

The Intersection of Climate Change and Economic Water Challenges

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Abstract: Climate change poses a significant, often neglected, threat to the economic availability and accessibility of freshwater resources, despite water's fundamental role as the economic basis for existence. The total costs of freshwater abstraction and treatment exceed one-quarter of global GDP, yet current management practices largely lack an effective economic framework, leading to misaligned investments and unintended economic unavailability. This study aims to bridge this gap by thoroughly examining the complex nexus between climate change and economic water challenges, exploring issues and prospects for sustainable management. We analyze the impact of climate change on water availability through a supply-side scenario, detailing changes in precipitation patterns, rising sea levels, and saltwater intrusion. The economic implications of water scarcity, particularly for the agricultural and industrial sectors, are discussed, highlighting potential GDP losses, increased food prices, and threats to political stability. The study also investigates viable solutions, including adaptation measures, infrastructure development, and effective governance structures, emphasizing the critical role of international cooperation. It links these efforts to global frameworks such as the Sustainable Development Goals (SDGs) and the Paris Agreement, arguing that treating water as a global common good is essential for averting widespread societal and economic disruptions and ensuring sustainable access to this indispensable resource.

Keywords: The Intersection; Climate Change; Economic; Water Challenges.

JEL codes: Q54 ; Q20 ; Q25.

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I- Introduction:

Climate change is expected to have a severe impact on the economic availability of freshwater resources and thus on people's economic access to water. This circumstance was and still is too often neglected, with or without knowledge. Few people know that the total costs of freshwater abstraction and treatment exceed one quarter of the world's annual gross domestic product (GDP). Water is, therefore, the economic basis for our existence. Yet freshwater resources are not managed in a clear economic manner. A vast body of research in environmental economics is dedicated to showing how to implement the economic basis of water in the management and valuation of these resources, but as of today, not a single country has implemented this economic basis in practice. Understanding the link between climate change and the economic availability of freshwater resources is crucial, and the economic basis for water management is described. The impact of climate change on the economic availability of water using a supply-side scenario of climate change impact on water resources is presented. Options are given to reduce this impact, and in-depth case studies on selected developing

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and developed countries are provided. Finally, possible responses to economic water unavailability are explored.

Economic development necessitates access to freshwater resources. However, over the past decades, it has become increasingly apparent that global freshwater resources are under severe stress. Water has, therefore, a unique position in the environmental discourse: it is an environmental good that is indispensable for life. This good is both vulnerable and relatively abundant. Nevertheless, unaware of its scarcity, its global average prices do become negative, while the economic basis for the successful management of scarcity - accurate water pricing structures - is missing. The global average water supply price is now less than 0.01 €/m³, the same order of magnitude as the price of seawater. Consequently, freshwater resources are abundant virtually everywhere. At the same time, with prices becoming negative, investments in providing supply-side solutions were misguided. The good is nevertheless too scarce. This indicates awareness of economic unavailability, which is unintentional. Changes in the global water cycle due to climate change are expected to have a severe impact on the economic availability of water resources and thus on people's access to economic water. Sudden economic unavailability could threaten political stability, as observed before in the case of the Arab Spring, kicked off by the global food crisis. A prime motivation for the choice of the topic is its importance to societal well-being and environmental sustainability. The aim is to provide insights into both the broader principles of the nexus and practicality of climate change impact on the economic availability of freshwater resources. To try to answer this, we raised this issue: How are the intersections between climate change and the economic challenges of water understood in terms of issues and prospects for sustainable management?

The main goal of this study is to thoroughly understand and analyze the complex connections between climate change and the economic challenges of freshwater resources. We'll specifically look at current issues and future possibilities for sustainable management. This involves delving into the broader principles of how climate change impacts the economic availability of water, highlighting the often-overlooked financial side of this vital resource and its fundamental role in human existence and economic growth. We also aim to present the practical effects of climate change on water's economic availability, using a supply-side scenario to illustrate these impacts. A key part of our objective is to identify and present viable options for reducing these negative impacts, supported by in-depth case studies from both developing and developed countries. Finally, the study will explore potential solutions to economic water unavailability, ultimately seeking to answer how the intersections between climate change and water's economic challenges are understood in terms of issues and prospects for sustainable management.

This study is incredibly important for several reasons. First, it addresses a crucial issue that's often ignored: the economic cost of freshwater. Many people don't realize that abstracting and treating freshwater costs over a quarter of the world's annual GDP. This study aims to bring this critical economic dimension to the forefront, emphasizing that water is essential for our economic survival. Second, the study highlights how a sudden lack of economically available water can threaten societal well-being and even political stability, as seen during the Arab Spring. Understanding this link is vital for preventing future crises.

Third, by clearly defining the economic basis for water management, this research provides a crucial foundation for more effective and sustainable resource allocation and valuation, which is currently lacking in practice worldwide. Fourth, the findings will inform policymakers, governments, and investors about the urgent need for action and the necessary strategies for water resource management.

This research also emphasizes water's unique position as an indispensable, vulnerable, yet often undervalued good. This understanding is key to encouraging responsible consumption and investment. Finally, by bridging the gap between existing research and practical implementation, this study offers concrete insights and case studies that can guide real-world applications. By exposing the severe stress on global freshwater resources and how misguided past investments were due to negative water prices, we hope to raise awareness and encourage proactive measures to secure our water future.

1. Background and significance:

Climate change is a massive problem and a universal danger. It is closely related to and has an enormous impact on many aspects of life, including living, economy, transportation, and many other domains. The deteriorating environment, like global warming, extreme rainfall, storms, floods, droughts, etc., hinders the development of economies, causing poverty in many parts of the world. On the other hand, climate change, being caused by the release of greenhouse gases through many economic activities, also affects the economy. Water and water-related problems are a very important part of this intersection. Climate change produces droughts and bad water quality. These produce adverse health effects and poverty on the poor people's juveniles. Also, many airports, especially in island regions, will be inundated due to the rise in sea level. This neglects the technological development of the nation. Water is essential for economics, industries, agriculture, transportation, energy, etc. So a problem in water will have its inevitable bad effects on many economic aspects. Climate change threatens the water supply and its quality, which are two major and huge looming problems. Water and climate change are mutually related. (Nhemachena et al. 2020)

Water is becoming a newfound treasure, and reclamation of wasteland is becoming an emerging trend to tackle the looming water scarcity. Many fresh surface rivers/canals are not suitable for irrigation or industrial use due to salinity ingress and high TDS. Moreover, there is also water pollution in rivers, lakes, and canals due to effluent release. All these pose a major problem in development, especially for agriculture, where poor farmers and their families are hard hit. Reclamation of these waters can convert wasteland into revenue-generating land. Technologies are in place for such reclamation. The proposed methodology is to promote a low-cost and decentralized bio-reclamation technology to remove contaminants, salinity, and TDS from fresh water surface water bodies. The methodology includes the development of treatment plants utilizing microbes, phytoremediation, and low-cost polymers. Economic benefits and employment generation are also added benefits. Presently, a demo project is functioning in the northeast region to evaluate the efficacy and sustainability of the concept. It is expected that if the project succeeds, the technology will be scaled up to combat the large-scale water rising problems.

Economic development entails an increase in gross regional product (GRP), which is associated with the growth of the industrial sector and an increase in energy consumption, water usage, and the release of pollutants. The implications of economic growth are multifaceted, depending on the nature of economic development and management approaches predominated in that region. The interconnections between socio-economic and environmental proxies can be complex and inferior, especially in rapidly growing economies. However, high pollution and resource depletion can threaten the sustainability of social and economic development. Greener economic growth is crucial in alleviating or avoiding severe environmental problems for fast-growing economies. Decoupling water use from economic growth means that society is able to pursue enhancement in economic output without increasing aggregate water consumption. The introduction of environmental regulations could enforce stringent control over excessive use of resources and thus alleviate environmental problems.

The joint efforts of governments, corporations, and individuals will make sure that the sustainable progress models are adopted in water-scarce and developing econometric regions. (Abbasi et al., 2021)

2. The impact of climate change on water resources:

Climate change has far-reaching implications for the planet's ecosystems, landforms, and atmosphere. Among the elements most severely impacted by climatic changes, water resources are paramount, as their decline can lead to food scarcities, increased migration, and subsequent unrest. Water resources refer to Earth's supply of fresh water, which is crucial for human survival and ecosystem balance. There are several different forms of water resources that differ both in quality and quantity. However, the two most crucial resources are freshwater and saline water.

Climate change is expected to have a significant impact on Earth's water resources. Precipitation patterns are largely governed by climatic conditions; therefore, the manifestation of climate change would impact these patterns directly. Over the last hundred years or so, several regions of Earth have been subjected to droughts, flooding, and other water-related catastrophes due to the changing trends of climate. Rain-fed agriculture in Central and South America, Southern Africa, and Asia has a variable response to the projected changes in precipitation due to climate change, according to a report prepared by the Intergovernmental Panel on Climate Change (IPCC) in 2007. Loss of snow and ice melting due to climatic changes has caused large water resource models to be grossly underestimated in the regions of Central Asia, the Himalayas, and the Andes, while vast regions of Russia and Canada have been shown to gain water resources because of increased precipitation, decreased marsh area, and increased runoff.

Climate change, owing to an increase in the surface temperature of the seas, could lead to the melting of polar ice caps and glaciers. The increase in the volume of ocean water due to the melting of ice caps and glaciers could lead to rising sea levels, thus inundating coastal zones and islands. Climate change cannot only affect the supply of the resource (precipitation), but it can also affect its quality (salinity). Coastal aquifers in delta regions face both natural and anthropogenic salinization. The natural salinization comes from the intrusion of saline water due to the tidal activity of nearby saline water. Climate change, due to predicted changes in precipitation and sea-level rise, is projected to intensify the salinization in coastal aquifers adversely. Moreover, water resources in many countries are already under fresh water stress. As countries try to adapt to this fresh water scarcity, they lean toward the over-extraction of groundwater resources. In coastal regions, this over-extraction is compounded with the rising sea levels and salinization. (Richardson et al.2024)

2.1. Changes in precipitation patterns

The Earth's climate is naturally variable over time due to changes in solar radiation receipt, the amount of greenhouse gases in the atmosphere, and other boundary conditions. However, human activity has caused this variability to be amplified, resulting in climate change. Numerous researchers and climate modeling groups have contributed to improving understanding and modeling of the Earth's climate. A subset of these groups has made climate model results available to the international research community through the Coupled Model Intercomparison Project (CMIP). More than 20 climate models were used to simulate future climate under a top-down approach consistent with IPCC Fourth Assessment Report (AR4) SRES emissions scenarios A1B, A2, and B1. In addition, downscaled meteorological data from five climate models is now available for a new and extensive analytical and modeling effort, at both the global and regional scales.

Various types of climate change scenarios are used, with models being used as a tool to explore the consequences of changes in atmospheric trace gases and other global boundary conditions on natural systems. A diverse collection of climate models are used to investigate various global change scenarios. These models differ in their complexity, with some being globally averaged energy balance models and others being comprehensive atmosphere-ocean-vegetation models.

The water cycle affects and extends into all components of the climate system. Although water vapor is a trace gas in the climate system, its unique properties give it a dominant role in the natural greenhouse effect and climate feedback processes. The warmer the air, the more humidity it can hold, and warmer air causes a positive feedback mechanism, further enhancing warming. Research has provided new insights into the water cycle and its role in climate change. The rate of increase in global annual precipitation is on the same order of magnitude as the increase in greenhouse gas radiative forcing. Climate models indicate that mean precipitation will increase with global warming. (Shonket al.2020)

Climate change is expected to affect the land-ocean distribution of rainfall, with more rainfall in the high latitudes and less in the subtropics. There is some evidence that changes in the hydrological cycle can be detected in observational data, although results remain ambiguous. Nevertheless, it is very clear that climate change will affect water resources in important ways. There will be changes in rainfall amount and variability; increased intensity and frequency of floods and droughts; and changes in the nature of rainfall (i.e., increase in short and intense storms) and potential satellite data are available and may be useful in some studies. Climate change is affecting tropical forests, cocoa production in Ghana, and snowfall in the Himalayan region, but there's less information available at the catchment and basin scale. (ECA et al.2020)

2.2. Rising sea levels and saltwater intrusion

Over the past century, the mean global sea level has risen by approximately 23 centimeters, and evidence suggests that this trend is accelerating. By the end of the twenty-first century, an increase in sea level of up to 1 meter is projected. Sea-level rise, resulting from melting glaciers and ice caps, changes in the volume of ice sheets in Greenland and Antarctica, and thermal expansion of seawater, can have detrimental effects on coastal freshwater sources. Sensitive ecosystems, such as coastal wetlands and beaches formed by sand, are expected to be gradually submerged or eroded away. However, the most immediate consequence of rising sea levels is the intrusion of saltwater into coastal aquifers and other freshwater sources.

Saltwater intrusion is the movement of saline water into freshwater aquifers due to both the decline of the freshwater-saltwater equilibrium and the subsequent displacement of freshwater. This can occur either gradually as sea levels rise or instantaneously due to subsidence, storm surges, or human activities. Urbanization generally exacerbates the effects of saltwater intrusion through the conversion of natural land coverings such as permeable sand dunes and wetlands into impermeable surfaces, resulting in groundwater recharge reduction. Large-scale groundwater exploitation can also play a role in the overall decline of the freshwater resource, making up for the unreplenished aquifer volume through the downward migration of seawater.

In the past several decades, many global coastal aquifers have been contaminated as sea levels rise or due to human activities to combat land subsidence, especially in developing countries. Once contaminated, it is difficult to recover the aquifer; therefore, preventing saltwater intrusion is a priority among coastal sea level rise adaptation strategies. A variety of strategies with distinct applicability

depending on local geology can be employed to prevent saltwater intrusion, including reducing groundwater abstraction, monitoring freshwater-recharge targets, and constructing injection wells to force the freshwater-saltwater equilibrium inland using pressure. (Bosselle et al., 2022)

3. Economic implications of water scarcity

In addition to being a public health issue, water scarcity is a significant economic concern. Already, a large number of people in both industrial and developing nations are being negatively impacted by water scarcity, and this number is set to dramatically increase in the coming decades. Most of the world's water resources are used in the agricultural sector. Important economic implications arise from water scarcity for this sector. Economic models of countries and world regions have been used to assess these implications for global food production, prices, and trade flows. In addition, the economic sector where water is a key input—industrial production—is discussed. Analyses of water scarcity in this sector are at an early stage. Water quantity can have an impact via water tariffs and greater supply uncertainty.

Population growth and rising living standards are predicted to significantly raise the demand for water for the agricultural sector in developing countries. Increased involvement of large-scale irrigation systems tends to confront water scarcity earlier than small-scale systems. Water scarcity is predicted to have a negative impact on agricultural GDP growth in both developed and developing countries. However, this negative impact is predicted to be much greater in developing countries. At the same time, water scarcity is predicted to result in a large increase in the prices of agricultural products in developing countries. Water scarcity is predicted to have a relatively modest impact on developing countries' participation in international agricultural trade during the transition period and to enhance their participation afterward. In developed countries, countries that depend heavily on irrigation agriculture, such as southern Europe and Scandinavia, are predicted to be negatively affected. In southern Europe, agricultural GDP is predicted to fall, with a gradual increase in land retirement. However, due to the gradual transition of southern European countries to a more mature water-abundant agricultural economy, a dramatic increase in water diversions is not predicted, so the impacts in southern Europe are expected to be relatively modest. However, the effects on agricultural sectors in countries such as Greece and Spain tend to be stark declines, with large economic impacts on rural areas with intensive agricultural production. Conversely, the agricultural sectors in countries in western and northern Europe that are less dependent on irrigation agriculture are predicted to see increases. (Zhang et al.2020)

Whereas the agricultural sector is the economic sector where water is most widely modeled, the industrial sector is another economic sector where water is a key input. Analyses of water scarcity in the industrial sector are at an early stage. Most consumer goods are produced with a significant water footprint, commonly in the form of not-easily-recycled fresh water. Fresh water is directly consumed as an input in the production processes of many goods. Water quantity is predicted to have an effect via water tariffs, which are expected to rise as a result of diminishing freshwater resources and increasing population. It is also predicted to affect a growing business risk via greater uncertainty in the supply. Growing global water scarcity is predicted to have economic effects on nationwide consumer good production, prices, and international trade flows. Most countries are predicted to switch to both agricultural and industrial production of goods that use less water and are still acceptable in consumption. This would be a gradual global societal transition that takes place over multiple decades (Mekonnen & Gerbens-Leenes, 2020).

3.1. Agricultural sector

At the intersection of climate change and economic water challenges, consistent feedbacks exist and continue to develop untouched. The agricultural sector is the first recipient of climate change impacts through changes in average climate, weather variability, growing season length, and crop distribution. Crop losses due to droughts are associated with GDP and economic losses, though loss distribution and drought resilience challenges are less researched and understood. The causes of disparities in economic water challenges between regions and countries and their consequences on growth and development are uncovered. Furthermore, the societal and environmental challenges deriving from the climate-economic-water nexus and their evolution under the business as usual projection are discussed. Evidence from a global multi-sector, multi-region assessment of the impacts of weather variability and climatic changes on wealth is presented. The analysis employs a hydro-economic model to assess climate impacts on water supply, water demand, irrigation water return flows, and water prices, and on 20 agricultural crops traded in a global economy with an emphasis on trade flows. Separate analysis of yield changes and water rental price changes provides further insights into losses than total economic impacts based on aggregate income losses. Economies rely differently on the sectoral three-fold chain income supply, and growing differences are developed under climate change impact streams. Feedback on growth pools is unevenly distributed over decades, with developing economies losing increasingly over time.

The agricultural sector is identified as the first recipient of climatic changes with an overwhelming share of extreme temperature and droughts. Variability losses associated with abnormal weather events, in particular extreme losses, are explored. Losses are observed to be more frequently distributed around the equator and low latitude with an abundance of droughts and floods or tropical cyclones. At the same time, a small share of these economically water-scarce countries are net exporters of typically irrigation-water-thirsty crops (i.e. rice, sugar, cotton, oilseeds, and animal feedstuffs), and the lost wealth remains uninsured by trade. With rapid population growth, the observed convergence into economic water scarcity between regions and countries derived from the unequal shared distribution of the water stock will only increase. A unique global dataset on temporal (1980 to 2012) and spatial (134 economies worldwide) gross economic losses caused by droughts and associated crop damages is developed, with emphasis on what functional forms best fit losses. These damages are assessed for up to six different economies. Flexible functional forms (variable elasticity forms), in particular the square root loss form, with functional adjustment for crop value, are observed to best capture losses, outperforming linear, logarithmic, Cobb-Douglas-like constant elasticity forms, and conventional input-based measures of damages. The standard quadratic loss form is largely used in modeling frameworks. However, in the case of crop damages, it is associated with a low R-squared and a poor distribution. (Thinda et al., 2020)

3.2. Industrial sector

The industrial sector plays a major role in economic development. However, the industrialization process often leads to heavy water requirements and pollution. As a consequence, water has emerged as a concern for economic growth and sustainable development. Climate change is expected to exacerbate the already critical situation of water scarcity, often leading to competition among different users.

Water abstraction accounts for economic losses, which are expected to increase due to weaker economic growth and relative price development. Water availability is critical for development. Chronic water scarcity is reported to lead to a substantial reduction in economic output. Industrial

water consumption, which is predicted to grow due to economic development, is often considered to be a key concern for economic growth, especially in water-scarce developing countries.

Industrial water use follows a U-curve along economic development, initially growing with economic development until some peak economic output, and later dropping due to water use efficiency improvement with more advanced technology. Water is often transferred to other sectors such as agriculture as the economy develops, leading to competition among different users. Already generous projections of water availability are expected to be further reduced due to climate change.

Climate models, which capture global warming to 2100 and water abstraction, household water consumption, and industrial water consumption under different climate scenarios, assess the economic effect of climate change on nationally reported water abstraction, household water consumption, and industrial water consumption. The Expected economic losses due to water abstraction increase almost linearly with the magnitude of economic development, with the relative damage reduction and proportion increase, which are very small, becoming negligible for more advanced economies. (Deineset al.2020)

The industrial sector was the first to abstract water, and the agricultural sector is predicted to catch up. Competition among different users is commonly predicted, and chronic water scarcity is expected to lead to a substantial reduction in economic output. Infrastructural development and institution establishment followed and were enhanced by broad economic development and national political stability. However, some cost-curtailed cultivation of crops with lower water requirements is predicted in highly water-scarce areas.

Both water abstraction and water consumption are expected to be reduced with the adoption of stronger policies, and the largest change is recorded for the developing country with intensively cultivated agriculture, suggesting that too low water prices lead to significant water misallocation to less intensive sectors such as low-value export crops. It is noted that water abstraction and water consumption econometric models differ significantly, revealing that changes in water availability impact on economic growth are often underlocked by the existing approach for modeling both income-related abstraction and consumption, and that ignoring macroeconomic adjustment largely misestimates the economic outcome. (Kim et al.2020)

4. Policy responses and international cooperation

Despite the complexity of the problems surrounding water management and climate change, there is significant room for optimism. There are clear solutions such as adaptation measures, the development of robust infrastructure, and the introduction of highly effective governance structures to mitigate the deleterious impact of climate change. Additionally, low-cost technologies utilizing the natural hydrological cycle to desalinate oceanic water are contemporaneously in development. Further, these scientific advancements could preserve twenty-first-century civilization for an indefinite future. However, none of the solutions can be implemented effectively without international cooperation with countries that do not see water and oceanic systems as a common good. The solution to these issues, therefore, depends on the international community viewing water as the world's greatest undervalued good and as a global common good. International cooperation can either avert human-induced planetary-scale disaster or channel all productive forces to preserve the hegemony of a small number of countries. This is why collective international attention surrounding water issues has continued to take precedence over climate.

An often-overlooked consequence of the Anthropocene is the extent to which unavoidable climate change (increases in temperature, precipitation changes, increased droughts, etc.) will impact water availability. A country's ability to manage its water resources will depend largely on its geology, geography, and climatic conditions, as well as its institutions, governance, and legal systems. States with different hydrological cycles can interact politically, economically, and socially in a way that produces either mutual benefits or exploitative relationships. Strategies need to be deliberated and implemented in order to satisfy both current and future demands for freshwater. This requires approaches similar to the Sustainable Development Goals (SDGs) and the objectives of the Paris Agreement. Central proposals of each approach are outlined, as well as suggestions for their further development and completion. (Heinke, 2021)

4.1. Sustainable development goals (SDGs)

While countries join forces to mitigate climate change, the consequences of rising temperatures will be further felt among heterogeneous populations. Their adaptive capacity will, to a large extent, determine how water scarcity affects economic development prospects. By 2030, the world aims to ensure universal access to affordable drinking water and sanitation and build resilience against water-related hazards to foster sustainable development. Climate change will make it even harder to achieve these targets (Sustainable Development Goals). Unfortunately, economically fragile countries are also the most vulnerable to climate change, compounding challenges to ensure societal development and stabilize economies.

Original stakeholders, focus, and issue of research. The research focuses on climate change, economic water scarcity, and what policy responses international cooperation can offer to address the issue. Furthermore, the United Nations' Sustainable Development Goals concerning climate change and economic water challenges are directly linked. The negotiation process that led to the Paris Agreement is the prime example of international cooperation. International cooperation refers to the unique predicament of heterogeneous nations pooling efforts and capabilities to overcome similar issues. Different interests, resources, and power relations prevail, which raise the question of how such cooperation can be achieved, and what specific policy measures to promote or strengthen it. The Sustainable Development Goals (SDGs), emerging from an inclusive process of negotiation and discussion, aim to straddle the line between broad topics and specific areas of concern. Ultimately, the SDGs embrace a holistic and multi-disciplinary perspective and call for global structural transformation.

Furthermore, the research narrows the focus down to two particular goals and their targets: SDG 6 Clean Water and Sanitation and SDG 13 Climate Action. Two instances of international cooperation are also examined: the SDG negotiation process and the Paris Agreement. Addressing climate change is paramount for sustainable development, while it will be increasingly difficult to provide adequate water supply due to climate change. Water scarcity poses societal challenges that should be overcome, urgently and in the context of long-term sustainability. Poverty eradication and economic development are at stake. The growing awareness of climate change and its consequences for a water-scarce world are of global concern, but little is known about how nations respond separately and, more importantly, jointly to tackle these issues on a global scale.

Davidson (2017) warns that "the significant synergies and trade-offs between the SDGs and the planet's boundaries must be recognized - put simply, there is no 'doughnut' without dealing with the climate crisis." The effects of climate change on freshwater systems are complex but can lead to such issues as changes in water temperature, salinity, water supply, higher risks of floods, and the

deterioration of wetland ecosystems. These effects will have differential impacts on countries, depending on their economic structure and adaptive capacities. The SDG targets on water and climate are formulated separately and do not consider the former's response to climate change, nor do they take mitigation effort disparities into account. In essence, developing countries cannot afford future freshwater deprivation without further support from developed countries. (Griffith & Gobler, 2020)

4.2. Paris agreement

The Paris Agreement, a historic milestone in the global response to climate change, was adopted by 196 Parties at the COP21 in Paris on 12 December 2015. Its long-term goal is to limit the increase in global average temperature to well below 2°C, preferably to limit the increase to 1.5°C. This ambitious goal recognizes that the worse impacts of climate change can be avoided only by means of very profound reductions of greenhouse gas emissions. It cannot be achieved by relying only on technological advances and economic growth. This implies that fossil fuels should remain in the ground, as their combustion would harm the climate system. A phase-out of coal, oil, and gas—including through a curtailment of exploration and development of new fossil fuel reserves and infrastructure—is thus necessary. Additionally, technologies for large-scale carbon capture and storage may also be necessary, alongside a substantial increase in CDR (carbon dioxide removal) through natural or engineered means.

However, phasing out fossil fuel emissions cannot be achieved without addressing a variety of other interlinked challenges and concerns. Poor people in developing countries who cannot afford modern forms of energy still rely on charcoal or kerosene and therefore climate change in several respects harms the poorest and the most vulnerable. Meanwhile, access to energy remains a challenge in mountainous and isolated parts of developing countries where there are no energy sources. Thus, cooperation internationally is by nature complex, especially as it relates to fossil fuel emissions.

The way countries feel about international cooperation on climate issues is also very complex, depending on energy endowments, technology and institutional development levels, and experiences with earlier attempts of cooperation. Climate change policies of developing countries are often seen as a way to undermine the competitive position of countries that invest in them. This reluctance is deepened by the fact that climate change, like other global issues, has had an unpromising history of international cooperation. The conditions surrounding past cooperative attempts remain unchanged for climate change and are viewed with a high degree of skepticism.

Using the Arctic region as a case study that involves several aspects of climate change, augmenting the description of the expected impacts of climate change with an illustration of the complex situation of nations and the Arctic region would help to create a better understanding of why cooperation is needed in the first place and the challenges that face this cooperation. This underlines that strategic responses to climate change risk mutual harm to nations and that it is in the interest of individual nations to cooperate (Vincent, 2020).

5. Technological innovations for water management

Innovative solutions for better water management are a focus of research and development efforts in both private companies and the public sector. Water recycling is an effective means of mitigating the growing demand for fresh water. Water recycling is a technological process that cleans previously treated water using additional purification steps to allow water from a variety of sources to be used for multiple purposes, such as irrigation of golf courses, parks, and agricultural fields.

On the one hand, the expansion of water recycling into the economic mainstream faces an acceptance problem caused by the "yuck factor" or consumer unease with drinking recycled water. On the other hand, water recycling is considered satisfactory technically, using advanced purification technologies such as reverse osmosis and high-tech membrane bioreactor processes. These allow water from various sources to fulfill the required standards for potable purposes, with only disinfectants and oxidation chemicals left as unwanted by-products.

Other technological innovations, such as energy generation and desalination technologies, play a fundamental role in the productive and efficient water management that indirectly mitigates its scarcity and vulnerability, as well as producing a fair and inclusive distribution of water resources. Energy use is crucial in all water management stages, from abstraction and treatment to distribution and use, because energy demand rises with water influxes and transportations. In developed countries, energy consumption per unit of water supplied is significantly lower than in developing countries; this is mainly due to the difference in energy prices, which in the case of Africa can be up to 7000 times cheaper than in the countries in Europe.

The mechanism of further outdoor treatment of the brine remaining after desalination processes is being researched, looking at the potential of various salinity gradient technologies that take advantage of the potential energy stored in salinity differences between seawater and freshwater at river estuaries. Sabkha systems, very crusty salt flats or tidal flats with a saline crust covering wet and muddy sediment, with salinities much greater than seawater, have been used from the perspective of seawater desalination technology. As the maturity and technical development exist in biogeochemical models of biosedimentary systems, it becomes promising and realistic to elaborate on modeling and simulation mechanistic mathematical models to define the techno-economics of this new system. (Gonzales et al.2021)

5.1. Desalination technologies

The growing frequency of extreme droughts triggered by climate change not only endangers freshwater resources but also ushers in increasing competition for water among industries, agriculture, and communities. During such water scarcity crises, drinking water becomes essential for survival and is prioritized over other uses. It therefore becomes necessary to find alternative sources of drinking water. Desalination, which filters seawater or saline groundwater, is one of the most promising alternatives to freshwater sources, yet it remains an energy-intensive process due to high temperatures and salt concentrations. When desalination is powered by fossil fuels such as natural gas, oil, or coal, it becomes an indirect consumer of freshwater resources and creates an environmental footprint of greenhouse gas emissions while competing with industries and agriculture for energy. Therefore, green desalination technologies powered by renewable energy sources, such as solar or wind power, are crucial.

Multiple desalination technologies exist to remove salts and other pollutants from saline water, making it suitable for drinking. The choice of desalination method is influenced by site conditions, energy sources, and economic feasibility. Distillation techniques, including multi-module distillation (MED), multi-effect distillation (MED), and vapor compression distillation (VC), are commonly used. However, membrane technologies such as reverse osmosis (RO) have dominated the desalination market due to lower energy requirements and costs. Membrane desalination technologies involve the filtration of saline water through semi-permeable membranes that allow fresh water to pass while blocking most salts and organic substances. Reverse osmosis (RO), a pressure-driven sodium exclusion process, is the most widely used technique commercially and in research, accounting for

about 80% of the installed water desalination capacities globally. Most of the current RO installations implement thin-film composite aromatic polyamide thin-film membranes.

Despite its commercial success, the RO technology suffers from several limitations, including the necessity for pretreatment of the feedwater to inhibit fouling and scaling. Membrane fouling not only deteriorates system performances but also drastically increases maintenance costs, with yearly membrane replacements of 20-50%. Other emerging pressure-driven processes that use similar membranes as RO are also possible routes but are still little explored. Unlike RO membranes, which are fully hydrophilic, the physisorbed surfactant anti-fouling mixtures produce fouling-resistant hydrophilic-hydrophobic membranes, showing little anti-fouling potential against realistic and oil-fouling conditions. As a mature technology, significant improvements in energy efficiency and selectivity of RO membranes became achievably challenging; therefore, alternative water treatment technologies are required. (Jarma et al., 2023)

5.2. Smart water grids

Water consumption is growing faster than the world population, and water supply is at risk due to climate change and deteriorating infrastructure. Meanwhile, open access to water data is increasing, new sensor and data analysis technologies are emerging, and widely distributed cheap devices for the Internet of Things are available. These pieces of evidence must be combined to develop solutions for water management. Smart water grids are increasingly presented as a solution for the confluence of all these factors. Their proper design can lead to substantially better water management solutions.

Concerns have been raised about the potential impact of climate change on water resources and the reliability of water infrastructure. These concerns are relevant because water demand and consumption are increasing faster than the world population. Moreover, there are two opposing processes putting water supply at risk: climate change and long-standing water infrastructure deterioration. Climate change is expected to produce changes in rainfall patterns, with increases and decreases in precipitation, as well as predicted changes in soil moisture locally. When rainfall patterns change, there can be water excess at certain periods, making water use for consumption or irrigation difficult due to infrastructure deficiencies, flooding, or contamination of aquifers. On the other hand, when rainfall decreases, severe droughts can occur. Even in regions where the total amount of rainfall does not decrease, droughts can occur as the amount of rainfall that reaches aquifers diminishes relative to that lost by evaporation. All these impacts are compounded by climate change, which is feeling less and less informational uncertainty.

Water systems are predicted to be more vulnerable in view of climate change. Moreover, water infrastructures are currently undergoing an unquestionable global process of deterioration. This process is partly due to their failure to accommodate changes in demand and rising costs associated with the maintenance of larger water systems. Overall, the global water infrastructure is perceived to be outdated, as it has been built and expanding since the mid-nineteenth century. Open access to water data provides quickly evolving technologies for capturing, storing, archiving, and understanding sensor data, and there is increasing interest in IoT, with widely distributed cheap devices being available. These three elements need not be further considered in detail. Smart water grids need to be considered instead. (Schilling & al.2020).

6. Case studies

This section discusses case studies of California drought and water management and the Australian experience in adapting to the impacts of climate change and variability in water supply and water quality. These examples demonstrate innovative solutions and successful results.

California Drought and Water Management

California is experiencing its worst drought in decades, prompting the governor to declare a state of emergency. In a state that is usually rich in water, ownership is a tricky political and legal issue. While the amount of precipitation is a key factor in sustainability, it is not the only factor. Overpopulation, depletion, and allocation of water exacerbate drought. Reservoirs are essential for capturing rain and snowmelt and holding it for later use. Currently, California's largest reservoirs are at historic lows. In January 2022, Lake Oroville was at about 24% of capacity, while San Luis Reservoir, California's second largest reservoir below risky levels, was only at 68%. The lack of precipitation threatens the stability, reliability, and sustainability of current reservoirs, making it imperative to adopt new policies, practices, and technologies.

One of these solutions is water reuse. Water is a precious resource in California, and demand has been continually exceeding supply. As population growth, economic development, and environmental protection increase pressure on limited water resources, reusing reclaimed water is a sustainable solution to meet the growing demand for water, providing multiple economic, environmental, and social benefits. However, despite efforts and investments made towards reclaiming and reusing water, water recycling in California has not met its standards. California's water recycling technology has hardly progressed. As of 2010, disinfection is the main technology employed for municipal wastewater treatment and recycling, having only increased by 53% since 1967, while secondary treatment increased 341%. On the other hand, dilution and filtration technologies, crucial steps in direct and indirect potable reuse projects, increased by only 29% and 14%, respectively since their first introduction in the 1990s.

Yet, innovative projects and technologies are driving the future of reclaimed water reuse in California. These efforts aim to increase recycled water capacity while addressing health concerns, public perception, and regulations. Successful results in the operation of two emerging treatment technologies allow for greater water quality control with reduced investment and energy costs. (Radcliffe & Page, 2020)

6.1. California drought and water management

California has long been susceptible to drought and flooding. Multiple scientific studies have shown how California's climate has fluctuated several times between wet and dry over the past 10,000 years, and multi-decadal periods of drought have been the norm rather than the exception. Over the past century, however, these natural climate fluctuations have clashed with competing demands for water by domestic, agricultural, and environmental users. Since the reservoir system was built, water management has been dominated by drought during wet years and wet during drought years. Thus, the balance was anticlimactic because there was only enough storage for people to survive on a year-to-year basis during the dry years; seasons of surplus, water flowed to the sea.

California's rainy season typically begins in October and usually ends by April. Snowpack tends to accumulate during this time, which helps store water for the dry summer months. The Sierra Nevada, a mountain range located just east of California's agricultural center, grows snowpack that supplies about one-third of California's total water supply and nearly 70% of the water supply for California's

agricultural croplands. Unfortunately, as temperatures continue to rise this century, California's snowpack is projected to decrease, while more precipitation will fall as rain instead of snow. Warmer temperatures will also increase snowmelt runoff so that the bulk of spring runoff will occur within weeks of the rainy season ending. The combination of these effects will reduce the Sierra Nevada's summertime dry-season water supply for California's agricultural and urban users. Further concern has been raised about how intensifying atmospheric rivers and their accompanying extreme floods will occur in a rapidly warming climate.

Adverse changes in local climate have also driven farmers to adopt sustainable water management practices. For example, the Karst and Laguerre basins in France experienced drought resulting in a water shortage, followed by a short period of flooding due to the rainy season. A similar climate effect has occurred in California, resulting in strict water management legislation being put in place. Some researchers used the Santa Clara Valley Water District, California, USA as a case study to quantitatively analyze and score the benefits of adopting low-impact development (ORM measures) under rapidly warming climate scenarios. Strategies designed to remove barriers and incentives for constructing green buildings, such as tax breaks, zoning bonuses, and public education campaigns, and technologies that include enhanced infiltration and storage designs that mimic natural systems were developed, implemented, and assessed. (Doran et al.2020)

7. Future outlook and recommendations

Addressing the challenges posed by the interlink of climate change and economic water challenges requires a multifaceted approach from local to national and international stakeholders. A few approaches and recommended actions are provided.

At the local level, efforts should focus on developing adaptation strategies that respond to both the economic water challenges and climate change impacts. These strategies should be based on good governance principles that are participatory, integrated, and proactive. Adaptive development strategies are needed that are robust in the face of uncertainty about future water supplies and demands. This means considering a range of options of alternative infrastructure development paths, land use changes, social equity, and economic development, and using decision-support tools such as multi-criteria analysis to evaluate different options. In addition, innovative and out-of-the-box solutions are needed to address interlink and feedbacks. For example, techniques such as natural infrastructure and ecosystem-based approaches to protect and restore wetlands and rivers should be employed. Attention should also be paid to critical uncertainties and risk management. For example, developing contingency plans in the case of drastic or structural changes. Moreover, the strategies should have clear, measurable, and prioritized targets in biophysical and socio-economic terms.

National governments should build a national knowledge base and support future planning at the local level. This can be done by developing national climate change and water scenarios and establishing a national water system observatory program. In addition, national guidelines and templates for local adaptation strategies, including planning frameworks and capacity building, should be developed. Furthermore, tools to facilitate the implementation of adaptation strategies at the local level should be provided, for instance, insurance and compensation funds.

At the level of international organizations such as the UN and World Bank, there is a call for financing adaptation strategies at the local and national level. There is a need to foster and support networks and partnerships between national governments, local authorities, researchers, NGOs, and the private sector to promote knowledge sharing and dissemination. In addition, local initiatives should be

supported through capacity building, training, and the development of biological models and scenarios. There is also a need to facilitate stakeholder dialogues and participate in local approaches to develop integrated water resource management programs and strategies to adapt to climate change and new economic water challenges.

7.1. Adaptation strategies

From the perspective of water-limited countries, large-scale adaptation strategies in 2050 include: (i) the recovery of groundwater resources in desert areas by artificial recharge of rainwater, (ii) the construction of a global water bank by supplying extra water from the wet areas through underground global pipes, (iii) the inter-basin transfer of surplus water by seawater desalination, and (iv) the direct control of the precipitation zones by the enhancement and maintenance of low-pressure systems. The expected economic benefits, i.e., the reduction of the economic surface value loss from 1,298 billion to 76 billion USD, are much larger than the projected costs of the large-scale adaptation strategies.

Adverse impacts of climate change on natural resources and agricultural productivity, potentially inducing food and economic insecurity, are serious concerns for all countries. The risks of sea-level rise, increasing extreme weather events, or intermittent droughts are particularly significant for water-limited countries. For such countries, climate change would change the water balance, leading to water deficiency in desert areas and water surplus in wet areas. Water surplus areas help their country partners by using the additional water to recover the desert areas. A simulation study for the year 2050, considering the negative impacts of climate change without any adaptation strategies, shows that a water-limited country with desert and wet areas in the same country is the most vulnerable under climate change.

Because of climate change, the net water deficiency in desert areas is projected to increase approximately four-fold, and net water surplus in wet areas would largely increase, leading to economic surface value loss equivalent to 2.5 times of the GDP. Four possible adaptation strategies to recover desert areas are quantitatively evaluated as follows: 1) recovery by artificial recharge of groundwater resources, rainfall supply from the global atmosphere model running without barrier; 2) building underground global pipes to send water from wet areas to recover desert areas; 3) recovery by seawater desalination and its inter-basin long-distance transportation; 4) the direct control of the precipitation zones by the enhancement and maintenance of the low-pressure systems in the area.

Conclusion:

the intricate relationship between climate change and the economic availability of freshwater resources presents a multifaceted global challenge with profound implications for societal well-being and environmental sustainability. As evidenced, the economic basis of water has been largely overlooked in practice, despite freshwater being the economic bedrock of our existence and its total abstraction and treatment costs exceeding a quarter of global GDP. Climate change exacerbates this precarious situation by altering precipitation patterns, increasing the frequency and intensity of extreme weather events, and causing rising sea levels and saltwater intrusion, all of which directly impact both the quantity and quality of available freshwater.

The economic ramifications of water scarcity are particularly severe for the agricultural sector, especially in developing countries, leading to significant GDP losses, increased food prices, and potential threats to political stability. While the industrial sector's water footprint is also substantial, analyses of its economic implications are still in early stages. Addressing these challenges necessitates

a paradigm shift in how water is valued and managed, moving towards accurate pricing structures and fostering greener economic growth that decouples water use from economic output.

Crucially, effective policy responses and robust international cooperation are indispensable. The Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action), alongside the Paris Agreement, provide frameworks for global action. However, their full potential can only be realized through concerted efforts that recognize water as a global common good and facilitate support for economically fragile, water-stressed nations. The transition to sustainable water management and resilient infrastructure, coupled with technological advancements like bio-reclamation, offers optimistic pathways. Ultimately, overcoming the looming economic water crisis demands an integrated, holistic, and globally cooperative approach to ensure equitable access to this vital resource for present and future generations.

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