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Climate change related problems to hydropower plants in the tropics and sub-tropics

by Dr. Jutta Lauf and Dr. Reiner Zimmermann

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Hydropower plants - their renewable energy comes at a cost

Hydropower plants are often deemed as a "silver bullet" to solve the climate crisis and securing energy security[1; 2]. Their electricity production is considered as renewable and free of greenhouse gas emissions GHG). Typically, hydropower plants use water stored in large reservoirs or lakes which had been created by dams, to drive electricity generating turbines. They possess high power producing capacities in the order of several hundred Mega Watt (MW) or more. In contrast to this, run-off-river plants can only produce electricity when the river carries enough water because they possess no or only very small water reservoirs. Globally, most very large river systems in terms of water flux (m^3/sec) originate in tropical and subtropical mountainous regions with high and often seasonally variable precipitation. This article focuses on problems emerging from climatic changes, caused primarily by climatic warming and changes in precipitation regime in the upper watersheds, for existing and projected downstream hydro dams and power plants in the tropics and subtropics.

Hydropower dams actually come with considerable GHG emissions and social costs. They are constructed with huge amounts of concrete, which has a high carbon footprint[3; 4]. The flooding of large areas, in the tropics often of pristine forests, is leading to GHG emissions, especially methane, which is a more potent greenhouse gas than CO_2[5]. Additional environmental costs are the degradation of the impounded river ecosystems. Without special precautions the migration of plant and animal species is generally blocked by the dams and reservoirs.[6] The downstream river sediment flow is also hindered by the dam and sedimentation may decrease the volume of the reservoir over time. Downstream of the dam, the missing sediment load causes erosion in the riverbed and the river delta. The social costs contain the resettlement of communities, sometimes without agreement and compensation for lost land, livelihoods, and cultural goods. The rights of indigenous people are often completely ignored, as they often are not represented in governments and institutions[1]. Also, serious and often violent cross border conflicts over water rights result. A recent example is the multinational political conflict between Ethiopia, Sudan and Egypt with respect to the construction of the Great Ethiopian Renaissance Dam on the Blue Nile.[8; 1; 7]

In 2016, worldwide about 3,500 hydropower dams were in operation or planned. Brazil alone operates more than 1,000 hydro dams, while the second most dams are located in Nepal (~250)[1]. Global electricity production from hydropower dams has more than doubled from 1985 (1,980 TWh) to 2021 (4,234 TWh) while the relative share was sinking from 20,3 % to 15,2% over the same period. In general, low-income countries produce greater shares of electricity with hydropower plants (average 67.7 % in 2021) than richer nations. Countries with shares of more than 90 % - in decreasing order – are Lesotho, Paraguay, Nepal, Democratic Republic of Kongo, Uganda, Tajikistan, and Zambia.

In contrast to this rise of hydropower dams in the tropics and subtropics, no new hydropower dams are approved in many industrialized western nations due to the associated social and environmental costs. The “Water Frame Directive” of the European Union for example does not allow the deterioration of the existing situation of a water bodies. This regulation renders new hydropower projects practically impossible.[9; 10] Industrialized countries with high share of hydropower are Norway, which produced 92 % of its electricity with hydropower in 2021, Iceland (71 %), followed by Canada (60 %), New Zealand (55 %), and Sweden (40%).[11]

Since most hydro dams are currently operated or planned in tropical and sub-tropical countries, often depending with a large share on this mean of electricity production, this article will present some examples from this region and discuss how climate change negatively affects hydropower plants in tropical and sub-tropical regions and look at subsequent consequences for people and economy.

Hydropower under Changing Climatic Conditions in Tropical and Subtropical Regions

The tropical zone is defined as the area between the Tropic of Cancer (~23,5° N) and the Tropic of Capricorn (~23,5° S). In this area, the suns zenith is at least once a year at an angle of 90°. The sub-tropical zones are defined as the adjacent areas north and south of the tropics up to a latitude of 35°, respectively.[13; 12]

Spatial distribution of very contrasting climate types varies considerably within the tropics and subtropics. From per-humid rainforests to hyper-arid deserts many intermediate climates and vegetation covers can be found within short distances along coastal areas and in mountainous regions. Therefore, a classification which accounts for temperature and precipitation – such as the Köppen-Geiger climate classification (see Box) - is useful for discussing hydropower plants. Therefore, “tropical” in this article refers to the tropical and subtropical climate types, rather than to the geographical zone.[12]

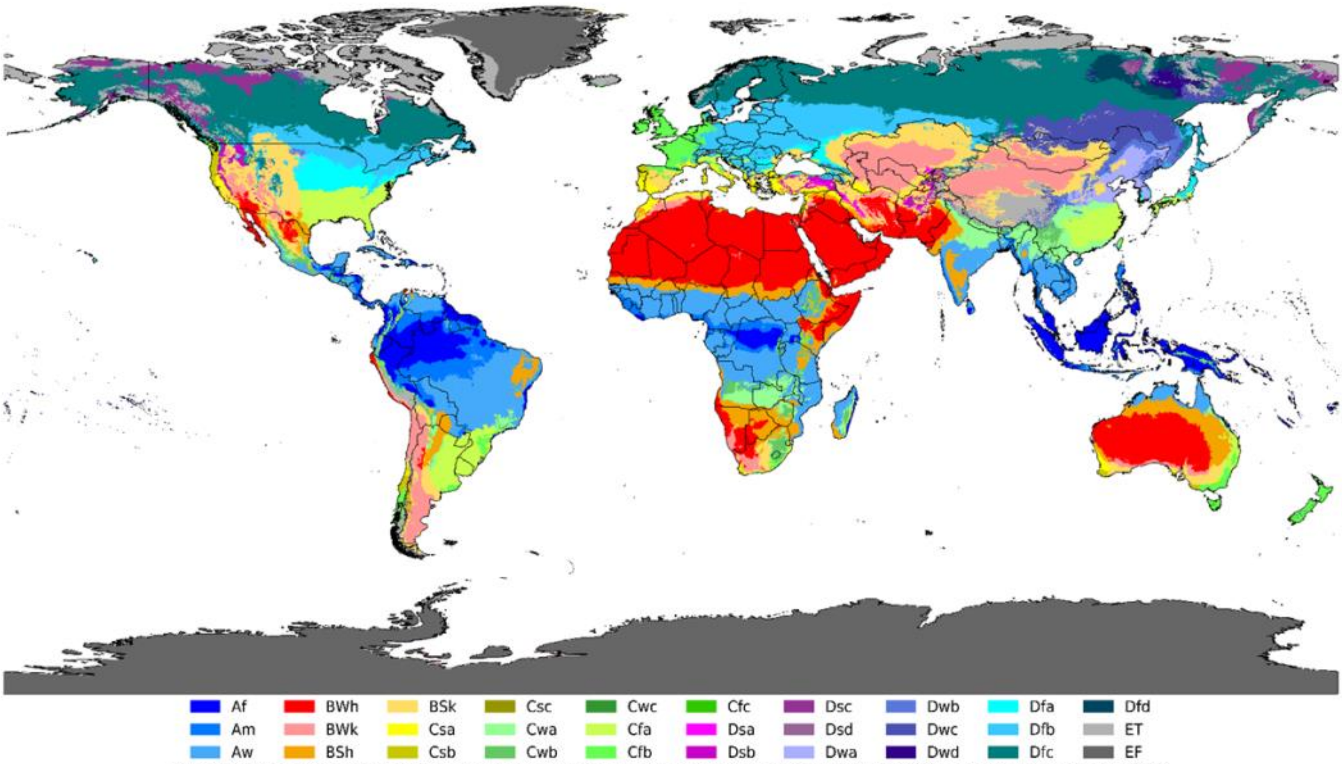
The typical climate pattern of the per humid tropics (Af) shows annually >2,000 mm of precipitation (without occurrence of dry or rainy seasons) and a minimum average air temperature of 18 °C. Such conditions are found near the equator in the Amazons- and Congo River Basins as well as on Indonesian Islands[14]. In contrast, sub-tropical climates are often characterized by hot summers, often coinciding with heavy rains and a dry season, sometimes with sporadic frost events in higher elevations. At high elevations like in the Himalayas, huge climatic variations in may occur within short distances and across the entire watersheds of large river systems.[13]

The Global Climate Zones

The Köppen-Geiger climate classification divides climates on the earth into five main groups based on typical seasonal precipitation and temperature patterns. The main groups are tropical A (Af = Rainforest

Am = Monsoon, Aw = Savanna, dry winter, As = Savanna, dry summer), arid B (BW = Arid Desert, BS = Semi-Arid or steppe, both with further subdivisions as h = Hot or k = Cold), temperate C (Cw = Dry winter, Cf = No dry season, Cs = dry summer, all three with further subdivisions into a = Hot summer

b = Warm summer, c = Cold summer), continental (D) and polar (E). The classification scheme is reworked regularly to update maps to the real-world situations, which is especially important with respect to climate change. Models which predict the possible shift in climate zones due to climate change until the year 2100 are published[15].

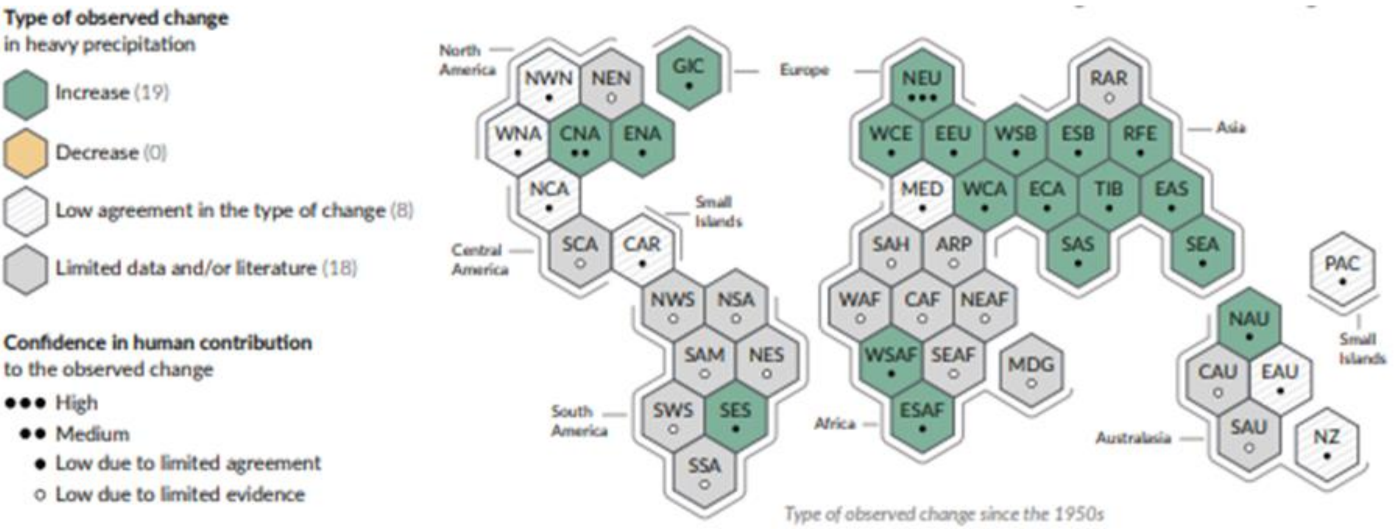


Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

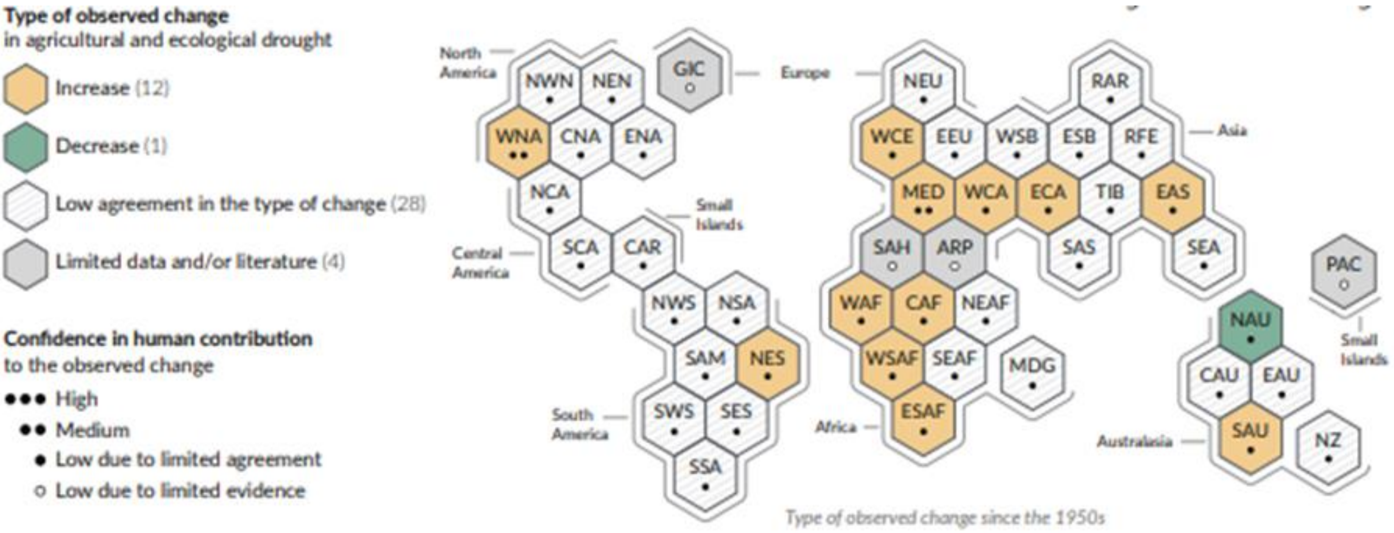
Figure 1: Köppen-Geiger classification of world climate zone. For tropical (A), dry (B) and temperate (C) regions see text. The classification for continental (D) and polar (E) regions are explained by Hylke E. Beck, et al. (2018).[15; 16]

Climate Change affects the water supply for hydropower plants

Hydropower plants depend on a steady and sufficient water supply. According to the 2021 report of the Intergovernmental panel on Climate change (IPCC), - the United nation's body for assessing the science related to climate change - climate change has already affected every inhabited region of the globe. Human influence contributed to many observed changes in weather and climate extremes. Expected climate changes and the likely human contribution to climate changes for different regions are shown in Figure 2.[17]. Increased numbers of hot weather events, heavy precipitation incidents, droughts, and generally more erratic weather patterns have direct consequences for the water available for hydropower plants.



(A) Assessment of observed change in heavy precipitation and level confidence in the human contribution to the observed changes in the world's regions[17].



(B) Assessment of observed changes in agricultural and ecological drought and confidence in the level of human contribution to the observed changes in the world's regions[17].

Figure 2: Assessment of observed change in heavy precipitation (A), agricultural and ecological drought (C) and level of confidence in human contribution to the observed changes in the world's regions. Each hexagon corresponds to one of the IPCC AR6 WGI global reference regions.[17]

Hot weather events and droughts may not only reduce the water supply to hydropower dams but also aggravate the conflicts for water use between energy production, irrigation for agriculture and industry. Heavy precipitation may also lead to flooding and increased soil erosion, both endangering hydropower dams by sedimentation and damage to turbines. Several of these weather anomalies can hit a region within short periods of time, not adding but potentise the impact of a single event.

Water in Electricity Production

The ability to generate electricity in a hydro power plant is directly coupled with the water content in the reservoir – in case of a dam – or of the riverbed in case of a run-of-water plant. Climate related dry seasons have to be covered by water provisions in the dam itself to secure a constant power supply. Run-of-river plants may not produce any power in dry seasons. Increasing intensity and duration of heat waves and droughts may lead to power cuts due to lack of water, especially when the water is also used as drinking water and in agriculture. On the other hand, dams may spill over due to extreme precipitation events, glacial melt downs or landslides endangering the population downstream of the dam.

The river water feeding into a reservoir, the water in the reservoir itself or its downward flow may additionally be needed for electricity production in fossil fuel or nuclear power plants. Generally, plants with a capacity of > 300 MW use river/reservoir water for the cooling of the electricity generating steam or gas turbines. Lack of water for cooling or water temperatures above the authorized limits will lead to shutdowns. During the hot summer of 2022 many nuclear power plants in France had to shut down, as the allowed river temperatures were reached, even after the authorities increased the allowed limits[18; 19]. Models suggest that an decrease of 0.2 – 0.6 % in electricity output has to be expected per degree centigrade increase in ambient air temperature.[20] In a recent report the French Court of Auditors (Paris)[21] expects that the number of forced nuclear power plant shutdowns during low river levels in summer may increase three to four times by 2050 with severe consequences electricity production[22; 23].

Hydropower in the tropics and subtropics affected by Climate Change

Hydropower generation in the tropics and subtropics is affected in two ways by the current climatic changes. The first effect is the loss of subtropical glacier volume during the next decades due to warming, while the second, much longer lasting effect will be an increasing frequency and severity of heavy rainfall events and droughts as a consequence of higher ocean surface evaporation and changing global weather patterns.

Increasing **terrestrial surface temperatures** destabilize existing glaciers and ice fields and cause ice avalanches, glacial outburst, and mudflows. Such catastrophic events may result in downstream dam failures and flooding. Here, we present two recent examples for hydro dam failures in the high mountain's regions of the Himalaya in India and Nepal. Such problems may occur during the next decades during a transitional phase when subtropical glaciers will lose significant ice masses.

The globally increasing **air and ocean temperature** leads to more intense rainfall, storms and monsoons as well as to droughts. To this end, we discuss examples from the lower basin of the Mekong River (Laos) and the Pangani, Rufiji and Zambesi rivers in south-eastern Africa (Tanzania and Zambia).

Ice avalanches: The glacial ice avalanche of 2021 in India's Himalayan Uttarakhand state

The stability of glaciated and perennially frozen high-mountain slopes is particularly sensitive to climate change. Air and surface temperatures have been increasing across tropical mountains and the subtropical region of the Himalayas in the last decades[24; 17]. Most glaciers are shrinking, thereby uncovering, and destabilizing mountain flanks and strongly altering the hydrological and thermal regimes of the underlying rock. Although the following example of an ice avalanche in Chamoli, India cannot be attributed to climate change it is likely to be related.[24]

In India approx. 99 % of the population has access to electricity[25]. In 2021 approx. 9 % of electricity was produced by hydropower dams and approx. 74 % by coal fired plants. Solar, wind, and gas plants contribute about 4 % each. The relative share of hydropower plants to the electricity mix is constantly shrinking (from ~ 28 % in 1985) although the absolute amount of hydro energy produced has more than tripled. This is due to s the accelerated development of India as well as its population growth.[11; 26]

Uttarakhand is a state in northern India (Figure 3 (A)). Most of its northern part is covered by Himalayan peaks and glaciers[27]. On 7 Feb 2021, a massive rock and ice avalanche from the 6,063 m a.s.l. high Ronti Peak generated a cascade of events that caused 204 deaths or missing persons, as well as damage or destruction of infrastructure that most notably included two hydropower projects in the Rishiganga and Dhauliganga valleys. 190 of the 204 victims were workers on these hydropower stations. Direct economic losses from damage to the hydropower structures alone amounted to more than 223 million $US.[24]

At 4:51 UTC about 26.9x106 m3 of rock and ice detached from the steep north face of Ronti Peak at an elevation of about 5,500 m asl and impacted the Ronti Gad valley floor about 1,800 m below. The average speed of the rock and ice avalanche was 205 – 216 km/h down the ~35° steep mountain face. The resulting scar has a vertical height of up to 180 m, up to ~80 m thickness and up to ~550 m width. The detached volume comprised 80% rock and 20% glacier ice[24].

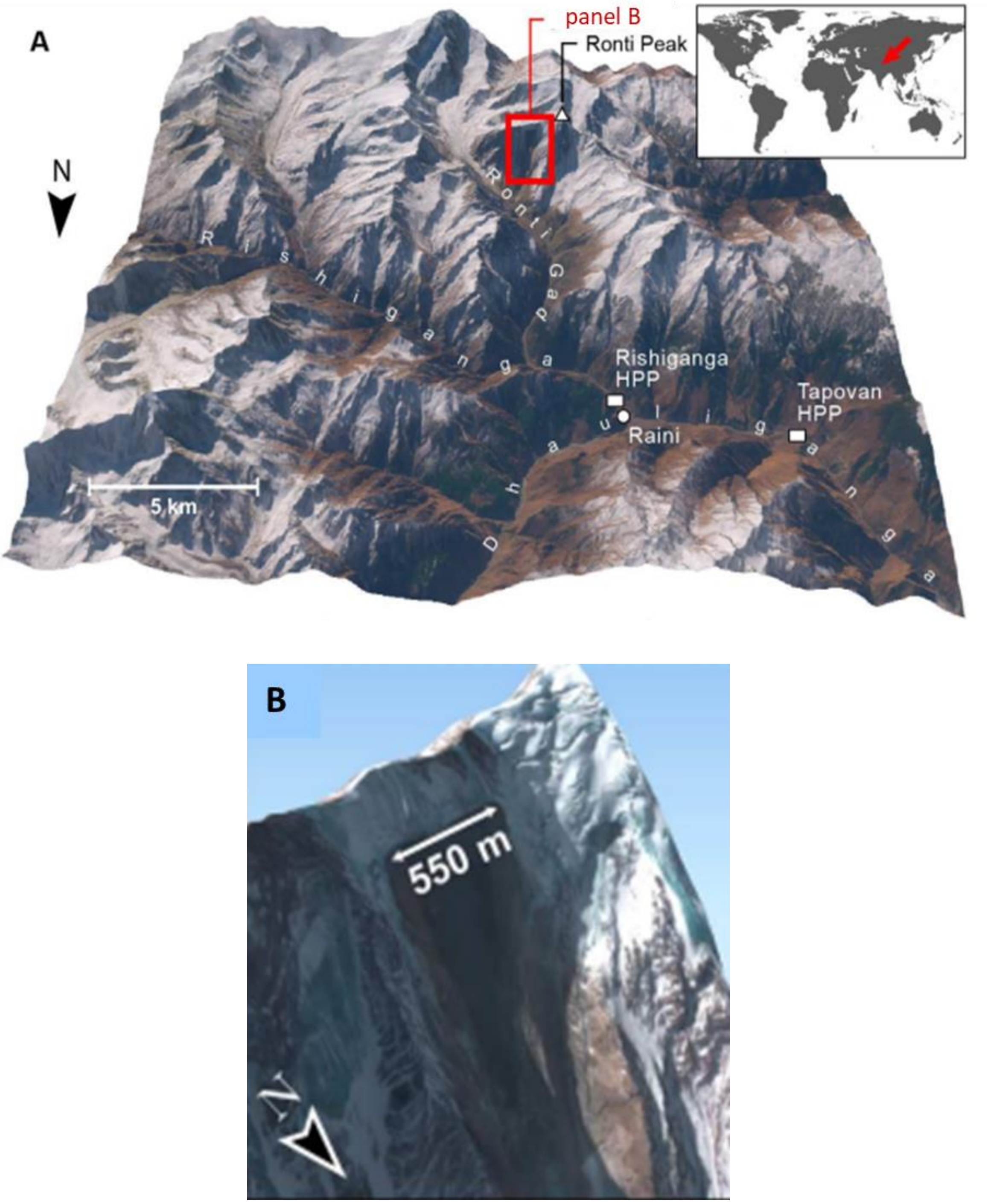


Figure 3: Overview of the Chamoli ice avalanche disaster in Uttarakhand, India on 7th of February 2021. (A) 3D rendering of the local geography, with labels for main place names mentioned in the text. HPP stands for hydropower project. B) Arial photo of the 550 m wide scar at a height of approx. 5,500 m asl in the north face of 6,063 m a.s.l. Ronti Peak two days after the landslide.[24]

The rock ice avalanche made its way down the valleys of Ronti Gad, Rishiganga, and Dhauliganga subsequently blocking the confluence of the Rishinganga river, where a lake was building up in the valley. Progressing down the valleys the ice melted, forming a mass flow of water, rocks, and debris. The Rishiganga hydropower project about 15 km downstream of the origin of the avalanche was reached 10 min after the ice avalanche had broken off the mountain. The Tapovan hydropower project located another 10 km downstream was reached after 20 min. Both dams were completely washed out.[24]

A sediment plume arrived 8 days after the avalanche in Delhi, which polluted the drinking water with suspended sediment (turbidity). The corresponding sedimentation in hydropower reservoirs and rivers can be substantial, and may cause increased erosion on turbine blades and infilling of reservoirs in the years to come.[24]

The missing power production capacity of the destroyed hydropower facilities may easily be covered by the existing coal power plants. As India has a high population growth coupled with high unemployment rates the necessary discussions with respect to the safety of hydropower dams may be pushed aside in favour of developing the economy, leaving workers and residents vulnerable to unpredictable risks as long as the Himalayan glaciers have not yet melted down completely.

Glacial lake outbursts: The mud flood of 1985 in Eastern Nepal

Glacial lake outburst floods can be triggered by mass movements entering the lake (e.g., landslides or avalanches), the self-destruction of the terminal moraine due to hydrostatic pressure, the melting of a buried ice core or earthquakes. Glacial lake outburst floods pose a significant threat to downstream communities and infrastructure due to their potential to rapidly unleash large quantities of stored lake water[28–30].

Nepal is a landlocked mountainous country in the central Himalayan region. It's climate is dominated by humid subtropical (Cwa) and subtropical oceanic highland (Cwb) climates with pronounced annual dry and rainy seasons (Figure 4 A)[15; 16]. It contains around 6,000 rivers and many glacial lakes which are fed by run off from snow-caps and glaciers in Nepal and the Tibetan Plateau as well as by the monsoon season.[31]

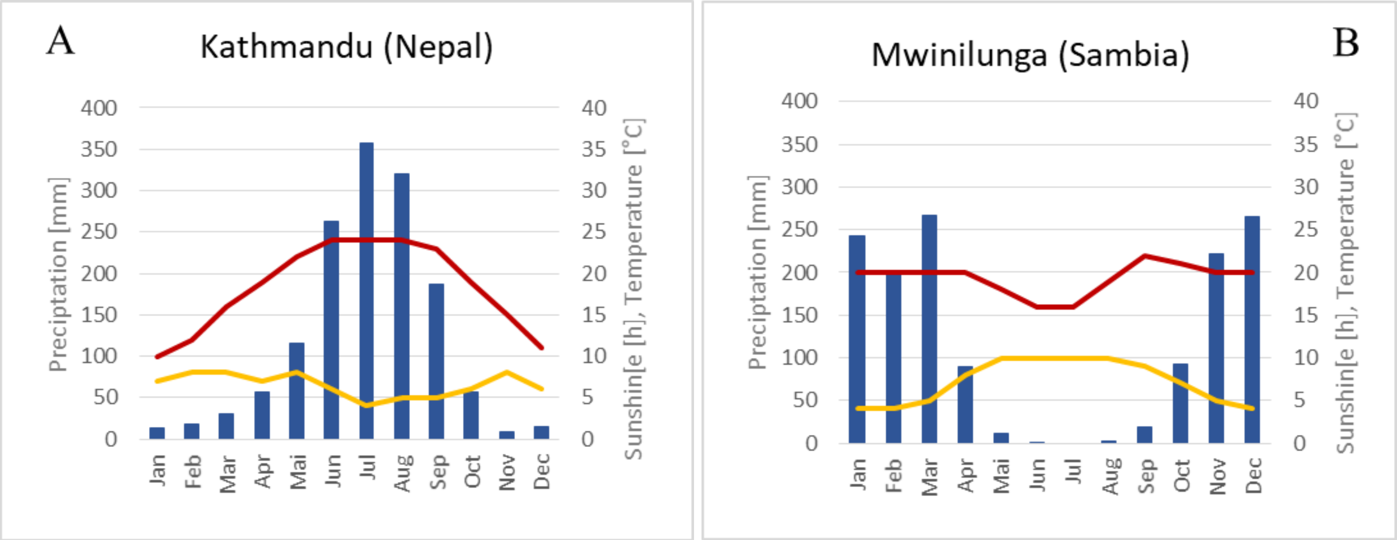


Figure 4: Climate graph from two subtropical weather stations. (A) Kathmandu (Nepal), Köppen-Geiger climate (Cwb), Latitude: 27° 42' N, Longitude: 85° 22 E, Altitude: 1,337 m. (B): Mwinilunga (Sambia), Köppen-Geiger climate (Cwb) Latitude: 11° 45' S, Longitude: 24° 26 E, Altitude: 1,362 m. Blue bars: Precipitation, Ø total of month [mm]. Red line: Temperature, monthly average [°C]. Yellow line: Sunshine duration, monthly average [h]. Modified after DWD (2023)[14].

In 2020 approx. 90 % of Nepal's population had access to electricity[25] and approx. 98 % of electricity was produced by hydropower plants[11]. Most are run-off-river plants with little or no water storage capacity[31]. Solar and wind farms contribute the missing 2 % of power production. Power production has plateaued since 2019.[11] Until 2017 and mainly during the dry winter season, load shedding (intentional detaching of areas from the power grid in order to prevent grid failure[32]) was common due to lack of water. Such daily power cuts have severe negative effects on businesses, health care facilities and private households, as smooth, continuous operations are not possible. Since 2017, domestic power generation capacity, improved load management and increased imports from neighboring India have eliminated load shedding completely.[33]

On 4th August 1985 the Dig Tsho glacial terminal moraine Lake in the Khumbu area burst down into the Bhote Kosi and Duh Kosi valleys in eastern Nepal. The breach of the moraine was triggered by an ice avalanche crashing into the lake.[34] The resulting flood destroyed a newly built hydroelectric power plant, 14 bridges, 30 houses, many hectares of arable land and trail networks. The debris was transported up to 40 km downstream.

Risk assessments for many glacial lakes in Nepal has been undertaken and published[28–30]. Such assessments are difficult, since the effects of climate change and the occurrence of earthquakes are unpredictable. Both, ice avalanches and glacial lake outbursts cause catastrophic floods and may beneath other disastrous effects result in downstream dam and hydropower plant destruction. While under future climate warming most glacial lakes will last much longer than the glaciers themselves, the same questions with respect to safety and operation as in the before mentioned example must be asked for downstream infrastructure projects. In the case of Nepal and with respect to electricity security even the failure of a single hydropower plant may cause power outages in Nepal's already squeezed electricity system.

1.1 Critical raw materials

Large hydropower dams which hold enormous amounts of water are found further downstream of large rivers in wide valleys or even lowlands. Climate warming in the tropics and subtropics will increase the intensity of rainfall and tropical storms[35] as well as increase unpredictable monsoon seasons (IPCC (Figure 2)[17]. Floods from such dams have even more devasting effects compared with upstream dams as they hold more water and affect larger populations. Destroyed large operational dams and the resulting damage to lives and infrastructure would possibly bring the ability of governments for rescue operations to its limits, also because the huge share of electricity produced by hydropower dams would no longer be available. Even neighboring countries might be heavily hit by power outages. On the long run much needed financial resources for cleaning up and reconstruction can may not be generated, as the electricity for export is available.

The following example from the spill over and structural dam failure of the Xepian-Xe Nam Noy hydropower dam in 2018 in the People's Democratic Republic of Laos demonstrates the danger and consequences of extreme precipitation events.

The People's Republic of Laos is a landlocked country in Southeast Asia. The Mekong River, originates in the Chinese Tibetan Plateau. It covers nearly 5,000 km and flows through Myanmar, Thailand, Laos, Cambodia and Vietnam to the South China Sea (Figure 5)[36; 37]. The upper basin – which is mostly located in the Peoples Republic of China (PCR) – contributes 15 – 20 % to its water flow. The western Mekong watershed area in Laos is dominated by tropical savanna (Aw) while the eastern watershed area is dominated by a tropical monsoon (Am) climate[15; 16]. The tropical savanna climate has a pronounced dry season from May to September with approx. 280 mm of precipitation per month.[14] Rainfall in the monsoon dominated areas from May to September is much higher (approx. 370 mm per month)[14] and as a result, seasonal floods are a common on the Mekong river.[37]

Since 2020 the entire Laotian population has access to electricity[25]. In 2021 71 % of electricity was produced by hydropower dams and ~27 % by coal fired plants and only 2 % by solar and biomass plants. From 2004 to 2014 hydropower dams where the only plants to produce power in Laos.[11] In 2020 Laos exported electricity worth of 1,93 x 109 US $ and this makes it the world's 3rd largest exporter of electric power. The neighboring countries Thailand (with ~91 % of the export value), Cambodia, Vietnam and Malaysia (in the order of trade volume) are the main customers.[38]

Figure 5: The Mekong watershed area encompasses China, Laos, Myanmar, Thailand, Cambodia and Vietnam[37]. Three new hydropower projects are marked, as well the existing Three Georges Dam in the PRC. (a) Three Gorges Dam (PRC), (b) Nam Chiane Hydropower Station (Laos), (c) Nam Ngum 3 Hydropower Station (Laos) and (d) Nam Tha 1 Hydropower Station (Laos)[39].

In the morning of the 23rd of July 2018, during a period of heavy rainfall in the rainy season, the Xepian-Xe Nam Noy hydropower dam on the Mekong River failed, releasing 5 x 109 m^3 of water in an instance. At that time, the earth-filled auxiliary dam -within a larger system of hydropower dams- was still under construction. The event caused an unknown number of fatalities (at least 49 were reported) and missing people, making 6,600 people homeless and flooding downstream large areas reaching into Cambodia.[40; 42; 41]

Information regarding the causes of the disaster remains opaque, even several years after the event. The from the Laotian government commissioned independent expert panel reported construction flaws of the dam. These allegations were immediately rejected by the project developer, who did not offer any credible evidence-based explanation for the failure. The full report of the expert panel was never published.[42]

Even in dry subtropical areas and downstream from the upper watershed, river floods are common, and a spillover of dams may occur. In 2022 the 39.3 km^3 reservoir of the huge 22,500 MW Three Gorges Dam on the Yangtze-River in the PRC[16] (Figure 5), was on the brink of a spill over (Figure 6). Officials of the PRC were keen to assure the public, that the dam would not fail. Such an event however, would endanger many millions of people downstream, since the normal river level there is already above the adjacent plains and only contained by extensive lateral dams while flowing through mega-cities like Wuhan, Nanjing and Shanghai. [43; 46; 44; 45]

In addition to its enormous power generation, the Three Gorges Dam has an important function for flood control. Major floods on the Yangtze-River occur regularly. One of the most devastating in recent time was the Yangtze-Huai flood in the summer of 1931, which lasted for three months. It was caused by a combination of the melting of an unusually amount of snow on the Tibetan plateau, heavy spring rains and a significantly higher number of tropical cyclones. It is estimated that about 150.000 people drowned in the event and in the aftermath an estimated 2 – 4 million people may have died due to the lack of clean water, food and the outbreak of diseases.[43; 46; 44; 45]

Figure 6: The Three Gorges Dam in China on 20th of August 2020 after several weeks of heavy precipitation had caused the water level in the reservoir rise to a critical level. Downstream floods had already caused inundations and the evacuation of thousands of residents.[43]

The largest threat to hydropower: Increased droughts

In contrast to catastrophic floods, dam spillovers and dam failures, the largest threat to hydropower generation in the tropics and subtropics under climate change is expected to result from increased droughts. Africa, due to its large continental land mass will most likely suffer most. We present examples from two African countries and their specific challenges with respect to hydro dams, hydropower generation, and the resulting economic problems. The first example is from Tanzania, where the hydropower share due to droughts has dropped to one third of the countries demand and efforts are now made to de-risk electric power generation by decentralization. The second case is Zambia in the subtropical region which depends almost entirely on a few large hydropower stations for electricity, and which encounters increasingly extreme droughts.

Recent droughts and diversification: Hydropower in Tanzania

Tanzania, located just south of the equator in Eastern Africa is characterized by a tropical climate. Large parts of Tanzania are highlands and mountains with peaks several thousand meters above sea level. The climate varies from tropical along the coast of the Indian ocean (Aw, Am) to temperate in the highlands (BWh, BSh, Csa, Csb, Cwb)[15; 16]. Unimodal seasonal rainfall regularly occurs from October/November to April in the central, southern, and southwestern highlands. A bimodal seasonal rainfall with a short rainy season from October to December that is followed by a long rainy season from March to June, occurs in the costal belt, the north-eastern highland and along Lake Victoria.[47]

In 2020, only 40 % of Tanzania's population had access to electricity[25]. Large parts of the country, especially rural areas, are not connected to the national grid. Small private grids fed by solar, or hydropower may be operated by cooperatives, NGO's, or local communities. In 2003 more than 95% of electricity in Tanzania was produced by hydropower and other power sources were insignificant. From 2000 to 2021 Tanzania's total electricity production has increased approx. 3.5 times and new oil (2006) and gas (2018) power plants were connected to the grid.[11] Since 2003 hydropower generation had increased by one third, but its share in the country's power consumption had fallen to 35 % by 2021.[48]

Hydropower in Tanzania has a long history dating back to the colonial era, when small hydropower plants – dams and run-off-river type – were installed by missionaries but many of them have been abandoned for various reasons. Currently, a total of 38,000 MW capacity of hydropower is installed in Tanzania. The Pangani and the Rufiji River systems are the most important in terms of hydropower production. These rivers flow from the central highland plateau eastward to the Indian Ocean. Many large hydropower plants (> 10 MW installed capacity) are located along these rivers and are connected to the national grid (Figure 7 A). The two largest complexes, the Kidatu-Mtera system of hydropower dams (284 MW installed capacity) and the Kihansi run-of-river plant (180 MW installed capacity) on the Rufiji River systems have suffered in the recent more than 15 years from droughts as annual rainfall has been reduced by up to 17 % recently. The current water shortage is aggravated by the fact that hydropower plants are located downstream of areas where the river water is increasingly used for irrigation and for drinking water.[47; 49]

The drought in 2022 in combination with high costs for oil and gas in the wake of the Russia-Ukraine war, led to increased load shedding and rising production costs for electricity. The installed fossil fuel electricity production capacity is not sufficient to replace the reduced hydropower capacity due to the drought.[11] The crippling effects of power cuts on a country's economy have already been described in the Nepal case study.[50] With only 40 % of Tanzania's population connected to the national grid[25] and a fast growing population[26], electricity demand will rise in the coming decades. Failing to meet the electricity demand of its population will slow down the development of the country and may lead to increased poverty and a downgrading from its current income status.

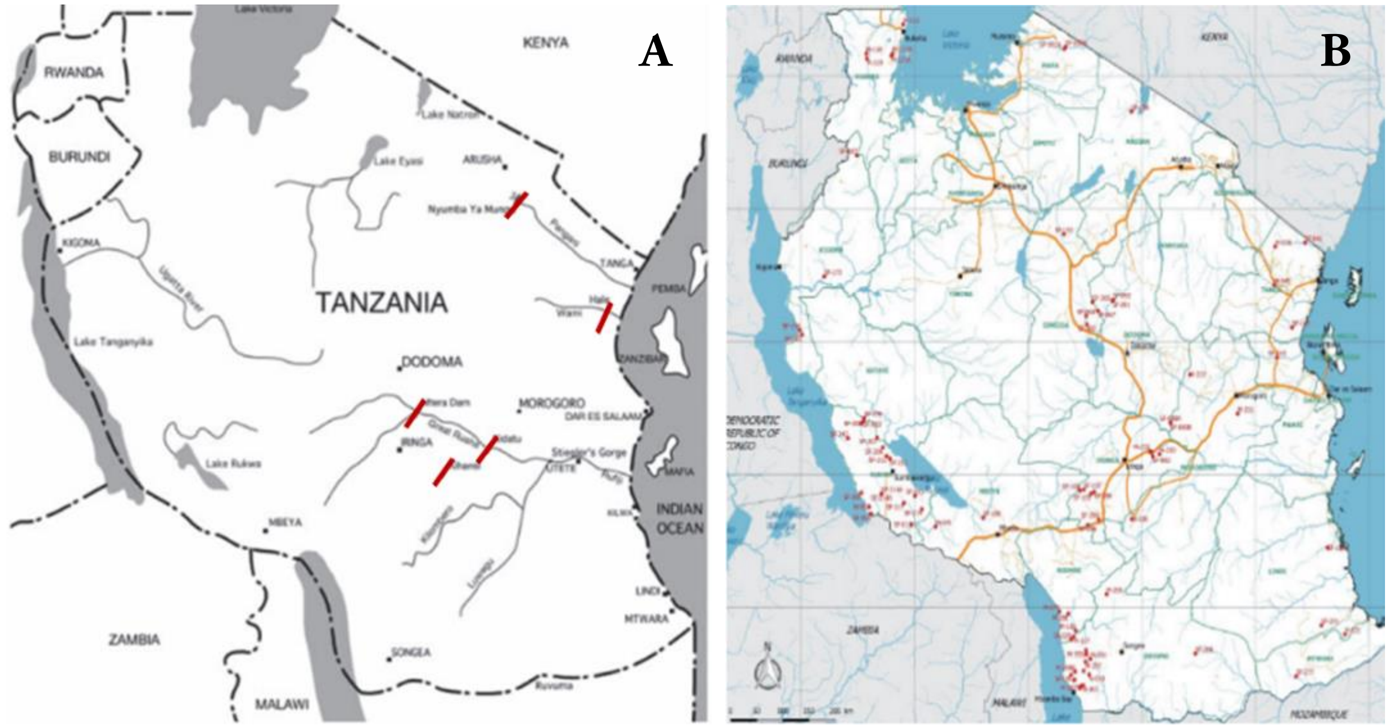


Figure 7: Left (A) Tanzania's key water ways and lakes. The five major hydropower plants are marked in red. Right (B) Potential sites for small renewable power plants in Tanzania. Red dots mark promising areas for small hydro-power sites. Modified after Kichonge (2018)[47].

Building new medium and large sized hydropower plants have become risky investments globally because of the effects of climate changes, social opposition, and other issues as described in the introduction. Small hydropower plants circumvent most of these issues and are favorable in Tanzania because of the precipitous flow of many smaller rivers from the central highland to the ocean. Additionally, they are well suited to supply remote rural areas without grid connection (Figure 8). For Tanzania, a hydropower capacity potential of 5.3 GW – including the existing plants - was calculated in 2018 when including rural areas and off-grid regions (Figure 7 B).

Tanzania has established various policies to promote and support new and existing hydropower plants, including guaranteed renewable energy feed-in tariffs into the national grid. The combination of all such measures has the potential to increase electricity production, especially in rural areas and the development of off-grid areas may also help to reduce poverty and internal migration to big cities with its related problems e.g., insecure housing in informal settlements. [47; 49]

Figure 8: Small hydropower station on Lake Tanganyika in Zambia.[51]

Future development of hydropower in Africa under Climate Change conditions

The IPCC published in 2021 a "Summary for Policymakers" where it observed an increase of hot weather events with probable human contribution for South Eastern Africa (SEAF e.g. Tanzania) and East Southern Africa (ESAF e.g., Zambia, data not shown). An increase in heavy precipitation related to human influence was found for Eastern South Africa, while conclusions for South East Africa were not possible due to the limited amount of available data. Agricultural and ecological droughts were increased due to human influence in ESAF while there was low agreement about the type of change in SEAF (Figure 2).[17]

The more detailed "Regional Fact Sheet Africa" presents changes until the mid of the 21st century for a minimum of 2 °C increase in global temperature (Figure 9). For South Eastern Africa an increase in frequency and/or intensity of heavy precipitation and pluvial flooding is projected. Snow caps and glaciers are projected to decrease while an increase of average tropical cyclone wind speeds and associated heavy precipitation is projected (category 4-5). For ESAF a decrease in mean precipitation is observed, while heavy precipitation and pluvial flooding are already increased and are projected to increase further. Aridity, agricultural and ecological droughts are already observed and are projected to increase. An increase in fire conditions and higher wind speeds are projected on land while an increase of average tropical cyclone wind speeds and associated heavy precipitation (category 4-5) is predicted to affect coastal areas.[52]

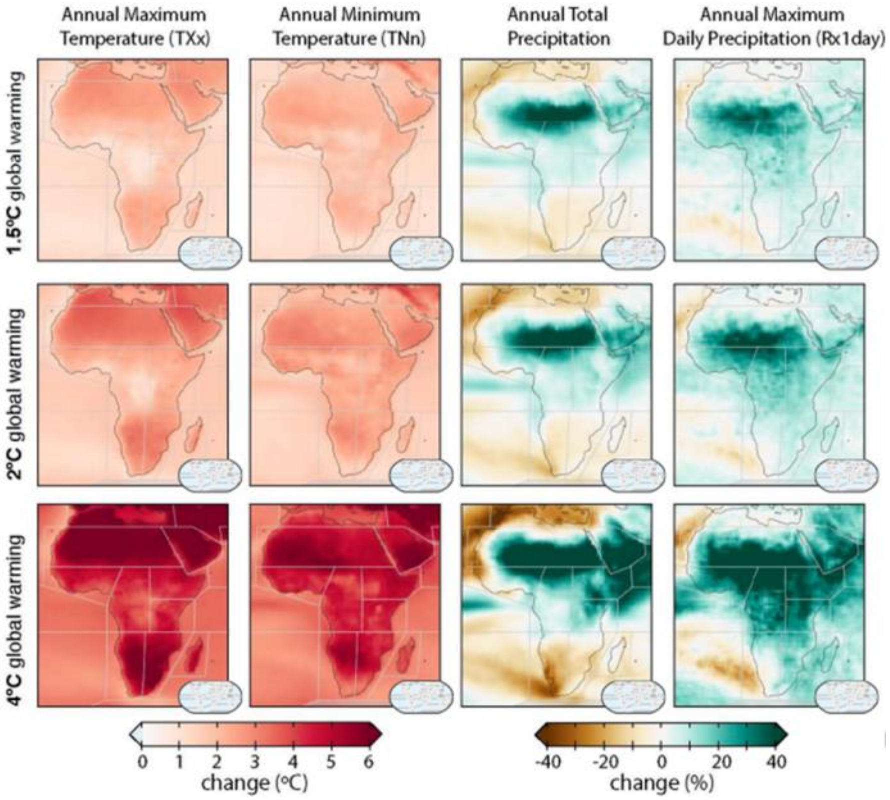


Figure 9: Projected changes in Africa for the midst of the 21st century in annual maximum temperature (TXx), annual minimum temperature (TNn), annual mean precipitation and annual maximum daily precipitation (RX1day) at 1.5 °C, 2 °C, and 4 °C of global warming (in rows) compared to 1851–1900.[52]

The International Energy Agency (IEA) is predicting also a technical reduction of the hydropower capacity factor of 3 % for the Kongo and Zambesi basin of in the below 2°C and also in the ~3 °C warming scenario. (The hydropower capacity factor describes the actual electricity generation compared to the nominal possible production capacity of a turbine.)[53]

Figure 10: Change in hydropower capacity factors in the 3 °C scenario. Each dot represents the relative value of the projected average hydropower capacity factor of selected plants in each country every five years.[53]

Severe droughts and large hydrodams: The Republic of Zambia and the Zambezi basin on the brink of a human catastrophy

The Republic of Zambia is a landlocked country on the Central African Plateau in southern Africa (Figure 11). About ¼ in the north of the country belongs to the Kongo watershed while most of its area lies within the Zambesi river catchment.[54] The watershed area of the Zambesi river belongs to 42 % to Zambia (Figure 11).[56; 55; 57]

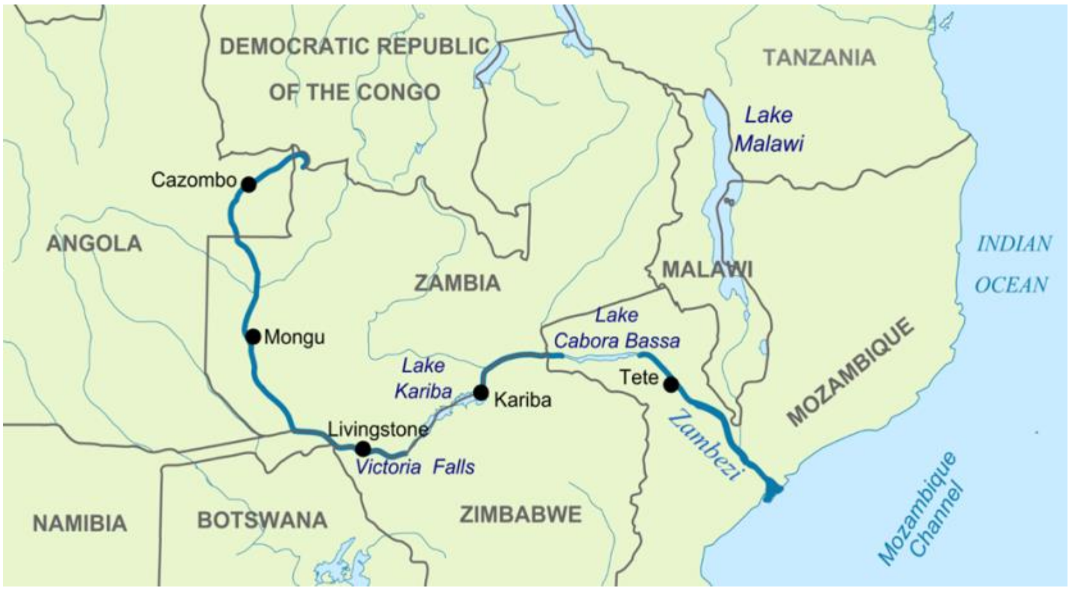


Figure 11: Zambia and the Zambesi River basin in Africa. Lake Kariba – the world largest artificial lake - was created by the Kariba dam and hydropower plant, which delivers electricity to Zambia and to Zimbabwe.[57]

Zambia has a mostly a humid subtropical climate (Figure 4 B) with a pronounced dry season (Cwa and Cwb) but also has pockets of tropical (Aw) and dry climates (BSh).[15; 16] Since 2019 the Zambesi basin has suffered from multiple severe droughts caused by changing weather patterns.[58; 51; 59]

In 2020 approx. 45 % of Zambia's population had access to electricity[25]. Until 2013 more than 99% of the country's electricity was produced by hydropower. While total electricity production has doubled since 2000, the share of hydropower has decreased depending on the availability of water for the power plants (down to 86 % in 2020)[11].

The recent and severe droughts have hit Zambia on several levels. In Lake Kariba (Figure 11) the water level has dropped by 6 meters from 2017 – 2020 resulting in daily load shedding of the power grid for several hours. The economy, social services as well as the private sector was hit hard by these emergency measures due to the unpredictable character of the power outages.[58; 51]

The droughts have also led to food shortages due to withering crops, and livestock dying of hunger and thirst. Even the wildlife was affected by the drought, which shows the severity of the water shortage.[58; 51] In 2023 the World Food Organisation stated that the combination of droughts and the economic slowdown due to the Covid-19 pandemic caused reductions in the tourism sector has left 48 % of Zambia's approx. 18 million people unable to meet their minimum nutritional requirements as well as approx. 38 % of Zambia's children stunted. Food aid is currently delivered by the World Food Organization to Zambia.[59] As a consequence, in 2022 the World Bank reclassified Zambia as a low-income country after a decade in the lower middle -income category. The reclassification followed sustained poor economic performance which resulted in more than half to the country's people now living below the poverty line.[59]

Conclusion

Hydropower generation potential is limited worldwide. It is environmentally problematic due to degradation of river ecosystems. The construction causes not only considerable GHG emissions but also social problems due to resettlement of communities and compensation for lost fertile land. Also, conflicts over water rights are pre-programmed, especially when two or more nations are involved.

Climate warming in the tropics and subtropics will cause higher ocean surface and air temperatures. The higher evaporation over the warmer oceans will lead to an increased but less predictable frequency and magnitude of heavy rainfalls and storms causing often catastrophic flood waves downstream of rivers. While the higher air temperatures may lead to unpredictable melting patterns of glaciers which in turn may lead to ice and mud outbreaks of glacial lakes, both events combined can result in intensive flood events. However, when the glaciers will be eventually have disappeared due to climate warming and glacier outbreaks and mudflows have become history, the buffer effect of snow and ice caps will also have disappeared. Resulting in the immediate runoff after strong precipitation events with increased risk of downstream floods and low water events and droughts during dry seasons and dry spells.

Both, the structural safety of hydro dams and the security of reliable and continuous hydropower generation in the tropics and subtropics are severely at risk due to the climate changes which lead to less predictable water flow patterns throughout the year. Poor technical quality of some infrastructure projects and lack of maintenance and investments in infrastructure aggravate these problems. This calls for a rigorous risk assessment of existing dams and the assessment of the economic viability and the social costs incurred by new hydropower projects. For future projects, a combination of power capacity downsizing and simultaneous upscaling of the number of hydropower plants may reduce risks.

Severe and long-lasting droughts are the biggest threat to the economics of hydropower generation. The tropics are expected to experience a higher variability of phases of drought and rainfall. Especially the subtropics will suffer in the future from a significantly reduced annual precipitation causing very severe droughts. Combined with an ever-increasing demand for water for irrigation and human consumption, this will bring many existing large hydropower projects in the subtropics to a critical point.

Competition for water resources will determine the future of many hydropower plants and projects in the tropics and subtropics. Conflicts over water rights, water storage and water use are rising globally. Giant hydropower projects are already bringing neighboring nations in Africa and the Near East to the brink of open confrontation. In the future the race for the access to the scarce and regionally dwindling clean freshwater resources will accelerate. All these factors considered, the climate change related problems for large scale hydropower generation in the tropics and subtropics are definitively increasing and allow - at least for the subtropical regions – only a bleak outlook to its future.

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