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Increased Water Risks to Global Hydropower in 1.5°C and 2.0°C warmer worlds

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Abstract

Hydropower plays an important role within the renewable energy sector and supports the achievement of international energy security targets. Yet this sector is also vulnerable to droughts which affect generation potential, and high flows which can cause structural and operational damage. Here we use river flows calculated using a multi-model ensemble to investigate the potential water risks which current and planned global hydropower generation capacities may face at 1.5°C and 2.0°C warmer worlds. We find that the global hydropower sector will have to face diverse, simultaneous, and compound water risks. We estimate that about 65% of current global hydropower installed capacity will be exposed to risk from recurrent high river flows (here understood as the change in the 1-in-100-years flow). Up to 75% of existing hydropower capacity in Europe, North America and MENA is located in areas where droughts are projected to become at least 10% longer when compared to historical conditions. Achieving a 1.5°C warming target would reduce these risks, compared to a 2.0°C scenario.

Key words: Climate change, Paris agreement, Floods, Droughts, Hydropower

1. Introduction

The hydropower sector contributed to approximately 15% of global electricity generation in 2019, supplying over 70% of global renewable energy (IEA, 2019). In that year, annual hydropower production was approximately 4,306 TWh (Bartle, 2016; IHA, 2020). By 2040 the energy output from hydropower sources is projected to reach about 7,000 TWh/year. This figure is expected to be reached by maintaining the current growth in installed capacity (about 15-25 GW/year) through rapid expansion in the developing world (Hoes et al., 2017; IEA, 2019).

Maintaining a reliable hydropower sector is important not just for country-level energy security interests but also to assist regional and global development ambitions (Dincer, 2000; Güney, 2019). Although hydropower expansion is both politically and environmentally controversial, sectoral estimates suggest that hydropower outputs need to be maintained at an average yearly increase of 2.5% in order to support the achievement of Sustainable Development Goals by 2030 (IEA 2019). Also, while about 10% of the world's hydropower facilities, especially in tropical areas, may emit as much greenhouse gases as conventional coal-fired power plants, hydroelectricity is still considered a low-carbon source of renewable energy (Demarty and Bastien, 2011; Edenhofer et al., 2014; Scherer and Pfister, 2016). Indeed, estimates suggest that emissions from most global hydropower projects are within the range of other renewable energies, especially when they are adequately planned, built, and operated (Almeida et al., 2019). At the same time, the high ramp rate of hydropower plants can serve to balance the variability and potential shortages in wind and solar generation. Thus the hydropower sector may support reliable integration of other renewable energies into supply grids (Berga, 2016; Dujardin et al., 2017; Graabak et al., 2019; Muller, 2019).

Acknowledging these opportunities (as well as limitations), the hydropower sector may also help achievement international climate goals. In particular, the Paris Agreement, apart from “limiting the increase in global average temperature to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (Christoff, 2016) also requires the promotion of sustainable energy sources as sources of mitigation and adaptation policies.

Yet, hydropower dam sites, and their expected benefits are vulnerable to various types of water risks. These risks are mainly connected to changes in the variability of seasonal hydrological conditions, low flows resulting in droughts, and the occurrence of high flows and floods (Blomfield and Plummer, 2014). This vulnerability has been evident in recent years as increases in hydropower production have been small or even negative in the period 2006-2008 and 2015-2017 (IEA, 2019). For instance, in 2017, severe drought in Brazil reduced the country’s yearly outputs by approximately 5% (Brazil alone accounts for nearly 40% of Latin America’s energy output) (British Petroleum, 2019). Similarly, declines of yearly average hydropower outputs of nearly 15% over Southern Africa coincided with the continuous droughts observed over the region between 2015-2017. Elsewhere the risks associated with low flows at the hydropower project-level have been widely documented (Gaudard et al., 2014; Harto et al., 2012; Kuusisto, 2004; Loisulie, 2010; Madani and Lund, 2010; Mukheibir, 2013; Piman et al., 2013; Rübbelke and Vögele, 2011; van Vliet et al., 2016a). As for high floods, record rainfalls and floodwaters in California in 2017 damaged the spillway of the Oroville Dam which resulted in the largest evacuation registered in California and nearly caused the complete failure of the tallest dam in the United States (Hollins et al., 2018). Similarly, stormwaters in the

Uttarakhand region in north India in 2013 are thought to have damaged about 70 hydropower dams and even inundating powerplants (Mishra, 2015; SANDRP, 2013).

In spite of the important previous efforts to estimate future risks and changes in hydropower production (Antwi and Sedegah, 2018; Koch et al., 2011; van Vliet et al., 2016b), the specific hydrological conditions facing the sector as it contributes to meeting the targets of the Paris Agreement are still not clear. This problem is particularly acute if the sector aims to build resilience to hydroclimatic conditions, to sustain its role in reducing the carbon footprint of energy systems. Ultimately, this is a key element for the Nationally Determined Contributions (NDCs) to reduce greenhouse gas emissions while being aligned to international climatic goals and the sustainable development agenda under the United Nations Framework Convention on Climate Change.

In this study, we characterize the type of hydrological conditions and potential water risks which current and planned global hydropower generation capacities may need to face in their contribution towards the Paris Agreement targets. To address this, we use river flow simulations derived from a multi-model ensemble to estimate future changes in potential water risks which may affect the hydropower sector. Here we define water risks as changes in mean flows and gross hydropower potential (GHP), changes in drought frequencies, durations, and intensities, and shifts in high flow conditions. These calculations are then used to examine exposure levels of current and future hydropower installed and planned capacities at major global regions.

2. Materials and Methods

2.1 Multi-Model ensemble

For the two climate target thresholds agreed in Paris we use generated river flows computed, from our previous study, under the Half a degree Addition warming, Projection, Prognosis, and Impacts (HAPPI) protocol (Mitchell et al., 2017; Paltan et al., 2018). HAPPI is a multi-model experiment which provides data from three 10-year simulation periods per ensemble member with prescribed atmospheric forcing, sea-surface temperature and sea-ice coverage. By using prescribed future Sea Surface Temperatures (SSTs) this framework reduces the influence of model sensitivity while simulating a narrowly defined range of future temperature targets (Mitchell et al., 2017). The three scenarios are: 1) The reference or historical period which ranges from 2006 to 2015, 2) a future decade that is 1.5 °C warmer than pre-industrial levels, and 3) a future decade that is 2.0 °C warmer than pre-industrial levels. In the HAPPI protocol, the 2006–2015 decade is chosen since it contains a range of different SST patterns which allows an assessment of how the ocean conditions vary on inter-annual timescales.

Also, each of the three scenarios contains the outputs of four HAPPI AGCMS: CanAM4 (100 ensemble members); CAM4-2degree (100 ensemble members); NorESM1-HAPPI (125 ensemble members), and MIROC5 (50 ensemble members). It is important to note that each simulation within an experiment differs from the others in its initial weather state. So, the use of 50-125 10-year time slices in reality provide us with 500-1250 years of data per scenario (including the 2006-2015 baseline). This extensive record in turn provides the basis for robust hydrological calculations.

2.2 Runoff Routing and River Flow

Daily runoff derived, or calculated, from the four AGCMS and their ensembles were routed following a grid-based hydrological routing scheme as presented by Dadson et al., (2011). This scheme follows a discrete approximation to the 1-D kinematic wave equation with lateral inflow using an approximation to the St. Venant equations for gradually-varying flow in open channels (Oki and Sud, 1998). Under this scheme, kinematic routing is applied separately to surface and sub-surface runoff, and the routing model also distinguishes between land and river pathways by using different wave speeds. Also, this scheme uses the river network derived from a vector-based network tracing method (NTM) which dictates river channel directions, paths, and locations (Olivera and Raina, 2003). Due to its simplicity and more realistic representation this method has been widely used for river routing large-scale studies (as this one). Further details about the validation as well as description of characteristics of the flows calculated under this approach and for this climatic protocol can be found in (Paltan et al., 2018)

The spatial resolution of river flows used in our study is half degree (0.5° x 0.5°). Our daily flow values do not include anthropogenic interventions such as impoundments, diversions or water abstractions.

2.3 Change in Gross Hydropower Potential

The calculation of Gross Hydropower Potential (GHP) is based on the approach following equation (1) (Gross and Roppel, 2012; Lehner et al., 2005):

$$GHP = Q * \rho * g * \Delta H \qquad (1)$$

Where *GHP* at each grid location is expressed in Watts; *Q* is volumetric flow rate expressed in m^3/s (derived from our multi-ensemble river flow data) for each grid point;

ρ is the density of water (1000 kg/m^3); g is the gravitational acceleration (9.807 m^2/s), and ΔH is the elevation difference (in meters) calculated within each grid cell.

Elevation differences within a grid cell were obtained from the GMTED2010 Global Grids DEM at 7.5-arc-seconds (~225 m)(Danielson and Gesch, 2011). Thus, this finer spatial resolution permits us to calculate elevation differences found within an input grid river flow grid cell (0.5° x 0.5°). Using Eq.(1) we obtained global daily GHP estimates for both climate scenarios (1.5°C and 2.0°C) and for the reference period at each grid location.

2.4 Change in Drought Conditions

We describe future changes in drought conditions in terms of the frequency (number of drought events), duration (length of drought events), and intensity (cumulative water deficit) of hydrological droughts at both climate targets, when compared with its historical flow values at each grid point. Hydrological droughts are diagnosed using the commonly-used threshold level method (Fleig et al., 2006; Hisdal and Tallaksen, 2003; Van Loon, 2015a; Van Loon and Van Lanen, 2012; Yevjevich, 1967). This technique is known for capturing the patterns and deficiencies in seasonal high-flows especially in areas with abrupt changes in river flows and is recommended for use in global scale studies (Beyene et al., 2014). With this technique, a drought episode is detected when river flow values fall below a determined threshold level. In this study, we assume that the threshold level for any given day is calculated based on the 80th percentile derived from the flow duration curve of flow in the 30-day-average time window for that day of the year. This time window is moved through the daily river flow time series in order to calculate threshold values per day. The 80th percentile threshold was chosen based on previous studies (Van Loon and Van Lanen, 2012)

Drought events are considered mutually-dependent and, consequently, they are pooled if the inter-event time is 10 days or less (Fleig et al., 2006). Next, minor droughts are eliminated if they are of 15 days duration or less. From here, the intensity measure used is the water deficit volume, which is obtained as the sum of the difference between the historical threshold level and the projected river flow at both scenarios (1.5°C and 2.0°C) (Zelenhasić and Salvai, 1987). More details on the definitions and applications of drought definitions, the variable threshold approach and smoothing procedures used in this study can be found in Van Loon, (2015b)

Last, shifts in frequency, duration, and intensity are represented by the ratio of changes between the historical and the two projected scenarios, as used in previous global hydrological risk studies (Hirabayashi et al., 2008). Ratios of Change (RC), at each grid location, is given by Equation (2):

$$RC = \frac{V_{Projected}}{V_{Reference}}, \tag{2}$$

where $V_{Projected}$ is the future state of each variable (frequency, duration, or intensity) under 1.5°C or 2.0°C warming scenarios. $V_{Reference}$ is the historical-reference state of such variable.

2.5 Changes in high river flows

The shift in extreme high flows was obtained by calculating the change in the probability (return period) of the historical 1-in-100-year river flow under both climatic scenarios. For this, we adjusted the annual maximum daily river flows of our scenarios to a twoparameter Gumbel distribution (Paltan et al., 2018).

2.6 Current and planned hydropower capacities and exposure levels

In order to estimate global and regional changes in exposure levels of current hydropower generation capacities, we use the Global Dams and Reservoir Dataset (GRanD) (Lehner et al 2011)[24]. From this dataset we selected those dams where the main or secondary use is for hydroelectricity generation out of multiple uses, resulting in obtaining 7,033 locations of dam assets around the world. For future hydropower projects, we obtained the spatial distribution of planned global hydropower projects from the Future Hydropower Reservoirs and Dams Database (FHReD) (Zarfl et al., 2015). This dataset consists of 3,700 records of hydropower dams with a capacity greater than 1 MW. Both datasets provide generation capacities for each hydropower project, from which we estimate total regional, and thus global, hydropower capacities expressed in GW. Note also that for various countries (such as Egypt) there is no information on current hydropower dams.

Next, for each hydropower asset we determine the level of exposure to each of the hydrological conditions described above. This is done by overlapping the spatial distribution of existing and planned hydropower assets with the layers describing the changes in GHP, hydrological droughts, and high flows. Asset-level exposures were then aggregated at the regional level by summing the total exposed capacity, within each region, describing shifts in a given hydrological condition.

Individual grid locations capture upstream catchment processes via the river routing approach described previously in section 2.2. So, single-point exposure levels, for the water risks examined here, already consider grid cells, and processes, upstream of individual dam sites. We acknowledge that while our single-dam grid approach does capture upstream processes, in some cases reservoir areas may expand over more than one grid cell. Yet, by overlapping GRanD reservoir extents for the current dam-sites used here, we find that less than 5% of them share two or more grids. In particular, in less than 1% of dams, their reservoirs span across five or more grid cells (51 largest global dams, list provided in Supplementary 1). As such, almost all global reservoirs (and their dams) and thus our hydropower and exposure level calculations fall within individual grid cells. As our dataset of planned dams does not have reservoir layers we assume that the same association is valid.

Overall, the aim of the above approach is to provide a high-level understanding of the potential implications of water risks on hydropower capacities. We recognize limitations of our approach and note that our assumptions result in a conservative assessment. Also, we have considered the dam sites and their production capacities to be constant in the future climate change scenarios.

Lastly, the presentation of our global results are split into the following major global regions we use are the following: Commonwealth of Independent States (CIS), East Asia, Europe, Latin America and the Caribbean (LAC), Middle East and North Africa (MENA), North America, South Asia and Oceania, and Sub-Saharan Africa

3. Results

Our results first project a slight increase in current mean global GHP for both climate scenarios. We estimate current global GHP (multi-model ensemble mean) at 61.40PWh/year (standard deviation of 16.40 PWh/year) while in the 1.5°C scenario, global GHP is 63.25 PWh/year (increase ~3%) and at 2.0 °C this value reaches 64.50 PWh/year (increase ~4.95%) (a map of GHPs spatial distributions is given in Supplementary Figure 2). We find the spatial distribution of GHP does not vary significantly across the four models used in our study (see Supplementary Figure 3) and our current GHP estimation is consistent with recent global GHP estimates (Bartle, 2002; Hoes et al., 2017; Pokhrel et al., 2008; Van Vliet et al., 2016). Also, our projected values are similar to previous estimates that also project an increase in GHP of 2.4% and 5.3% for the RCPs 2.6 and 8.5 scenarios, correspondingly (van Vliet et al., 2016b).

3.1 Changes in Hydropower Potential

The increase in GHP leads to about 215GW of global capacity (or approximately 20% of the total) seeing a growth in GHP of at least 10% under a 1.5°C scenario (See Figure 1). The global region where this is important is East Asia. Nonetheless, existing and planned hydropower potentials in other global regions may be severely diminished.

Considerable generation potentials and plants in both existing and planned hydropower assets in Latin America, the Caribbean (LAC) and Sub-Saharan Africa will be at risk of reductions in GHP for both climatic scenarios. In LAC about 20% (~35 GW) of current capacity and about 30% (about 55 GW) of that planned would see GHP decreasing by 10% or more, at a 1.5 °C scenario. In Sub-Saharan Africa about 5% of current (6 GW) and 10% (2.5 GW) of planned hydropower capacities would lose 10% or more GHP under a 1.5 ºC scenario.

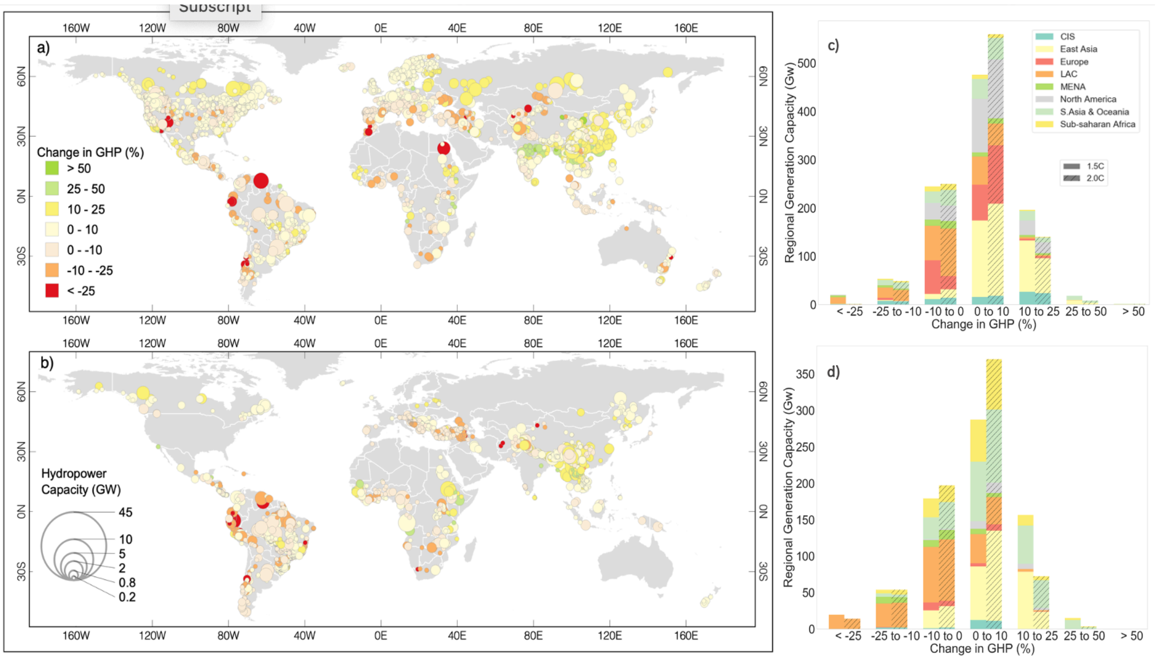

Figure 1. Global hydropower dam sites exposed to changes in GHP at 1.5 ºC for a) current and b) planned hydropower projects; multi-model ensemble global mean of total generation capacity exposed to levels of change in GHP at 1.5 ºC and 2.0 ºC scenarios for c) current and d) planned hydropower capacity. Exposure maps for a 2.0 ºC scenario are found in the Supplementary Section 7.

3.2 Hydropower Exposure Levels to Changes in Drought Frequencies

Our results in Figure 2 indicate that most of the current and planned hydropower generation plants may benefit from less frequent droughts under either climate scenario. For instance, less than 5% of current installed capacity and none of that planned would experience RC > 1.25 at a 1.5ºC. By contrast, ~900GW (or ~85%) of global installed capacity would experience either no change or less frequent droughts. This apparent benefit may be explained by the general global decrease in the frequency of droughts at 1.5ºC and 2.0ºC scenarios (yet some regions in LAC and East Asia may experience more frequent droughts) (see Supplementary Figure 4). This in turn may be due to the projected increase in the number of days with precipitation found between the two climate scenarios in various global regions including West-central North America and Siberia (within CIS).

Yet, within these estimates, it should be noted that about 20% of current and planned installed capacity in East Asia (about 70 GW) is in areas where the frequency of droughts will tend to generally increase in a 1.5°C warmer world. More importantly, in this region the total amount of planned hydropower capacity which would be at risk of the most frequent droughts would increase twofold under a 2.0°C scenario.

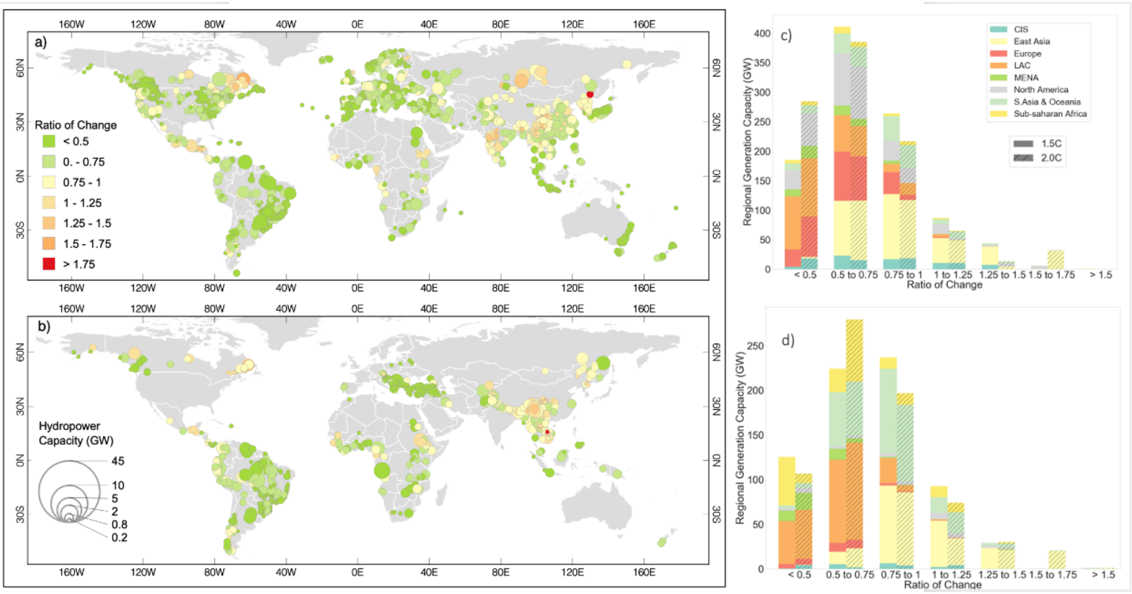

Figure 2. Exposed hydropower generation capacity to changes in drought frequencies at 1.5 °C relative to the historical baseline, for a) current and b) planned hydropower projects. Exposure maps at a 2.0 °C scenario are found in the Supplementary Section 7. Panels on the right show total exposure values for key global regions at 1.5 °C and 2.0 °C scenarios for c) current and d) planned hydropower capacity. Change in exposure represents the mean value calculated across the ensemble members of the four AOGCMs used in this study.

3.3 Hydropower Exposure Levels to Changes in Drought Durations

Opposite to changes in GHP and drought frequencies we find that the exposure levels of global hydropower to drought durations importantly increase in both scenarios (Figure 3(c)). Globally, about half of global current hydropower (about 500GW) capacity would be exposed to droughts at least 10% longer (RC>1.1) than the historical ones in a 1.5 ºC scenario. For planned hydropower projects, about 15% (120GW) of such projects will be exposed to longer droughts under 1.5 ºC scenario. In a 2.0 ºC scenario, the hydropower capacity at risk progressively increases to 400GW and 140GW for current and planned projects, accordingly. This global trend may be explained by the projected decrease in the number of rainy days (and drying trends) which has been previously identified in areas such as the Mediterranean basin (here within Europe and MENA) , Central and Northern regions of Europe, various areas in South America (within LAC) , and Australia (within East Asia and Oceania) (Lehner et al., 2017; Schleussner et al., 2016). See Supplementary Figure 5 and Supplementary 6 for an expanded discussion on changing droughts characteristics at both scenarios across the range of AOGCMs used here.

The regions where most of its current plants are expected to be at risk of longer droughts include Europe (~70% of total capacity, or 115GW at a 1.5 ºC scenario), North America (~40% of current capacity or 70GW), and the Middle East and North Africa (MENA) region (~16%; 5.5GW). Also, in both, North America and Europe about 35% of their existing hydropower capacity is located in areas with expected RC > 1.25. In Europe it is worth noticing that the total hydropower capacity located in areas where drought durations rise by 50% or more (RC > 1.5) would increase four-fold from a 1.5 ºC to a 2.0 ºC scenario (from ~12 GW to ~50 GW).

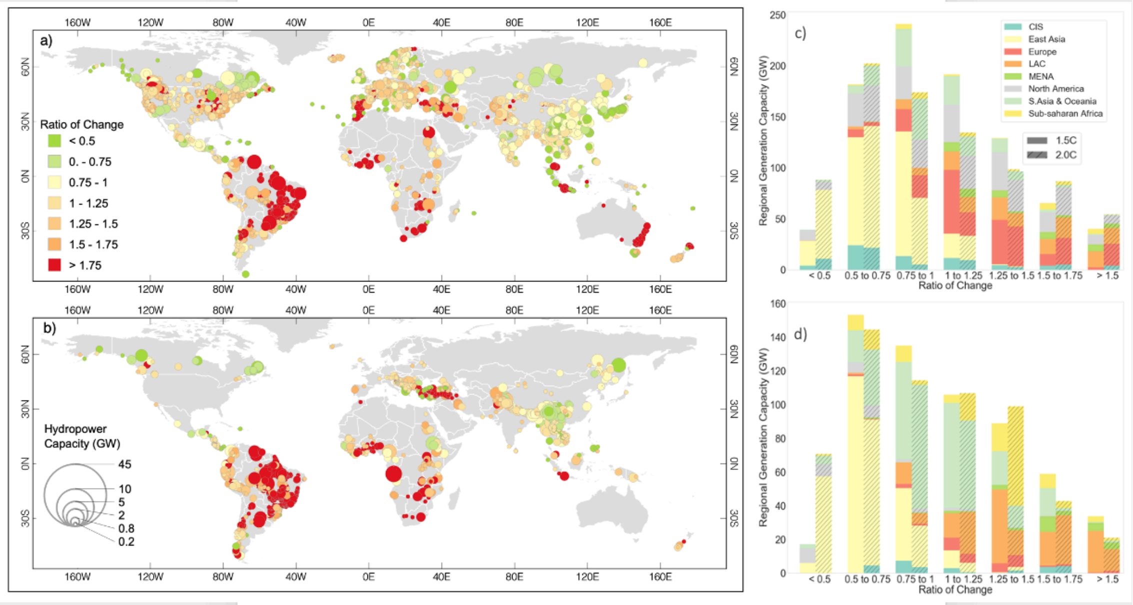

Figure 3. Exposed hydropower generation capacity to changes in drought durations at 1.5 °C relative to the historical baseline, for a) current and b) planned hydropower projects. Exposure maps at a 2.0 °C scenario are found in the Supplementary Section 7. Panels on the right show total exposure values for key global regions at 1.5 °C and 2.0 °C scenarios for c) current and d) planned hydropower capacity. Change in exposure represents the mean value calculated across the ensemble members of the four AOGCMs used in this study.

Moreover, a major and critical share of planned hydropower capacity is also expected to be affected by longer droughts in LAC, Africa Sub-Saharan, South Asia and Oceania, and CIS (Figure 3b,d). In these regions about 80%, 70%, 60%, and 25%, correspondingly, of planned hydropower projects may have to face droughts which are at least 10% longer. Also, unlike drought frequencies, hydropower assets in East Asia may expect to experience a decrease in duration of historical dry periods.

3.4 Hydropower Exposure Levels to Changes in Drought Intensities

Next, we find that, globally, ~240 GW of global installed capacity (~25% of total) and ~100GW (~60%) of planned hydropower capacity is exposed to droughts which are 10% more intense, or more, under a 1.5 °C scenario (Figure 4). In a 2.0 °C scenario these estimates increase to ~340 GW (~35%) for current capacities, whereas for planned ones, the estimates just increase by 5 GW.

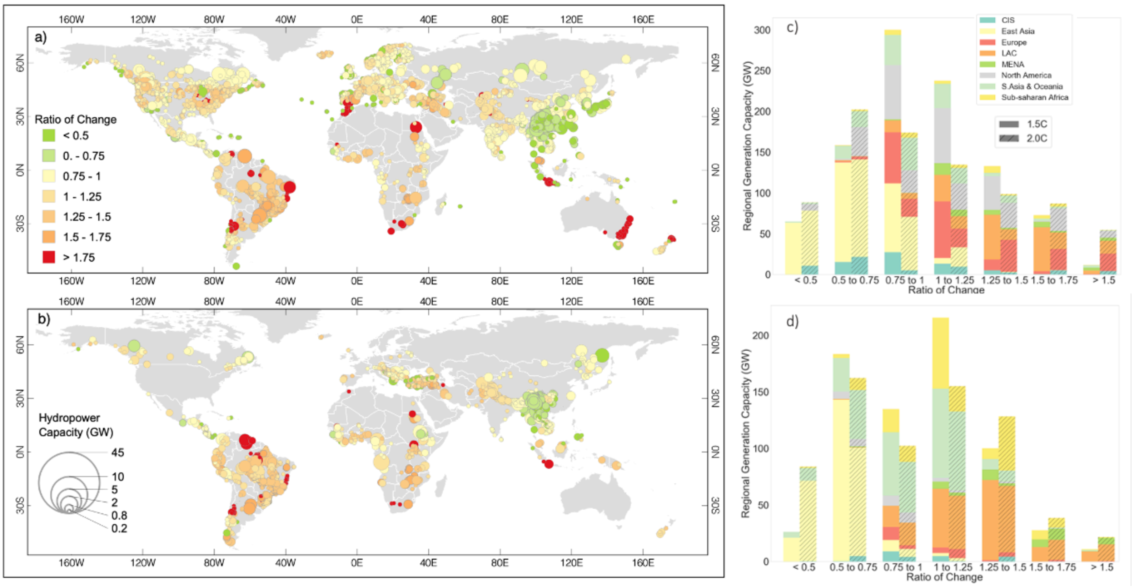

Figure 4. Exposed hydropower generation capacity to changes in drought intensities at 1.5 °C relative to the historical baseline, for a) current and b) planned hydropower projects. Exposure maps at a 2.0 °C scenario are found in the Supplementary Section 7. Panels on the right show total exposure values for key global regions at 1.5 °C and 2.0 °C scenarios for c) current and d) planned hydropower capacity. Change in exposure represents the mean value calculated across the ensemble members of the four AOGCMs used in this study.

For current plants, the most affected regions in a 1.5 °C scenario include Europe (50%, or 80GW), LAC (70%) or 130GW, North America (55% or 100GW), and MENA (75% or 25GW). Yet it is important to note particular regional clusters exposed to more intense droughts in specific sub-regions. For instance, large existing hydropower plants are exposed to more intense droughts in South East Australia, South Africa, and the Iberian Peninsula; this in turn may reduce energy generation potentials in these regions.

Moreover, while in most of these regions a 2.0 °C scenario leads to minor increases in hydropower exposed, maintaining a 1.5 °C scenario reduces future hydropower losses in Europe. In this region, a 2.0 °C scenario would expose an additional ~30GW of hydropower capacity to more intense droughts; thus putting about 70% of the continent's existing capacity at risk. Hydropower dams in other regions such as CIS and East Asia are also expected to experience increases in drought intensities, yet of less severity.

On the other hand, an important proportion of planned hydropower plants in regions such as LAC (~80% or 140GW), Africa Sub-Sahara (~75% or 80GW) and South Asia and Oceania (~60% or 70GW), are at risk of more severe droughts in a 1.5 °C climate scenarios. In these regions, a 2.0°C scenario would cause only a negligible increase in the total planned hydropower capacity at risk (< 5GW across all these regions).

3.5 Exposure Levels to Changes in Extreme High Flows

Last, we identify the global hydropower capacity at risk due to changes in high flow conditions. In a 1.5 °C scenario, about 65% (about 600GW) of current global hydropower would face more frequent extreme high flows (the historical 1-in-100 years flow occurring with a frequency of 1-in-75 years or less; Figure 5). Approximately 50% (or 90GW) of planned hydropower capacity would have to face this type of risk. At a 2.0 °C scenario the fraction of exposed hydropower capacity increases to ~66% (~690GW) of current installed capacity and to ~72% (~125GW) of planned. This change may be explained by the general wetting trend observed under both scenarios and particularly the reported increase in global high flow characteristics (Paltan et al., 2018), particularly in Asia and Africa where considerable hydropower investments are planned.

We find a significant fraction of East Asian capacity is at risk from high flows. Here over 90% of both its current and future hydropower capacities will see an increase in high flows at a 1.5 ºC scenario. Similarly, South East Asia and Oceania will see an important share of their current and planned capacities at a greater risk (~80% and 55 GW; ~75% and 70 GW, accordingly). In LAC and CIS about 50% of both current and planned capacities are expected to be at risk. It is important to note that the difference between 1.5 ºC and 2.0 ºC scenarios is highly relevant across all these regions. For example, in East Asia an extra 30% of current installed capacity would be at risk of more recurrent high flows (the historical 1-in-100 years flow occurring with a frequency of 1-in-25 years) at a 2.0 ºC scenario.

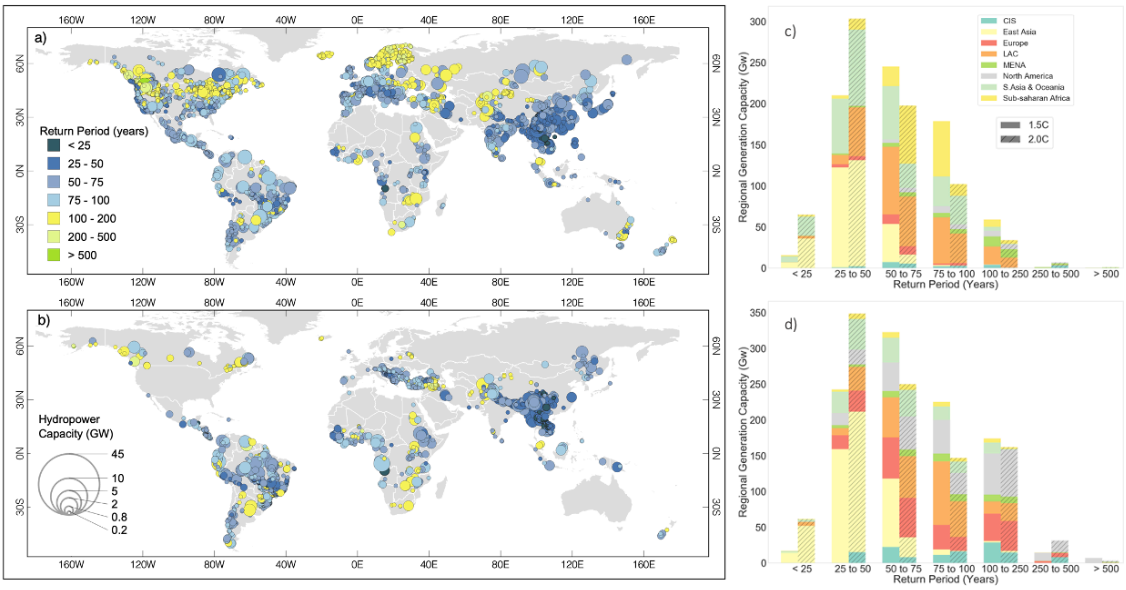

Figure 5. Exposed hydropower generation capacity to changes in occurrences of high flows (100-year return period) at 1.5 ºC relative to the historical baseline, for a) current and b) planned hydropower projects. Exposure maps at a 2.0 ºC scenario are found in the

Supplementary Section 7. Panels on the right show total exposure values for key global regions at 1.5 ºC and 2.0 ºC scenarios for c) current and d) planned hydropower capacity. Change in exposure represents the mean value calculated across the ensemble members of the four AOGCMs used in this study.

4. Discussion

In this study we have described the water risks that the global hydropower sector may have to face in its path towards achieving the climatic goals agreed in Paris. Here, by calculating exposure levels of hydropower capacities, we provide an initial diagnostic which could be used as a first screening which identifies potential vulnerable regional hotspots. Our findings would facilitate the application of more sophisticated approaches (including more advanced modelling and methodological techniques) which estimate energy production vulnerabilities and, indeed, risk at finer resolutions.

Our results show that the global hydropower sector will have to face diverse, simultaneous, and compound water risks. We find that the increase in high river flow frequencies (in this study understood as the change in the 1-in-100-years flow) would be the dominant water risk that existing and planned hydropower sites may have to face in the future. As such, we find that, about 65% (about 600GW) of current global hydropower installed capacity will be exposed to more frequent high flows at a 1.5ºC scenario (the historical 1-in-100 years flow occurring with a frequency of 1-in-75 years or less). In particular, about 90% of installed capacity and 50% of that planned in East Asia will be exposed to this type of water risk. While the actual extent at which specific global sites would be damaged or not by these increases depend primarily on their design characteristics, more frequent extreme flows may lead to shifts in sedimentation rates and the subsequent reduction of the available reservoir depth and volume (diminishing the hydropower generation potentials), structural damage to dams which may result in dam failures, inundation of key infrastructure such as powerplants, inundation of downstream lands (as result of contingency floodwater releases), or general diminishing of life expectancies of hydropower projects. In this case, decision makers in these affected areas may look to strategies looking to modify operational rules of projects, provide additional flood mitigation interventions at the catchment scale (traditional or green), or even reinforce and change the structural characteristics of such projects.

We also find that low flows would be an important risk to the hydropower sector across multiple regions as most, existing or planned, hydropower projects would be exposed to one or more type of droughts. For instance, in East Asia more frequent droughts would expose about 20% of both their current and planned hydropower capacities. In Europe, North America, LAC, and the MENA region we find that between 40 and 75% of current installed hydropower capacity would have to face longer and/or more intense droughts. In fact, in Europe, maintaining a 1.5ºC scenario avoid about additional 40 GW of installed capacity to be exposed to droughts which are 50% longer and more intense. Furthermore, we also find that up to 80% of planned capacities in LAC, South Asia and Oceania, and Sub-Sahara would experience at least 10% more intense or longer drought at both scenarios.

Low flows would threaten expected energy generation while also increasing competition for water with other sectors. Thus, other sectoral strategies would have to be considered including looking at diversification of energy production sources, modification of grid types, and management of energy demands. Similarly, our results emphasize that activities in the energy sector in areas affected by low flows require coordinated actions with water users in other sectors such as household and industrial consumption and irrigation looking to minimize and manage water competition.

We also find that the global aggregate of current and planned hydropower plants may benefit from both greater GHP and less frequent droughts. In line with this, other studies have also suggested how climate change would lead to more hydropower global production in the regions highlighted here (e.g. the South Asia region) (Ali et al., 2018; Antwi and Sedegah, 2018; Hamududu and Killingtveit, 2012; Van Vliet et al., 2016). Yet our results suggest that while, indeed, global GHP, and in consequence global electricity generation, may increase in the future as the world warms, there may be regional imbalances in electricity production as well as other type of water risks which would exacerbate water competition with other sectors. This is particularly important for developing regions since important amounts of their planned hydropower capacities and plants are located in areas which would experience more intense and longer droughts or high flows risk.

Thus, in regions with depleting GHP energy security agendas as well as plans to decarbonize energy systems, and potential commitments to meet the Paris Agreement, may be compromised. Accordingly, in these regions, our results suggest the need of decision makers to evaluate the tradeoffs between the costs (financial, social, environmental, or others) of the potential interventions which may be needed to address the type of risks discussed here, apart from the traditional costs that hydropower projects have, vis-a-vis the benefits obtained from them. Such tradeoffs and potential risks need to be considered in the broader context, at regional or global spheres, when addressing strategies to meet climatic goals, such as the ones agreed in Paris. Ultimately, failing to address the risks discussed here, may threaten not just energy security goals at national scales but may also limit the ability of the hydropower sector to contribute to climate change mitigation.

5. Conclusions

Our results are expected to provide the general water context which decision makers in the hydropower sector may have to face while delivering the Paris climate goals. We first find that high river flow frequencies and potential floods would be the dominant water risk (65% of global installed hydropower capacity exposed to more frequent high flows). At the same time, we find that most existing or planned hydropower projects would be exposed to one or more types of drought. In general, our results find that in various global regions, mainly in the developing world, up to 80% of existing and planned hydropower capacities are located in areas where droughts are projected to become at least 10% longer, compared to historical conditions, and where historical 1-in-100 year flows would occur with a frequency of at least 1-in-75 years.

Yet, we also acknowledge the other technical, social, environmental or economic factors that describe a hydropower project as well as other sectorial metrics which are not considered here. This includes additional detailed understandings of the roles of compounding and reservoir characteristics. We do not consider the complex dynamics which dominate hydropower and energy demand which may aggravate the impacts discussed here. For example, water shortages resulted from more intense droughts in the key regions described here may affect local communities and the surrounding environment of a hydropower project causing knock-on effects on hydropower generation; especially if water is diverted for agriculture, industry and municipal drinking water supplies. Similarly, we do not consider dam operational characteristics which would help to understand electricity generation dynamics and in turn the vulnerability of generation rates to future change. So our results should be interpreted considering these limitations. Incorporating this wide range of factors and their interplay, along with project-level hydroclimatic characteristics, could ultimately describe the specific level of risk of energy generation and conditions of energy security of the regions discussed here.

We do not expect that the patterns described here would substantially differ when evaluated using CMIP6 model outputs. Recent estimates suggest similar overall patterns of increase and decrease in runoff and flood frequency between CMIP5 models used here and those from CMIP6 (Hirabayashi et al., 2021). Also, various of the drought hotspots identified here such as the Amazon, Southern Africa, and Australia, have also been acknowledged in recent studies (Cook et al., 2020). Yet, it is important to note that the HAPPI ensemble used in this study is designed to quantify the relative risks associated with 1.5°C and 2°C warmer worlds, rather than looking at specific emission scenarios.

Taken together, the results of this study help to determine whether, at the regional scale, the cost of designing in water-risk resilience and adaptation strategies would outweigh the benefits expected from such hydropower projects. In turn, this analysis could help align the international hydropower sector towards climatic and sustainable development agendas.

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6. References

Ali, S.A., Aadhar, S., Shah, H.L., Mishra, V., 2018. Projected Increase in Hydropower Production in India under Climate Change. Sci. Rep. 8, 12450. https://doi.org/10.1038/s41598-018-30489-4

Almeida, R.M., Shi, Q., Gomes-Selman, J.M., Wu, X., Xue, Y., Angarita, H., Barros, N., Forsberg, B.R., García-Villacorta, R., Hamilton, S.K., 2019. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nat. Commun. 10, 1–9.

Antwi, M., Sedegah, D.D., 2018. Climate Change and Societal Change—Impact on Hydropower Energy Generation, in: Sustainable Hydropower in West Africa. Elsevier, pp. 63–73.

Bartle, A., 2016. World Atlas & Industry Guide 2016. Aqua-Media International.

Bartle, A., 2002. Hydropower potential and development activities. Energy Policy 30, 1231–1239.

Berga, L., 2016. The role of hydropower in climate change mitigation and adaptation: a review. Engineering 2, 313–318.

Beyene, B.S., Van Loon, A.F., Van Lanen, H.A.J., Torfs, P., 2014. Investigation of variable threshold level approaches for hydrological drought identification. Hydrol. Earth Syst. Sci. Discuss. 11, 12765–12797.

Blomfield, A., Plummer, J., 2014. The allocation and documentation of hydrological risk H. Int. J. Hydropower Dams 5, 94–108.

British Petroleum, 2019. BP Statistical Review of World Energy Report, BP: London, UK.

Christoff, P., 2016. The promissory note: COP 21 and the Paris Climate Agreement. Env. Polit. 25, 765–787.

Cook, B.I., Mankin, J.S., Marvel, K., Williams, A.P., Smerdon, J.E., Anchukaitis, K.J., 2020. Twenty-first century drought projections in the CMIP6 forcing scenarios. Earth's Futur. 8, e2019EF001461.

Dadson, S.J., Bell, V. a., Jones, R.G., 2011. Evaluation of a grid-based river flow model configured for use in a regional climate model. J. Hydrol. 411, 238–250. https://doi.org/10.1016/j.jhydrol.2011.10.002

Danielson, J.J., Gesch, D.B., 2011. Global multi-resolution terrain elevation data 2010 (GMTED2010). US Geological Survey.

Demarty, M., Bastien, J., 2011. GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH4 emission measurements. Energy Policy 39, 4197–4206.

Dincer, I., 2000. Renewable energy and sustainable development: a crucial review. Renew. Sustain. Energy Rev. 4, 157–175. https://doi.org/https://doi.org/10.1016/S1364-0321(99)00011-8

Dujardin, J., Kahl, A., Kruyt, B., Bartlett, S., Lehning, M., 2017. Interplay between photovoltaic, wind energy and storage hydropower in a fully renewable Switzerland. Energy 135, 513–525.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., 2014. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Clim. Chang. 1–11.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Demuth, S., 2006. A global evaluation of streamflow drought characteristics. Hydrol. Earth Syst. Sci. Discuss. 10, 535–552.

Gaudard, L., Romerio, F., Dalla Valle, F., Gorret, R., Maran, S., Ravazzani, G., Stoffel, M., Volonterio, M., 2014. Climate change impacts on hydropower in the Swiss and

Italian Alps. Sci. Total Environ. 493, 1211–1221. https://doi.org/https://doi.org/10.1016/j.scitotenv.2013.10.012

Graabak, I., Korpås, M., Jaehnert, S., Belsnes, M., 2019. Balancing future variable wind and solar power production in Central-West Europe with Norwegian hydropower. Energy 168, 870–882.

Gross, C.A., Roppel, T.A., 2012. Fundamentals of electrical engineering. CRC press.

Güney, T., 2019. Renewable energy, non-renewable energy and sustainable development. Int. J. Sustain. Dev. World Ecol. 26, 389–397. https://doi.org/10.1080/13504509.2019.1595214

Hamududu, B., Killingtveit, A., 2012. Assessing climate change impacts on global hydropower. Energies 5, 305–322.

Harto, C.B., Yan, Y.E., Demissie, Y.K., Elcock, D., Tidwell, V.C., Hallett, K., Macknick, J., Wigmosta, M.S., Tesfa, T.K., 2012. Analysis of drought impacts on electricity production in the Western and Texas interconnections of the United States. Argonne National Laboratory (ANL).

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., Kimoto, M., 2008. Global projections of changing risks of floods and droughts in a changing climate. Hydrol. Sci. J. 53, 754–772. https://doi.org/10.1623/hysj.53.4.754

Hirabayashi, Y., Tanoue, M., Sasaki, O., Zhou, X., Yamazaki, D., 2021. Global exposure to flooding from the new CMIP6 climate model projections. Sci. Rep. 11, 1–7.

Hisdal, H., Tallaksen, L.M., 2003. Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark. J. Hydrol. 281, 230–247.

Hoes, O.A.C., Meijer, L.J.J., Van Der Ent, R.J., Van De Giesen, N.C., 2017. Systematic high-resolution assessment of global hydropower potential. PLoS One 12, e0171844.

Hollins, L.X., Eisenberg, D.A., Seager, T.P., 2018. Risk and resilience at the Oroville Dam. Infrastructures 3, 49.

IEA, 2019. World Energy Outlook 2019, IEA, Paris. Paris.

IHA, 2020. Hydropower Status Report. London.

Koch, F., Prasch, M., Bach, H., Mauser, W., Appel, F., Weber, M., 2011. How will hydroelectric power generation develop under climate change scenarios? A case study in the upper danube basin. Energies 4, 1508–1541. https://doi.org/10.3390/en4101508

Kuusisto, E., 2004. Droughts in Finland–past, present and future. Hydrol. Days 2004, 143–147.

Lehner, B., Czisch, G., Vassolo, S., 2005. The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 33, 839–855.

Lehner, F., Coats, S., Stocker, T.F., Pendergrass, A.G., Sanderson, B.M., Raible, C.C., Smerdon, J.E., 2017. Projected drought risk in 1.5°C and 2°C warmer climates. Geophys. Res. Lett. n/a--n/a. https://doi.org/10.1002/2017GL074117

Loisulie, S., 2010. Vulnerability of Tanzania hydropower production to extreme weather events, in: The Joint ICTP-IAEA Workshop on Vulnerability of Energy Systems to Climate Change and Extreme Events.

Madani, K., Lund, J.R., 2010. Estimated impacts of climate warming on California's high-elevation hydropower. Clim. Change 102, 521–538. https://doi.org/10.1007/s10584-009-9750-8

Mishra, A., 2015. Cloudburst and landslides in Uttarakhand: a nature's fury. Mausam

66, 139–144.

Mitchell, D., Achutarao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., Forster, P.M., Fuglestvedt, J., Gillett, N., Haustein, K., Ingram, W., Iversen, T., 2017. Half a degree additional warming , prognosis and projected impacts (HAPPI): background and experimental design 571–583. https://doi.org/10.5194/gmd-10-571-2017

Mukheibir, P., 2013. Potential consequences of projected climate change impacts on hydroelectricity generation. Clim. Change 121, 67–78.

Muller, M., 2019. Dams have the power to slow climate change. Nature 566, 315–317.

Oki, T., Sud, Y.C., 1998. Design of Total Runoff Integrating Pathways (TRIP)—A global river channel network. Earth Interact. 2, 1–37.

Olivera, F., Raina, R., 2003. Development of large scale gridded river networks from vector stream data. J. Am. Water Resour. Assoc. 39, 1235–1248. https://doi.org/10.1111/j.1752-1688.2003.tb03705.x

Paltan, H., Allen, M., Haustein, K., Fuldauer, L., Dadson, S., 2018. Global implications of 1.5 °C and 2 °C warmer worlds on extreme river flows. Environ. Res. Lett.

Piman, T., Cochrane, T., Arias, E., Green, A., Dat, D., 2013. Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin. J. Water Resour. Plan. Manag. 139, 723–732. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000286

Pokhrel, Y.N., Oki, T., Kanae, S., 2008. A grid based assessment of global theoretical hydropower potential. Proc. Hydraul. Eng. 52, 7–12.

Rübbelke, D., Vögele, S., 2011. Impacts of climate change on European critical infrastructures: the case of the power sector. Environ. Sci. Policy 14, 53–63.

SANDRP, 2013. Uttarakhand Floods of June 2013: Curtain Raiser on the events at

NHPC’s 280 MW Dhauliganga HEP. Delhi.

Scherer, L., Pfister, S., 2016. Hydropower’s biogenic carbon footprint. PLoS One 11, e0161947.

Schleussner, C.-F., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., Schaeffer, M., 2016. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. Earth Syst. Dynam. 7, 327–351. https://doi.org/10.5194/esd-7-327-2016

Van Loon, A.F., 2015a. Hydrological drought explained. WIREs Water 2:359–392. https://doi.org/10.1002/wat2.1085

Van Loon, A.F., 2015b. Hydrological drought explained. Wiley Interdiscip. Rev. Water 2, 359–392.

Van Loon, A.F., Van Lanen, H.A.J., 2012. A process-based typology of hydrological drought. Hydrol. Earth Syst. Sci. 16, 1915.

van Vliet, M.T.H., Sheffield, J., Wiberg, D., Wood, E.F., 2016a. Impacts of recent drought and warm years on water resources and electricity supply worldwide. Environ. Res. Lett. 11, 124021.

Van Vliet, M.T.H., van Beek, L.P.H., Eisner, S., Flörke, M., Wada, Y., Bierkens, M.F.P., 2016. Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob. Environ. Chang. 40, 156–170.

van Vliet, M.T.H., Wiberg, D., Leduc, S., Riahi, K., 2016b. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat. Clim. Chang. 6, 375–380. https://doi.org/10.1038/nclimate2903

Yevjevich, V.M., 1967. An objective approach to definitions and investigations of continental hydrologic droughts. Hydrol. Pap. (Colorado State Univ. no. 23.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. Aquat. Sci. 77, 161–170.

Zelenhasić, E., Salvai, A., 1987. A method of streamflow drought analysis. Water Resour. Res. 23, 156–168.