 square kilometers, the dam will have 59.2 billion cubic meters of active storage generating approximately 15,700 GWh of energy per annum. Damming of the river in Ethiopia (and associated reservoir surface evaporation) may diminish flows available to agriculture and water supply downstream in Sudan and Egypt, regions which are likely to require additional water in a warmed climate (International Non-partisan Eastern Nile Working Group, 2015). This is summarized in Figure 3 as: precipitation increase (solid icon for high confidence) and increased variability (hollow icon for low confidence).

2.2.2 | West Africa

In West Africa, the Niger, Volta, and Senegal River basins have large hydropower potential (Gyamfi et al., 2018). Precipitation in the last century has been highly variable, characterized by a very wet period 1950–1970, a dry period 1970–1990 (Le Barbe et al., 2002), and a moderate increase in rainfall after the 1990s (Maidment et al., 2015). Correspondingly, runoff is also highly variable (Roudier et al., 2014). Increasing trends in both flood magnitude and frequency in the Sahelian zone have been observed, 1960–1999, though the increase was not seen in the Sudanian zone (Nka et al., 2015). Despite high precipitation uncertainty and disagreement among climate projections, a decrease of more than 10% in runoff in the Senegal, Gambia, and Guinea-Bissau River basins has been predicted, as opposed to an increase of more than 10% in runoff in the region including Liberia and Côte d'Ivoire (Stanzel et al., 2018). Aich et al. (2016) predicted an increase in flood magnitude in the Niger River basin with climate change. Opportunities exist to reduce the negative effects of high streamflow variability. For example, simulations of reservoirs in the Upper Niger and Bani River basins (UNBB) in West Africa suggested that the losses via evaporation and seepage by the end of 2045 could be reduced by 20% if hydropower facilities were operated as RoR projects instead of reservoir storage facilities (Liersch et al., 2019). This is summarized in Figure 3 as: floods (solid icon for high confidence) and increased variability (solid icon for high confidence).

2.2.3 | Southern Africa

The Zambezi River basin in Southern Africa houses major hydropower generation facilities including Cahora Bassa (2075 MW), Kariba (960 MW), Kafue Gorge (900 MW - Upper, 750 MW - Lower), and Itezhi-Tezhi (120 MW). The level of understanding of the effect of climate change in Southern Africa is hampered by high interannual variability, complex oceanic-atmospheric dynamics, and an incomplete historical record (Ziervogel et al., 2014). Historically, the level of Lake Malawi, which feeds the Shire River and subsequently the Zambezi River, has fluctuated due to large precipitation variability (Nash et al., 2018). Precipitation in Malawi is projected to change between −20% and +20% from its historical observations by mid-century (Taner et al., 2017), a range centered on "no change." Bhave et al. (2020) simulated the variation of the level of Lake Malawi by to end of 2050 and reported that one-third of the evaluated GCMs predict a future with devastating floods, and about one-third of the GCMs predict a drier future in which lake levels are so low that there would be no outflow. Yamba et al. (2011) warned that hydropower generation in the Zambezi basin over the next 60 years is likely to decrease due to droughts. Tanzanian hydropower production, which has suffered from insufficient generation during drought years and high siltation due to excessive erosion during wet years, can expect the challenges associated with streamflow variability to increase in the future (Loisulie, 2010). This is summarized in Figure 3 as: increased variability (solid icon for high confidence); droughts (hollow icon for low confidence).

In sum, the basins of East Africa will likely benefit from a warmer climate with increased precipitation, the basins of West Africa will likely experience negative impacts with increased flood and variability, and the basins of Southern Africa will likely experience negative effects due to amplified variability. These conclusions are consistent with the review of Falchetta et al. (2019) and IEA (2020b) on the anticipated impacts of climate change on African hydropower.

2.3 | North America

The Columbia River in the Pacific Northwest of the United States produces more than 40% of the nation's hydropower, while the Northeast US has the highest number of powerplants (∼600) (U.S. Department of Energy, 2018). In Canada, the majority of hydropower projects are situated in the eastern provinces (Quebec, Ontario, Newfoundland, and Labrador) and British Columbia to the west.

2.3.1 | Northeast North America

Flood magnitude and frequency in this region are increasing, coincident with increasing extreme precipitation events (Burn & Whitfield, 2016; Collins, 2019; Douglas & Fairbank, 2011; Zhang et al., 2000). Thibeault and Seth (2014) projected an increase in winter wet extremes for the northern and interior regions of the Northeast US by 2070. An increase in temperature and winter precipitation is expected in the future, especially along the northeast coast (Hayhoe et al., 2008). In the Nordic-Quebec region of eastern Canada, a decrease in summer discharge, and increases in winter, spring, and fall discharge are projected (Minville et al., 2008). This is summarized in Figure 3 as: extreme precipitation (solid icon for high confidence); precipitation increase (hollow icon for low confidence); floods (solid icon for high confidence).

2.3.2 | Western North America

The Pacific Northwest receives winter precipitation from atmospheric rivers (Dettinger et al., 2011; Ralph et al., 2018). Mountain snowpack melts in late spring, recharging aquifers (Winograd et al., 1998) that supply baseflow for dry summers. In the past few decades, precipitation has increasingly occurred as rain instead of snow (Knowles et al., 2006), and the seasonal snowpack volume has decreased (Kapnick & Hall, 2012). With earlier snowmelt, summer low flows are diminishing (Dierauer et al., 2018; Newton et al., 2019), and a reduction of hydropower generation in the summer months is projected in the future (Hamlet et al., 2010). Studies of hydropower projects in the High Sierra (Vicuna et al., 2008) and Upper Colorado basin (Kopytkovskiy et al., 2015) suggest that the large reservoirs in the region may be sufficiently resilient to changes in hydrologic seasonality, though these findings are yet untested. Western North America also faces multiyear droughts that are worsening with climate change (AghaKouchak et al., 2014; Diffenbaugh et al., 2015). The Western US electric grid system is vulnerable to insufficient generation in summer (Voisin et al., 2016), with a decrease in streamflow and an increase in cooling demands due to higher temperature (Kern et al., 2020; Turner et al., 2019). This is summarized in Figure 3 as: earlier snowmelt (solid icon for high confidence); droughts (hollow icon for low confidence); streamflow decrease (hollow icon for low confidence).

2.3.3 | Southern North America

The Tennessee Valley Authority (TVA) operates 29 hydropower dams in the Tennessee River Systems (US Department of Energy, 2018). The total annual demand and the peak hourly demand are projected to increase in the TVA with climate change (Fonseca et al., 2019). Assessment of the Norris Dam within the TVA suggested that modification to the reservoir operating rules to account for climate change could reduce the operational penalties by 22%–37% (Rungee & Kim, 2017). Cavazos et al. (2020) observed significant decreases in precipitation in parts of the southern US and northwest Mexico, 1980–2010, and the droughts (Mitra & Srivastava, 2017), are likely exacerbated by climate change (Seager et al., 2009). This is summarized in Figure 3 along with the conclusion of Central America.

In sum, in the Northwest US (and parts of western Canada), the melting of snow earlier in the year, and rain-on-snow events, would have a double negative impact on the hydropower sector, increasing winter/spring flood flow and decreasing summer low flow. In Quebec and the Northeast US, with increasing frequency and intensity of winter precipitation, hydropower is likely to face risks with increasing flooding. The Southeast US will likely suffer from increased droughts; however, the impact of climate change on hydropower there is unclear.

2.4 | Latin America

Hydropower supplies over 45% of the total electricity in Latin America. This section discusses the effect of climate change on Central America and South America, where the potential for future hydropower development is high. ENSO influences the climate of much of South America, typically observed during the El Niño phase as flooding along the west coast, and droughts in the Amazon and northeast region of the continent (Cai et al., 2020).

2.4.1 | Central America

Hydropower is a major contributor to the electricity supply in Central America. For example, in Costa Rica, hydropower supplies over 80% of the electricity needs, with strong potential for future development (see

Figure 1). There has been evidence of increased winter precipitation and decreased summer precipitation in Mexico and the Caribbean during the El Niño ENSO phase, which is projected to strengthen in the future (Magrin et al., 2014). In the past couple of decades, the maximum annual temperature has increased in Central America (Aguilar et al., 2005), and Mexico City (Behzadi et al., 2020). Limitations in ground-based meteorological observations in Central America including Mexico and the Caribbean (Cavazos et al., 2020) make it difficult to evaluate the suitability of climate models for future projections. The median of an ensemble of 30 GCMs projects reductions in precipitation (by as much as 5%–10%) and runoff (by as much as 10%–30%) in northern Central America in the period 2050–2099 (Hidalgo et al., 2013), with an increase in drought severity. This is summarized in Figure 3 as: droughts (solid icon for high confidence); increased variability (solid icon for high confidence); and precipitation decrease (hollow icon for low confidence).

2.4.2 | Western South America

In South America along the tropics, the temperature is relatively steady throughout the year, but there are distinct wet and dry seasons, which are heavily influenced by ENSO (especially in Peru, Colombia, and northeast Brazil). Accelerated glacier retreat has been observed since the 1980s in the Andes (Ramirez et al., 2001; Seehaus et al., 2019), and losses are also observed with sublimation (Winkler et al., 2009). Projected future glacier shrinkage with continued warming is likely to lead to a long-term reduction in dry season river discharge in all glaciated catchments of South America (Vuille et al., 2018), which are located principally in Chile, Peru, and Bolivia. In the future, the potential increase in rainfall due to stronger El Niño could be nullified by a reduction in rainfall due to warming, as evident in Central Chile (Cai et al., 2015. This is summarized in Figure 3 as: glacier melt (solid icon for high confidence); and precipitation decrease (hollow icon for low confidence).

2.4.3 | Eastern South America

Brazil has the largest installed hydropower capacity (114 GW) in South America, and a large potential for future development (da Silva Soito & Freitas, 2011). The majority of dams, including the largest in energy generation, the 14 GW Itaipu Hydroelectric Power Plant (Brazil-Paraguay), are located on the transboundary Paraná River (von Sperling, 2012). Historical observations in the Paraná River basin indicate positive trends in total annual rainfall attributed mostly to increases in heavy rainfall events (Zandonadi et al., 2016). Floods in the region (e.g., the extreme flood of 1983) are highly affected by large-scale climate oscillations (Antico et al., 2016), which are likely to be impacted by climate change (Cai et al., 2015). There is general agreement among the GCMs that the future will be marked by a decrease in rainfall and an increase in temperature during the peak rainfall season (March–April–May), coupled with less precipitation during the dry season in Northeast Brazil (Marengo et al., 2017).

The São Francisco River in Brazil also has large dams built to produce electricity (Paiva & Schettini, 2021), and has recently been experiencing severe drought. Some studies have attributed the drought to an intensified El Niño phase of ENSO (Sun et al., 2016), while some have attributed it to increased agricultural and livestock activities (dos Santos et al., 2020). Small hydropower projects in semi-arid regions of Brazil have experienced a reduction in electricity generation (approximately 3.2 MWh/year) despite an increase in precipitation, as scarce water resources have been prioritized for irrigation and water supply purposes (Medeiros et al., 2021).

At a regional scale, an increase in the precipitation in the northern Amazon and the southern la Plata basin is projected with increased wind and moisture flux, and a decrease in the precipitation in the northern la Plata basin is projected with decreased rain in the South American Monsoon System by the end of the century (Gomes et al., 2021). This is summarized in Figure 3 as: precipitation increase (solid icon for high confidence); increased variability (hollow icon for low confidence); and droughts (hollow icon for low confidence).

In sum, increased temperature and reduced precipitation are projected for Central and South America, which is likely to negatively affect hydropower generation in the region. In South America, dry-season glacier melt in the Andes is likely to add to hydropower generation in the short term but decrease in the long term once glaciers have diminished to critically small volumes.

2.5 | Europe

In addition to existing hydropower projects in the Alps, the Nordics, and the Baltics, hydropower investments are increasing in Southeastern Europe, and more are planned to be built in the Dinaric Alps (Huđek et al., 2020), and in Turkey (see Figure 1).

2.5.1 | The Alps

The European Alps feed four large river basins: the Danube, Rhine, Rhone, and Po, and it contributes to hydropower generation in France, Italy, Switzerland, and Austria. With global warming, Alpine glaciers (permanent storage) and snow-cover (seasonal storage) are diminishing. Despite some increase in glacier mass in the last century (1960–1980s) (Beniston et al., 2018), Alpine glaciers have lost almost 50% of their area since the 1850s (Zemp et al., 2006). In Switzerland, the increased glacier-melt since the 1980s (Fischer et al., 2015) has increased hydropower generation by 3%–4%, but a decrease of approximately 3% is projected by the end-of-century as glacier volumes shrink (Schaefli et al., 2019). The mean monthly snow depth between November–May has been decreasing (1971–2019) at an average rate of 8.4% per decade in the Alps (Matiu et al., 2021). Loss in snowpack volume could change the electricity production in the upper Rohne basin (Fatichi et al., 2015) and reduce hydropower generation from some Italian RoR projects by about 10% by mid-century (Maran et al., 2014). The impact on Swiss hydropower production from the shift in streamflow seasonality (from summer to winter) is not uniform and depends on local conditions (Savelsberg et al., 2018). This is summarized in Figure 3 as: earlier snowmelt (solid icon for high confidence); and glacier melt (solid icon for high confidence).

2.5.2 | The Nordics and the Baltics

More than 95% of the electricity in Norway is supplied by hydropower, and recent increases in average streamflow have incentivized hydropower extension projects (IHA, 2017). A significant increase in rain-on-snow events occurred from 1981–2010 relative to 1961–1990 in the southern mountain region for both winter and spring (Pall et al., 2019). An increase in winter discharges with earlier snowmelt has been observed, and climate models project a continuation of past trends, as well as an increase in the autumn discharge with a projected increase in precipitation in the future (Wilson et al., 2010). A case study of a hydropower project in southern Norway projects a 9%–20% increase in energy generation with an 11%–17% increase in annual inflow due to earlier peaks and larger spring flow (Chernet et al., 2013), under constant reservoir operation strategies. In the eastern Baltic countries (Lithuania, Latvia, Estonia), the total annual precipitation may have decreased since the mid-20th century (low statistical confidence), and an upward shift in winter precipitation has accompanied an increase in winter discharge, with a decrease in spring floods (Apsite et al., 2013; Jaagus et al., 2018). This is summarized in Figure 3 as: earlier snowmelt (solid icon for high confidence); precipitation increase (solid icon for high confidence); and streamflow increase (hollow icon for low confidence).

2.5.3 | The Mediterranean and Turkey

In the past few decades, the Mediterranean region has been much drier than the past 900 years (Cook et al., 2016). A study of the Mediterranean Llobregat River basin in the Iberian Peninsula suggests that hydropower generation may drop an additional 5%–43% by 2070 (Bangash et al., 2013).

Turkey is Europe's leading market for future hydropower development (IHA, 2015), and hydropower supplied more than 30% of the national energy demands in 2019 (REN21., 2020). Turkey has already achieved its 2023 clean energy targets and has ambitious plans for further investments in renewable energy (Erat et al., 2021). Past studies have observed long-term persistent drought conditions in Eastern Turkey with a negative trend starting in the 1990s (Altin et al., 2020), and drying of the Upper Tigris basin since 1990 (Ozkaya & Zerberg, 2019). Lelieveld et al. (2012) identified a projected increase in the maximum daily temperature and a decrease in the annual precipitation in GCM projections. Despite the large investment planned in the hydropower sector, scientific literature on the potential impact of climate change on Turkish hydropower is scarce. This is summarized in Figure 3 as: precipitation decrease (hollow icon for low confidence); and droughts (solid icon for high confidence).

To summarize, all the rivers fed by the Alps face a seasonal loss in natural storage due to a reduction in snow-cover duration and a permanent loss in storage due to glacier melt. However, the impact on hydropower generation is location-specific and project-dependent. The potential for increasing floods in Europe with climate change is not spatially uniform. In snowmelt-dominated catchments, earlier snowmelt with warmer temperatures will likely increase the winter flow and reduce the magnitude of summer floods (Madsen et al., 2014). Earlier snowmelt is also observed in the Nordics. Hydropower projects throughout the Mediterranean and Turkey are likely to suffer from generally drier conditions, and increased droughts.

2.6 | Australia

Hydropower facilities in Australia are mainly concentrated in the Southeast. Future expansion of hydropower in Australia can be expected to be in small-scale hydroelectric projects, upgrading of existing infrastructure (Bahadori et al., 2013), and potential investment in pumped storage projects (IHA, 2018a).

Hydropower generation is concentrated in Southeast Australia and Tasmania, which are subject to prolonged periods of drought (Watterson, 2010), and diminishing rainfall (CSIRO, 2010). Hydropower generation declined on average by 4.2% per year between 1999 and 2008 during the Millennium Drought (Bahadori et al., 2013). In the future, an increase in positive Indian Ocean Dipole events is expected to bring drier conditions from winter to spring (CSIRO, 2012), and a drier future overall (Alexander & Arblaster, 2017). Modeling potential future streamflow using 15 GCMs, Chiew et al. (2009) projected a change in a mean runoff between −17% and +7% with global warming of 0.9°C, with the majority of the modeling results indicating a future reduction in runoff. This is summarized in Figure 3 with a solid icon for droughts (high confidence).

Table 1 presents the rationale for the symbology (hollow vs. solid symbols) adopted in Figure 1. Interested readers can find the expanded itemization in the Appendix S1. The categories of the climate change effects reported in Table 1 and Figure 1 were informed by the frequency of citation in the published literature. Some categories, such as increased variability, may include more than one climate change effect, depending on the conclusion made in the paper. For instance, for Africa, among the cited references, only one paper explicitly discussed droughts, and seven papers listed under increased variability discussed droughts and floods together.

3 | CLIMATE CHANGE IMPACTS ON GLOBAL HYDROPOWER: PRIMARY MECHANISMS

Four primary mechanisms by which climate change impacts the hydropower sector, each distinct in terms of impact on hydropower productivity, were identified in the global survey:

1. **Depletion of the permanent glacier and ice storage with increasing temperature.**
   Process: Increased warming has already resulted in substantial loss of ice mass worldwide (Huss et al., 2017; Sorg et al., 2014). Melt from retreating glaciers results in increased streamflow in the short term, and reduced streamflow in the long term as glacier mass disappears (e.g., Vuille et al., 2018; Zemp et al., 2006).
   Effects: Glacier meltwater is beneficial to power production in the dry season, but in the wet season could lead to increased flood, and the net effect might be insignificant depending on the overall melt contribution. For instance, in the Andes, the loss of glaciers has is projected to reduce the dry season streamflow (Vuille et al., 2018). In Central Asia where glacier melt and the monsoon precipitation coincide, flood severity can be expected to increase with increased glacier melt. In the Alps, although the loss of glaciers is significant (50% loss of Alpine glaciers to date, Zemp et al., 2006), hydropower production has not so far been negatively impacted (e.g., overall, 3%–4% increase in Swiss Hydropower, Schaefli, 2015), because many of the catchments are also snow-fed and reservoir capacity is large. In Northeast Asia, glacier melt in the headwater basins has had a limited impact on downstream basins where most of the hydropower is generated (Chen et al., 2014; Yang et al., 2003). Additionally, newer hydropower projects planned closer to the headwaters in the Himalayas have an increased risk of GLOFs (Schwanghart et al., 2016).

2. **Reduction in seasonal snow storage with warmer winters.**
   Process: Increased temperature and rain-on-snow events (e.g., Beniston & Stoffel, 2016; Musselman et al., 2018; Pall et al., 2019) affect both the timing and rate of snowmelt (e.g., McCabe & Clark, 2005; Musselman et al., 2017), and reduce the snowpack volume. The high mountains also suffer from a loss in snow mass with sublimation, that is, the direct transition of solid-phase snow to water vapor. Sublimation has been observed in mountains in the Andes (Winkler et al., 2009), Canadian Rockies (MacDonald et al., 2010), in the Alps (Bernhardt et al., 2012; Vionnet et al., 2014), and the Himalayas (Stigter et al., 2018).
   Effects: A shift in the hydrologic regime is observed in regions where snow accumulation season is out-of-phase with the melt season, such as in Norway or Quebec, but not in the Himalayas where monsoon precipitation occurs in the summer (Schaefli, 2015). Moreover, RoR projects (e.g., Maran et al., 2014) or projects with smaller reservoir capacity are more likely to be negatively affected (e.g., Kopytkovskiy et al., 2015; Vicuna et al., 2008).
3. **Increased precipitation variability and intensification of precipitation extremes.**
   Process: A clear signal between the ENSO and hydropower generation has been observed globally (Ng et al., 2017), and floods are affected by the large-scale oscillation cycles (Kundzewicz et al., 2019). With warmer temperatures, the water holding capacity of the atmosphere increases (Lenderink et al., 2017; Skliris et al., 2016) which could result in increased precipitation intensity (Fischer & Knutti, 2016; Trenberth et al., 2003; Westra et al., 2014).
   Effects: Intensification of ENSO under climate change may negatively affect hydropower generation (e.g. Cai et al., 2015). In the Northeast US and southeast Canada, winter precipitation and floods are projected to increase in the future (e.g., Burn & Whitfield, 2016; Hayhoe et al., 2008; Minville et al., 2008; Thibeault & Seth, 2014). In basins relying on monsoon precipitation (e.g., Bhave et al., 2020; Kitoh et al., 2013; Taner et al., 2017), historical natural variability is expected to increase.
4. **Increased evaporation and water demand.**
   Process: With increased temperature, the evaporation rate will increase (Laine et al., 2014; Zhang et al., 2016), implying a loss of reservoir storage. The impact on evapotranspiration is a subject of active research, with evidence that the CO_2-induced reduction of stomatal conductance in most places will reduce transpiration more than it is increased by warmer temperatures (Kirschbaum and McMillan, 2018). In those locations where evapotranspiration increases, competition could increase for scarce water resources (Bijl et al., 2018; Florke et al., 2018) especially if the timing of peak electricity demands and agricultural demands coincide (Zeng et al., 2017). The loss of forest and/or change in the land cover also contributes to changes in the interannual variability of hydropower generation. Arias et al. (2020) demonstrated a method to quantify the combined effects of climate change and deforestation for hydropower planning.
   Effects: Increased water losses from reservoir surfaces and increased competition for water with agriculture are projected for the future (e.g., International Non-partisan Eastern Nile Working Group, 2015; Reyer et al., 2017).

4 | QUANTIFICATION OF CLIMATE CHANGE RISKS TO THE HYDROPOWER SECTOR

Though the impacts presented in Section 3 are global, the seasonality of temperature and precipitation, timing of peak electricity demand, type of project (RoR or storage reservoir), basin characteristics (e.g., catchment properties, downstream/upstream development), and design of the hydropower facility (e.g., dam height, reservoir storage, installed capacity, operational regimes), all have potential to create favorable, unfavorable or no change to the hydropower generation at a regional or local scale. Climate change risk assessment at a project and/or basin level is therefore necessary. Such assessments involve the superimposition of future climate projections on a wide range of simulation results produced by a sequence of models that usually consists of hydrologic, hydraulic, infrastructure, and financial models. The conclusion on the future of the hydropower project is bound by large uncertainties that are susceptible to misinterpretation if not quantified/communicated properly. Additionally, sometimes nonclimate factors could have a greater influence than climate change (e.g., Lumbroso et al., 2015; Schaefli, 2015; Vaidya et al., 2021). Potential transboundary river diversions (Yang et al., 2016), or uncertainty in capital costs, market price, and discount rate (Ray et al., 2018) might pose a greater risk than climate change, and basin-wide planning may be required to develop climate change resilience in hydropower projects (e.g., Hurford et al., 2020). In this section, we discuss the challenges associated with the quantification of climate change risks at a local or regional scale.

4.1 | Approaches

Groundbreaking early studies quantifying climate risks to water infrastructure include assessments of the Sacramento-San Joaquin Basin (Gleick, 1987; Lettenmaier & Gan, 1990), the Delaware River basin (Mccabe & Ayers, 1989), and a regional assessment of basins throughout the United States (Hamlet & Lettenmaier, 1999). These studies used down-scaled GCM output as input to local or regional hydrologic models and used the hydrologic models to develop input to project-specific (or system-specific) water infrastructure (and policy) models. This sequence of models remains the core structure for climate change risk assessments on water system infrastructure to date (e.g., Laghari et al., 2012; Sharma & Shakya, 2006; Zhong et al., 2019). In the past 15 years, however, there has been a shift from the scenario-led studies (that begin with a select subset of GCM output) to robustness-based, bottom-up stress tests (that begin with either a full ensemble of GCM output or systematically sampled output of a stochastic climate model, i.e., a weather generator [e.g., Steinschneider & Brown, 2013; Steinschneider et al., 2019]). Robustness-based approaches (e.g., Brown et al., 2012; Lempert et al., 2004; Prudhomme et al., 2010) focus on understanding project sensitivity to changing climate inputs and identifying thresholds beyond which the system would perform unacceptably (Herman et al., 2015). The likelihood of occurrence of the unfavorable conditions identified during the robustness-based "stress tests" is superimposed at a later step in the risk assessment process, allowing analysts the flexibility to update those likelihoods as newer information becomes available (e.g., Taner et al., 2019).

4.2 | Challenges

Regardless of the approach used, the quantification of climate risks to hydropower is associated with large uncertainties cascading through the modeling chain. One of the earliest examples of a study involving a large number of climate models and quantification of the associated uncertainties in the modeling chain is presented in Schaefli et al. (2007).

A schematic for a bottom-up modeling approach for climate change risk assessment and the associated uncertainties is illustrated in Figure 4. Hydro-climatic data required for climate risk assessments are of varying quality depending on location, and other factors including the historical investment of the local government in maintaining a hydro-climatic database. These data feed into the hydrologic models, which cannot perfectly represent the true dynamics of distributed and heterogeneous watersheds (Bloeschl et al., 2019), introducing additional uncertainty (Renard et al., 2010).

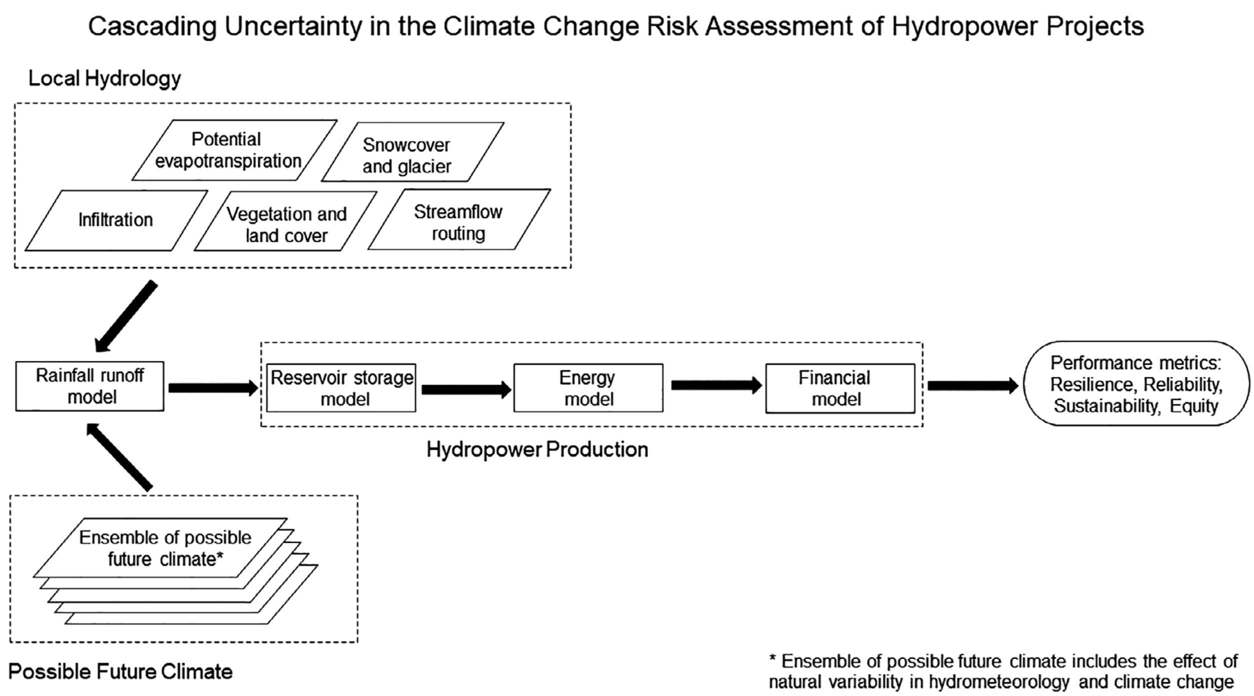

FIGURE 4 Model framework for climate change risks assessment of hydropower projects. Possible future climate includes the effect of natural variability and climate change

The simulated streamflow is further routed through a reservoir model, an energy generation model, and sometimes a financial model, each imperfect, resulting in a cascade of uncertainty (Wilby & Dessai, 2010). When projecting the potential performance of a hydropower project into the future, GCMs add a level of data-related uncertainty (Gaudard et al., 2016). If a top-down approach is used, the downscaling of the climate models introduces additional uncertainties (e.g., Chen et al., 2011). Although GCMs capture many key aspects of the large-scale global climate, they are not generally skillful in the reproduction of trends and seasonal variations at a local scale (e.g., Cannon et al., 2015; Rocheta et al., 2014). Discrepancies in projections of future climate between GCMs lead to substantial differences in the projections of long-term hydropower generation and resulting economic benefit (e.g., Carvajal et al., 2017; Mishra et al., 2020).

Previous efforts to better characterize climate-related uncertainties to water system performance have explored uncertainties in future hydrology stemming from both hydrologic and climate models (e.g., Steinschneider et al., 2015). Studies have noted that, despite the tendency to assign to GCM projections most of the blame for uncertainty in future hydropower-sector performance, major contributors to uncertainty can vary; it is, therefore, important to account for all sources of uncertainty in hydrologic impact studies under climate change (Chen et al., 2011; Honti et al., 2014).

4.3 | International practice

Guidelines on the design of climate-resilient hydropower projects are available. Some examples include the "Decision Tree Framework" (Ray & Brown, 2015), "Climate Risk Informed Decision Analysis" (UNESCO, 2018), the "Climate Resilience Guide for the Hydropower Sector" (IHA, 2019a), "Climate Risk Management in ADB Projects" (ADB, 2014), and "Addressing Climate Vulnerability for Power System Resilience and Energy Security: A focus on Hydropower Resources" (USAID, 2017).

Generally, these approaches and others like them adopt the robustness-based decision-making approach discussed in the previous section, where risk is estimated as a product of impact and likelihood, and likelihood is assigned to a projected impact in a post-processing step. These institutional approaches also tend to be hierarchical, meaning that incrementally larger effort analyzing and adapting to climate change risks is applied only where justified based on screening-level preliminary analysis of overall risk. A time-and-resource-intensive process for evaluating adaptation options is engaged only in response to definitive concerns identified during the climate change stress test.

4.4 | Room for improvement

The current international standard of practice for the assessment of climate change risks to the hydropower sector is underdeveloped in the consideration of: (1) floods; and (2) sediment and landslide effects.

Flood risk estimation is difficult for several reasons. First, there is large uncertainty in the estimation of the magnitude of historical flood risk, as often the period of available data is not long enough to estimate large flood frequency return periods with precision (e.g., Serinaldi & Kilsby, 2015) and with climate nonstationarity, uncertainty bounds on historical flood frequency return periods increase (Read & Vogel, 2015). Second, the uncertainty associated with the simulation of precipitation extremes in GCMs is large (Kharin et al., 2013; Rocheta et al., 2014; Sillmann et al., 2013). Third, the flood risk at a particular location is dependent not only on the intensity and duration of precipitation, but also on the spatial extent of such events, the antecedent conditions (e.g., snowpack volume, soil moisture saturation), and interactions with other flood-causing variables (Westra et al., 2014) such as rain-on-snow (Musselman et al., 2018; Pall et al., 2019), which are also changing with climate change.

Several modifications have been proposed to the techniques for estimation of the flood events accounting for nonstationarity (e.g., Lopez & Frances, 2013; Strupczewski et al., 2001; Vogel et al., 2011). Salas et al. (2018) concluded that there are disagreements on the underlying definitions, concepts, and methods for modeling flood nonstationarity, and thus the appropriate magnitude of future design flood is highly uncertain. Recent studies have progressed in the estimation of shifts in extreme precipitation by conditioning likelihoods on changing climate drivers, such as weather regimes (e.g., Steinschneider et al., 2019), or sea surface temperature (e.g., Schlef et al., 2018), which GCMs can reproduce with relatively greater skill. However, the rigor and depth required for these types of assessments make them not easily applicable to the hydropower design projects, which often allot only limited time and budget to climate change analysis.

An increase in soil erosion rate and river sediment concentration is expected with global-warming-intensified runoff (Mukundan et al., 2013; Nilawar & Waikar, 2019), mobilization of previously frozen soil with retreating glaciers (Beniston et al., 2018; Huss et al., 2017), and/or increased soil exposure to rain with a decrease in snow cover (Maruffi et al., 2022). However, the impact of increased sediment load on the hydropower sector under climate change is largely unstudied, and further discussion of this topic is beyond the scope of this review.

There is room for improvement also in our understanding of the impact of potential future changes in other factors such as energy demand or competing demands for water. Only a few studies (e.g., Chowdhury et al., 2021; Kern et al., 2020; Turner et al., 2019) have coupled hydrological models with power system models to evaluate the combined effects on the power grid. Studies of the integration of hydropower with other renewables to meet the increasing energy need under climate change are also limited (e.g., Dujardin et al., 2017; Kies et al., 2016).

4.5 | Socioeconomic perspective

Though this paper has focused on the perspective of hydropower owners and planners, hydropower-related impacts on local populations must not be overlooked. Failures of hydropower-related infrastructure elements would likely be borne by the local populations, more so than the investors or government agencies responsible for them. Johnston et al. (2012) demonstrated that environmental problems are linked to human rights problems. In addition to population displacement, some social and political dynamics associated with hydroelectric dams include elite rent capture, international tension over water resources, skyrocketing debt, delays in construction, outside political agendas, and changes in demand from the initial point of planning to the point of generation (Dorcey et al., 1997; Folch, 2019; Poff et al., 2003; Schapper et al., 2020; Wolf, 1999). After evaluating the consequences of dam building in the 20th century, the multi-stakeholder World Bank and International Union for Conservation of Nature (IUCN) workshop participants in Dorcey et al. (1997) argued that the adverse social impacts (both immediate and long term) of hydroelectric projects had been grossly underestimated. As a way to address these unintended impacts, there has been an effort to gather multiple stakeholders as part of the decision-making process, and now "public acceptance" is seen as a crucial component of water system design (Freeman et al., 2020).

Cernea (2004) identified risks and negative social impacts associated with hydropower, based on examples from Africa, Asia, and Latin America, often stemming from insufficient planning and resource allocation for the negative human impacts of dam construction. Instead of attempting to counteract them ex post, Cernea (2004) recommended "*ex ante* preemptive social-economic planning". The proposed "Impoverishment Risks and Reconstruction" model was developed to better resettle displaced populations by understanding the constitutive parts of displacement and then crafting a united strategy to mitigate the risks faced by a specific population. Although the model put forth by Cernea (2004) was not originally designed to address climate change, the common impoverishment risks associated with hydroelectric dam building in the model are similar to those associated with climate vulnerability: landlessness, joblessness, homelessness, marginalization, increased morbidity and mortality, food insecurity, loss of access to common property, and social disarticulation (Shah et al., 2019). This suggests that the Impoverishment Risks and Reconstruction model offers an important complement to engineering-focused climate change adaptation (Jones & Bull, 2020). Future efforts along these lines will partner engineers with social scientists to center on vulnerable populations, as opposed to vulnerable infrastructure.

5 | CONCLUSION

Hydropower is the world's largest source of renewable energy, able to store energy and provide a sustainable baseload to complement the intermittency of other renewable energy technologies, with relatively low maintenance costs, making it likely to play a prominent role in the transition to a lower-emission future. However, because nearly all existing hydropower projects are river-based, they are susceptible to climate change phenomena that impact rivers, such as: (1) depletion of the permanent glacier and ice storage with increasing average annual temperature; (2) depletion of seasonal snow storage with warmer winters; (3) intensification of precipitation extremes, and variability; and (4) increased evaporation and water demand. The impact of these global phenomena at the local scale cannot easily be guessed without a targeted study of the local context.

Though several national and international guidelines have recently been developed for climate change impact assessment in the hydropower sector, ample room for improvement remains. The cascade of uncertainty from historical data through the modeling chain should be recorded, and any adopted climate change projections should be referenced with the degree of credibility warranted by their skill in the reproduction of the climate phenomena of relevance to the risk assessment. Because our ability to project future climate with accuracy at a local scale is limited, real-time continuous monitoring of climate change indicators such as streamflow and precipitation at a local scale is important. Improved capabilities in short-term forecasting (e.g., Schaefli, 2015), regular updating of reservoir operation rules, coupling of existing hydropower projects with other renewable energy sources, and periodic analysis of energy markets help manage hydropower projects under climate change.

The conclusions made in this review are based mostly on historical observation and future projections from the CMIP5 ensemble. The projection of future droughts is longer and more consistent in CMIP6 compared to CMIP5 (Ukkola et al., 2020). According to CMIP6, the Asian-Northern-African monsoon is likely to become wetter, while the North American monsoon is likely to become drier (Wang et al., 2020). Further, variability in the global monsoon precipitation systems, and the severity of wet and dry events, have likely been underestimated in CMIP5 and previous generations of IPCC reports (IPCC, 2021). Were the studies summarized in this review conducted using CMIP6 rather than CMIP5, findings regarding risks resulting from increasing precipitation variability would likely be stronger than stated here.

CONFLICT OF INTERESTS

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Asphota Wasti: Conceptualization (equal); data curation (lead); methodology (lead); project administration (supporting); resources (lead); visualization (lead); writing – original draft (equal); writing – review and editing (supporting). **Patrick Alexander Ray:** Conceptualization (equal); project administration (lead); resources (supporting); supervision (lead); visualization (supporting); writing – original draft (equal). **Sungwook Wi:** Resources (supporting); visualization (supporting); writing – original draft (supporting). **Christine Folch:** Writing – original draft (supporting); writing – review and editing (supporting). **María Ubierna Ubierna:** Data curation (supporting); resources (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Pravin Karki:** Writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

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