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WATER IN A CHANGING CLIMATE: NAVIGATING RISKS AND PATHWAYS TO A MORE RESILIENT FUTURE

IIHS WORKING PAPER

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Citations

Bazaz, A., Ghoge, K., Krishnaswamy, J., Revi, A., 2024, **Water in a Changing Climate: Navigating Risks and Pathways to a More Resilient Future**, Bangalore, India, The Indian Institute for Human Settlements and the Global Commission for the Economics of Water.

Design & Layout: Nawaz Khan | Reviewed by Prachi Prabhu & Padma Venkataraman IIHS Communications & Design

ISBN: 9788195847358
DOI: https://doi.org/10.24943/9788195847358

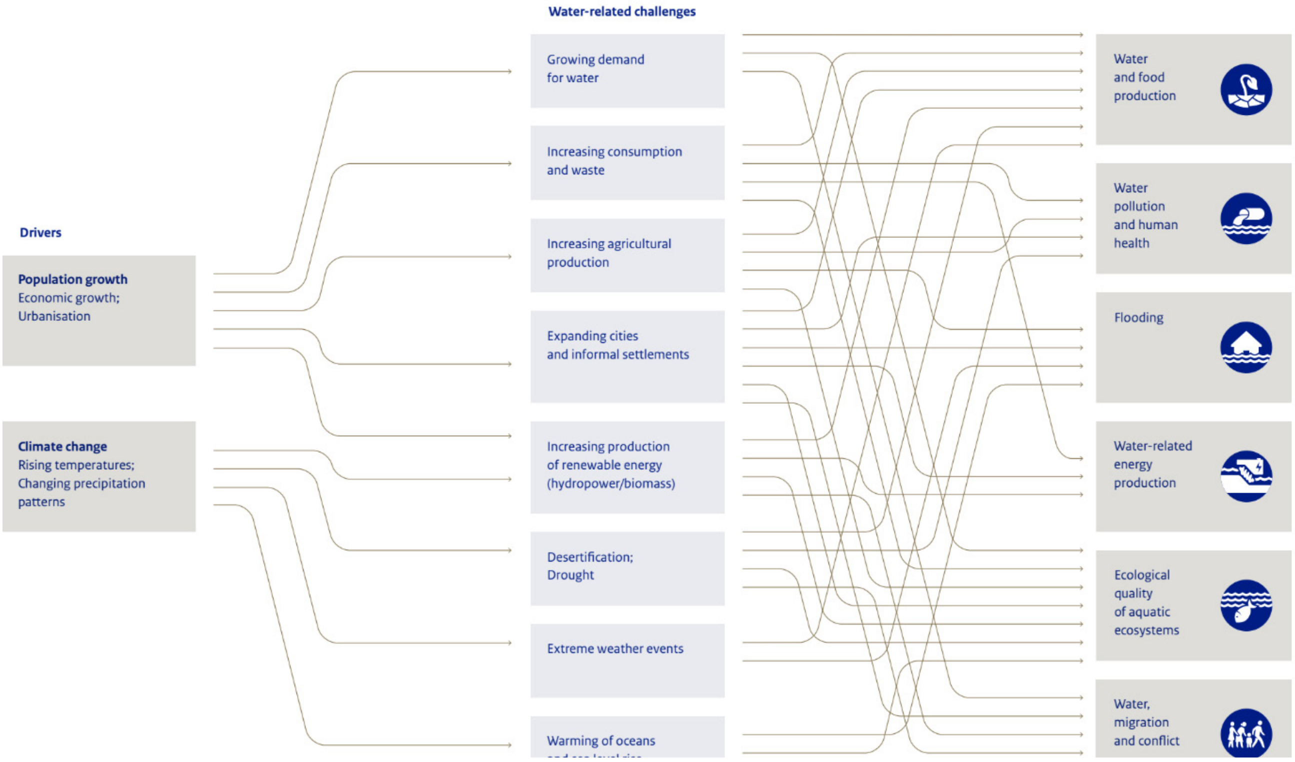
First published in Bangalore, September 2024

This paper is part of a series of working papers commissioned by the Global Commission for the Economics of Water (GCEW).

1. Introduction

The world stands at a critical juncture regarding the sustainability of the global water cycle. Rapid urbanisation, global population growth, rising demand fueled by economic prosperity, and escalating ecological stress intensified by climate change are swiftly altering the water cycle worldwide (PBL, 2018). Manifested as too little (water scarcity), too much (excessive floods), and too dirty (water pollution), the systemic water crisis affects millions of people today, and is the reason behind several local to global complex sustainable development challenges (Grafton et al., 2023). In the coming decades, the global water crisis can worsen climate risks as we overshoot 1.5° C, accelerate the biodiversity crisis, and lead to severe economic and social impacts ranging from increased food insecurity to conflict (Grafton et al., 2023). A sustainable future necessitates a deep understanding of the evolving risks linked to water and climate change between now and 2050 (PBL, 2018). The global water cycle and climate change are intricately interlinked as indicated in the figure below and climate impacts are often felt through water.

Figure 1: Linkages between climate and water-related challenges



Source: PBL, 2018

This working paper reviews current assessment and scholarship on the links between climate change and water, the impacts of climate-induced water risks, and water adaptation challenges and constraints. It makes a case for Climate Resilient Development (CRD) as negotiated by the IPCC in its Sixth Assessment to integrate water, climate, biodiversity and sustainable development agendas to bring about transformational change and briefly states key enabling conditions that can accelerate this change.

The next section of the paper (2) assesses how climate change is reshaping the global water cycle paper, followed section 3 that examines climate-induced water challenges, and section 4 that looks at vulnerability and adaptation to climate-induced water impacts. Section 5 discusses climate resilient development as an overarching framework to address climate and water crisis along with key enabling conditions to accelerate CRD.

2. Climate change is reshaping the Global Water cycle

The latest assessment from the IPCC on the physical science basis of climate change brings together robust scientific evidence on the climate impacts on hydrology and the water cycle. The impact of climate change on the global water cycle is evident in reduced snow cover, variations in precipitation, an increase in the frequency and intensity of extreme events such as floods and droughts and rising sea levels. IPCC assessments show that climate change has been altering the global water cycle since the mid-20th century and will continue to significantly change it at both global and regional levels (IPCC, 2021a). Many of the impacts of continued warming are expected to worsen in high emission scenarios in a world with temperatures above 2°C by 2060s.

Global warming is projected to increase variability in precipitation, surface water flows, and the severity of both wet and dry events. Projections suggest that average annual global land precipitation may rise by 0–5 per cent under very low greenhouse gas (GHG) emissions (Shared Socioeconomic Pathways (SSPs)[1] 1-1.9), 1.5–8 per cent under intermediate GHG emissions (SSP2-4.5), and 1–13 per cent under very high GHG emissions (SSP5-8.5) scenarios by 2081–2100 compared to 1995–2014 (IPCC, 2021a). While precipitation is expected to increase over high latitudes and parts of the equatorial Pacific and monsoon regions, decreases are projected over subtropical and select tropical areas under intermediate, high, and very high emission trajectories of SSP2-4.5, SSP3-7.0, and SSP5-8.5 (IPCC, 2021a). Continued warming is also likely to lead to an earlier onset of spring snow melt, leading to heightened peak flows and reduced summer flows in snow and glacier melt-dominated regions worldwide (IPCC, 2021a).

Warmer climate is also likely to impact flood and drought occurrence but the specifics of these extreme events in terms of their location, frequency and intensity hinge on other projected changes in regional atmospheric circulation, including monsoons. For instance, rainfall variability associated with El Nino-Southern Oscillation is likely to be magnified in the latter half of the 21st century under intermediate and high emission scenarios (IPCC, 2021a).

In the foreseeable future, climate models predict that monsoon precipitation is expected to rise world-wide, particularly impacting South and Southeast Asia, East Asia, and West Africa (IPCC, 2021a), although the uncertainty in some regions such as South Asia is higher. However, the monsoon season is likely to have a deferred onset in North and South America, West Africa, and a delayed withdrawal over West Africa. Non-monsoonal systems such as Western Disturbances that contribute significantly to regional water security are also likely to show shifts in timing and intensity leading to damaging impacts as already observed in recent years

Over the 21st century, droughts are also likely to become more frequent and severe and impact larger land areas. Agricultural and ecological droughts are likely to heighten in some regions due to increased evapotranspiration fueled by human-induced climate change (IPCC, 2021b). There is evidence to show that land-use changes and water extraction for irrigation also significantly impact local and regional water cycles by creating water imbalances including across transboundary aquifers with ‘groundwater stress hot spots’ showing up in the Indo Gangetic basin, Iran, Arabian Peninsula, and some parts of South Africa (Rodella et al., 2023).

Rising temperatures can also exacerbate demand for water due to increase in crop water demand, and dropping yields, leading to further groundwater depletion. Bhattarai et al. (2023) point out that in India, the net withdrawals are projected to increase by three times from 2041 to 2080. India is the world’s largest user of groundwater for irrigation, covering more than half of the country’s total irrigated agricultural area, responsible

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[1] SSPs are climate change scenarios of projected global socioeconomic changes up to 2100 as defined in the IPCC’s AR6 assessment reports. They are used to derive greenhouse gas emission scenarios with different climate policies. Representative Concentration Pathways (RCP) are climate change scenarios to project future GHG emissions.

for 70 per cent of food production (IPCC, 2022b). However, excessive extraction of groundwater is depleting aquifers across the country, leading to shrunken water tables in large areas, especially in the northwestern states, where the Green Revolution started.

Estimates indicate that over abstracted groundwater in India could be in the range of 122 to 199 km^3 between 1996 and 2016 alone (Rodella, Zaveri, and Bertone, 2023). The World Bank working paper by these authors points to significant groundwater depletion world's arid and semi-arid regions, with most evident impacts in the Middle East and South Asia (Rodella, Zaveri, and Bertone, 2023). They state that while ground water has cushioned the worse impacts of climatic variability in the past, given the depletion levels, it may be unable to do so in the face of future adverse climatic impacts. Overall, the variability of the water cycle and associated extremes are expected to outpace mean changes across most regions globally, regardless of emissions scenarios (IPCC, 2021b).

A warming climate has also led to a rise in the global mean sea level, primarily due to loss of ice on land and the expansion of sea water caused by ocean warming (IPCC, 2021a). Between 1971 and 2018, thermal expansion accounted for half of the sea level rise, while glacier melt contributed 22 per cent, ice sheets 20 per cent, and changes in land-water storage 8 per cent (IPCC, 2021a). It is also estimated that extreme sea levels that occurred once per century in the recent past will occur about 20 to 30 times more frequently by 2050 and 160 to 530 times more frequently by 2100 across all major emissions scenarios (IPCC, 2021a).

3. Climate-induced water-related challenges

The number of people facing water stress is likely to increase in the face of rising higher average temperatures, variability in precipitation due to climate change, along with growing competition for water resources (PBL, 2018). Projections indicated in this report point to 25 per cent increase in global water consumption by 2050 largely driven by increased demand from agriculture, industries and settlements and The maximum water use stems from agriculture, more than 80 per cent, more so in South and East Asia, followed by industry, households and then electricity (PBL, 2018). Water stress and climate-induced changes to the water cycle have implications for agriculture and food security, freshwater ecosystems and biodiversity, energy production, and on our cities and infrastructure as discussed below.

3.1 Impacts on Agriculture

Droughts have been identified as a major driver for adversely impacting climate change and food insecurity, while the evidence of impact of floods on food production is limited (IPCC, 2022a). Climate variability and extremes account for 20–49 per cent of crop yield anomaly variance, with 18–45 per cent attributed to droughts and heatwaves (Vogel et al., 2019). Drought emerges as a leading cause of global yield reductions, supported by various studies (Anderson et al., 2019; Leng & Hall, 2019; Lesk et al., 2016; Zipper et al., 2016).

For instance, in Europe, droughts have had a detrimental impact on yields, with losses increasing threefold between 1964 and 2015 (Beillouin et al., 2020; Brás et al., 2021) . In West Africa, altered climate conditions, including drought, led to millet and sorghum yield losses between 10 per cent and 20 per cent, and 5 per cent and 15 per cent, respectively, from 2000 to 2009 (Sultan et al., 2019). Furthermore, between 2006 and 2016, droughts led to food insecurity and malnutrition in northern, eastern, and southern Africa, Asia, and the Pacific (IPCC, 2022a).

Modelled impacts of blue water and heat stress on global food production and hunger up to 2050 also show that global food supply could reduce by 6 per cent, 11 per cent, and 14 per cent on an average under the Representative Concentration Pathways (RCPs) and SSPs : RCP 4.5, RCP 8.5 SSP-2, and RCP 8.5 SSP-3 (Grafton et al., 2022). The extent of food supply losses however differ widely across regions and different climate scenarios. For instance, food supply in USA is projected to decrease by 4.8 per cent under RCP 4.5 and by 13 per cent under RCP 8.5 SSP-3 scenario, while in China, food supply is projected to fall by 9 per cent under RCP 4.5 and by 22 per cent under RCP 8.5 SSP-3 scenario.

The impact of climate-induced water-related hazards on agriculture also varies among populations and genders. Subsistence farmers, particularly in low-latitude regions with hotter and drier climates, face significant food insecurity risks due to hydroclimatic factors (Shrestha & Nepal, 2016; Sujakhu et al., 2016). These farmers, heavily dependent on agriculture for their livelihoods, historically bear the brunt of observed climate-induced hydrological changes (Savo et al., 2016). At the same time indigenous and local communities, deeply rooted in agriculture, possess valuable knowledge of observed changes, crucial for shaping farmers' perceptions and adaptation strategies (Caretta & Börjeson, 2015; Savo et al., 2016; Sujakhu et al., 2016).

3.2 Impacts on Freshwater Ecosystems and Biodiversity

There has been significant evidence of loss and degradation of freshwater ecosystems due to climate change although human abstraction is still the dominant driver of wetland loss. IPCC's special report (2019) on climate change and land has also reported on loss of wetlands since the 1970s.

Changes in precipitation in timing and intensity and enhanced snow melt can significantly impact river flow dynamics leading to unpredictable low and high discharges, increasing frequency of both droughts and floods and bringing more complex challenges to river basin management. Climate change also emerges as a critical driver impacting freshwater ecosystems through various avenues such as increased temperatures and declining rainfall (Díaz et al., 2019; Dziba et al., 2019). These changes induce physiological stress or mortality among species, disruption and limiting food supplies, prompting migration to new habitats, where possible, and potentially escalating competition with existing fauna in these new areas. Other drivers such as land use changes, water pollution, and invasive species often act synergistically with climate change or worsen due to climate change (Convention on Wetlands, 2021; Ramsar Convention on Wetlands, 2018).

It has been recorded that temperature fluctuations contribute to shifts in freshwater species distribution patterns, with warming temperatures driving poleward and up-elevation range shifts, ultimately leading to reduced range sizes, particularly affecting species in tropical regions (IPCC, 2022a). Tropical regions include the most biodiverse river basins and there has been a steady decline in their quality, which is projected to decline further up to the 2050s (PBL, 2018). The strongest decline in quality of freshwater systems with biodiversity is estimated from Sub-Saharan Africa and parts of Latin America and Asia, with the most decline having occurred in Europe and North America (PBL, 2018).

The Ramsar Convention on Wetlands (2018) highlighted a 35 per cent decline in freshwater wetland areas between 1970 and 2015. Notably, Madagascar and Indian Ocean islands (43 per cent), Europe (36 per cent), the tropical Andes (35 per cent), and New Zealand (41 per cent) recorded high levels of overall proportion of threatened species. Globally, about 75 per cent of projected freshwater biodiversity loss will be caused by a decline in wetland area and increasing eutrophication from increased nutrient emissions from cities and agriculture (PBL, 2018). A quarter of biodiversity loss is likely to result from hydrological disturbances caused by buildings thousands of new dams (PBL, 2018).

Evidence also suggests a warming trend in lakes, with summer surface water temperatures increasing by 0.34°C per decade between 1985 and 2009 (O' Reilly et al., 2015). However, individual lake responses vary based on local characteristics, with warming sometimes exacerbating eutrophication impacts . The main drivers for freshwater ecosystems decline and loss of biodiversity are population growth and unsustainable economic development including pressures from urbanisation, industries, agriculture that results in change of land use and pollution

(PBL, 2018). This is further compounded by climate change-induced impacts like increase in temperatures, declining rainfall, snow cover, and increased consumptive use of freshwater. These factors collectively lead to the decline and threaten the extinction of numerous freshwater-dependent populations.

3.3 Climate Change Mitigation and Energy Production

The profound climate change impact on future hydro-climatic patterns extends to the energy sector with significant consequences across the system (Fricko et al., 2016; Vliet, Beek, et al., 2016; Vliet, Sheffield, et al., 2016). The reliance on fossil fuels for power production means that climate-induced reduction in water availability and increased stream temperatures have significant impact on thermoelectric power generation, primarily reliant on water for cooling purposes (Larsen & Drews, 2019). Water also serves other functions in power generation, including pollution control, dust management, and cleaning processes (Larsen & Drews, 2019). Presently, 98 per cent of electricity generation hinges on thermoelectric (81 per cent) and hydropower (17 per cent) sources (IPCC, 2022b).

As the efforts to decarbonise the energy sector progress, renewable energy including hydropower, wind and solar photovoltaics will play a pivotal role in the energy mix. Hydropower accounted for 2.5 per cent and wind, and solar energy constituted1.8 per cent of the global primary energy supply in 2017 (IEA, 2019). By 2028, it is estimated that renewable energy sources will contribute over 42 per cent of the global electricity production, with wind and solar accounting for 25 per cent (IEA, 2023). While wind and solar energy operate independently of water, their efficiency is influenced by atmospheric conditions intertwined with hydrological processes.

In contrast, hydropower's operation directly hinges on water availability, serving as a crucial mitigating factor against seasonality, climate variations, and diurnal production fluctuation compared to wind and solar energy (IPCC, 2022b). But hydropower plants, particularly those lacking storage capacity, are susceptible to climate-induced variability such as drought, when there is not enough water to generate electricity (IPCC, 2022b). Increased warming, and more surface evaporation will also lead to less water storage and loss of generation efficiency, leading to potential conflicts over the water use for irrigation and power production Warmer water also accelerates biological growth, heightening the risk of water intake blockage. Increased precipitation can also impact power production by increasing debris accumulation and vegetation growth (IPCC, 2022b).

Overall, analyses indicate that the global impact of climate change on hydropower is relatively small but regional impacts are large and can be both good and bad. The projected gross global hydropower potential for the 2050s shows a slight decrease (Hamududu & Killingtveit, 2012), ranging between 0.4 per cent under low emission scenario and 6.1 per cent under high emission scenarios for the 2080s compared to the baseline scenario period of 1971-2000 (Vliet, Beek, et al., 2016).

Regional variations are larger with increases ranging from 5 to 20 per cent in high latitude areas and decreases in the same range for drought-prone areas (IPCC, 2022b). Since many thermoelectric plants rely on water for cooling, their proximity to rivers and coastal areas makes them vulnerable to flooding. Rising water temperature or limitations in cooling water availability pose risks to both hydroelectric and thermoelectric facilities. For instance, a mere 1°C increase in coolant water temperature can result in a power output decline of 0.12–0.7 per cent (IPCC, 2022b). While certain regions might witness capacity increases under climate change, globally, mid-century projections suggest thermal power plant capacity reductions ranging from 7 per cent to 12 per cent, depending on global emissions (IPCC, 2022b).

3.4 Impacts on Cities and Infrastructure

Climate change presents existential challenges to cities and urban areas across the world. By 2070, 7 billion people, nearly 70 to 75 per cent of the global population will be living in cities or urban areas, within a coastal area, river basin, delta or a dryland region (PBL, 2023). Cities and urban populations especially in the developing world will face greater water and climate-induced risks largely because of the concentration of people, buildings, infrastructure, economic activity, along with vulnerability and poverty and inequality.

Climatic impact drivers including heat, precipitation variability, cyclones, storm surge and sea level rise are projected to increase incidence of heatwaves, drought, water scarcity, floods, coastal erosion and flooding, tropical cyclones, and wind hazards in urban areas (Gallardo et al., 2022). In the future, as warming increases, cities will also face increasing cascading risks from compound and simultaneous climate events – drought with heat waves, heavy rains with floods and storm surges, tropical cyclones, floods and wind hazards - that can paralyse urban lives. Many of these risks will multiply as temperatures rise. Water is an essential requirement for performance of urban blue and green infrastructure for heat stress mitigation under climate warming. For instance, an additional 350 million living in urban areas are estimated to experience severe drought and water scarcity at 1.5°C, this number grows to around 410 million at 2 °C warming (Adelekan et al., 2022). By 2100, coastal flooding in cities is likely to impact up to 510 million people and expose infrastructure worth nearly USD 7.9 to 12.7 billion to flood damage and risks (Adelekan et al., 2022). For instance, by 2050, 60 per cent of Mumbai will be located in flood-prone areas; this area can increase even further with a one-meter rise in the sea-level (PBL, 2018). In many coastal cities, especially in the Asian delta, groundwater abstraction is adding to climatic risks, leading to subsidence and could impact an area larger than Spain, spanning 0.5 million Km2by 2070 (PBL, 2023).

People living in informal settlements in cities are most vulnerable to water and climate-related disasters, whether it is coastal flooding or water borne diseases. Ensuring a healthy living environment in urban areas through climate resilient infrastructure and services, including safe and adequate access to water and sanitation, especially to the urban poor is one of the most critical challenges of the future (PBL, 2023).

4. Vulnerability and Adaptation to Climate-induced Water impacts

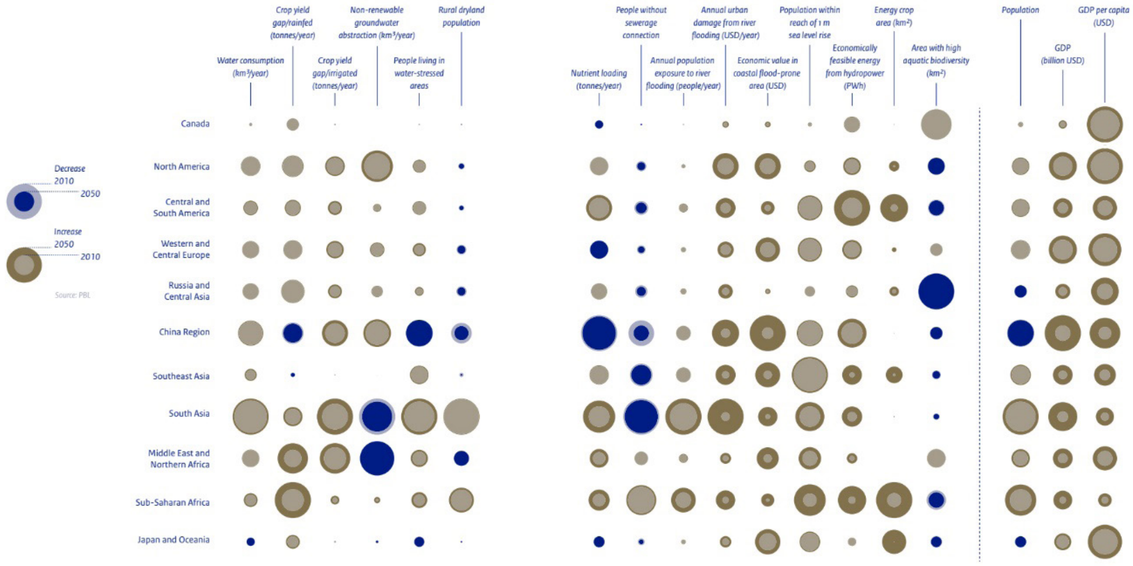
There is increased vulnerability to water-induced disasters such as flood, drought, and other hydrological changes across most sectors and regions (IPCC, 2022a). For instance, at 2°C of warming, several climate-induced changes linked to the water cycle and storms are likely to impact large areas and lead to region-specific changes compared to the recent past.

In Southern Africa, the Mediterranean, North Central America, Western North America, the Amazon regions, South-Western South America, and Australia, there are likely to be increases in droughts, aridity, and fire weather that can affect the agriculture, forestry and health sectors, and ecosystem health (IPCC, 2021b). In regions like North-Western, Central, and Eastern North America, the Arctic, North-Western South America, Northern, Western and Central and Eastern Europe, Siberia, Central, South and East Asia, Southern Australia and New Zealand, decreases in snow and ice or increases in river flooding is anticipated, which can impact winter tourism, energy production, river transportation, and infrastructure IPCC, 2021b).

Having said that, climate and water-related stress and risks are not borne by all people and regions equally. Evidence shows that regions and people with higher development constraints and deficits have higher vulnerability to climate hazards. Climate extreme events have exposed millions to increasing food security and water scarcity with the highest adverse impacts being observed in Africa, Asia, Central and South America, Least Developed Countries (LDCs), small islands and the Artic (IPCC, 2023). Globally the impact is borne disproportionately by indigenous peoples, small-scale food producers, low-income households, minorities, and women.

It is also projected that under a business-as-usual scenario, Sub-Saharan Africa and South Asia are likely to face the largest increase in water and climate-linked stress and challenges from 2010 to 2050, followed by Middle East and North Africa, and Central and South Africa (PLB, 2018). The figure below sourced from PBL (2018) shows the projected changes across regions for about 15 water and climate indicators including urban damage from river flooding, rainfed crop yield gaps, and people living in water-stressed areas, among others.

Figure 2: Water and climate-induced challenges across the globe



Source: PBL, 2018

The figure shows that economic damages from river flooding and coastal flooding across all regions is slated to increase from 2010 to 2050. Additionally, rainfed-crop yield gaps are likely to increase significantly in the Middle East, North Africa and Sub-Saharan Africa region. In China and South Asia, water-and climate-linked challenges, which are already severe are likely to get even more grim by 2050, specifically with regards to flood-related damages and fall in crop-yields. Major climate adaptation challenges linked to water include issues of water scarcity, heightened risks of floods and droughts, and adverse impacts of rising water temperatures on both water quality and biodiversity (PBL, 2018).

Evidence shows that business-as-usual development trajectories amplify exposure and/or vulnerability to water and climate change hazards, disproportionately affecting poorer regions. At the same time, developed countries also have to adapt to the changing climate and sea level rise by retrofitting much of their urban infrastructure and operations of many sectors that continue to be based on expectations of an older climate. While there has been progress on adaptation responses, much of the existing adaptation globally is 'fragmented, incremental, sector-specific, and unequally distributed across regions' (IPCC, 2023, p.8). Significant adaptation gaps exist across all geographies and climate-induced water impacts like flooding, droughts, and food security, with adaptation gaps being the largest for poorer populations across regions (IPCC, 2023).

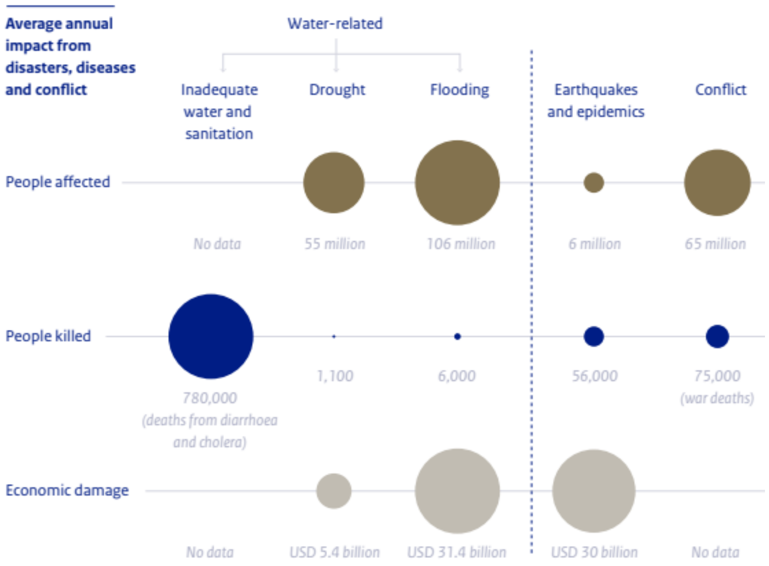
Structural failures in adaptation, as highlighted by the World Economic Forum among its top 10 global risks, underscore the urgent need for crafting collective adaptation frameworks to navigate the uncertainties ahead (PBL, 2018). Unlike climate mitigation pathways for reducing emissions, global adaptation frameworks that can align national efforts, and monitor and evaluate progress towards shared goals are yet to materialise (PBL, 2018).

Such frameworks are essential to guide strategies and interventions across multiple scales, addressing interconnected challenges and trade-offs, and coordinating the actions of diverse stakeholders (PBL, 2018). These can serve as the foundational step to fostering climate resilient development (CRD). CRD, a development framework introduced in the IPCC's Sixth Assessment Report, brings together sustainable development, climate action (both adaptation and mitigation), and biodiversity goals based on complementary development interventions rather than trade -offs between climate action and sustainable development (IPCC, 2022 ; IPCC, 2023; Stern and Stiglitz, 2023).

Figure 3 below shows the severity of potential impact in terms of damages and fatalities due to too little, too much and too dirty water. The projected annual fatalities from poor water quality due to water-borne diseases like cholera and diarrhoea stands at 0.8 million. The average annual economic damages from floods and droughts are estimated to be worth USD 31 billion and 5 billion (PBL, 2018). Further, without adequate adaptation, future water-related impacts of climate change on various sectors of the economy are estimated to lower the global GDP from 6 to 12 per cent by the 2050s, with higher losses projected in low- and middle-income countries (GCA, 2019; World Bank, 2016).

The World Bank report (2016) estimates up to 6 per cent GDP losses, pushing some regions into sustained negative growth post 2050s. And the GCA report (2019) projects losses from 7 to 12 per cent in the absence of effective water adaptation in countries like India, China, besides Central Asia and GDP loss of 6 per cent for much of Africa. Nearly 70 per cent of all risk to infrastructure stems from climatic hazards like storm surges, floods, landslides from deluge, with only 30 per cent associated with geological hazards like earthquakes and tsunamis (CDRI, 2023). CDRI (2023) report estimates the total average annual loss to infrastructure including buildings, health, and education sectors to be in the range of USD 732 to 845 billion, or 0.8 percent of current global economic output.The cost of these impacts underlines the need to accelerate adaptation to respond to an overshoot of 1.5°C in the near future and prepare for potential global warming that can exceed 2.5°C for a sustained period in this century.

Figure 3: Impact of water-related risks



Source: PBL, 2018

While global adaptation frameworks are yet to take shape, at least 170 countries and many cities have taken the first few steps to include adaptation in their climate policies and action plans (IPCC, 2023). There are several tried and tested adaptation interventions implemented across the globe, depending on local contexts with documented benefits.

Many of these effective adaptation options including those that ecosystem-based like the restoration of wetlands and natural water bodies, urban greening, sustainable water management practices including wastewater and stormwater recycling, and nature-based solutions like sponge cities are aimed at adapting to changes in freshwater ecosystems and addressing water challenges like urban floods, water scarcity and drought, and coastal flooding (IPCC, 2022a; IPCC, 2023; PBL, 2023). PBL report (2023) argues for adopting a river-basin and ecosystem approach towards spatial development and planning so that nature based solutions in design and planning, restoring natural habitats, regulating water and sediment dynamics, water proofing infrastructure gets mainstreamed in development plans.

Other effective adaptation options include sustainable land management practices, crop diversification techniques, irrigation, agroforestry, besides social infrastructure measures like early warning systems, disaster risk management, and social safety nets (IPCC, 2022a). For example, water and soil conservation practices, such as reduced tillage, mulching, are widely acknowledged as effective adaptation strategies for mitigating water-related climate impacts (IPCC, 2022a). These measures rank among the top four adaptation responses across all continents except Australasia. Water and soil conservation techniques also have economic advantages, positively impact vulnerable communities, offer significant water saving potential, and yield positive ecological and socio-cultural benefits (IPCC, 2022a).

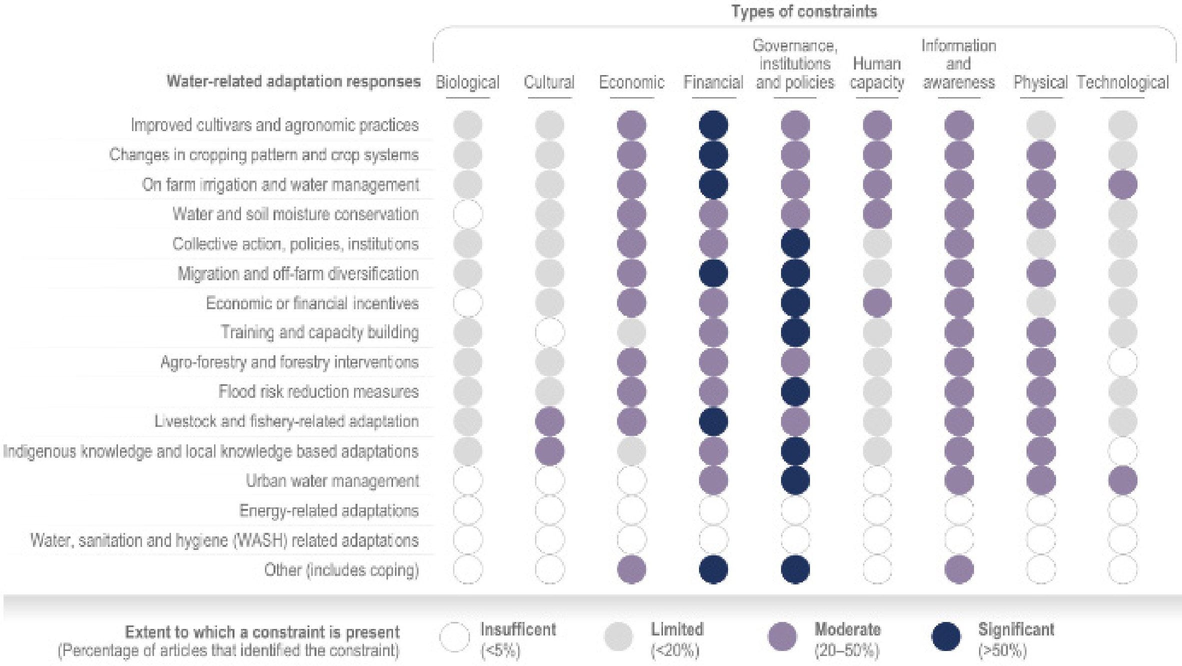
The effects of ecosystem-based adaptation and most water-linked interventions, decrease with increasing temperatures (IPCC, 2023). Hence, it's important to note that adaptation comes with limits – soft and hard – especially as warming increases. Soft limits currently being faced by small scale farmers and low-lying coastal households can be overcome with better policies, institutional responses, and finances. Hard limits are largely a point of no return when adaptation is no longer possible in the face of intolerable risks like sea level rise, that can force cities and settlements to retreat from the coastline. Some polar, coastal, and mountain ecosystems have reached hard adaptation limits (IPCC, 2023).

4.1 Water-linked Adaptation Constraints

Major barriers to adaptation include inadequate finances, lack of institutional, governance capacity, lack of private sector participation, low climate awareness, lack of political will, and slow uptake of technology (IPCC, 2023). Adaptation constraints for water-related adaptation can be biological, technological, financial, cultural, economic, physical, institutional, etc. as shown in the figure below. The IPCC assessment (2022a) shows that institutional constraints including governance, policy, and institutional arrangements, along with operational factors like path dependency, inadequate financial resources, and limited access to information pose significant challenges to implementing adaptation interventions in the water sector (see figure below).

Despite the implementation of various adaptation measures, water-related losses and damages are likely to persist in various regions of the world, particularly impacting vulnerable populations. Adverse climate impacts will also lead to increased losses and damages, and thereby reduce the scope for adaptation finance (IPCC, 2022a). In small islands with limited water resources and regions dependent on glaciers and snow melt, there are significant constraints to adaptation, with evidence pointing to hard limits (IPCC, 2022a).

Figure 4: Water-linked adaptation constraints across different dimensions



Water-related adaptation responses	Types of constraints								
	Biological	Cultural	Economic	Financial	Governance, institutions and policies	Human capacity	Information and awareness	Physical	Technological
Improved cultivars and agronomic practices	◍	◍	◉	●	◉	◉	◉	◍	◍
Changes in cropping pattern and crop systems	◍	◍	◉	●	◉	◉	◉	◉	◍
On farm irrigation and water management	◍	◍	◉	●	◉	◉	◉	◉	◉
Water and soil moisture conservation	○	◍	◉	◉	◉	◉	◉	◉	◍
Collective action, policies, institutions	◍	◍	◉	◉	●	◍	◉	◍	◍
Migration and off-farm diversification	◍	◍	◉	●	●	◍	◉	◉	◍
Economic or financial incentives	○	◍	◉	◉	●	◉	◉	◍	◍
Training and capacity building	◍	○	◍	◉	●	◍	◉	◉	◍
Agro-forestry and forestry interventions	◍	◍	◉	◉	◉	◍	◉	◉	○
Flood risk reduction measures	◍	◍	◉	◉	●	◍	◉	◉	◍
Livestock and fishery-related adaptation	◍	◉	◉	●	◉	◍	◉	◉	◍
Indigenous knowledge and local knowledge based adaptations	◍	◉	◍	◉	●	◍	◉	◉	○
Urban water management	○	○	○	◉	●	○	◉	◉	◉
Energy-related adaptations	○	○	○	○	○	○	○	○	○
Water, sanitation and hygiene (WASH) related adaptations	○	○	○	○	○	○	○	○	○
Other (includes coping)	○	○	◉	●	●	○	◉	○	○

Extent to which a constraint is present
(Percentage of articles that identified the constraint)
○ **Insufficent** (<5%) ◍ **Limited** (<20%) ◉ **Moderate** (20–50%) ● **Significant** (>50%)

Source: IPCC, 2022

5. Implementing Climate Resilient Development

Effective climate action to address climate- and water-linked challenges requires CRD. CRD anchored in principles of equity, justice, and inclusion integrates adaptation, mitigation, and sustainable development, into everyday activity. However, CRD cannot be implemented through siloed or sector-specific actions, it requires systems transitions across 5 key areas including urban and infrastructure, land, freshwater and ocean ecosystems, energy, industry, and societal behaviour tied to consumption and lifestyle choices.

Water is not only pivotal for each of the systems transitions, but it also cuts across and links all 17 SDGs. The majority of the SDGs cannot be met without access to adequate water (Ait-Kadi, 2016; Mugagga & Nabaasa, 2016). Over the years, water has also shown its potential to be a catalyst for cooperation rather than contention. It can serve as a unifying force, facilitating the convergence of interests, breaking through barriers, and fostering a collective vision for the future (PBL, 2018).

It is hence vital to mainstream water-led adaptation interventions in developmental frameworks and ensure synergies between mitigation and adaptative actions instead of trade-offs. This is important since there is evidence that both adaptation and mitigation actions can be maladaptive by leading to higher GHG emissions or causing water scarcity (IPCC, 2022a). For example, several mitigation pathways, including use of solar pumps, treatment and use of wastewater and desalination projects, depending on their contexts, can have adverse results such as depletion of groundwater, higher emissions due to energy-intensive processes, etc. (IPCC, 2022a). Similarly, increased demand for renewables in the face of energy transition is slated to increase in hydropower dam projects but these have considerable adverse impacts in terms of loss of freshwater biodiversity and fisheries, sediment flows to deltas and coastal zones that is required to counter sea level rise and subsidence (PBL, 2023).

Presently, adaptation strategies in developing countries often lean towards autonomous and incremental approaches, primarily focusing on mitigating water-related risks in agriculture (IPCC, 2022a). Conversely, developed countries tend to adopt more policy-driven measures, with a particular emphasis on urban areas (IPCC, 2022a).

While human activities are expected to be the major driver for future water scarcity at a global level, regional analysis shows that the uncertainty surrounding climate change means that reduced water availability is likely in several major river basins (IPCC, 2022a). This uncertainty persists even in basins where projections suggest an increase in precipitation and gross water availability due to a shifting climate. Uncertainties regarding projected water scarcity will be an important consideration contributing to future integrated water management policies and planning. Consequently, areas forecast to experience significant rises in water scarcity with substantial uncertainty, present the most formidable hurdles for both surface and groundwater management (IPCC, 2022a).

5.1 Accelerating Climate Resilient Development

IPCC (2022) outlines seven enabling factors that can help implement and accelerating CRD while achieving water security, facilitating systems transitions, and attaining the sustainable development goals. These include polycentric water governance, political support, gender, equity and social justice, adequate financing, the use of appropriate technologies, inclusion of indigenous and local knowledge, and participative and bottom-up engagement (IPCC, 2022a). We discuss five of these enabling principles below:

Polycentric water governance and political support:

Polycentric governance refers to an absence of central or unique authority and existence of multiple centres of decision-making. It has been shown to lead to better environmental outcomes and improvements in water governance (IPCC, 2022a). Enhanced governance and environmental outcomes are often attributed to more fairer decision-making processes that involve local communities, women, and indigenous people. Empirical evidence shows that polycentric water governance and management can support participatory, decentralised, and deliberative adaptation by bringing together diverse stakeholders across sectors such as irrigation, industrial, domestic use, and watershed institutions, operating across different levels from local to national governments (Baldwin et al., 2018; McCord et al., 2017; Pahl-Wostl & Knieper, 2014). For instance, a study by Baldwin et al. (2018) in Kenya's Upper Ewaso Ng'iro basin found that collective action among water users was enhanced by overlapping authority and effective coordination between local, regional, and national units.

However, polycentric governance can also deepen existing inequalities if existing social hierarchies are reinforced, excluding marginalised actors such as indigenous people, minorities, and women from decision-making processes. For example, during a water crisis in Sao Paulo, existing power dynamics undermined polycentric governance due to a bias of the governance structures and elites towards certain political and social interests at the cost of environmental ones (Frey et al., 2021).

Using overarching principles of polycentric governance, a shared water agenda can be achieved through a multi stakeholder and multiscale process. This can help set clear goals and targets across national and local levels that is currently missing in water security and climate adaptation pathways (PBL, 2023).

A the same time, achieving a shared water agenda requires political awareness and support at national and global level. For example, putting water on the UN agenda can highlight its centrality in achieving global climate, sustainable development and global biodiversity goals and provide an enabling environment for international cooperation (PBL, 2023).

Gender, Equity and Social Justice:

Climate- and water-linked risks and impacts exacerbate existing inequalities associated with gender, class, social status, race, and education, compounding both existing and future vulnerabilities. Evidence shows that poor, socially marginalised individuals, and women often have limited adaptive capacities and are more vulnerable to water hazards such as droughts and water scarcity. Women, in particular, are excluded are excluded from decision-making processes regarding water access and management due to patriarchal norms, despite being primarily responsible for fetching water over long distances during scarcity (IPCC, 2022a). For instance, in India, caste and gender intersections continue to shape access to water due to deeply entrenched societal norms, even within government programs, and nongovernmental initiatives (Behl & Kashwan, 2024). Therefore, it is important to mainstream gender, equity, and social justice concerns in water adaptation strategies and actions to achieve CRD. This requires a justice framework to conceptualise and articulate water issues in a way that addresses structural inequalities and promotes sustainable water governance (Gupta et al., 2023; GCEW, 2024).

The GCEW report (2024) argues that this framework needs to bring together various strands of justice — interspecies, intergenerational, and intragenerational justice — so that the costs of inaction are not disproportionately borne by the most vulnerable, who have contributed the least towards the water crisis. This approach calls for governing water and the hydrological cycle as a public common good rather than a commodity, ensuring access to water as a legally binding human right, reallocating water budgets based on priority of use after water, sanitation and hygiene (WASH) needs are met, and recognising the rights of indigenous people (Gupta et al., 2023; GCEW, 2024).

Adequate Financing:

While 80 per cent of developing countries have developed adaptation plans, with a majority focusing on water, the financing available for climate adaptation is woefully inadequate (IPCC, 2022a; PBL, 2023). As of 2020, tracked green finance was about USD 83 billion, of which only USD 29 billion or about 34 per cent was for adaptation (PBL, 2023). The central costs of adaptation are estimated to be about USD 240 billion annually up to 2030, in the range of USD 130-415 billion every year, about 0.6 per cent of GDP (2021) for all developing countries (UNEP, 2023).

The highest adaptation costs are for water-linked projects like river and coastal flood protection and infrastructure in East Asia, Pacific, Latin America and the Caribbean (UNEP, 2023). UNEP (2023) estimates coastal protection adaptation costs at about USD 56 billion (until 2030) and flood protection and other water-linked events to be about USD 54 billion (until 2050) annually for developing countries. International finance flows for adaptation to developing countries is about ten to 18 times less than what is required (UNEP, 2023).

This shortfall in adaptation finance is due to various reasons, including bias in favour of mitigation, difficulty in monitoring and tracking adaptation finance due to its close links with development, local and context-specific nature of adaptation responses, and multi-dimensional risk profiles (Srinivasan et al., 2023). Traditionally, adaptation has been financed through public expenditure and domestic budgets, but its quantum is inadequate.

Given the climate vulnerabilities of the majority of developing country residents, prioritizing adaptation finance becomes crucial. This calls for mainstreaming adaptation in national programmatic frameworks and budgets to build adaptive capacity across vulnerable sectors, including water, reduce climate vulnerabilities and climate-linked physical asset risks (Srinivasan et al., 2023). To mainstream adaptation, climate risks will have to be integrated into decision-making processes at the national, regional and local governments, through legal mandates, appropriate financial resources and enhanced staffing and institutional capacity. At the same time, private adaptation finance needs to be incentivized through financial and policy interventions by development banks, governments, and financial institutions. International finance needs to be leveraged for adaptation especially in low-income countries. Adaptation investments need to focus on building resilient infrastructure and making up for the deficit in ecosystem services.

Use of Appropriate Technologies:

Technologies enhance water efficiency and reduce carbon emissions contribute towards successful climate adaptation. However, their benefits are contingent on avoiding negative distributional impacts. Historically, agricultural water management has leveraged technology, such as the widespread use of groundwater pumps in South Asia during the 1970s, which improved livelihoods but also increased agriculture's carbon footprint (IPCC, 2022a). More recent innovations, like drip and sprinkler irrigation, and the integration of Internet of Things, aim to improve water use efficiency. However, while use of drip and sprinkler irrigation can improve water efficiency, it can also be counterproductive when used for overextraction or to cultivate water guzzling crops, as has been seen in various regional contexts (Grafton et al., 2018).

Technological advancements in wastewater recovery and recycling for agriculture, creating potable water through desalination and solar-powered water management to reduce reliance on fossil fuels are also being used as effective adaptation options (Caldera & Breyer, 2020; Salgot & Folch, 2018).

Additionally, advancements in wastewater recovery, desalination, and solar-powered water management are becoming more prevalent. Machine learning and AI are being introduced in various water-use sectors, although mostly in high-income countries and often on an experimental basis. Remote sensing technologies coupled with geographic information systems (GIS) have been developed towards achieving sustainable coastal management (Kankara et al., 2014; Roy & Datta, 2018) such as to monitor coastal habitats, landforms, shoreline, water quality; classify coastal habitats; and conduct impact assessment of hazards such as cyclones, tsunami and sea level changes (Nayak, 2017).

The adoption and effectiveness of these technologies depend heavily on financial resources, suitability to local contexts, and strong institutional and governance frameworks. Furthermore, the unequal distribution of technological benefits, often favouring the wealthy, poses challenges to equitable adaptation. Ultimately, while technology plays a crucial role in water adaptation strategies, its success is influenced by broader societal factors, including governance, equity, and justice considerations (IPCC, 2022a).

Inclusion of Indigenous Knowledge and Local Knowledge (IKLK):

There is a strong consensus that genuine partnerships with indigenous peoples and local communities can improve adaptive capacities, reduce vulnerability and help decolonise water management and biodiversity conservation (IPCC, 2022a). For instance, there is robust evidence supporting the notion that indigenous peoples-led freshwater management can foster culturally inclusive decision-making and collaborative planning processes at both local and national levels (Harmsworth et al., 2016; Parsons & Fisher, 2020).

Community-led initiatives and restoration measures are proving instrumental in mitigating climate change and offering refuge to threatened freshwater species like adaptation strategies implemented by the Skolt Sami community in Finland to support the survival of Atlantic salmon populations in the Naatamo watershed (IPCC, 2022a). Atlantic salmon populations had declined with the increase in northern pike (that preys on salmon) in response to warming temperatures. Indigenous knowledge and management techniques including identifying and protecting spawning beds of salmon, increasing catch of pike helped in ecological restoration in this case. In Bangladesh's hill tracts, indigenous people working with local governments are help restore springs and natural wells (Sultana et al., 2019). 'Braiding' of indigenous knowledge with western approaches offers diverse benefits including improving understanding of socio-ecological systems and connections, implementing evidence-based action for biodiversity conservation, developing context-specific water and eco system protection (Mehltretter et al., 2023, p. 5).

Conclusion

The hydrological water cycle is increasingly out of balance from local to global scales due to many decades of unsustainable anthropogenic water use, massive land use and landcover change across most regions and climate change, accompanied by widespread mismanagement and pollution of ground and surface water (GCEW, 2024). The result is a global water crisis, which is set to worsen under business-as-usual development trajectories, leading to severe social, economic and ecological challenges ranging from increased food and water insecurity, vulnerability and losses borne by the most vulnerable, and expanding biodiversity loss that can exacerbate current and trigger new conflicts.

Climate change is a significant driver of the global water crisis. It is intricately linked with the global water cycle, with dislocations in each intensifying the other, through powerful feedback processes that are driven by contemporary development processes and the dynamics of national and the global economy. Many climate change impacts are manifested through water, including precipitation variability, reduced snow cover, an increase in extreme events such as excessive floods and droughts, and sea level rise (IPCC, 2022).

These climate-and water-risks can severely impact and endanger human life and well-being, ecosystem integrity, food security and hence, the global economy. Every degree increase in global mean temperature will further reshape the water cycle, affecting water availability and amplifying climate-induced water risks. For example, an additional 3 billion and 4 billion people will face water scarcity at 2°C and 4°C warming (GCEW, 2024).

Climate-induced water risks, including water scarcity, food insecurity, water-borne diseases, and economic losses, are not faced equally by all people and regions. They disproportionately impact regions and countries with higher development deficits, particularly affecting economically and socially marginalized groups, including minorities, women children and the aged.

While climate vulnerability, experienced through extreme weather events such as excessive floods, droughts, storm surge, wildfires, has forced countries to react and initiate adaptation plans, these actions are largely fragmented and sector specific. They fall short of addressing existing climate adaptation gaps across regions and systems. Unlike climate mitigation pathways that aim to reduce emissions in line with the shared vision of the Paris Climate agreement, there are no clear global climate adaptation pathways that can effectively mobilise collective action, secure financing, or align national efforts.

Most known and effective adaptation pathways, including those related to water are implemented from local to national-levels. Structural challenges to climate and water cycle adaptation pathways are constrained by poor and fragmented governance, inadequate and mistargeted finance, institutional constraints and lack of capacity, inappropriate technological choice and often climate maladaptation, lack of participation and access to technology and innovation, and gaps in information and knowledge.

Despite these challenges, a range of effective adaptation strategies have been implemented across regions and systems within local contexts, with documented benefits. Actions such as nature-based solutions in design and planning, water proofing of infrastructure, and restoring natural habitats like mangroves can be scaled based on a long-term adaptive strategy that balances human land use with river basins and ecosystems functioning (PBL, 2023). Other actions like improving adaptive capacities and reducing climate vulnerabilities have several co-benefits with the sustainable development goals like increasing social security nets for the poor, creating climate resilient affordable housing, and providing universal access to environmental services like sanitation, solid waste disposal, wastewater management.

Given this context, a resilient and sustainable future demands that we value water as a critical resource and the basis of all life, recognise the interlinkages between climate change, the global water cycle, regenerative agriculture, sustainable cities and communities and biodiversity. This implies a radical shift from existing 'value systems, policies and economic practices' and business-as-usual development frameworks (PBL, 2023, p.182). Climate Resilient Development (CRD), as outlined by the IPCC in its Sixth Assessment report, offers a new development paradigm for the Anthropocene. It integrates climate change (adaptation and mitigation) agenda with biodiversity and the SDGs. CRD, anchored in principles of equity and justice can be operationalised through five key systems transitions ¬: land, water and ecosystems, urban and infrastructure, energy, industries and societal systems (IPCC, 2023, IPCC, 2022)

Water can play a key role in achieving CRD as it is central to all systems transitions and all 17 SDGs (Ait-Kadi, 2016; Mugagga & Nabaasa, 2016). For years, it has served as a unifying force, converging interests and proving to a catalyst for cooperation (PBL, 2018). Under CRD, the water adaptation agenda and climate risks assessment can be mainstreamed into development trajectories, policy planning, financing and decision-making across systems and all levels from local to global, ensuring there are synergies between adaptation, mitigation and development goals.

Achieving a water-secure future and CRD is not going to be easy. However, water security, along with CRD, can be accelerated through key enabling conditions, which are discussed in this paper. These include polycentric and multilevel governance, adequate finance, use and access to appropriate technologies and innovation, gender, equity and social justice, and inclusion of indigenous and local knowledge (IPCC, 2022a).

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