Climate impacts on water reservoirs and coastal processes: Integrating big data, physically based modeling and remote sensing

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ABSTRACT

Hydrological systems are highly dynamic, shaped by the complex interplay of atmospheric and climatic conditions and they, in turn, profoundly influence the environment. This dissertation investigates the bidirectional interaction between climate and water systems, employing an interdisciplinary approach that integrates big data analytics, physically-based modeling and remote sensing. By analyzing diverse hydrological systems across different scales and geographical contexts, this work contributes to understanding how atmospheric variability drives changes in hydrological systems and their subsequent environmental impacts.

The first study examines the inland migration of coastal wetlands under projected sea level rise (SLR). It highlights the challenges posed by human-made barriers that inhibit natural wetland adaptation, leading to noteworthy ecosystem loss, particularly in regions like the Wadden Sea. This work underscores the necessity of considering both natural and anthropogenic constraints in climate adaptation strategies.

The second study explores land loss implications of SLR along Colombia's coasts, under various climate change scenarios. It identifies socio-economic and environmental vulnerabilities in regions at risk, emphasizing the compounded challenges faced by coastal communities due to rising seas and extreme weather events. The findings call for targeted policies that address local and regional dynamics in mitigating the effects of climate change.

The third study focuses on evaporation dynamics in the largest reservoirs located in water-stressed regions. By employing a physically-based modeling framework combined with remote sensing data, the study quantifies evaporative losses and their implications for water management. It provides actionable insights into optimizing reservoir operations to reduce water loss and sustain ecological and hydrological balance in a warming climate.

The fourth study narrows in on the Helmand River Basin shared by Afghanistan and Iran, where reservoir evaporation interacts with regional scarcity and transboundary tensions. By combining satellite observations with hydrological modeling, the research demonstrates how evaporative losses influence basin-scale water balances, contribute to atmospheric moisture recycling, and intensify political challenges between riparian states.

Together, these studies reveal the intricate interdependencies between climate systems and water bodies, offering a comprehensive framework to predict, analyze and mitigate the impacts of climatic variability. This work not only advances scientific understanding but also informs policy, management and governance strategies essential for addressing global water and environmental challenges.

ZUSAMMENFASSUNG

Hydrologische Systeme sind äußerst dynamisch und werden durch das komplexe Zusammenspiel von atmosphärischen und klimatischen Bedingungen geformt, wobei sie ihrerseits die Umwelt maßgeblich beeinflussen. Diese Dissertation untersucht die wechselseitigen Interaktionen zwischen Klima- und Wassersystemen und verfolgt dabei einen interdisziplinären Ansatz, der Big-Data-Analysen, physikalisch basierte Modellierung und Fernerkundung integriert. Durch die Analyse vielfältiger hydrologischer Systeme über unterschiedliche Skalen und geografische Kontexte hinweg trägt diese Arbeit dazu bei, besser zu verstehen, wie atmosphärische Variabilität Veränderungen in hydrologischen Systemen antreibt und welche Auswirkungen diese auf die Umwelt haben.

Die erste Studie untersucht die Landmigration von Küstenfeuchtgebieten infolge des prognostizierten Meeresspiegelanstiegs (SLR). Sie beleuchtet die Herausforderungen, die durch menschengemachte Barrieren entstehen, welche die natürliche Anpassung von Feuchtgebieten verhindern und zu erheblichen Verlusten von Ökosystemen führen, insbesondere in Regionen wie dem Wattenmeer. Diese Arbeit unterstreicht die Notwendigkeit, sowohl natürliche als auch anthropogene Einschränkungen in Klimaanpassungsstrategien einzubeziehen.

Die zweite Studie erforscht die Auswirkungen des Meeresspiegelanstiegs auf Landverluste entlang der kolumbianischen Küsten unter verschiedenen Klimawandelszenarien. Sie identifiziert sozioökonomische und ökologische Verwundbarkeiten in gefährdeten Regionen und hebt die vielfachen Herausforderungen hervor, denen Küstengemeinden durch steigende Meeresspiegel und extreme Wetterereignisse ausgesetzt sind. Die Ergebnisse plädieren für gezielte politische Maßnahmen, die lokale und regionale Dynamiken berücksichtigen, um die Auswirkungen des Klimawandels zu mindern.

Die dritte Studie konzentriert sich auf die Dynamik der Verdunstung in den größten Stauseen, die sich in wasserarmen Regionen befinden. Mithilfe eines physikalisch basierten Modellierungsrahmens in Kombination mit Fernerkundungsdaten quantifiziert sie Verdunstungsverluste und deren Auswirkungen auf das Wassermanagement. Die Studie liefert praxisorientierte Erkenntnisse zur Optimierung des Stauseemanagements, um

Wasserverluste zu minimieren und das ökologische und hydrologische Gleichgewicht in einem sich erwärmenden Klima zu erhalten.

Die vierte Studie richtet den Blick auf das Helmand-Flusseinzugsgebiet, das zwischen Afghanistan und Iran geteilt wird. Hier wird gezeigt, wie Stauseeverdunstung nicht nur die lokalen Wasserbilanzen beeinflusst, sondern auch transnationale Spannungen verschärfen kann. Durch die Kombination von Satellitenbeobachtungen mit hydrologischer Modellierung verdeutlicht die Untersuchung, dass Verdunstungsverluste sowohl wasserwirtschaftliche als auch geopolitische Implikationen haben und zudem durch atmosphärische Rückkopplungen über die Beckenränder hinauswirken.

Zusammen offenbaren diese Studien die komplexen Wechselwirkungen zwischen Klima- und Wassersystemen und bieten einen umfassenden Rahmen, um die Auswirkungen klimatischer Variabilität vorherzusagen, zu analysieren und zu bewältigen. Diese Arbeit leistet nicht nur einen wissenschaftlichen Beitrag, sondern liefert auch entscheidende Impulse für Politik-, Management und Governance-strategien zur Bewältigung globaler und grenzüberschreitender Wasser- und Umweltprobleme.

CONTENT

ABBREVIATIONS

ENSO	El Niño-Southern Oscillation
GMSL	Global Mean Sea Level
GRACE	Gravity Recovery and Climate Experiment
LISFLOOD	GIS-based distributed rainfall-runoff and flood simulation model
MODIS	Moderate-resolution Imaging Spectroradiometer
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathway
SWAT	Soil and Water Assessment Tool
VIC	Variable Infiltration Capacity model

1. Introduction

1.1. Research Gaps

Hydrological systems, being central to global water cycles, are increasingly under strain from anthropogenic influences and a changing climate, which have cascading effects on ecosystems, societies and economies (Haddeland et al., 2014; Intergovernmental Panel On Climate Change (Ipcc), 2023). These pressures manifest through altered precipitation patterns, intensified droughts and increased frequency of extreme weather events, significantly impacting water availability and quality (Intergovernmental Panel On Climate Change (Ipcc), 2023; Vörösmarty et al., 2010). Changes in precipitation regimes and the hydrological cycle disrupt ecosystems, agricultural productivity and water resource management, creating complex challenges for both developed and developing regions (Poff et al., 2007; Rockström et al., 2009). While progress has been made in understanding the implications of these changes, critical gaps remain in hydrological research, hindering effective adaptation and mitigation strategies (Granata and Di Nunno, 2025; Wang and Li, 2025).

Hydrological systems operate across spatial and temporal scales, yet existing research often focuses on either localized impacts or global trends, neglecting the interconnected dynamics between these scales. Recent studies highlight the lack of comprehensive approaches that integrate local hydrological data with global climatic drivers to fully understand cascading impacts. Granata and Di Nunno, 2025, for instance, investigate hydrological resilience strategies under extreme events, emphasizing the need for multi-scale models that link global climate projections with localized flood and drought data. Mehmood and Rathnayake, 2025 extend this discussion by examining agricultural vulnerabilities in the Lower Mekong Basin, identifying the disconnect between regional hydrology and global climatic phenomena, such as El Niño-Southern Oscillation (ENSO), which complicates effective adaptation. While these studies underline the importance of scale integration, actionable frameworks to operationalize such models across diverse regions remain lacking. Developing these frameworks is critical to ensuring locally adaptive yet globally informed solutions to hydrological challenges. These findings underscore the underutilization of interdisciplinary methodologies that combine hydrological modeling with socio-economic and ecological assessments, leaving a gap in actionable, multi-scale insights.

Coastal wetlands provide vital ecosystem services, such as biodiversity support, carbon sequestration, and coastal protection. However, wetlands face dual pressures from sea level rise (SLR) and human-made barriers that limit their adaptive migration potential. Recent work suggests that existing models inadequately account for the interaction between natural processes and anthropogenic interventions. Srivastava et al., 2025 review hydrological modeling techniques and highlight the limitations of current frameworks in predicting wetland responses under SLR, particularly in urbanized regions where physical barriers prevent inland migration. The IPCC (Intergovernmental Panel on Climate Change (IPCC), 2023) emphasizes the need for region-specific studies that integrate topographical, ecological and socio-economic variables, enabling tailored conservation strategies. These insights reveal an urgent need for hybrid approaches that incorporate both natural restoration efforts and engineered solutions, such as managed retreat or floodgate systems, to sustain wetland ecosystems under future climate scenarios.

SLR significantly impacts coastal communities, particularly in low- and middle-income countries where socio-economic vulnerabilities exacerbate environmental risks. Studies such as Siddik, 2025 highlight the limited availability of region-specific socio-economic data needed to design adaptive policy frameworks. For example, the study examines how SLR affects agricultural and fishing communities in South Asia, revealing gaps in the integration of local economic data into broader climate models. Alasan et al., 2024 expand on this by emphasizing the challenges faced by resource-constrained regions in the Global South, where adaptation strategies must account for cultural and economic factors unique to the area. More broadly, research into socio-economic dimensions of SLR has yet to comprehensively address compounding stressors, such as urbanization, poverty and extreme weather events. Addressing these intersections is crucial for developing inclusive adaptation frameworks. These gaps hinder the development of inclusive strategies to protect the most vulnerable populations.

Reservoirs are critical infrastructures for water storage, power generation and flood control, particularly in arid and semi-arid regions. However, evaporative losses, driven by climatic and operational factors, are often oversimplified in existing hydrological models. Granata and Di Nunno, 2025 propose integrating physically-based models with high-resolution remote sensing data to improve the accuracy of evaporation loss estimates. Likewise, recent advances demonstrate how remote sensing can support such efforts: long-term monitoring of reservoir surface dynamics has been achieved with Landsat imagery (Liu et al., 2021), and novel machine learning methods have been introduced for consistent global reservoir detection and monitoring (Soesbergen et al., 2022). Beyond technical aspects, recent case studies reveal that evaporation also carries transboundary and political dimensions, as losses from shared reservoirs can fuel tensions between riparian states (Hossen et al., 2023). At the same time, research shows that reservoir evaporation contributes to atmospheric moisture recycling, redistributing water beyond basin boundaries and linking local management decisions to regional hydroclimatic patterns (Keys et al., 2012). While these developments are promising from a technological standpoint, practical barriers to implementing such techniques, including cost and technical expertise in water-stressed regions, require further exploration. Addressing these challenges is key to translating theoretical advances into real-world applications. These studies highlight the potential for improved methodologies to enhance water resource management in regions facing acute water scarcity.

Despite significant progress in hydrological science, translating research findings into actionable policy frameworks remains limited. Ng et al., 2024 identify a lack of collaboration between researchers and policymakers, which results in strategies that fail to balance socio-economic realities with hydrological data. Their study, focusing on eco-geotechnics under climate change, recommends stakeholder-inclusive approaches to co-create policies that reflect both environmental and societal needs. Such co-creation processes could further benefit from the integration of scenario planning tools, which enable policymakers to evaluate trade-offs between different hydrological and socio-economic outcomes. Bridging this gap will require interdisciplinary collaboration and the development of tools that connect scientific findings with decision-making processes.

Hydrological systems are increasingly subject to compound climate extremes, such as concurrent droughts and heatwaves or sequential floods. These phenomena exacerbate vulnerabilities, but current research does not sufficiently explore their mechanisms or multi-scale impacts. Srivastava et al., 2025 emphasize the need for innovative modeling approaches capable of simulating interactions between different extreme events. For example, their work demonstrates how hydrological cycles can amplify the impacts of sequential climate extremes, creating feedback loops that intensify vulnerabilities across scales. Expanding these models to capture interactions between compound extremes and socio-economic systems, such as impacts on food production and urban resilience, would significantly enhance their utility for adaptation planning. These findings stress the importance of integrating multi-event scenarios into future hydrological models.

This dissertation addresses these research gaps by employing an integrative and interdisciplinary framework that combines big data analytics, physically-based modeling and remote sensing across diverse hydrological systems and geographical contexts. By exploring the dynamics of water systems under various climatic and anthropogenic pressures, this work seeks to provide actionable insights that support sustainable water management and climate adaptation strategies.

1.2. Objectives

The primary scientific goal of this dissertation is to investigate the complex interactions between climate systems and hydrological processes in order to address the critical challenges of a changing climate and its multiple impacts on water systems and ecosystems. This research aims to contribute to a deeper understanding of these phenomena through an interdisciplinary framework that integrates big data analytics, physics-based modeling and remote sensing. The specific objectives of the research are described below:

1. Investigating the interactions between climate variability and hydrological systems:

Climate variability plays a key role in shaping hydrological systems, which, in turn, influence environmental and socio-economic conditions. This dissertation aims to explore the bidirectional interplay between atmospheric dynamics and hydrological processes to uncover the mechanisms driving these changes. By analyzing diverse hydrological systems across different geographical and temporal scales, the research seeks to provide a general understanding of how climatic fluctuations influence water systems and their subsequent effects on the environment.

2. Assessing the adaptation and vulnerability of coastal wetlands to sea level rise (SLR):

Coastal wetlands are among the most vulnerable ecosystems to climate-induced sea level rise, providing critical ecological functions such as carbon sequestration, biodiversity preservation and coastal protection. This research focuses on the inland migration potential of coastal wetlands and the constraints posed by both natural and human-made barriers, such as urban infrastructure and protective dikes. Special attention is given to regions like the Wadden Sea, one of the world's largest coastal wetland systems, where human-made barriers restrict the natural adaptation of wetlands. The objective is to delineate the implications of these constraints and propose adaptive strategies to mitigate ecosystem loss.

3. Quantifying the socio-economic and environmental impacts of land loss due to SLR:

Sea level rise poses significant challenges for coastal communities, threatening infrastructure, livelihoods and ecosystems. This research investigates the scale of potential land loss along Colombia's Caribbean and Pacific coasts under different climate change scenarios. By assessing the socio-economic and environmental vulnerabilities in these regions, this study aims to identify the compounded risks faced by coastal populations. The findings will contribute to targeted policy recommendations that address both local and regional dynamics, supporting resilience-building in the face of rising seas and extreme weather events.

4. Analyzing evaporative losses in large reservoirs in water-stressed regions:

Large-scale reservoirs are critical infrastructures for multiple purposes, including water storage and supply, hydropower generation, flood control, irrigation and even supporting aquatic ecosystems. In arid and water-stressed regions, they serve as essential buffers against water scarcity, ensuring the availability of freshwater for drinking, agriculture and industrial use, while also playing a key role in energy production and transport systems. However, evaporative losses from reservoirs are often overlooked, leading to inefficiencies in water management and reduced operational effectiveness. This research employs a physically-based modeling framework, complemented by remote sensing data, to quantify evaporation rates and identify their driving factors in some of the world's largest reservoirs. By enhancing understanding of evaporative losses and their implications, this study aims to support the development of informed strategies and frameworks that can aid in optimizing reservoir performance and promoting sustainable water management under a changing climate.

5. Examining transboundary and atmospheric implications of reservoir evaporation:

Reservoir evaporation has greater implications than issues at the basin level. Afghanistan and Iran are two examples of how losses can worsen political tensions between upstream and downstream riparian governments in shared river basins. Evaporation also plays a role in the recycling of atmospheric moisture, therefore decisions made at the local level may have an impact on rainfall patterns outside of basin borders. In order to emphasize the necessity of combining local infrastructure management with regional governance and atmospheric feedbacks, this dissertation also takes into account evaporation as a transboundary and climatic element in addition to being a hydrological process.

6. Integrating multi-scale and interdisciplinary approaches:

Given the complexity of interactions between climate systems and hydrological processes, this research employs an integrative approach that synthesizes big data analytics, remote sensing techniques and physically-based modeling. By applying these methodologies across varied spatial and temporal scales, the research seeks to generate insights that are applicable to a wide range of hydrological contexts, from local ecosystems to global water systems.

7. Informing climate adaptation and water management strategies:

A central objective of this dissertation is to translate scientific findings into practical solutions for climate adaptation and water management. This research aims to develop evidence-based strategies that address the dual challenges of preserving ecological integrity and meeting human water demands. The findings will support the development of policies that enhance resilience to climate change, mitigate environmental degradation and promote sustainable use of water resources.

Together, these objectives form a comprehensive framework to advance our understanding of the complex interdependencies between climate and water systems. They provide a foundation for predicting, analyzing and mitigating the impacts of climate variability on hydrological processes, while offering actionable solutions for policy and management strategies that are essential to addressing global environmental challenges.

1.3. Structure of the thesis

This dissertation has been prepared in cumulative form and is based on four peer-reviewed scientific articles, which are included in the appendix. The main text provides the overarching framework, synthesizes the findings, and places the individual contributions into a broader scientific and societal context. The cumulative dissertation explores the multifaceted interactions between hydrological systems and climate change, with particular attention to sea-level rise, wetland adaptation, and evaporative losses in reservoirs. Each of the four articles addresses a specific research gap, but together they provide an integrated understanding of water-related vulnerabilities and adaptation strategies across different geographical and ecological contexts.

The structure of the thesis is as follows:

Chapter 1 introduces the scope of the dissertation, outlines the central research gaps, and defines the objectives. It frames the overall problem of how climatic and meteorological variability shapes water systems and motivates the need for interdisciplinary approaches.

Chapter 2 reviews the theoretical background and state of the art. It situates the work within existing research on climate–hydrology interactions, wetland responses to sea-level rise, coastal vulnerability, and reservoir dynamics, while also highlighting methodological innovations in modeling and remote sensing.

Chapter 3 presents the main achievements of the dissertation. It summarizes the contributions of each article, explaining how they address their respective research questions and how they connect to the overarching aims of the work.

Chapter 4 synthesizes the findings from the four studies. It identifies cross-cutting themes, methodological advances, and implications for hydrological modeling and climate adaptation, linking the case studies across scales and contexts.

Chapter 5 concludes the dissertation. It reflects on the contributions, discusses limitations, and outlines future research directions needed to strengthen both scientific understanding and applied water management.

Appendices contain the full versions of the four peer-reviewed scientific articles on which this dissertation is based. Their inclusion ensures transparency and allows readers to consult the original studies while also understanding how they are integrated into the broader framework of the thesis.

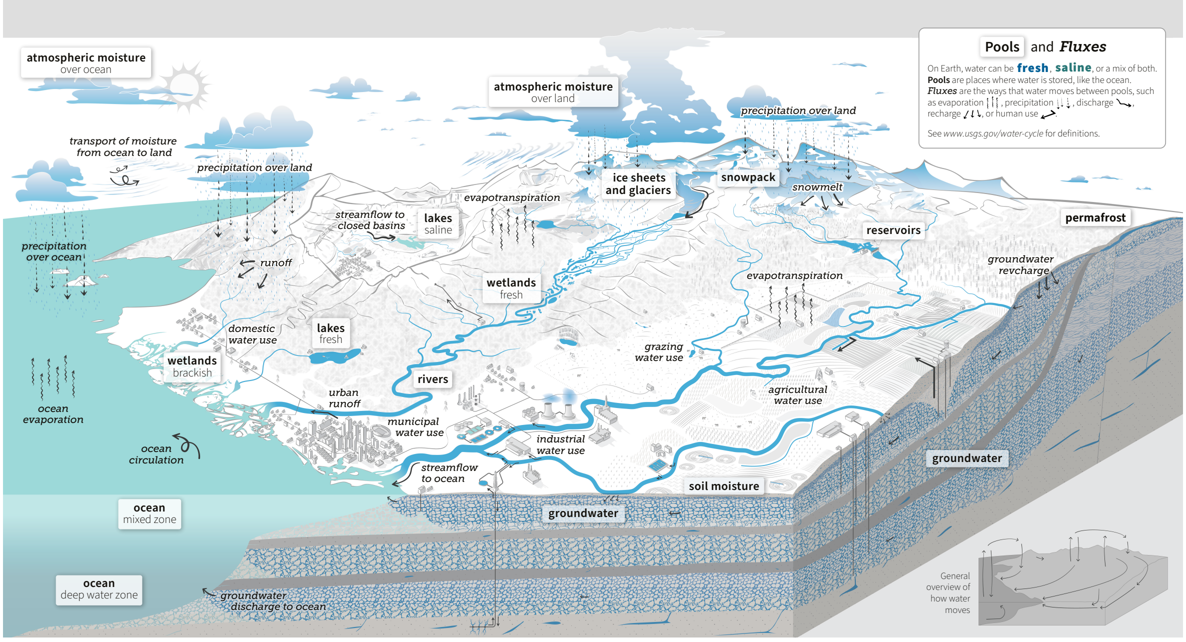
Together, these components form a coherent and interdisciplinary investigation into the challenges and opportunities of managing hydrological systems under climate change. The cumulative format makes it possible to address different scales and processes, wetland migration, coastal vulnerability, and reservoir evaporation in both global and transboundary contexts, while also drawing them together into a unified perspective on climate–water interactions.

2. Theoretical Background and State of the Art

2.1. Hydrological Systems in a Changing Climate

Hydrological systems are among the most sensitive components of the Earth’s climate system, responding dynamically to changes in temperature, precipitation, land use and atmospheric circulation patterns. This sensitivity arises from the physical nature of hydrological processes, which involve constant energy exchange through phase changes, such as evaporation and condensation and their dependence on temperature and land-surface conditions. Even minor shifts in climate or land use can lead to large nonlinear responses in runoff, infiltration and evapotranspiration (Figure 1). As the climate continues to warm, the global hydrological cycle is undergoing intensification, characterized by more extreme and spatially variable patterns of rainfall, evaporation, snowmelt and runoff (Huntington, 2006; Trenberth et al., 2005). These changes are not only altering water availability and distribution but are also reshaping the functioning of ecosystems, challenging traditional water management approaches and exacerbating socio-economic vulnerabilities. In addition to climatic drivers, human interventions such as groundwater pumping, river diversion and urban expansion further destabilize natural hydrological regimes. These disruptions also pose growing challenges for sustainable development, water governance and transboundary water cooperation.

At the global scale, the Clausius-Clapeyron relationship suggests that the atmosphere can retain approximately 7% more water vapor per 1°C increase in temperature (Allen and Ingram, 2002), a relationship reaffirmed in more recent assessments (Intergovernmental Panel on Climate Change (IPCC), 2023). This enhanced moisture-holding capacity increases the potential energy available to weather systems, fueling convective storms and amplifying latent heat release, which intensifies hydrological extremes. This has direct implications for the intensity and frequency of extreme hydrological events such as droughts and floods. Intensified precipitation events, combined with increased evapotranspiration, contribute to an amplified hydrological variability, leading to more severe wet and dry periods (Intergovernmental Panel on Climate Change (IPCC), 2023). Observational records and satellite datasets confirm that atmospheric water vapor and high-intensity rainfall events have been increasing globally since the late 20th century (Allan et al., 2020; Trenberth et al., 2005), lending empirical support to modeled predictions.



On Earth, water can be **fresh**, **saline**, or a mix of both. **Pools** are places where water is stored, like the ocean. ***Fluxes*** are the ways that water moves between pools, such as evaporation ⇡⇡⇡, precipitation ⇣⇣⇣, discharge ↝, recharge ↙↓↘, or human use ↔.

See *www.usgs.gov/water-cycle* for definitions.

Figure 1: The hydrological cycle, showing storage of water in the atmosphere, on the land surface, and underground, as well as transfers between these stores. Water occurs as liquid, solid, or gas, and is influenced by both natural processes and human actions, including water use, storage, and quality. Adapted from Corson-Dosch et al. (2022), U.S. Geological Survey Water Science School, Water cycle diagrams (Public Domain).

Regional hydrological responses vary depending on climatic, geographic and anthropogenic factors. In the tropics, increased convective rainfall events and warmer sea surface temperatures are contributing to more intense and erratic precipitation, elevating flood risks, particularly in regions such as the Amazon Basin and Southeast Asia. In contrast, subtropical and mid-latitude regions, including the Mediterranean, southern Africa and the southwestern United States, face heightened drought frequency, largely driven by poleward shifts in the jet stream and weakening soil moisture feedbacks (Greve et al., 2014). These processes are further compounded by land cover changes. Urban expansion introduces impervious surfaces that disrupt natural infiltration and increase surface runoff, while heat island effects exacerbate localized warming and storm intensification. Deforestation, especially in tropical zones, impairs evapotranspiration and weakens regional rainfall recycling, leading to longer-term declines in rainfall and streamflow (Vörösmarty et al., 2010). As a result, the interplay between climatic shifts and land-use change is reshaping regional hydrological regimes in highly context-specific ways.

Cryospheric contributions to hydrological systems particularly from glacier melt, snowpack reduction and shifting snow-to-rain ratios are introducing increasing uncertainty in seasonal water availability, especially in high-altitude regions (Immerzeel et al., 2010). As global temperatures rise, glaciers in mountain systems such as the Himalayas, Andes and Alps are retreating rapidly, affecting the timing and volume of river discharge. The accelerated retreat of glaciers often triggers an initial increase in meltwater, known as the "peak water" phase, after which runoff declines as ice reserves are depleted. This dynamic threatens long-term water security in glacier-fed basins, particularly where dry-season flows are crucial for agriculture, hydropower and drinking water. In the Indus Basin, for instance, over 40% of annual river flow originates from snow and glacial melt, making it highly sensitive to changes in cryospheric inputs (Immerzeel et al., 2010). In the Cordillera Blanca of Peru, the rapid loss of ice cover is already diminishing downstream water supply during critical agricultural periods, especially in the Santa River watershed (Baraer et al., 2012). These trends challenge current water resource management frameworks, which often assume stable snowmelt patterns and reservoir inflows.

The increasing occurrence of compound climate extremes represents a critical challenge for hydrological systems and their management. Compound events can be classified into different types, including concurrent extremes, such as droughts and heatwaves occurring simultaneously, sequential events, like multiple flood pulses and multivariate hazards where interacting drivers exacerbate system vulnerability, such as coastal storm surges amplified by sea-level rise (Zscheischler et al., 2020). These events are not only becoming more frequent but also more complex, with interactions that amplify their impacts across ecological, agricultural and urban systems. Recent examples include the 2010 Pakistan floods, driven by a convergence of intense monsoon rainfall and glacier melt in the upper Indus Basin (Immerzeel et al., 2013) and the 2021 North American heatwave, which intensified regional drought and wildfire risks across the western U.S. and Canada (Philip et al., 2022). Despite growing evidence of such risks, most climate and hydrological models still assess hazards in isolation, lacking the capacity to simulate interrelated extremes. Bridging this methodological gap requires multi-hazard modeling frameworks that integrate climate, land and socio-economic feedbacks to improve forecasting and risk reduction strategies.

Recent research has emphasized the dynamic and bidirectional feedbacks between hydrological systems and human activities. Land-use changes and agricultural intensification, particularly irrigation, can substantially modify regional climate patterns through altered albedo, soil moisture and evapotranspiration dynamics (Seneviratne et al., 2010). For instance, extensive irrigation in the Indo-Gangetic Plain has been shown to reduce surface temperatures and modify monsoon circulation by altering atmospheric humidity and land–atmosphere energy fluxes (Douglas et al., 2009; Syed et al., 2008). Similarly, irrigation in California's Central Valley exerts a strong local cooling effect, reducing daytime temperatures by up to 5°C and enhances regional moisture recycling, influencing precipitation patterns across the southwestern United States (Kueppers et al., 2007; Lo and Famiglietti, 2013). In parallel, large-scale water infrastructure, such as dams, reservoirs and diversions, can significantly reshape river flow regimes. In transboundary river basins like the Nile and Mekong, upstream dam regulation has disrupted seasonal discharge cycles, exacerbating downstream water insecurity and challenging agricultural adaptation. Beyond flow regulation, reservoirs also modify basin-scale water balances through substantial evaporation losses, which can create hidden pressures in already water-scarce basins and fuel transboundary tensions, as highlighted in recent studies from Central and South Asia. These feedbacks may, paradoxically, amplify vulnerability in the face of climate change, especially where infrastructure design assumes historical hydrological stability (Wada et al., 2017). This growing body of evidence is central to the field of socio-hydrology, which examines the co-evolution of human and water systems and calls for coupled models that account for adaptive behavior, governance responses and long-term trade-offs.

To address the increasing complexity of hydrological risks under climate change, the field must adopt integrative, multi-scale approaches that bridge the gap between global climate dynamics and local water system responses. This requires combining high-resolution remote sensing platforms such as MODIS, GRACE and Sentinel missions with process-based hydrological models like SWAT, VIC and LISFLOOD to capture spatial and temporal variability across river basins, deltas and urban catchments (Haddeland et al., 2011; Jiang and Wang, 2019). For reservoirs, the integration of energy-balance modeling with satellite-derived surface dynamics has emerged as a key advance in capturing evaporation losses more accurately, linking atmospheric variability with local water management. However, a persistent challenge lies in the mismatch of scales. Climate models often operate at coarse resolutions of 50 to 100 kilometers, while hydrological decision-making and ecosystem responses occur at much finer spatial scales, for example at the catchment or sub-basin level. Bridging this gap necessitates downscaling techniques, ensemble scenario modeling and the coupling of physical models with socio-economic and land-use datasets (Blöschl et al., 2019).

Furthermore, the increasing role of human systems in shaping water outcomes demands the integration of interdisciplinary methods that draw from socio-hydrology, resilience theory, Earth system modeling and sustainability science. These frameworks allow for the inclusion of governance structures, infrastructure development, livelihoods and behavioral adaptation within hydrological assessments (Sivapalan et al., 2012). Ultimately, advancing hydrological science in the 21st century means moving beyond isolated process models toward holistic, data-rich and stakeholder-engaged platforms that support anticipatory water management. This dissertation embraces such an approach by applying physically based models, big data analytics and socio-environmental analysis across diverse hydroclimatic contexts to generate actionable insights for climate adaptation and water governance.

2.2. Coastal Wetlands under Pressure

Coastal wetlands, including salt marshes, mangroves and tidal flats, are among the most productive and ecologically valuable ecosystems on Earth. They play a central role in regulating water quality, storing carbon, supporting biodiversity and protecting coastlines from erosion and extreme weather events (Millennium Ecosystem Assessment (Program), 2005; Mitsch and Gosselink, 2015). Through their complex interactions of vegetation, hydrology and sedimentation, wetlands maintain ecological stability in dynamic coastal environments and contribute significantly to human well-being. The economic value of the services they provide, including flood protection and nutrient cycling, is substantial, with early estimates placing their worth among the highest of all global ecosystem types (Costanza et al., 1997). Despite their importance, these ecosystems are under mounting pressure from both natural drivers, such as sea-level rise and anthropogenic factors, including urban development, pollution and hydrological modification.

One of the primary adaptation mechanisms of coastal wetlands is inland migration in response to rising sea levels. This landward movement depends on several factors, including topographic gradients, sediment supply and vegetation resilience. In many regions, anthropogenic barriers such as dikes, seawalls and urban infrastructure create a “coastal squeeze” effect, restricting wetlands between the rising sea and fixed landward boundaries as illustrated in Figure 2 (Doody, 2013). This results in habitat loss, ecosystem fragmentation and a decline in ecosystem services over time. The Wadden Sea, one of the world’s largest tidal wetland systems, exemplifies this tension between natural processes and human-imposed limits. Although the region is recognized for its ecological significance and is part of UNESCO’s World Heritage network, its adaptive capacity is constrained by embankments and land reclamation, which limit sediment deposition and vegetative expansion inland.

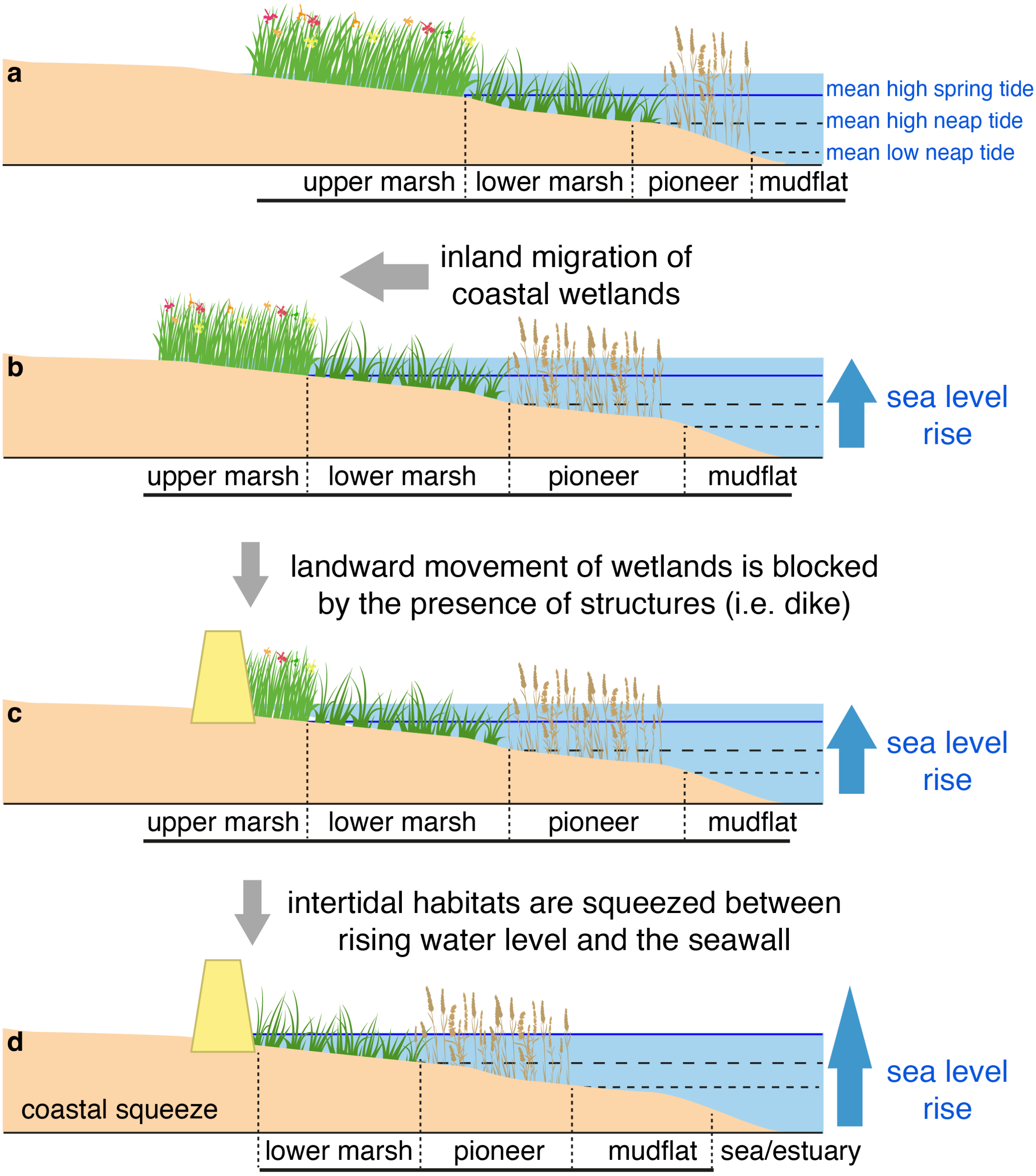


Figure 2: Illustration of coastal wetland responses to sea-level rise: (a) natural inland migration of coastal wetlands, (b) habitat adjustment with rising sea levels in a natural setting, (c) the onset of coastal squeeze due to a dike, and (d) the progression of coastal squeeze leading to wetland loss. Adapted from Esteves (2016), in Kennish, M.J. (Ed.), Encyclopedia of Estuaries. Springer, Dordrecht, p. 123.

Traditional elevation-based models, such as the Sea Level Affecting Marshes Model (SLAMM), simulate habitat transitions under sea-level rise using topographic thresholds and probabilistic rules. While they are useful for identifying zones of wetland loss and migration potential, these models often simplify or omit key processes like sediment dynamics, infrastructure constraints and land-use change (Clough et al., 2016). More advanced process-based models aim to incorporate feedbacks between topography, vegetation and hydrodynamics. However, as demonstrated in global-scale assessments (Schuerch et al., 2018), even these models face limitations in spatial resolution, calibration data and the integration of socio-ecological complexity. Particularly in densely populated or fragmented landscapes, translating model outputs into policy-relevant strategies remains a major challenge.

From a governance perspective, adaptation options for wetland conservation increasingly emphasize hybrid solutions that combine natural processes with engineered interventions. Approaches such as managed retreat, landward buffer zoning and the use of permeable structures aim to reconcile ecological restoration with human safety and land use priorities. Yet these strategies often encounter institutional, legal, or financial obstacles, especially in densely populated deltaic regions. The IPCC (2023) underscores the urgent need for context-specific, integrative planning frameworks that account for both ecological dynamics and human constraints.

Moreover, the loss or degradation of wetlands has cascading implications for climate mitigation efforts. Coastal wetlands are significant carbon sinks. Their destruction not only releases stored carbon but also diminishes future sequestration potential (Mcleod et al., 2011). Ensuring their persistence is therefore not only a matter of local adaptation but also a component of global climate strategies.

The persistence of coastal wetlands under future climate scenarios relies on both biophysical adaptability and informed human decision-making. Although significant progress has been made in understanding processes such as sediment–vegetation feedbacks and migration thresholds, substantial gaps remain in translating these insights into actionable strategies within real-world planning contexts. As discussed in the first article of this dissertation, current modeling approaches primarily focus on physical parameters and spatial constraints, while recognizing the critical need for future integration of socio-economic variables and governance considerations. Advancing wetland conservation will require interdisciplinary frameworks that bridge ecological modeling with policy-relevant decision support, enabling more context-specific and adaptive responses to climate-driven coastal change.

2.3. Coastal Vulnerability and Sea-Level Rise

SLR is increasingly recognized as one of the most pervasive threats to coastal systems and societies. The global mean sea level has already risen by more than 20 centimeters since 1900, primarily due to thermal expansion of seawater and the accelerated melting of glaciers and polar ice sheets. Additional contributions come from changes in land water storage, including groundwater depletion and reservoir impoundment, while local and regional variations are further shaped by land subsidence, tectonic uplift and ocean dynamics (Intergovernmental Panel on Climate Change (IPCC), 2023). In the 21st century, this trend is expected to intensify. Projections under high-emissions scenarios, such as SSP3-7.0 and SSP5-8.5 (Shared Socioeconomic Pathway), indicate possible increases of more than one meter by 2100, with profound implications for low-lying deltas, coastal cities and small island states (Figure 3) (Hinkel et al., 2014; Nicholls and Cazenave, 2010). These changes will not only drive permanent inundation but will also amplify storm surges, disrupt drainage systems and contribute to the salinization of coastal aquifers.

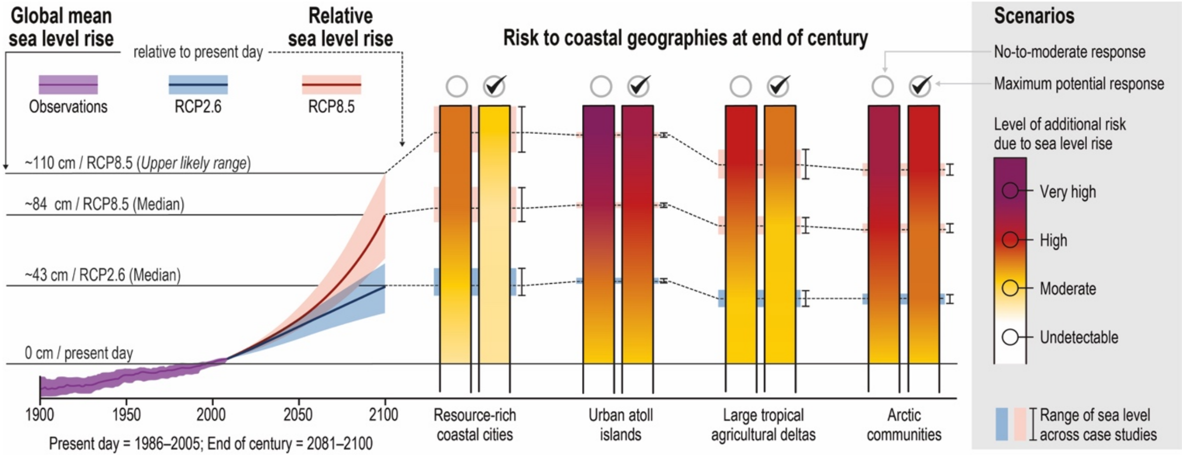


Figure 3: Projected risks from sea-level rise (SLR) for low-lying coastal areas by 2100. The left panel shows observed global mean sea-level (GMSL) rise from 1986–2005 and projections under RCP2.6 (low emissions) and RCP8.5 (high emissions) scenarios. The middle panel shows additional SLR-related risks to key coastal regions. Source: IPCC (2019), Figure 4.3, in Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA. Licensed under CC BY 4.0.

In the Global South, and particularly in Latin America, these risks intersect with rapid urban growth, informal development patterns and governance limitations. Many coastal regions face multiple, compounding pressures, including land subsidence due to groundwater extraction, erosion driven by altered sediment flows and socio-economic vulnerability arising from poverty, limited infrastructure and dependence on coastal ecosystems for livelihoods (Neumann et al., 2015). As (Reguero et al., 2018) argue, the effectiveness of adaptation planning depends not only on accurate hazard modeling but also on incorporating land use, governance and socio-economic realities into decision-making frameworks.

Colombia exemplifies the complex challenges faced by coastal nations under climate change. With over 3000 kilometers of coastline, including approximately 1600 km on the Caribbean Sea and 1300 km along the Pacific Ocean, its exposure to SLR is significant but spatially varied. The Caribbean coast is marked by large lowland expanses, extensive port infrastructure and rapidly expanding urban centers such as Cartagena, Barranquilla and Santa Marta. These areas are particularly vulnerable due to flat topography, population density and the presence of critical economic assets within one kilometer of the shoreline. In contrast, the Pacific coast features a more rugged topography, high precipitation, dense mangrove systems and relatively low development pressure, but still faces risks associated with ecological degradation and poor adaptive infrastructure.

The second article of this dissertation builds on this national context by applying an elevation-based inundation model to assess permanent land loss under five SSPs. Using elevation data and sea-level projections aligned with the IPCC Sixth Assessment Report, the study quantifies the total area of land potentially lost under each scenario and distinguishes between Colombia’s Caribbean and Pacific coastal fronts. The results reveal a notable distinction: under the highest-emissions scenario (SSP5-8.5), approximately 2232 km^2 of land along the Caribbean could be permanently inundated, compared to 609 km^2 on the Pacific coast. These patterns are largely shaped by local topography, subsidence processes and the historical placement of urban development in vulnerable coastal zones.

To better understand the implications of this land loss, the study also incorporates a socio-ecological classification of land use types. Urban areas, agricultural zones, conservation regions and water bodies were mapped and overlaid with projected inundation areas, providing insight into the types of socio-economic assets at risk. Municipalities with high exposure include strategic cities such as Cartagena, as well as smaller, often overlooked jurisdictions in departments like Bolívar, Atlántico and Magdalena. The analysis also identifies Pacific municipalities in Chocó and Nariño that, although less exposed in terms of area, face heightened vulnerability due to lower adaptive capacity and limited infrastructure investment.

While the study does not model policy or governance dynamics directly, it provides a high-resolution, spatially explicit baseline for national and subnational adaptation planning. By linking physical exposure with land classification and regional administrative units, the results help identify priority zones for intervention and potential synergies between conservation and adaptation. The work also underscores the need for further integration of dynamic socio-economic scenarios, stakeholder engagement and governance capacity assessments to develop actionable strategies that are both locally grounded and nationally coordinated.

2.4. Reservoir Evaporation and Water Management

Reservoirs are central to water supply systems in many regions of the world, particularly in drylands where natural storage is scarce and rainfall variability is high. They are built to secure drinking water, support irrigation and hydropower, and to regulate floods, but at the same time they introduce new inefficiencies into the hydrological cycle. One of the most significant of these inefficiencies is evaporation from open water surfaces, a process that is often underestimated in basin-scale water balances and climate adaptation planning. Rates of evaporation depend not only on climate variables such as temperature, wind, humidity and radiation but also on the geometry of the reservoir (surface-area-to-volume ratio, depth, shoreline complexity) and on operational practices such as drawdown regimes. These interacting drivers mean that evaporation is a highly dynamic process, yet in many global assessments it is simplified or left out entirely.

The scale of the problem is considerable. Global estimates suggest that reservoir evaporation exceeds 150–200 km^3 annually, making it one of the largest forms of human-driven consumptive water use (Wada et al., 2017). In some regions the proportion of water lost is even more striking. In the western United States, for example, Friedrich et al., 2018 reported that shallow reservoirs can lose more than 20% of their capacity to evaporation, highlighting the particular vulnerability of arid-zone storage systems. Comparable findings have been reported in China, where Tian et al., 2021 estimated substantial evaporative losses across a national sample of reservoirs, with direct implications for agriculture and urban water supply.

Recent work has started to move beyond traditional pan-evaporation methods by combining physically based energy-balance models with remote sensing. These approaches can better capture the temporal and spatial variability of evaporative losses by linking satellite observations of reservoir surface areas with meteorological forcing data. In my own research, I developed such a framework and applied it to ten of the largest reservoirs in water-stressed regions worldwide. The results showed annual evaporation rates in excess of 3,200 mm, with cumulative losses of around 26.5 km^3 per year. In some cases, this amounted to nearly 16% of total storage capacity, underscoring the need to explicitly include evaporation in long-term planning for water allocation and conservation (Nevermann et al., 2024).

Further studies examined at how evaporation occurs in politically sensitive basins, building on this global perspective. For instance, evaporation from reservoirs was found to be responsible for significant amounts of storage loss in the Helmand River Basin, which is shared by Afghanistan and Iran. This has obvious implications for downstream water availability and transboundary relations (Nevermann et al., 2025). The study also emphasizes that not all of the water that evaporates is lost permanently; some of it is recycled back into the hydrological cycle through atmospheric moisture, where it may fall as precipitation inside or outside the basin. When assessing reservoir evaporation, this dual role emphasizes the importance of taking into account both local scarcity and larger climatic connections.

The consequences of neglecting these losses extend well beyond hydrological calculations. For water managers, evaporation reduces the reliability of supply for cities, irrigation schemes and hydropower production, often in places that already face acute scarcity. For ecosystems, lower storage volumes can alter downstream flow regimes, degrade aquatic habitats and shift sediment dynamics. Climate change adds another layer of risk, as rising temperatures, altered rainfall regimes and more variable drought–flood cycles are expected to increase evaporative demand in most regions (Intergovernmental Panel on Climate Change (IPCC), 2023).

Different strategies have been tested to reduce evaporation from reservoirs. Chemical monolayers can lower losses by 30–70%, although their effectiveness is highly variable and often constrained by wind, wave action and ecological concerns (Barnes, 2008). Floating or suspended covers, such as modular shade structures or membranes, can achieve reductions above 90% but are costly to install and maintain, and their environmental side effects are still under debate (Pittaway et al., 2018; Zhang et al., 2010). Reviews emphasize that these measures may work on smaller storages but are less feasible for large-scale reservoirs due to costs and durability concerns (Craig et al., 2005; Pittaway et al., 2023). More recently, floating photovoltaic (PV) systems have attracted interest as they can both reduce evaporation and generate renewable energy, offering a potential integrative solution (Pittaway et al., 2018).

The paradox, therefore, is that the very infrastructure designed to secure water supply under scarcity can itself become a source of substantial hidden losses. Addressing this paradox will require not only technical measures but also improved monitoring, more accurate incorporation of evaporation into basin-wide water assessments, and stronger integration of climate–hydrology interactions into decision-making frameworks (Granata and Di Nunno, 2025). This dissertation contributes to this broader agenda by applying physically based models and remote sensing to quantify evaporation and to assess its implications for water management under changing climatic and socio-environmental conditions.

2.5. Integrated and Interdisciplinary Approaches

The challenges discussed in the preceding sections, such as climate-induced shifts in hydrological systems, the pressures on coastal wetlands, the risks associated with sea-level rise, and the hidden losses from reservoir evaporation, point toward the conclusion that water security under climate change is shaped by complex and interacting processes that cannot be analyzed in isolation. Each domain has generated important insights, yet taken separately, they risk presenting a fragmented view of reality. Hydrology without governance underestimates human agency. Coastal modeling without socio-economic data overlooks differential vulnerability. Evaporation quantification without allocation analysis ignores the political economy of water. The need, therefore, is not simply for better models of individual processes, but for frameworks that connect them in meaningful ways.

Crossing scales and domains

One of the persistent problems is the mismatch of scales. Global climate models operate at grid sizes of 50–100 km, but many relevant hydrological decisions, whether to build a reservoir, drain a wetland or implement coastal defenses, take place at the scale of catchments, deltas, or municipalities . This mismatch produces uncertainty and reduces the usability of climate information for local water governance. Remote sensing partly helps to bridge this gap by providing high-resolution observations of land, water, and vegetation dynamics (MODIS, GRACE, Sentinel), but the challenge remains of translating these observations into models that can guide adaptation.

Another challenge lies in the interaction of natural and human systems. Hydrological systems do not simply respond passively to climate forcing as they are shaped by irrigation, dams, urbanization, and land-use change. Coastal wetlands are not only ecological systems but also socio-ecological landscapes constrained by manufactured dikes. Reservoir evaporation is not just a physical flux but a contested component of basin allocation, sometimes even with transboundary and geopolitical consequences, and it is closely entangled with energy production and agricultural policy. Recognizing these interdependencies requires approaches that go beyond isolated disciplinary domains.

Emergence of integrated frameworks

Several fields of research have moved in this direction. Socio-hydrology (Blöschl et al., 2019; Sivapalan et al., 2012) explicitly studies the co-evolution of water and society and asks how human decisions, feedbacks, and institutional responses alter hydrological outcomes. Resilience theory (Folke, 2016) has emphasized the adaptive capacity of coupled human–natural systems under stress and uncertainty. Earth system science brings hydrology into the larger context of climate, carbon, and land-use feedbacks whilst making it clear that water cannot be managed separately from energy systems, ecosystems, and human development.

More recently, joined approaches have gained popularity, especially the water–energy–food (WEF) nexus (Ringler et al., 2013). These frameworks highlight the trade-offs and synergies between sectors, such as when water stored in reservoirs supports food production and hydropower but is simultaneously lost through evaporation. At the same time, evaporation is not only a technical issue but also a governance and allocation challenge, particularly in water-scarce and transboundary basins, where competing national and sectoral demands can increase its significance. Similarly, the planetary boundaries framework (Rockström et al., 2009) situates water within global limits, stressing the interconnectedness of freshwater use with climate stability, land change as well as biodiversity.

Methodological integration

In addition to theoretical frameworks, a growing toolkit for integrating data and models is available. Advances in Earth observation make it possible now to monitor precipitation, soil moisture, evapotranspiration, and terrestrial water storage at high temporal resolution. These satellite-derived products, such as those from MODIS, GRACE, and Sentinel missions, are increasingly being integrated with process-based hydrological models including SWAT, VIC, and LISFLOOD to improve spatially explicit assessments of water availability and variability (McCabe et al., 2019, 2017; Miralles et al., 2011). Recent work on large reservoirs further demonstrates the potential of such integration, where remote sensing of surface water dynamics is combined with energy-balance modeling to estimate evaporative losses across diverse climatic and geographic settings (Zhao et al., 2022; Zhao and Gao, 2019). Big data analytics and machine learning add the capacity to detect patterns and predict extremes across scales. Meanwhile, methods that involve people participating and tools that support decision-making incorporate local knowledge and governance aspects into the modeling process. This helps make sure the results are not only technically correct but also relevant to society (Pahl-Wostl, 2015).

Despite this progress, integration is rarely straightforward due to differences in data availability, resolution, and disciplinary assumptions which make it difficult to couple models seamlessly. There are also differences in organizations and methods of understanding due to the fact that engineers often prefer models focused on efficiency and optimization, ecologists highlight feedback loops in systems, and social scientists pay attention to how rules and decision-making processes change over time. Therefore, interdisciplinary approaches require negotiation not only across datasets and scales but also through modes of generation and exchange of knowledge.

Implications for water governance

The integration of physical and social perspectives is not only a scientific necessity but also a political one. Climate change impacts water in ways that cut across administrative boundaries, creating transboundary tensions and multi-level governance challenges. The Nile Basin, the Mekong, and the Andes are clear cases where upstream reservoir construction and operation reshape downstream vulnerabilities, affecting flow regimes, ecosystems, and human water security (Best, 2019; Grill et al., 2015; Kuenzer et al., 2013). Coastal wetlands face trade-offs between conservation and urban expansion, often handled by separate organizations. Sea-level rise threatens national structures but requires local adaptation. Without integrative frameworks, policies risk either being too narrow in scope or too detached from reality.

Adaptive governance literature suggests that successful management during times of uncertainty requires multidisciplinary governance systems (Ostrom, 2017), iterative learning, and the involvement of a variety of interest groups. Interdisciplinary science can inform such governance by clarifying risks, trade-offs, and potential adaptation pathways. However, it must also recognize uncertainty as a structural aspect of water-climate interactions and acknowledge the limitations of prediction. This dissertation's case studies demonstrate the challenge: wetland adaptation is limited by land-use policies, coastal resilience in Colombia relies on institutional capacity, and reservoir management needs to combine hydrological realities with conflicting demands from agriculture, energy, and urban areas. These examples show how governance decisions affect the risks that research around climatic changes aims to analyze.

Positioning this dissertation

The work presented in this dissertation belongs within this integrative and interdisciplinary approach to investigate climate-water interactions. Rather than addressing individual processes in isolation, the four articles together explore how hydrological systems are shaped by both climatic drivers and human interventions across a range of scales. Each paper contributes a distinct perspective: one investigates wetland adaptation under sea-level rise, another examines socio-ecological vulnerability along Colombia’s coasts, a third quantifies evaporation from some of the world’s largest reservoirs, and the fourth analyzes evaporation within the politically sensitive Helmand Basin shared by Afghanistan and Iran. Taken together, these studies span ecological, national, global, and transboundary contexts.

By connecting physical modeling with remote sensing and socio-environmental analysis, the dissertation illustrates how climate variability and human pressures interact in ways that cannot be captured by single-discipline or single-scale approaches. Its contribution lies less in isolated findings than in demonstrating the value of bringing ecological processes, infrastructure, and governance into a shared analytical framework. In doing so, it positions hydrological research as both a scientific and a societal attempt, one that links natural variability to the institutional and political settings in which water decisions are made.

3. Achievements

3.1. Overview

The research presented in this cumulative dissertation builds on four peer-reviewed scientific articles that together form the main contributions of the work. While each paper addresses a specific research gap described in the introductory chapters, collectively they provide a comprehensive and interdisciplinary understanding of climate–water interactions across different spatial scales and socio-ecological settings.

The first article focuses on coastal wetland adaptation under sea-level rise with a case study of the Wadden Sea in northwestern Europe. The results highlight how natural processes of inland migration are increasingly constrained by anthropogenic barriers, leading to coastal squeeze and a loss of ecosystem services. This paper provides insights into the shortcomings of conventional elevation-based modeling approaches, while underscoring the importance of incorporating socio-ecological and governance dimensions into wetland adaptation strategies.

The second article extends the scope to the national scale, analyzing coastal vulnerability in Colombia under multiple sea-level rise scenarios. By integrating high-resolution inundation modeling with a socio-ecological land classification, the study analyzes both physical land loss and the socio-economic assets at risk. This work shows the uneven spatial distribution of risks between the Caribbean and Pacific coasts, highlighting the importance of governance capability and adaptive infrastructure in shaping vulnerability.

The third article shifts focus to reservoir evaporation in global water-stressed regions, a less visible but increasingly critical component of climate–water interactions. Using a physically based energy-balance modeling framework combined with remote sensing observations of surface water dynamics, the study quantifies evaporative losses across some of the world's largest reservoirs. The findings demonstrate that evaporation can account for a substantial fraction of total storage capacity, positioning it as a hidden but significant inefficiency in water management and allocation.

The fourth article narrows in on the Helmand River Basin shared by Afghanistan and Iran, where reservoir evaporation interacts directly with transboundary politics and regional water scarcity. By combining satellite observations with hydrological modeling, the study shows how evaporative losses influence basin-scale water balances, downstream availability, and geopolitical tensions. It also points to the atmospheric dimension of evaporation, highlighting its contribution to moisture recycling beyond basin boundaries.

Together, these four studies range from ecosystem-scale processes (wetland migration), to country-scale vulnerability (Colombia’s coasts), to global-scale infrastructure challenges (reservoir evaporation) , and finally to the transboundary and geopolitical context of reservoir management (Helmand Basin). They illustrate how changes in climate may reshape hydrological and coastal systems not only through physical drivers, but also through the socio-ecological and institutional circumstances in which these systems are embedded. By combining physically based modeling, remote sensing, and socio-environmental analysis, this dissertation contributes to an integrated assessment that emphasizes both scientific understanding and policy relevance.

3.2. Coastal wetlands

Paper 1:

Nevermann, H., AghaKouchak, A., & Shokri, N. (2023). Sea level rise implications on future inland migration of coastal wetlands. Global ecology and conservation, 43, e02421.

The purpose of this study is to address a fundamental question, namely to what extent can natural processes of inland wetland migration compensate for SLR in the presence of human-made barriers such as dikes and embankments?

To answer this, the analysis applies an elevation-based inundation model to high-resolution topographic data of the Wadden Sea region. The model simulations are combined with spatial data on dike locations and reclaimed land to capture the constraints imposed by anthropogenic infrastructure. This approach makes it possible to contrast the theoretical potential of wetlands to migrate inland with the reduced adaptive capacity observed under current land-use conditions.

The results show that while significant areas of wetland could shift landward in response to SLR, in practice coastal protection structures obstruct these migration pathways. This so called "coastal squeeze" effect results in the progressive loss of wetland habitats and associated ecosystem services, including biodiversity support, carbon sequestration, and storm buffering. The findings show the shortcomings of conventional modeling approaches that often only take topographic thresholds in consideration, while neglecting socio-ecological realities.

Main contributions of the article include:

- *Demonstrating how physical and anthropogenic constraints jointly shape wetland adaptation potential under sea-level rise.*
- *Providing one of the first systematic examples of elevation-based modeling in the Wadden Sea that specifically integrates human-made barriers.*

- *Presenting policy-relevant information for hybrid adaptation strategies, that take into account ecological and social priorities like managed retreat and landward buffer zoning.*

This paper therefore contributes to the broader goals of the dissertation by illustrating how ecological processes, infrastructure, and governance interact to determine adaptation outcomes, and by highlighting the need for interdisciplinary approaches that go beyond purely physical models.

3.3. Coastal Land Loss in Colombia

Paper 2:

Nevermann, H., Gomez, J. N. B., Fröhle, P., & Shokri, N. (2023). Land loss implications of sea level rise along the coastline of Colombia under different climate change scenarios. *Climate Risk Management*, *39*, 100470.

This study extends the scope of the dissertation to the national scale, examining how SLR may reshape Colombia's Caribbean and Pacific coastlines. The main research question is which socio-ecological systems are most at risk and the spatial extent of potential land loss under future SLR scenarios.

The methodology combines an elevation-based inundation model with high-resolution topographic datasets and sea-level projections aligned with the IPCC Sixth Assessment Report. A socio-ecological land classification that distinguishes between urban areas, agricultural land, conservation regions, and other land uses strengthens the modeling framework even further. In addition to quantifying the actual land loss, this integrated methodology makes it possible to identify the kinds of assets that are most vulnerable to flooding.

Results show a pronounced difference between Colombia's two coastlines. The Caribbean coastline is particularly vulnerable due to its large low-lying areas, dense urban settlements, and critical infrastructure. Under high-emission scenarios (SSP5–8.5), up to 2,232 km² of land are expected to be inundated. In contrast, the Pacific coast faces less extensive land loss (609 km² under the same scenario), however its high ecological value and low adaptive capacity increase its vulnerability. The analysis emphasizes how governance capacity, infrastructure, and land-use patterns shape risk differently across regions.

Main contributions of the article include:

- *Quantifying the spatial extent of potential land loss in Colombia under multiple SLR scenarios.*
- *Linking physical exposure to socio-ecological classifications, thereby identifying which assets and communities are most at risk.*

- *Providing actionable insights for national and subnational adaptation planning by distinguishing between the uneven vulnerabilities of the Caribbean and Pacific coasts.*

By situating SLR impacts within both ecological and socio-economic contexts, this paper advances understanding of how physical drivers interact with governance capacity and development pathways. It contributes to the dissertation's broader aim of providing spatially explicit, policy-relevant insights into socio-ecological vulnerability.

3.4. Reservoir Evaporation

Paper 3:

Nevermann, H., Aminzadeh, M., Madani, K., & Shokri, N. (2024). Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions. *Environmental research*, *262*, 119860.

This study shifts its focus to a less visible but increasingly important aspect of climate–water interactions: evaporation from large reservoirs. The guiding question is to what extent evaporative losses weaken the effectiveness of reservoirs as water security infrastructures, especially in regions already facing acute water scarcity.

The methodology combines a physically based energy-balance model with remote sensing observations of reservoir surface areas, using multisource satellite datasets to capture temporal variability in water levels and meteorological forcing. The analysis was applied to ten of the world's largest reservoirs situated in arid and semi-arid regions.

Results reveal annual evaporation rates exceeding 3,200 mm in some reservoirs, with cumulative losses of approximately 26.5 km^3 per year. In several cases, this corresponded to up to 16% of the total storage capacity. Such magnitudes position evaporation as a substantial but often overlooked driver of water loss, with consequences for how water is allocated across competing demands.

Main contributions of the article include:

- *Quantifying evaporative losses at a global scale using a combined modeling and remote sensing framework.*
- *Demonstrating how evaporation can rival or exceed other consumptive water uses in arid-zone reservoirs.*
- *Providing evidence for integrating evaporation explicitly into basin-scale water balances and adaptation planning.*

By showing evaporation as both a hydrological process and a management challenge, this paper illustrates the paradox that reservoirs built to secure water can also contribute to substantial hidden losses. It contributes to the dissertation’s broader aim of linking physical processes with governance challenges to inform sustainable water management strategies in a changing climate.

3.5. Transboundary Reservoir Evaporation (Helmand Basin)

Paper 4:

Nevermann, H., Madani, K., Zampieri, M., Hoteit, I., & Shokri, N. (2025). Struggling over water, losing it through evaporation: The case of Afghanistan and Iran. *Journal of environmental management, 375,* 124319.

This paper narrows the scope from the global assessment of reservoir evaporation to a politically sensitive transboundary river basin. The central question is how evaporation from reservoirs in the Helmand River Basin, shared between Afghanistan and Iran, influences water availability, basin-scale balances, and regional political tensions.

The methodology integrates remote sensing of reservoir surface areas with energy-balance modeling of evaporation. In addition to quantifying annual evaporative losses, the study links these findings to downstream availability and to existing water-sharing disputes between the riparian states. The analysis also considers the atmospheric dimension, noting that evaporated water contributes to regional moisture recycling, which may redistribute precipitation beyond basin boundaries.

The results indicate that evaporation in the Helmand Basin is considerable, with annual losses contributing a significant amount of the stored water. These losses occur in a basin already characterized by scarcity, lack of governmental cooperation, and political disputes about how to allocate resources. The study illustrates how the magnitude of evaporative losses can exacerbate tensions in international water relations through a physical hydrological process.

Main contributions of the article include:

- *Quantifying reservoir evaporation in a transboundary basin with acute water scarcity.*
- *Demonstrating how physical water losses intersect with geopolitical tensions and governance weaknesses.*
- *Highlighting the atmospheric role of evaporation, linking local reservoir management to regional hydroclimatic feedbacks.*

This paper contributes to the dissertation’s broader objectives by situating reservoir evaporation not only as a hydrological challenge but also as a transboundary and political issue. It underscores the need for management approaches that integrate physical modeling, remote sensing, and governance analysis in order to address both scarcity and cooperation in shared river basins.

4. Conclusion

The aim of this dissertation was to investigate how water systems respond to climatic and meteorological variability across different regions and social–ecological settings. To do so, it combined physically based modeling with remote sensing and socio-environmental analysis. This made it possible to capture not only the physical processes that drive hydrological change, but also the wider conditions that influence how societies adapt to them. The four case studies address distinct questions and scales: coastal wetlands, coastal vulnerability in Colombia, reservoir evaporation at the global scale, and evaporation in a politically sensitive transboundary basin. Taken together, however, they show how climate pressures and human activities interact to reshape water systems in ways that are both physical and social.

One of the main conclusions of this work is that physical pressures and human constraints are deeply intertwined. In the Wadden Sea, wetlands could in theory migrate inland as sea levels rise, yet this natural response is blocked by dikes and reclaimed land, leading to the well-known problem of coastal squeeze and the loss of habitat. In Colombia, the challenge is different but the pattern is similar in which low-lying Caribbean municipalities are highly exposed and that exposure is made worse by rapid urban expansion and weak governance structures. Reservoirs show this paradox from another perspective. They were built partly to protect societies against scarcity, yet they may also lose vast amounts of water through evaporation, which adds pressure to basins already under stress. In the Helmand Basin, evaporation is not only a hydrological inefficiency but also a geopolitical factor, influencing water allocation between Afghanistan and Iran and amplifying political tensions. Taken together, these cases illustrate that climate-related risks cannot be separated from the infrastructures, land uses, and institutions that shape them.

Another key conclusion concerns the scale at which vulnerability plays out, and the fact that it rarely looks the same from one setting to another. In the wetland case, ecological processes unfold across entire landscapes, but their response to sea-level rise is determined by very local land-use choices. The Colombia study shows how vulnerability shifts not only between communities but even between coasts, shaped by contrasts in topography, infrastructure, and the capacity of institutions to act. The global study on reservoirs, in turn, shows how a seemingly uniform process, evaporation on open water, varies considerably depending on the climate zone, the geometry of the reservoir, and how the system is operated. The Helmand case extends this insight by showing that evaporation has transboundary implications: its impacts cascade across borders and are entangled with international politics as well as regional hydroclimatic feedbacks. Together, these cases suggest that broad climatic drivers can only be understood properly when set against the diversity of regional conditions and management practices.

Methodologically, this dissertation demonstrates the value of integrative approaches that combine physically based models with remote sensing and socio-ecological framing. Elevation-based inundation models, when enriched with data on dikes and reclaimed land, reveal migration constraints otherwise invisible. National-scale inundation models in Colombia gain policy relevance when coupled with land-use classifications that capture urban and ecological assets. Evaporation estimates are often simplified in basin-scale assessments but will achieve higher accuracy when energy-balance models include data from satellite observations. In transboundary basins, such as the Helmand, this integration further demonstrates the political salience of technical hydrological estimates, since quantifying evaporation directly informs allocation debates and international negotiations. These methodological advances are not purely technical, since they provide actionable insights by linking the quantification of physical processes to the realities of governance, land use, and policy decision-making.

An additional contribution of this work is its relevance for policy and governance. Effective conservation solutions for wetlands must integrate engineering measures with ecological restoration as elevation models and topographic thresholds alone will not suffice. In Colombia, adaptation planning has to be regionally tailored, since the Caribbean and Pacific coasts face different kinds of risks and have unequal capacities to respond. Reservoir management, likewise, should begin to treat evaporation as part of the allocation problem, while also exploring potential collaborations with new approaches such as floating solar installations. In shared basins, accounting for evaporation is equally critical, as it may not only affect water balances but also the political stability of riparian relations. The Helmand Basin case makes clear that physical processes can become triggers for wider geopolitical conflict if they are not addressed transparently in cooperative frameworks. When combined, these results demonstrate that hydrological research is most useful when it influences and at the same time is influenced by societal decisions about infrastructure, water, and land.

Finally, this work confirms the argument that water security cannot be considered in isolation in an ever-changing climate. The displacement of wetlands or coastal squeeze, coastal flooding, and evaporation from reservoirs are not separate problems, but interconnected effects of the same broader challenge of how societies can adapt their water systems in the face of climatic fluctuations and long-term environmental change. The addition of the transboundary perspective emphasizes that these challenges extend beyond single basins or countries, and that future adaptation will require not only technical solutions but also cooperative and diplomatic ones. To meet this challenge, approaches are needed that combine ecological, infrastructural, and governance perspectives while taking into account uncertainties and unavoidable compromises.

In conclusion, this dissertation adds to scientific knowledge while also offering insights for the practice of water governance. It demonstrates how the relationship between water and climate can be investigated in ways that are thorough at the spatial level, based on reliable methodologies, and considering the social circumstances in which choices are made. While each of the four case studies offers new perspectives in their respective fields, taken as a whole, they highlight a greater need for research that crosses disciplines, scales, and takes governance challenges into account. This not only increases the likelihood that measures for reservoirs, wetlands, and coastlines will remain effective as climate pressures continue to grow, but also strengthens the potential for cooperative solutions in politically sensitive water basins.

5. Summary and Outlook

This dissertation has explored ways hydrological systems adapt, or struggle, to climatic and meteorological shifts across diverse ecological and societal landscapes. It addressed four different but related issues using a combination of satellite data, physical modeling, and socio-environmental perspectives: the potential inland shift of wetlands due to sea level rise, the uneven vulnerabilities along Colombia's coasts, the significant evaporative water losses from important reservoirs in regions prone to water scarcity, and the geopolitical dimensions of evaporation in the Helmand River Basin shared by Afghanistan and Iran. A recurrent theme that emerged from these investigations is the interaction of human decisions on infrastructure, land management, and policy frameworks with climate-related variables. This supports the principle that when physical mechanisms are seen as integrated into their larger environmental and social contexts rather than as isolated components, hydrological studies become more precise and useful.

This work creates a number of opportunities for further future development and application. By combining regional satellite images with evolving data on land use and governance structures, for example, there is a genuine chance to strengthen the connections between remote sensing and modeling. Such measures might narrow the divide between large-scale climate assessments and local decisions. For wetlands, advancing models that integrate geomorphological and biological dynamics with societal barriers could inform more practical conservation strategies, balancing natural limits against regulatory and community constraints. In coastal planning, upcoming efforts should aim to go beyond fixed inundation maps to embrace dynamic factors like population movements, city expansion, and evolving governance paths. Furthermore, it is essential to consider the optimization of evaporation reductions along with energy outputs and ecosystem integrity in reservoirs, particularly as solutions such as large-scale floating solar panels gain popularity. Equally, in transboundary basins, future research must expand to explicitly include evaporation in allocation frameworks and to explore its atmospheric feedbacks, since these losses have implications not only for local scarcity but also for international stability and cooperation.

This dissertation highlights how crucial it is to take into account various scales and ensure collaboration between multiple disciplines when addressing the challenges surrounding water, given that the climate continues to undergo changes and warming in some places. Wetlands, shorelines, and reservoirs should not be treated as isolated systems as they are parts of broader socio-ecological networks in which natural dynamics and human decisions interact and, at times, might amplify one another. Transboundary rivers in particular demonstrate how physical processes can spill over into governance and diplomacy, underscoring the need for scientific work that supports cooperative solutions alongside technical adaptation. Future research will therefore need to continue combining insights from the natural sciences, engineering, and policy, while also acknowledging uncertainties and the possibility of sudden system shifts.

In summary, the studies presented in this dissertation show that understanding water systems under climatic and meteorological fluctuations requires approaches that are both technically grounded and also consider the context in which they are applied. By combining physics-based modeling, remote sensing, and socio-ecological analysis, this dissertation has demonstrated how processes such as wetland migration, coastal flooding, and reservoir evaporation can be studied with greater precision and relevance. The addition of the transboundary case study further illustrates that hydrological science has geopolitical dimensions, and that physical water balances cannot be separated from international relations and cooperative governance. While challenges remain in relation to varying scales, data gaps, and disciplinary perspectives, the results point to opportunities for more integrated and resilient approaches to water management in a changing climate. Ultimately, wetlands, coasts, and reservoirs will continue to play a critical role in protecting societies and ecosystems from variability, and the methods developed here provide a foundation for further development of both scientific research and practical adaptation in the years to come.

6. Bibliography

Alasan, D.M., Tepa-Yotto, G., Adomaa, F.O., 2024. Climate action triggers new decisions and investments for resilient food systems: policy actions to operationalize the National Framework for Climate Services (NFCS) and the Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD) in Ghana. https://doi.org/10.1111/nyas.14337

Allan, R.P., Barlow, M., Byrne, M.P., Cherchi, A., Douville, H., Fowler, H.J., Gan, T.Y., Pendergrass, A.G., Rosenfeld, D., Swann, A.L.S., Wilcox, L.J., Zolina, O., 2020. Advances in understanding large-scale responses of the water cycle to climate change. Ann. N. Y. Acad. Sci. 1472, 49–75. https://doi.org/10.1111/nyas.14337

Allen, M.R., Ingram, W.J., 2002. Constraints on future changes in climate and the hydrologic cycle. Nature 419, 224–232. https://doi.org/10.1038/nature01092

Baraer, M., Mark, B.G., McKenzie, J.M., Condom, T., Bury, J., Huh, K.-I., Portocarrero, C., Gómez, J., Rathay, S., 2012. Glacier recession and water resources in Peru's Cordillera Blanca. J. Glaciol. 58, 134–150. https://doi.org/10.3189/2012JoG11J186

Barnes, G.T., 2008. The potential for monolayers to reduce the evaporation of water from large water storages. Agric. Water Manag. 95, 339–353. https://doi.org/10.1016/j.agwat.2007.12.003

Best, J., 2019. Anthropogenic stresses on the world's big rivers. Nat. Geosci. 12, 7–21. https://doi.org/10.1038/s41561-018-0262-x

Blöschl, G., Bierkens, M.F.P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., et al., 2019. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. Hydrol. Sci. J. 64, 1141–1158. https://doi.org/10.1080/02626667.2019.1620507

Clough, J., Polaczyk, A., Propato, M., 2016. Modeling the potential effects of sea-level rise on the coast of New York: Integrating mechanistic accretion and stochastic uncertainty. Environ. Model. Softw. 84, 349–362. https://doi.org/10.1016/j.envsoft.2016.06.023

Corson-Dosch, H., Nell, C., Volentine, R.E., Archer, A.A., Bechtel, E., Bruce, J.L., Felts, N., Gross, T.A., Lopez-Trujillo, D., Riggs, C.E., Read, E.K., 2022. Water cycle diagrams. U.S. Geological Survey, Water Science School. https://www.usgs.gov/special-topics/water-science-school/science/water-cycle-diagrams

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0

Craig, I., Green, A., Scobie, M., Schmidt, E., 2005. Controlling evaporation loss from water storages. National Centre for Engineering in Agriculture Publication 1000580/1, USQ, Toowoomba.

Doody, J.P., 2013. Coastal squeeze and managed realignment in southeast England, does it tell us anything about the future? Ocean Coast. Manag., Managing Estuarine Sediments 79, 34–41. https://doi.org/10.1016/j.ocecoaman.2012.05.008

Douglas, E.M., Beltrán-Przekurat, A., Niyogi, D., Pielke, R.A., Vörösmarty, C.J., 2009. The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation — A mesoscale modeling perspective. Glob. Planet. Change, Changes in land use and water use and their consequences on climate, including biogeochemical cycles 67, 117–128. https://doi.org/10.1016/j.gloplacha.2008.12.007

Esteves, L.S., 2016. Coastal Squeeze. In: Kennish, M.J. (Ed.), Encyclopedia of Estuaries. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-8801-4_405

Folke, C., 2016. Resilience (republished). Ecol. Soc. 21.

Friedrich, K., Grossman, R.L., Huntington, J., Blanken, P.D., Lenters, J., Holman, K.D., Gochis, D., Livneh, B., Prairie, J., Skeie, E., Healey, N.C., Dahm, K., Pearson, C., Finnessey, T., Hook, S.J., Kowalski, T., 2018. Reservoir Evaporation in the Western United States: Current Science, Challenges, and Future Needs. Bull. Am. Meteorol. Soc. 99, 167–187. https://doi.org/10.1175/BAMS-D-15-00224.1

Granata, F., Di Nunno, F., 2025. Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. Earth Syst. Environ. https://doi.org/10.1007/s41748-024-00567-x

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., Seneviratne, S.I., 2014. Global assessment of trends in wetting and drying over land. Nat. Geosci. 7, 716–721. https://doi.org/10.1038/ngeo2247

Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C., Reidy Liermann, C., 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environ. Res. Lett. 10, 015001. https://doi.org/10.1088/1748-9326/10/1/015001

Haddeland, I., Clark, D.B., Franssen, W., Ludwig, F., Voß, F., Arnell, N.W., Bertrand, N., Best, M., Folwell, S., Gerten, D., Gomes, S., Gosling, S.N., Hagemann, S., Hanasaki, N., Harding, R., Heinke, J., Kabat, P., Koirala, S., Oki, T., Polcher, J., Stacke, T., Viterbo, P., Weedon, G.P., Yeh, P., 2011. Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. J. Hydrometeorol. 12, 869–884. https://doi.org/10.1175/2011JHM1324.1

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256. https://doi.org/10.1073/pnas.1222475110

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. 111, 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hossen, M.A., Connor, J., Ahammed, F., 2023. How to Resolve Transboundary River Water Sharing Disputes. Water 15, 2630. https://doi.org/10.3390/w15142630

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. J. Hydrol. 319, 83–95. https://doi.org/10.1016/j.jhydrol.2005.07.003

Immerzeel, W.W., Pellicciotti, F., Bierkens, M.F.P., 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nat. Geosci. 6, 742–745. https://doi.org/10.1038/ngeo1896

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate Change Will Affect the Asian Water Towers. Science 328, 1382–1385. https://doi.org/10.1126/science.1183188

IPCC, 2019. Figure 4.3 in Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157964

Intergovernmental Panel On Climate Change (Ipcc), 2023. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (IPCC) (Ed.), 2023. Water Cycle Changes, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 1055–1210. https://doi.org/10.1017/9781009157896.010

Jiang, D., Wang, K., 2019. The Role of Satellite-Based Remote Sensing in Improving Simulated Streamflow: A Review. Water 11, 1615. https://doi.org/10.3390/w11081615

Keys, P.W., van der Ent, R.J., Gordon, L.J., Hoff, H., Nikoli, R., Savenije, H.H.G., 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. Biogeosciences 9, 733–746. https://doi.org/10.5194/bg-9-733-2012

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V.Q., Dech, S., 2013. Understanding the impact of hydropower developments in the context of upstream–downstream relations in the Mekong river basin. Sustain. Sci. 8, 565–584. https://doi.org/10.1007/s11625-012-0195-z

Kueppers, L.M., Snyder, M.A., Sloan, L.C., 2007. Irrigation cooling effect: Regional climate forcing by land-use change. Geophys. Res. Lett. 34. https://doi.org/10.1029/2006GL028679

Liu, C., Tang, H., Ji, L., Zhao, Y., 2021. Spatial-temporal water area monitoring of Miyun Reservoir using remote sensing imagery from 1984 to 2020. https://doi.org/10.48550/arXiv.2110.09515

Lo, M.-H., Famiglietti, J.S., 2013. Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle. Geophys. Res. Lett. 40, 301–306. https://doi.org/10.1002/grl.50108

McCabe, M.F., Miralles, D.G., Holmes, T.R.H., Fisher, J.B., 2019. Advances in the Remote Sensing of Terrestrial Evaporation. Remote Sens. 11, 1138. https://doi.org/10.3390/rs11091138

McCabe, M.F., Rodell, M., Alsdorf, D.E., Miralles, D.G., Uijlenhoet, R., Wagner, W., Lucieer, A., Houborg, R., Verhoest, N.E., Franz, T.E., 2017. The future of Earth observation in hydrology. Hydrol. Earth Syst. Sci. 21, 3879–3914. https://doi.org/10.5194/hess-21-3879-2017, 2017

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9, 552–560. https://doi.org/10.1890/110004

Mehmood, H., Rathnayake, R.M.P.J., 2025. Spatial and temporal assessment of agriculture in Lower Mekong countries.

Millennium Ecosystem Assessment (Program) (Ed.), 2005. Ecosystems and human well-being: wetlands and water synthesis: a report of the Millennium Ecosystem Assessment. World Resources Institute, Washington, DC.

Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. https://doi.org/10.5194/hess-15-453-2011, 2011

Mitsch, W.J., Gosselink, J.G., 2015. Wetlands. John Wiley & Sons.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLOS ONE 10, e0118571. https://doi.org/10.1371/journal.pone.0118571

Nevermann, H., Aminzadeh, M., Madani, K., Shokri, N., 2024. Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions. Environ. Res. 262, 119860. https://doi.org/10.1016/j.envres.2024.119860

Nevermann, H., Madani, K., Zampieri, M., Hoteit, I., Shokri, N., 2025. Struggling over water, losing it through evaporation: The case of Afghanistan and Iran. J. Environ. Manage. 375, 124319. https://doi.org/10.1016/j.jenvman.2025.124319

Ng, C.W.W., Zhang, Q., Guo, H., Ni, J., Wang, Y., Leung, A.K., Zhou, C., 2024. Eco-geotechnics under climate change: A state-of-the-art review. Biogeotechnics 100158. https://doi.org/10.1016/j.bgtech.2024.100158

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. science 328, 1517–1520. https://doi.org/10.1126/science.1185782

Ostrom, E., 2017. Polycentric systems for coping with collective action and global environmental change, in: Global Justice. Routledge, pp. 423–430. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Pahl-Wostl, C., 2015. Water Governance in the Face of Global Change: From Understanding to Transformation, Water Governance - Concepts, Methods, and Practice. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-21855-7

Philip, S.Y., Kew, S.F., van Oldenborgh, G.J., Anslow, F.S., Seneviratne, S.I., Vautard, R., Coumou, D., Ebi, K.L., Arrighi, J., Singh, R., van Aalst, M., Pereira Marghidan, C., Wehner, M., Yang, W., Li, S., Schumacher, D.L., Hauser, M., Bonnet, R., Luu, L.N., Lehner, F., Gillett, N., Tradowsky, J.S., Vecchi, G.A., Rodell, C., Stull, R.B., Howard, R., Otto, F.E.L., 2022. Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. Earth Syst. Dyn. 13, 1689–1713. https://doi.org/10.5194/esd-13-1689-2022

Pittaway, P., Hancock, N., Scobie, M., Craig, I., 2018. Minimizing evaporation loss from irrigation storages, in: Advances in Agricultural Machinery and Technologies. CRC Press, pp. 289–306.

Pittaway, P., Scobie, M., Schmidt, E., 2023. Evaporative loss and environmental impact of covers on water storages: A review. J. Environ. Qual. 52, 241–257. https://doi.org/10.1002/jeq2.20454

Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. 104, 5732–5737. https://doi.org/10.1073/pnas.0609812104

Reguero, B.G., Beck, M.W., Bresch, D.N., Calil, J., Meliane, I., 2018. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLOS ONE 13, e0192132. https://doi.org/10.1371/journal.pone.0192132

Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5, 617–624. https://doi.org/10.1016/j.cosust.2013.11.002

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561, 231–234. https://doi.org/10.1038/s41586-018-0476-5

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Sci. Rev. 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Siddik, M.A.B., 2025. Energyshed to Watershed: Linking Water and Energy Consumers to Their Environmental Impact and Water Resources.

Sivapalan, M., Savenije, H.H., Blöschl, G., 2012. Socio-hydrology: A new science of people and water. Hydrol Process 26, 1270–1276. https://doi.org/10.1002/hyp.8426

Soesbergen, A. van, Chu, Z., Shi, M., Mulligan, M., 2022. Dam reservoir extraction from remote sensing imagery using tailored metric learning strategies. https://doi.org/10.48550/arXiv.2207.05807

Srivastava, A., Sridhar, V., Kumari, N., 2025. Application of Various Hydrological Modeling Techniques and Methods in River Basin Management. Water 17, 83. https://doi.org/10.3390/w17010083

Syed, T.H., Famiglietti, J.S., Rodell, M., Chen, J., Wilson, C.R., 2008. Analysis of terrestrial water storage changes from GRACE and GLDAS. Water Resour. Res. 44. https://doi.org/10.1029/2006WR005779

Tian, W., Liu, X., Wang, K., Bai, P., Liu, C., 2021. Estimation of reservoir evaporation losses for China. J. Hydrol. 596, 126142. https://doi.org/10.1016/j.jhydrol.2021.126142

Trenberth, K.E., Fasullo, J., Smith, L., 2005. Trends and variability in column-integrated atmospheric water vapor. Clim. Dyn. 24, 741–758. https://doi.org/10.1007/s00382-005-0017-4

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. https://doi.org/10.1038/nature09440

Wada, Y., Bierkens, M.F.P., de Roo, A., Dirmeyer, P.A., Famiglietti, J.S., Hanasaki, N., Konar, M., Liu, J., Müller Schmied, H., Oki, T., Pokhrel, Y., Sivapalan, M., Troy, T.J., van Dijk, A.I.J.M., van Emmerik, T., Van Huijgevoort, M.H.J., Van Lanen, H.A.J., Vörösmarty, C.J., Wanders, N., Wheater, H., 2017. Human–water interface in hydrological modelling: current status and future directions. Hydrol. Earth Syst. Sci. 21, 4169–4193. https://doi.org/10.5194/hess-21-4169-2017

Wang, Z., Li, D., 2025. Big data and artificial intelligence-driven risk assessment and response for water resources: Model applications and future perspectives. Adv. Resour. Res. 5, 414–434. https://doi.org/10.50908/arr.5.1_414

Zhang, H., Lemckert, C., Brook, A., Schouten, P., 2010. Evaporation reduction by suspended and floating covers: overview, modelling and efficiency.

Zhao, G., Gao, H., 2019. Estimating reservoir evaporation losses for the United States: Fusing remote sensing and modeling approaches. Remote Sens. Environ. 226, 109–124. https://doi.org/10.1016/j.rse.2019.03.015

Zhao, G., Li, Y., Zhou, L., Gao, H., 2022. Evaporative water loss of 1.42 million global lakes. Nat. Commun. 13, 3686. https://doi.org/10.1038/s41467-022-31125-6

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347. https://doi.org/10.1038/s43017-020-0060-z

Appendix A Declarations

A 1. Contribution of the author

The papers that constitute this dissertation were prepared in collaboration with several co-authors, with the author serving as the lead contributor and first author. The scientific findings presented were achieved as part of the PhD research. The author played the primary role in the theoretical framework, data analysis, interpretation of results and manuscript preparation for all the papers included in this dissertation. The author's supervisor, Prof. Nima Shokri, provided guidance, oversight and critical review throughout the research and publication process.

A 2. Permissions

The author has obtained the licenses to reprint the publications that are included in this thesis:

Paper 1:

Nevermann, H., AghaKouchak, A., & Shokri, N. (2023). Sea level rise implications on future inland migration of coastal wetlands. Global ecology and conservation, 43, e02421.

Paper 2:

Nevermann, H., Gomez, J. N. B., Fröhle, P., & Shokri, N. (2023). Land loss implications of sea level rise along the coastline of Colombia under different climate change scenarios. *Climate Risk Management*, *39*, 100470.

Paper 3:

Nevermann, H., Aminzadeh, M., Madani, K., & Shokri, N. (2024). Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions. *Environmental research*, *262*, 119860.

Paper 4:

Nevermann, H., Madani, K., Zampieri, M., Hoteit, I., & Shokri, N. (2025). Struggling over water, losing it through evaporation: The case of Afghanistan and Iran. *Journal of environmental management, 375,* 124319.

Appendix B Reprinted publications

Paper 1:

Nevermann, H., AghaKouchak, A., & Shokri, N. (2023). Sea level rise implications on future inland migration of coastal wetlands. Global ecology and conservation, 43, e02421.

This published paper was incorporated as Chapter 3.2. (with permission from Elsevier).

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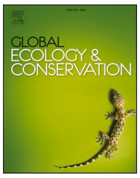

Sea level rise implications on future inland migration of coastal wetlands

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ABSTRACT

Coastal wetlands provide essential ecosystem functions, including coastal protection, improvement in water quality and carbon sequestration, which are threatened due to sea level rise (SLR) – a well-documented aspect of anthropogenic climate change. While there are numerous articles on SLR impacts on wetlands, data about the interactions between natural or human-made barriers and future SLR projections e.g. coastal squeeze are still sparse. If wetlands are bounded by natural formations or human-made structures, coastal wetlands could be permanently lost in a warming climate. Here we delineate impacts of SLR on wetland inland migration under a changing climate in six locations around the world with a particular focus on the consequences of human-made structures along coastlines in Europe, specifically along the largest continuous coastal wetland system in the world, the Wadden Sea. Various locations around the world (North America, South America, Europe, Africa, Asia and Australia) were chosen to analyze the impacts of regional SLR on wetland dynamics under climate change scenario. Our results show that places like Bangladesh, India and Myanmar have much larger areas at risk with nearly 10% of their coastal wetlands, whereas the wetlands in northern Australia seem to have a low area at risk to be lost with not even 1%. For the North Sea coast, wetlands where we had access to data from human-made infrastructure, we show that due to the built infrastructure, the wetland areas do not have the opportunity to evolve landward and hence, are expected to disappear permanently.

1. Introduction

Wetlands are identified as areas of land that are permanently or temporarily covered with water and are considered among the most valuable and productive ecosystems in the world to (Mitsch and Gosselink, 2015). Their importance was particularly emphasized in the 1971 UNESCO Ramsar Convention aimed to enhance international cooperation to foster wetland conservation. To date almost 90% of UN member states have joined and declared over 2400 wetlands “Ramsar Sites”, distributed in all climate zones, covering more than 2.5 million km^2 (Ramsar Convention Secretariat, 2021).

Coastal wetland ecosystems maintain vital functions and provide services that are crucial to humans and nature and include, among others, coastline protection (Chung et al., 2021; Costanza et al., 2014; Perillo et al., 2018; Sun and Carson, 2020), carbon sequestration (Morris et al., 2012; Nahlik and Fennessy, 2016) and biodiversity preservation, as they provide habitats for numerous plant, fish and bird species (Yang et al., 2017; Russi et al., 2013).

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The IPCC's latest Working Group I contribution to the Sixth Assessment Report, highlighted once more the threat that climate change and sea level rise (SLR) impose on coastal wetlands. The studies show that under the different climate scenarios, the projected rising sea levels exceed the levels of SLR reported in previous assessments (Masson-Delmotte et al., 2021). The Wadden Sea, for example, is one of the largest coherent coastal wetland ecosystems, and emerged around 8000 years ago along with the deceleration of the post glacial SLR (Reise et al., 2010). The Wadden Sea ecosystem adapted dynamically during the slow rate of the rising sea level, however, the projected acceleration in future SLR endangers this development (Graph inside Fig. 1).

The adaptive capability of coastal wetlands during rising sea levels can be attributed to sediment accumulation from sediments transported landwards by waves and sea tides (Reise et al., 2010) or from rivers. If the sediment supply is insufficient to make up for the SLR, the landward migration of the ecosystem during marine transgression can help to preserve coastal wetlands (Fig. 2a). However, coastal areas worldwide are home to hundreds of millions of people, and predictions show that the global coastal population will exceed one billion people this century (Hauer et al., 2020). To protect the coast from storms, floods and other SLR related hazards, a variety of structures were installed along coastlines. These structures along with natural barriers, like cliffs, prevent the landward migration of wetlands and can result in permanent disappearance of wetlands (Fig. 2b) this process is also known as coastal squeeze (Borchert et al., 2018; Torio and Chmura, 2013).

This study aims to analyze the impact of future SLR on coastal wetlands around the world with a focus on whether the wetlands have the opportunity to evolve into a new wetland environment. Our analysis includes natural or human-made barriers (Fig. 2), located alongside the North Sea coast in Europe adjacent to the largest coherent coastal wetland system in the world, that can be fatal to the future of some wetlands. In order to achieve this, locations in North America, South America, Europe, Africa, Asia and Australia were chosen (boxes labeled Zone 1 to Zone 6 in Fig. 1), that also have their significance as Ramsar Sites.

2. Methods

We used a geographic information system to assess the vulnerability of coastal wetlands to a 1 m SLR. In order to get information on the area that is at risk to be lost, we combined bathymetry data, digital elevation models as well as a database on the global extent of wetlands (see Figs. 3 and 4).

2.1. Digital elevation models and bathymetry

As a data source for our bathymetric information, we used the GEBCO_2021 Grid data. This global terrain model for ocean and land provides elevation data with a spatial resolution of 15 arc-seconds (GEBCO Compilation Group (2020). However, this data has a relatively coarse resolution, which might be challenging in shallower water depths that are more susceptible to changes in morphology due to tidal and wave action. For the land and terrain elevation information we could use the SRTM 1 Arc-Second Global elevation data offering a much higher resolution than the GEBCO grid data (Earth Resources Observation and Science (EROS) Center, 2017, Farr

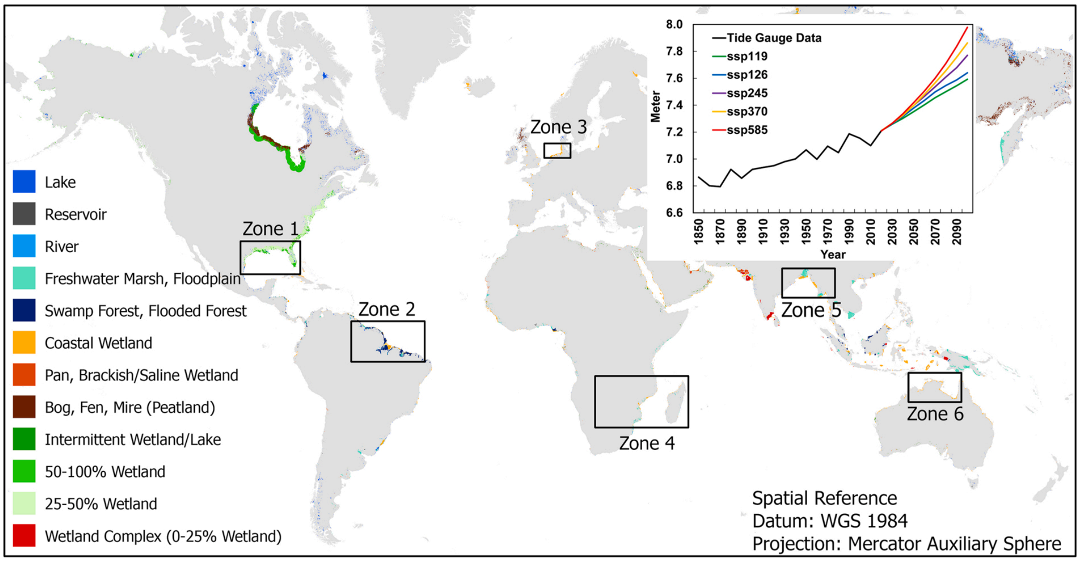

Fig. 1. Global map that shows the different types of wetlands within 100 km of the coast. The graph over Asia shows the measured sea level change over the past 170 years in black and the different projected SLR scenarios in color for the tide gauge station Cuxhaven 2, located in Germany. The black boxes show the six study areas (Zone 1 to Zone 6) that are investigated in this study.

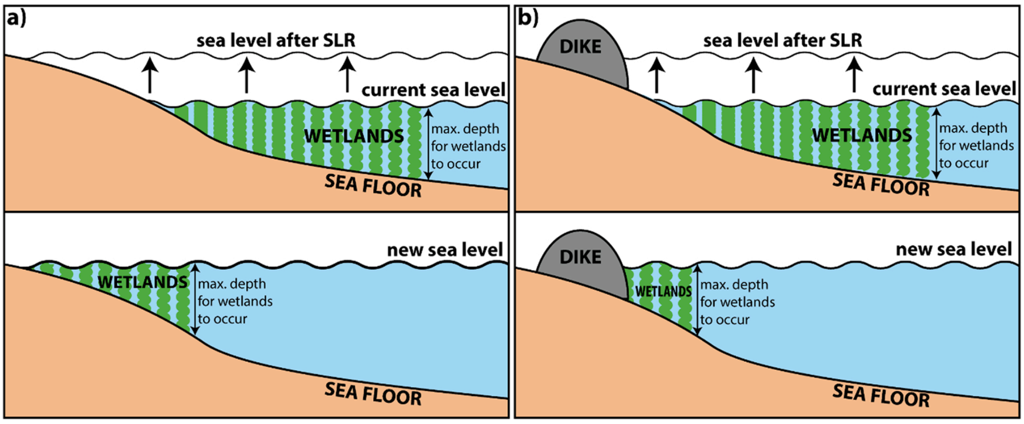

Fig. 2. Illustration of a) wetlands moving landwards due to SLR; b) coastal morphology, natural barriers or human-made structures/cities could prevent the wetlands from naturally migrating inland under SLR.

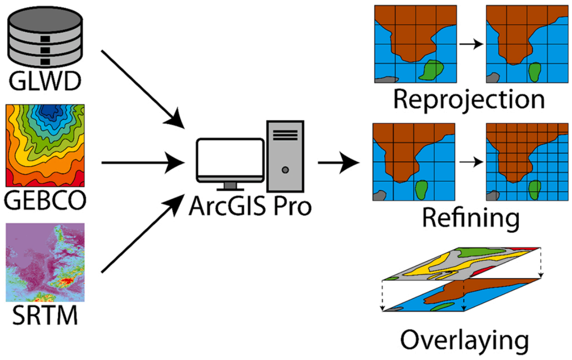

Fig. 3. Flowchart showing an overview of the basic steps of the workflow used in this study.

et al., 2007). The GEBCO_2021 Grid was refined via resampling to the cell size of the SRTM grid.

2.2. Wetland database

The main source for the distribution and classification of the wetlands was the Global Lakes and Wetlands Database (GLWD), which is a combination of several existing datasets and provides a good representation of the maximum extent of global wetlands with a spatial resolution of 30 arc-seconds (Lehner and Döll, 2004). There are various types of coastal wetlands such as salt marshes, freshwater marshes, seagrass beds, mangrove swamps as well as forested swamps. The GLWD contains one layer for coastal wetlands that includes mangroves, estuaries, deltas and lagoons. However, there are also separate layers for freshwater marshes, swamps and flooded forests, saline wetlands and also different layers that are categorized as wetland complexes with varying percentages that can be included as coastal wetlands. To include the different wetland categories appropriately, a coastal zone had to be chosen in which those wetland types that are not clearly classified as coastal wetlands are included. We chose the coastal zone that was defined in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment (Program), 2005) which includes an area that is closer than 100 km from the sea but that doesn’t exceed 50 m elevation. Towards the sea we decided to choose areas that don’t exceed water depth of 60 m due to depth limitation of sea grass beds.

2.3. Sea level projections

The data used for the different sea level projections was created by the Working Group 1 contribution to the Intergovernmental Panel on Climate Change’s Sixth Assessment Report. We used sea level projections created from CMIP6 models for this assessment (Fox-Kemper et al., in press).

Fig. 3 shows how the various data sources were combined using the ArcGIS Pro 2.7.0 software. To work with the different types of

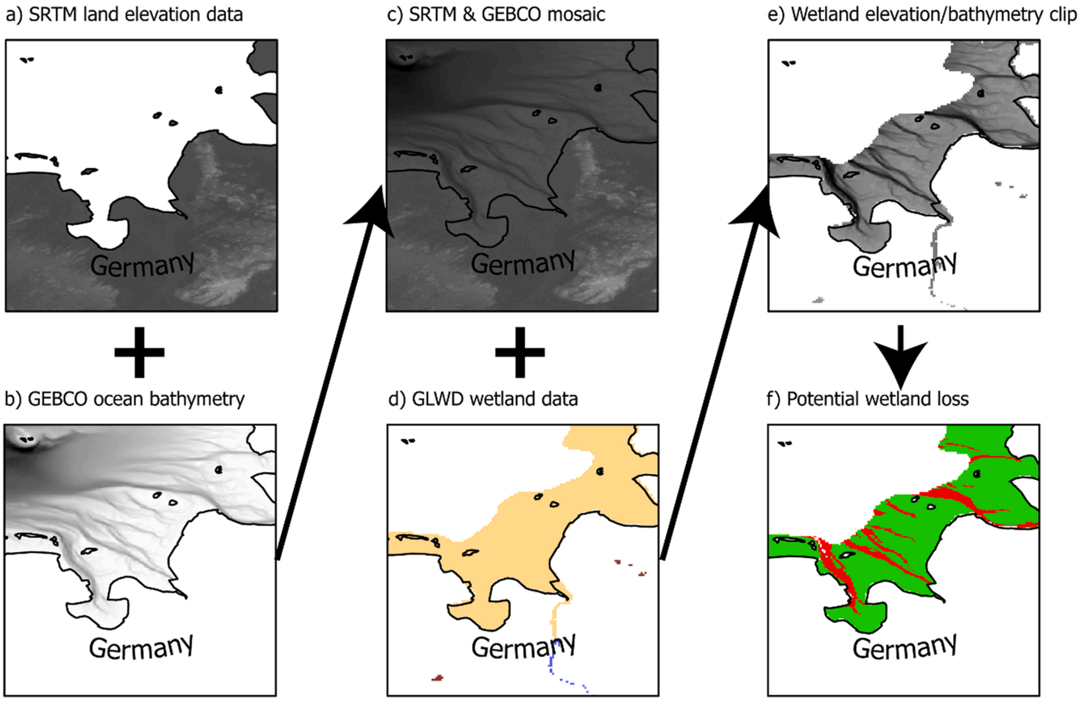

Fig. 4. Flowchart showing detailed steps of the overlaying process used to analyze the data.

data, we had to firstly project the data in appropriate coordinate system for each of the six zones. The second step encompasses refining the data in order to have identical cell sizes throughout our datasets. Once the data is refined, through the method of resampling, we could create mosaic datasets from the SRTM land elevation data and the GEBCO ocean bathymetry (Fig. 4a), b) and c)). The last step in Fig. 3 depicts the overlaying of the data. This is necessary to be able to use different geoprocessing tools such as clipping the data. Once the wetland data from the GLWD (Fig. 4d)) is clipped with the previously created mosaic (Fig. 4c)), more geoprocessing tools, e.g. raster calculator can be applied. An important step is the overlaying of the data to use different geoprocessing tools such as the raster calculator. Fig. 4f) shows how results from calculations of the raster data (Fig. 4e)) might look.

3. Results

In this study, we considered coastal wetlands on all continents, besides Antarctica, categorized into six zones (Fig. 1). Zone 1 is located in North America and comprises nearly the entire southern coast of the USA (Fig. 5). Our analysis showed that the majority of wetlands in this zone were classified as “Intermittent Wetland/Lake”, “50–100% Wetland” and “25–50% Wetland”. The extent of wetlands is nearly 19 million ha and ranges from around 50 m below sea level to 50 m above sea level (Fig. 6).

Located in South America is Zone 2, which includes large parts of the Brazilian coast (Fig. 5). Wetlands in this area were classified as “Coastal Wetland”, “Swamp Forest, Flooded Forest” and “Freshwater Marsh, Flooded Forest” and range from 95 m below sea level to 50 m above sea level (Fig. 6) making up an area of around 16.7 million ha. On the European continent we choose the Wadden Sea for our analysis which makes up Zone 3. As presented in Fig. 5, this entire area was classified as “Coastal Wetland” and spreads over the North Sea Coast of Germany, Netherlands and Denmark. Wetlands were mapped from 40 m below sea level to 50 m above sea level (Fig. 6) and cover an area of around 1.2 million ha.

Zone 4 is located in the southwest of the African continent and spreads mainly along Mozambique and South Africa (Fig. 5). “Coastal Wetland” and “Freshwater Marsh, Floodplain” make up the entirety of the wetland area in this zone covering an area of 1.3 million ha and ranges between 100 m below sea level and 50 m above sea level (Fig. 6). The wetlands in Zone 5 are mainly located in Bangladesh, India and Myanmar (Fig. 5) and were chosen as our study area for Asia. An area of around 10.4 million ha were mapped as “Coastal Wetlands” and “Freshwater Marsh, Floodplain”. The extent of the mapped wetlands in this zone varies from 100 m below sea level to 50 m above sea level (Fig. 6). The coastline of the Northern Territory and some of Queensland, Australia make up our area of interest on the Australian continent, Zone 6. The wetlands along the coastline were classified as “Coastal Wetlands” and have an extent of around 3 million ha (Fig. 5). They range from 85 m below sea level and 50 m above sea level (Fig. 6).

The classification used for the Global Lakes and Wetlands Database (GLWD), shows clear differences in the identification of wetland

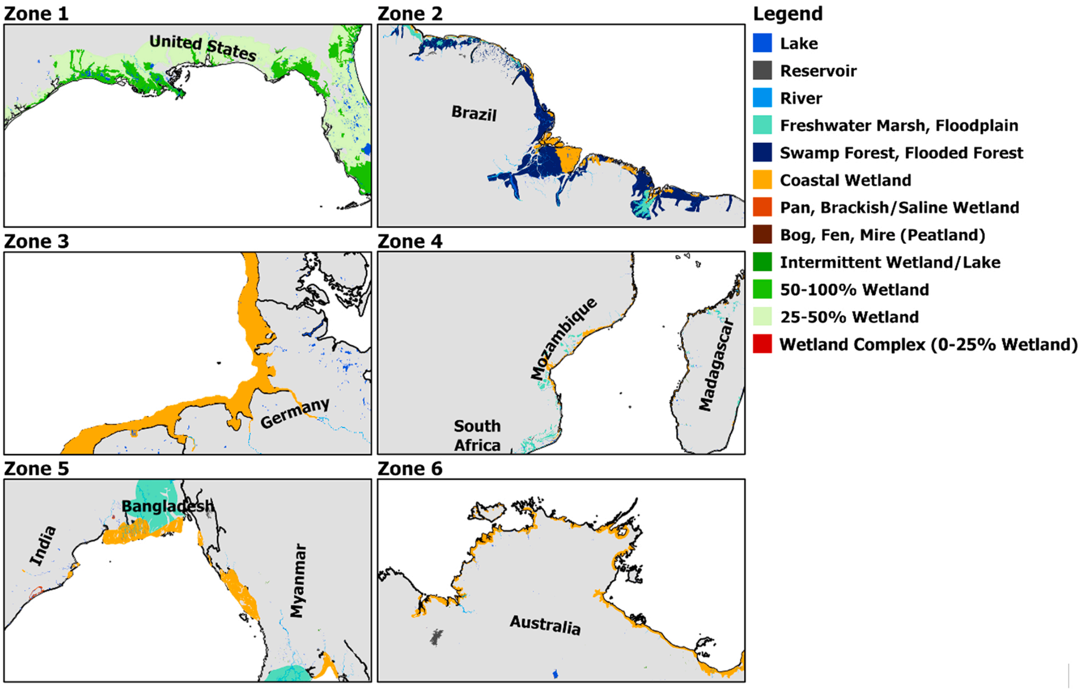

Fig. 5. Close up maps of the six zones highlighted in Fig. 1.

areas in coastal regions. For our analysis, we generated overlays of the wetland data with the bathymetry and land elevation data, allowing us to visualize the impacts of current and future sea levels based on wetlands elevation information (see the Methods section for more details). Fig. 5 shows that Zone 1 has a very large wetland area along the coast, however, it is not classified as "Coastal Wetland" but as a combination of wetlands, virtually a wetland complex. In all other zones the classification includes "Coastal Wetlands". Our data shows that the water depth in which coastal wetlands were mapped is much deeper in all six zones than what would occur naturally. This can be observed, for example in Fig. 6, where it shows depths of coastal wetlands in Zone 2, 4 and 5 of ~100 m below sea level, which is far too deep even for seagrass beds in tropical regions (Durako et al., 2003). This might be due to the coarse resolution of the GLWD. If we look at the distribution of the mapped wetlands over depth of occurrence, we can see in our data that in Zone 1, 2 and 4 (Fig. 6) large areas were mapped above sea level. In all three zones over 90% of the mapped wetlands were between 0 m and 50 m. In order to make better estimates of percentage losses of wetlands by zone, we only looked at wetland regions mapped below sea level up to a depth of 6 m (Fig. 7). The area of coastal wetlands in that range are much smaller than the mapped extent. From our analysis we estimate that only ~630 thousand ha of coastal wetlands are located between 0 m and 6 m water depth in Zone 1 (Fig. 7). Zone 2 has ~400 thousand ha, Zone 3 ~670 thousand ha, Zone 4 only ~22 thousand ha, Zone 5 has nearly 940 thousand ha and Zone 6 has ~770 thousand ha in the range between 0 m and − 6 m (Fig. 7).

Our results indicate that the area of wetland that is at risk of permanent loss due to 1 m SLR is largest in Zone 5 with nearly 10% (see Fig. 7). The second most affected area is Zone 2 with over 6%, followed by Zone 4 with ~5%, and Zone 1 and Zone 3 with both around 2.6%. Zone 6 wetlands appear to show the lowest area at risk with nearly 0.5%.

This study shows that vast areas that are currently classified as "Coastal Wetlands" and also wetlands that are just in coastal areas, are above sea level and a large fraction is not expected to entirely "drown" under 1 m of SLR. However, using a threshold of 6 m water depth for wetland definition, indicates that up to 10% of wetlands in some areas (Fig. 7 Zone 5) are at risk of permanent disappearance. The results indicate that coastal areas most threatened by SLR area in are in Bangladesh, India and Myanmar (Zone 5 in Fig. 7). These results are in line with the concerns discussed in other studies regarding the areas that seem to be greatly vulnerable to SLR (Hooijer and Vernimmen, 2021; Kibria and Yousuf Haroon, 2017). Northern Australia (Zone 6), where the environment is relatively pristine compared to other areas exhibits the lowest risk. However, the results confirm that permanent loss of coastal wetlands are expected globally and in all climate zones due to SLR consistent with other findings though with different rates (Blankespoor et al., 2014; Crosby et al., 2016; Rodríguez et al., 2017; Spencer et al., 2016; Woodruff, 2018). We note that the percentages presented here correspond to fraction of wetlands lost permanently due to 1 m SLR. In practice, a much larger area will be impacted due to the rising baseline that will also affect tidal range and enhance storm future storm surges. For this reason, the estimated loss reported here should be considered as the lower bound of future impacts.

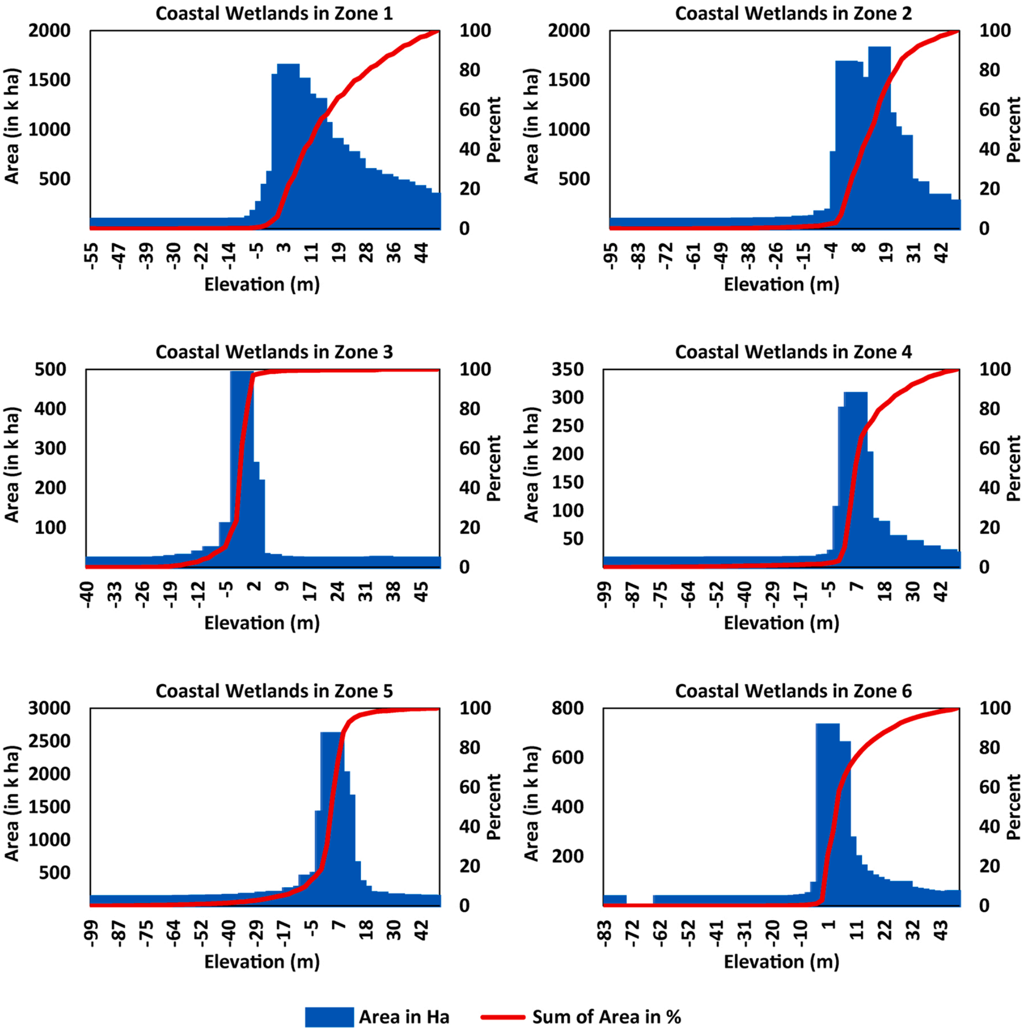

Fig. 6. Area of coastal wetlands plotted over elevation for every zone.

3.1. *Influence of human-made barriers*

The influence of human-made barriers built for coastal protections on the landward migration of the coastal wetlands has been rarely discussed in literature partly due to lack of data. Currently, conducting such analysis for the entire globe considering human-made infrastructure is not possible as there is not such global product. Here, we show the adverse consequence of such built environments on the fate of coastal wetland extending along the entire North Sea coast of Germany, called the Wadden Sea, where such data is available. The Wadden Sea is one of the world's largest intertidal wetlands registered on the UNESCO World Heritage List (Huismans et al., 2022). Fig. 8 shows the expansion of the Wadden Sea along Germany in green, and in red the area of the wetland that is at risk under 1 m SLR. Also shown in this figure is the blue colored area that displays the parts of the mainland that would be flooded at a 1 m SLR. This flooded area is large enough to compensate for the ecosystem at risk of drowning, however, the thick black line shows the location of dams, walls and dikes that are built as protection structures along the entire North Sea coast of Germany. The dikes have a height of around 8 m above the mean sea level and are expected to be elevated to over 9 m due to projected future SLR (D. J. Hofstede, 2008; D. J. (MLUR) Hofstede, 2022.; J. Hofstede and Hamann, 2022).

Since the entire coastline has a protective barrier, the event conceptualized in Fig. 2b is expected to occur. Our analysis reveals that more than 2,5% of the coastal wetlands in Zone 3 (Fig. 7), which mainly comprises of the German North Sea coast, will be under risk of being lost. Due to the presence of the human-made structure along the coast, there will be no opportunity for the wetland to evolve into

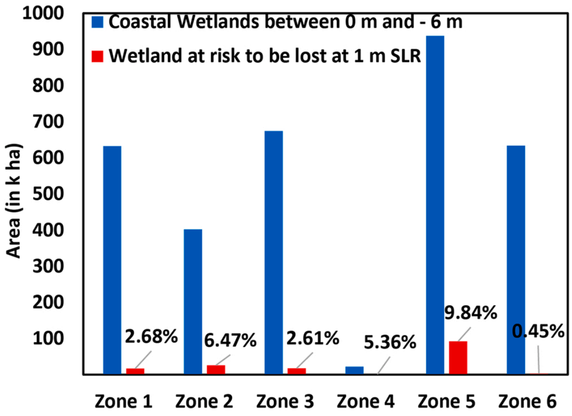

Fig. 7. Area of coastal wetland that lies extents between sea level and 6 m water depth (blue). In red is the area that is at risk at a SLR at 1 m. The locations of the zones were illustrated in Figs. 1 and 5.

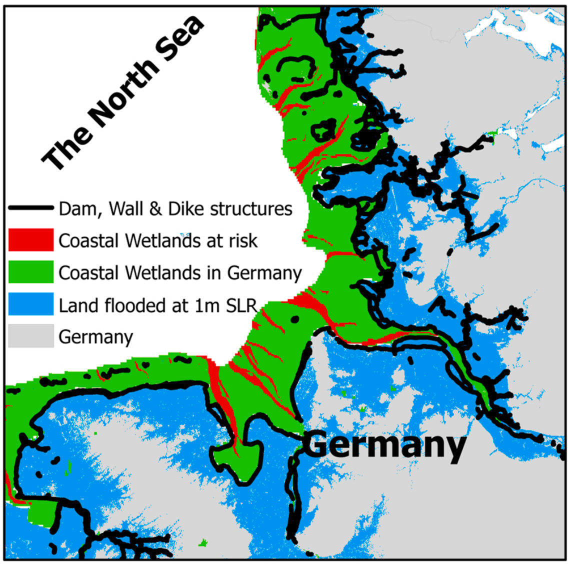

Fig. 8. Map of the German North Sea coast.

a new system by moving landward and thus, these wetlands (facing human-made barriers) may be lost permanently leading to severe consequences on ecosystem. Given that significant populations live close to the coastal areas (Hauer et al., 2020), it can be concluded that wide areas along the shorelines will be protected by structures. An increase in the coastal population will also lead to an increase in the number of protective structures to be constructed and prevent the wetlands from migrating landwards.

4. Summary and Conclusions

In this study, we investigated the implications of climate change and the accompanying SLR on the evolution of coastal wetlands. Our results showed that there are wetlands at risk on all continents, however it is unclear how much of the ecosystem will be lost and how much can adapt through a landward migration. It should be noted that the vertical growth of biomass has not been considered in this analysis that may contribute to the survival of the wetland. Quantifying dynamic changes in wetland ecosystems can be challenging due to several unknown parameters related to driving forces. Under certain conditions involving high sediment influx into coastal areas, there could be even an increase instead of a decrease in coastal wetlands (Schuerch et al., 2018). That being said, in this analysis, we examined only the horizontal shift of wetlands and did not assume any increase in sedimentation. To examine this closer, we analyzed the migration possibilities of one of the world's largest coastal wetland systems. This could be done due to the data availability in Europe. Information on natural or human-made barriers in other locations are not readily available. Such information is vital to have an accurate understanding of the complex coupling between wetland dynamics and human-made structures. This information is needed to devise the necessary action plans for coastal wetland protections.

Digital elevation models have improved greatly over the past decades, however, it is still challenging to obtain global datasets with very fine horizontal and vertical resolutions for studying wetlands. The same applies for global bathymetry datasets, especially close to the coast, as in our study. Coastal wetlands usually occur in water depths too shallow for vessels recording bathymetry. Hence, the accuracy and reliability of the bathymetry data in water depths below 10 m is hard to evaluate. The relatively coarse resolution of datasets, vertical usually 1 m or more, horizontal even more than 100 m, makes it almost impossible to determine fluctuations of sea level changes that are in the centimeter range. Due to those limitations, we assumed a sea level increase of 1 m, which is most likely expected to happen under scenario SSP3–7.0 and SSP5–8.5 in all of our locations by the year 2150 and in Zone 1 even under scenario SSP2–4.5. The changes between the different scenarios are too fine, only several centimeters or decimeters, to make valid predictions using the datasets available to us. Elevation data, obtained by lidar, has substantially improved vertical accuracy over the past decades (Gesch, 2009) however, we could not obtain those fine datasets for the areas of interest in our study. Datasets with a higher spatial resolution could significantly improve the analysis of wetlands in coastal zones. It would allow us to make more accurate statements about the distribution of these ecosystems.

Another limiting factor is the variability of coastal areas, not only on land but also below the water surface. Tidal activity and natural alterations can change the morphology of the area under investigation in a relatively short time. Heavy storms for example, can erode or modify the ground in the order of several centimeters during a single event. Therefore, it is very difficult to make clear statements about long-term changes. Since we did not have fine resolution bathymetry data, we had to exclude tidal activity in this study, although tidal activity has an impact on morphology and the overall ecosystem.

Inundation models, used in this study, for SLR have many advantages but also disadvantages e.g. areas of inundation are often overestimated when the connectivity of water is ignored (Mcleod et al., 2010). In our analysis we only counted areas that had connections to the ocean to counter this problem. Another disadvantage of the inundation model for this analysis is that it does not account for possible feedbacks on wetland accretion. We discounted this in our study due to the rapid increase in SLR, which is expected to be much faster than in previous times where sedimentary accumulation was more likely to happen (Graph inside Fig. 1).

The Global Lakes and Wetlands Database (GLWD), that was used to identify wetland areas in this study, is very comprehensive but it has some limitations. This global dataset was created by combining data from different datasets with various levels of accuracy and resolution. As a result, the information the accuracy is not necessarily consistent across space, primarily because, unlike lakes and rivers, partially under water areas cannot be mapped easily via satellites. In some locations, coastal wetlands were mapped in areas with water depths of more than 100 m. Coastal wetlands cannot even remotely exist at those depths and it is likely that the mapping was done with horizontal resolutions that were too coarse and in areas with deep slopes close to the shore. Another issue with the GLWD is that the classification is not consistent globally. In Zones 2, 3, 4, 5 and 6 the coastal wetlands were classified as "Coastal Wetland", whereas in Zone 1 nearly the entire southern coast of the USA was classified as "25–50% Wetland" or "50–100% Wetland". This makes the analysis very difficult, especially since that area is so large and at a very low elevation. It is likely that wetland types such as coastal wetlands, floodplains, swamps, bogs and others are included in that "25–50% Wetland" or "50–100% Wetland" layer. Although global datasets of wetland types, that also occur in coastal regions, exist in a finer resolution e.g. mangroves and salt marshes (Giri et al., 2011; Mcowen et al., 2017) the GLWD seemed to be the most complete dataset of global coastal wetlands that we could acquire.

Considering the variety of different study areas spread over six continents in different climatic zones, we used a rather simple model for our analysis. We decided not to use the finest datasets available, which are only for certain types of coastal wetlands in certain regions, but instead the datasets that we considered to cover the different areas with a similar accuracy. Another consideration of this assessment is the variety of biota that makes up the coastal wetlands. The six zones looked at in this study are located in different climatic zones, resulting in different plant populations. The location might also be affected by the angle of the sun, e.g. if the wetlands are closer to the equator, the sun might penetrate the water to deeper levels, allowing plant growth at greater water depths. In our analysis, we neglected the effects of such differences on wetland inland migration and we assumed that all types of coastal wetlands behave the same. In reality, different wetlands may react differently to the projected SLR but such an assumption could serve the purpose of our analysis which was to investigate and highlight the extent and possible consequences of built structure or natural barriers on inland migration of coastal wetlands. According to (Mitsch and Gosselink, 2015) coastal wetlands exist to a water depth of 6 m at low tides. The tides can vary, depending on the location, by up to several meters. However, in some regions there are sea grass beds, that are also considered as coastal wetlands, that exist at much greater depths. Sea grass beds can exist up to 50 m water depth (Durako et al., 2003) and some sea grass species (Halophila decipiens) are apparently located even deeper at ~80 m. The reliability of results in areas that contain sea grass beds at such depths is questionable. Therefore, we considered coastal wetlands in our study up to a bathymetry depth of 6 m.

Previous studies have shown that SLR impacts the loss of coastal wetlands much less than direct human modification (Kirwan and Megonigal, 2013). Coastal wetlands have the ability to compensate the "drowning" by transgression and also by geomorphological feedback mechanisms e.g. vertical sediment accretion (Kirwan et al., 2016; Kirwan and Megonigal, 2013; Schuerch et al., 2018). However, wherever humans create urban areas close to the coast it is likely there will be protection infrastructure, constructed to prevent areas from inundation. Those act as barriers and will generate coastal squeezing and that can result in coastal wetland losses (Enwright et al., 2016). The survival of coastal wetlands depends on a number of dynamic factors whose mechanisms of interaction have not been well understood. In this analysis, we only considered the landward migration and the effect of coastal squeeze by human-made structures. Important factors that need further study include the impact of socio-economic pathways or the potential availability of buffer zones for coastal wetland ecosystems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are already available with the required references provided in the paper.

Acknowledgments

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References

Blankespoor, B., Dasgupta, S., Laplante, B., 2014. Sea-level rise and coastal wetlands. AMBIO 43 (8), 996–1005. https://doi.org/10.1007/s13280-014-0500-4.

Borchert, S.M., Osland, M.J., Enwright, N.M., Griffith, K.T., 2018. Coastal wetland adaptation to sea level rise: quantifying potential for landward migration and coastal squeeze. J. Appl. Ecol. 55 (6), 2876–2887. https://doi.org/10.1111/1365-2664.13169.

Chung, M.G., Frank, K.A., Pokhrel, Y., Dietz, T., Liu, J., 2021. Natural infrastructure in sustaining global urban freshwater ecosystem services. Nat. Sustain. 4 (12), 1068–1075. https://doi.org/10.1038/s41893-021-00786-4.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Change 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Crosby, S.C., Sax, D.F., Palmer, M.E., Booth, H.S., Deegan, L.A., Bertness, M.D., Leslie, H.M., 2016. Salt marsh persistence is threatened by predicted sea-level rise. Estuar., Coast. Shelf Sci. 181, 93–99. https://doi.org/10.1016/j.ecss.2016.08.018.

Durako, M.J., Kunzelman, J.I., Kenworthy, W.J., Hammerstrom, K.K., 2003. Depth-related variability in the photobiology of two populations of Halophila johnsonii and Halophila decipiens. Mar. Biol. 142 (6), 1219–1228. https://doi.org/10.1007/s00227-003-1038-3.

Enwright, N.M., Griffith, K.T., Osland, M.J., 2016. Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise. Front. Ecol. Environ. 14 (6), 307–316. https://doi.org/10.1002/fee.1282.

Farr, T.G., et al., 2007. The shuttle radar topography mission. Rev. Geophys. 45, RG2004. https://doi.org/10.1029/2005RG000183.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A., Yu, Y., 2023. Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (In Press).

GEBCO Compilation Group (2020) GEBCO 2020 Grid (⟨doi:10.5285/a29c5465-b138–234d-e053–6c86abc040b9⟩).

Gesch, D.B., 2009. Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. J. Coast. Res. 10053, 49–58. https://doi.org/10.2112/SI53-006.1.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20 (1), 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x.

Hauer, M.E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., Wrathall, D., 2020. Sea-level rise and human migration. Nat. Rev. Earth Environ. 1 (1), 28–39. https://doi.org/10.1038/s43017-019-0002-9.

Hofstede, D.J. (2008). Küstenschutz in Schleswig-Holstein. 11.

Hofstede, D.J. (M.L.U.R.), 2022. Gen. Küstenschutz Des. Landes Schleswig-Holst. Fortschreibung 2022, 110.

Hofstede, J., & Hamann, M. (2022). The 1872 catastrophic storm surge at the Baltic Sea coast of Schleswig-Holstein; lessons learned? [Application/pdf/a]. 21 pages. ⟨https://doi.org/10.18171/1.092101⟩.

Hooijer, A., Vernimmen, R., 2021. Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. Nat. Commun. 12 (1), 3592. https://doi.org/10.1038/s41467-021-23810-9.

Kibria, G., Yousuf Haroon, A.K., 2017. Climate Change Impacts on Wetlands of Bangladesh, its Biodiversity and Ecology, and Actions and Programs to Reduce Risks. In: Prusty, B.A.K., Chandra, R., Azeez (Hrsg.), P.A. (Eds.), *Wetland Science: Perspectives From South Asia* (S. Springer, India, pp. 189–204. https://doi.org/10.1007/978-81-322-3715-0_10.

Kirwan, M.L., Megonigal, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504 (7478), 53–60. https://doi.org/10.1038/nature12856.

Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Change 6 (3), 253–260. https://doi.org/10.1038/nclimate2909.

Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296/1–4, 1–22.

Masson-Delmotte, V., Zhai, P., Priani, A., Connors, S.L., Péan, C., Berger, S., 2021. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,, Cambridge, UK.

Mcleod, E., Poulter, B., Hinkel, J., Reyes, E., Salm, R., 2010. Sea-level rise impact models and environmental conservation: a review of models and their applications. Ocean Coast. Manag. 53 (9), 507–517.

Mcowen, C.J., Weatherdon, L.V., Bochove, J.-W.V., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C.S., Spalding, M., Fletcher, S., 2017. A global map of saltmarshes. Biodivers. Data J. 5, e11764 https://doi.org/10.3897/BDJ.5.e11764.

Mitsch, W.J., Gosselink, J.G., 2015. Wetlands. John Wiley & Sons,.

Morris, J.T., Edwards, J., Crooks, S., Reyes, E., 2012. Assessment of carbon sequestration potential in coastal wetlands (S.). Recarbonization of the biosphere. Springer,, pp. 517–531 (S.).

Nahlik, A.M., Fennessy, M.S., 2016. Carbon storage in US wetlands. Nat. Commun. 7 (1), 13835. https://doi.org/10.1038/ncomms13835.

Perillo, G., Wolanski, E., Cahoon, D.R., Hopkinson, C.S., 2018. Coastal wetlands: an integrated ecosystem approach. Elsevier,.

Reise, K., Baptist, M., Burbridge, P., Dankers, N., Fischer, L., Flemming, B., Oost, A.P., & Smit, C. (2010). The Wadden Sea-a universally outstanding tidal wetland. In *The Wadden Sea 2010. Common Wadden Sea Secretariat (CWSS); Trilateral Monitoring and Assessment Group: Wilhelmshaven. (Wadden Sea Ecosystem; 29/editors, Harald Marencic and Jaap de Vlas)* (Bd. 7).

Rodríguez, J.F., Saco, P.M., Sandi, S., Saintilan, N., Riccardi, G., 2017. Potential increase in coastal wetland vulnerability to sea-level rise suggested by considering hydrodynamic attenuation effects. Nat. Commun. 8 (1), 16094. https://doi.org/10.1038/ncomms16094.

Russi, D., ten Brink, P., Farmer, A., Badura, T., Coates, D., Förster, J., Kumar, R., Davidson, N., 2013. The economics of ecosystems and biodiversity for water and wetlands. IEEP, Lond. Bruss. 78.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561 (7722), 231–234. https://doi.org/10.1038/s41586-018-0476-5.

Spencer, T., Schuerch, M., Nicholls, R.J., Hinkel, J., Lincke, D., Vafeidis, A.T., Reef, R., McFadden, L., Brown, S., 2016. Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Glob. Planet. Change 139, 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018.

Sun, F., Carson, R.T., 2020. Coastal wetlands reduce property damage during tropical cyclones. Proc. Natl. Acad. Sci. 117 (11), 5719–5725. https://doi.org/10.1073/pnas.1915169117.

Torio, D.D., Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. J. Coast. Res. 29 (5), 1049–1061. https://doi.org/10.2112/JCOASTRES-D-12-00162.1.

Woodruff, J.D., 2018. Future of tidal wetlands depends on coastal management. Nature 561 (7722), 183–185. https://doi.org/10.1038/d41586-018-06190-x.

Yang, H., Ma, M., Thompson, J.R., Flower, R.J., 2017. Protect coastal wetlands in China to save endangered migratory birds. Proc. Natl. Acad. Sci. 114 (28), E5491–E5492. https://doi.org/10.1073/pnas.1706111114.

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Land loss implications of sea level rise along the coastline of Colombia under different climate change scenarios

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ABSTRACT

The sea level has risen notably in recent decades compared to the most recent millennia. This poses serious threats to infrastructure, local jobs, environment and human population over the next century, especially in coastal zones. In this paper, the most up-to-date understanding of the climate system and climate change was used to investigate impacts of sea level rise on potential land loss along the Caribbean and Pacific coastlines of Colombia. Sea level rise projections published in August 2021 by the Intergovernmental Panel on Climate Change in the Sixth Assessment Report were used to identify the area at risk of land loss. Moreover, the potential socio-economic implications of these changes were discussed in regions affected by the projected sea level rises. We examined five Shared Socioeconomic Pathways for the 21st century (SSP1-1.9, SSP1-2.6, SSP2-4.5. SSP3-7.0, SSP5-8.5). Our results suggest a sea level rise of 1.04 m in the worst-case scenario (SSP5-8.5) which would threaten an area of 2840.64 km^2. The land use in the affected zones was determined. The area at risk will impact 12 departments or 86 municipalities with different social, environmental, economic, and cultural conditions along the coastline of Colombia, that need to be considered when devising and implementing mitigation policies.

1. Introduction

Sea level rise (SLR) is one of the consequences of climate change and may pose serious environmental and socio-economic challenges, especially in coastal environments. SLR exacerbates the impacts of extreme sea level events as well as coastal hazards, and has several detrimental effects on marine ecosystems and services (Moftakhari et al., 2017; Fagherazzi et al., 2020; Masson-Delmotte et al., 2021; Martyr-Koller et al., 2021; van den Hurk et al., 2022). The United Nations states that about 40 % of the world's population lives in coastal regions, i.e. within 100 km of the coastline (Barbier, 2015; Montgomery, 2007). The land area that is less than 10 m above sea level is just 2 % of the world's total land area, yet it is home to 10 % of the world's population and 13 % of the world's urban population (McGranahan et al., 2007). SLR, extreme sea level events, and land subsidence have the potential to significantly affect landscapes, land use, infrastructure, morphology and ecosystem services, therefore coastal areas are among the most vulnerable regions in the world (Nicholls & Cazenave, 2010; Davtalab et al., 2020). Estimations from the Intergovernmental Panel on Climate Change (IPCC) suggest a future increase in Global Mean Sea Level (GMSL) rise. Such a trend can already be observed when, for example, comparing the rate of change of 3.7 [3.2 to 4.2] mm/yr between 2006 and 2018 with the rate of 1.9 [0.8 and 2.9] mm/yr between 1971 and 2006 (Masson-Delmotte et al., 2021). In order to effectively develop ways to adapt, regional and local drivers must first be determined. Authorities and stakeholders require information regarding how sea level rise will impact specifically their local

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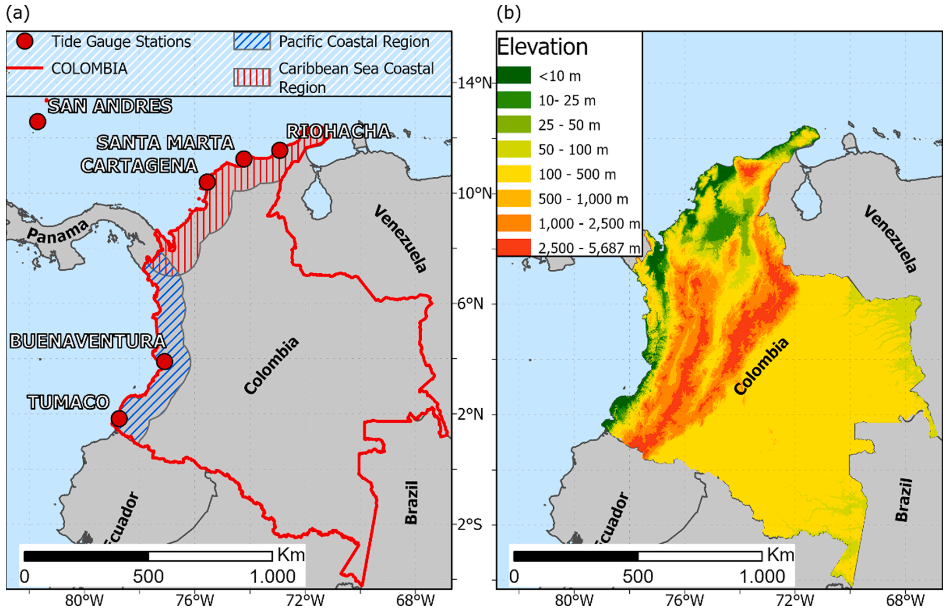


Fig. 1. (a) Map of Colombia showing tide gauge stations as well as the 100 km coastal zone for the Pacific and the Caribbean coasts (hatched zones). (b) Elevation of Colombia. The legend indicates the elevation above the sea level.

area in order to implement future development plans.

This study aims to analyze impacts on the coastline of Colombia. Colombia extends from north to south between 12°N and 4°S and from east to west between 67°W and 79°W (Fig. 1a) with a total area of nearly 1.14 million km^2 and it is home to nearly 51.3 million people (The World Bank, 2022). It is composed of 32 departments (subnational divisions) plus the capital district of Bogota, and it shares borders in the North with Panama, in the East with Venezuela and Brazil and in the South with Ecuador and Peru. The climate is predominantly tropical along the coast and in the eastern plains, whereas the highlands are characterized by a cooler climate. The overall coastline of Colombia is more than 3000 km in length, with over 1600 km on the Caribbean Sea and about 1400 km along the Pacific Ocean (Fig. 1a).

Rising sea levels and an increase in the occurrence of extreme events are recognized as key climate concerns by policymakers and the global public (Oppenheimer and Alley, 2016). Sea level rise threatens coastal areas through a combination of hazards and impacts, including intensification of episodic, temporary flooding, as well as permanent inundation of land, inundation of groundwater, and salinization of ground and surface waters (Magnan et al., 2022). Additionally, marine and terrestrial coastal ecosystems will undergo significant changes by the end of this century, which include the loss of biodiversity and ecosystem functions (Albright et al., 2018; Blankespoor et al., 2014; Borchert et al., 2018; Coldren et al., 2019; Perry et al., 2018).

Similar to other regions around the globe, SLR in Colombia is expected to cause flooding and coastal erosion (Restrepo-Ángel et al., 2021). This study analyses three different aspects of SLR consequences along the Colombian coasts. Firstly, by using different IPCC scenarios, potential land loss due to SLR will be determined. Secondly, the current land use of these threatened areas will be assessed. Finally, a socio-economic discussion will be presented to delineate the potential impact of SLR with the associated land loss on the local population.

2. Methods

2.1. Elevation information from Colombia

Digital Elevation Model (DEM) data is needed to assess land elevation compared to SLR and thus determine potential land loss as a result of the projected SLR. The data used in this study is a high accuracy Multi-Error-Removed Improved-Terrain DEM (MERIT DEM) with a resolution of 3 arc seconds (~90 m at the equator), that was created by removing the key error components from existing DEMs (NASA SRTM3 DEM, JAXA AW3D DEM, Viewfinder Panoramas DEM) (Yamazaki et al., 2017). Yamazaki et al. (2017) used a multi-step method to improve the accuracy of the global DEM. Firstly, strip noise was removed, then the absolute bias and the tree height bias were identified and removed and as a last step the speckle noise was removed by using adaptive smoothing filters. Each dataset represents 5° (latitude) by 5° (longitude) tiles. For the analysis, we merged several tiles in a mosaic dataset using the same geographic coordinate system (WGS 1984). Fig. 1b illustrates the results of DEM analysis.

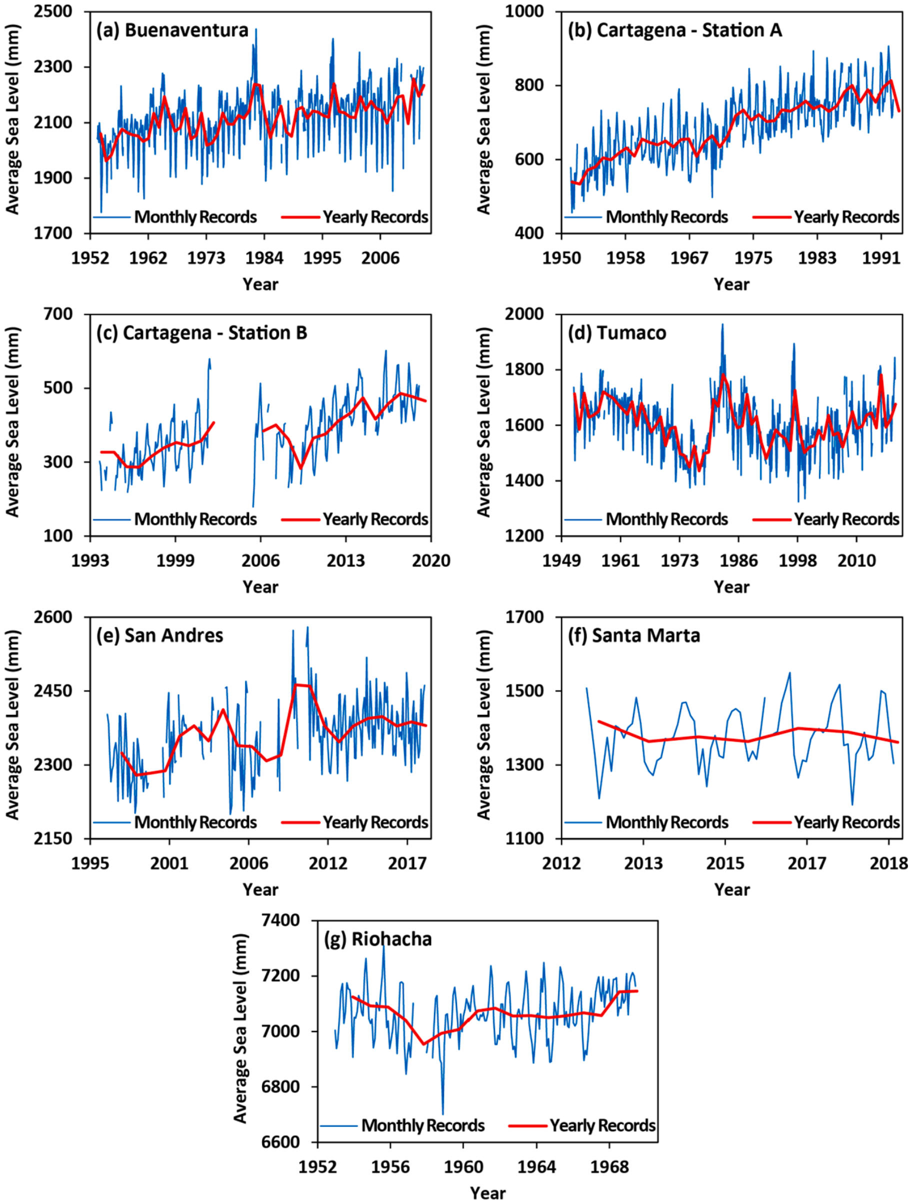


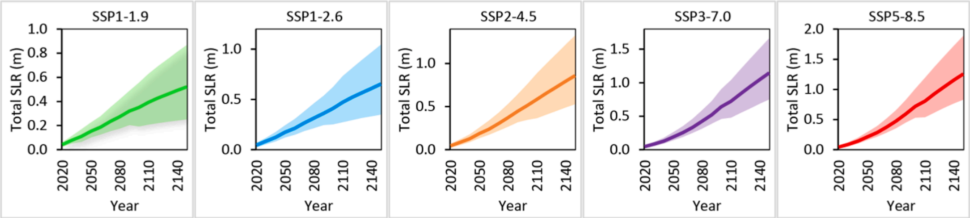
Fig. 2. Sea level rise values based on the monthly and annually averaged data measured by the tide gauge stations shown in Fig. 1a.

For the predicted future scenarios, the inundated area is calculated according to the elevation value from the DEM. For each scenario, the area is determined by connected pixels that have a value less than or equal to the sea level rise.

2.2. *Tide gauge information from Colombia*

Two organizations, the Permanent Service for Mean Sea Level (PSMSL), which offers a global data bank for long-term sea level change information including, the Global Sea Level Observing System (GLOSS), and the University of Hawaii Sea Level Center (UHSLA), collect tide gauge data on the coasts of Colombia. The two tide gauge stations located on the Pacific coast are Buenaventura and Tumaco and the four stations located on the Caribbean coast are San Andres, Cartagena, Santa Marta and Riohacha (Fig. 1a). Each

(a) Buenaventura - Pacific Ocean



(b) Cartagena - Caribbean Sea

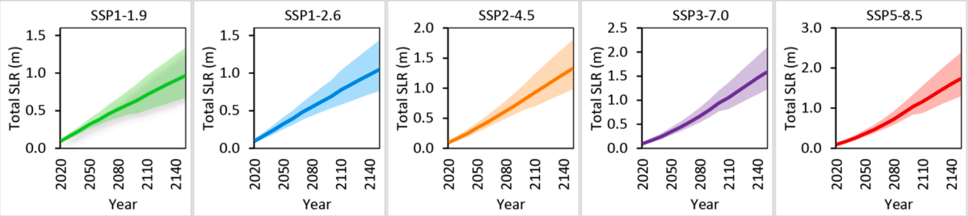


Fig. 3. Buenaventura (a) and Cartagena (b) total sea level rise. Shaded zones show the 17th-83rd percentile ranges. Projections are relative to a 1995–2014 baseline.

tide gauge station is part of a network of stations belonging either to the PSMSL - GLOSS or to the UHSLC. The quality assessment of the sea level data can be found in their metadata. There are two different types of datasets available for each station. One is fast delivery data, which is released within 1–2 months of data collection and receives only basic quality control which focuses on large sea level shifts and obvious outliers. The other data type is "science-ready" data which follows an in-depth quality control process that is time-consuming and results in research quality data. However, this process may take up to 2 years until data release. In our analysis, data in research quality was used from PSMSL – GLOSS for the tide gauge stations Buenaventura, Cartagena and Tumaco. Fast delivery data from the UHSLC was used for the stations Buenaventura, Cartagena, Tumaco, San Andres and Santa Marta. The recorded data from these stations are presented in Fig. 2.Note that the tide gauge recordings start at different years and there was a recording gap in Cartagena – Station B.

2.3. Projected climate changes and sea level rises

The IPCC has developed sea level scenarios by establishing emissions-dependent probabilistic projections and discrete scenarios-based methods (Pachauri et al., 2014). Each emissions scenario is represented by a Representative Concentration Pathway which describes different climate futures, depending on the volume of greenhouse gases emitted in the coming years. Moreover, the climate change research community has developed different scenarios incorporating future changes in climate and society to explore different alternatives for mitigation and adaptation (O'Neill et al., 2017). These scenarios, known as Shared Socioeconomic Pathways (SSP), include key aspects of society such as demographics, human development, economy and lifestyle, policies and institutions, technology and environment and natural resources and are assessed to identify challenges that are due to mitigation and adaptation. In the most recent report published by the IPCC (Masson-Delmotte et al., 2021), Integrated Assessment Models (IAM) are being used to create different scenarios of energy use, air pollution, land use, and greenhouse gas emission. The implementation of mitigation policies or lack of them could develop numerous emission scenarios for each SSP (Riahi et al., 2017). The IPCC's Sixth Assessment Report (Masson-Delmotte et al., 2021) relates an SSP with a radiative force level at the end of the 21st century depending on the mitigation and adaptation and the emission future within the IAM modeling framework. For example, the SSP1-1.9 scenario represents the SSP1-Sustainability together with a policies and emission framework that would reach a radiative forcing of 1.9 W/m^2 value by 2100. The core SSP scenarios used in the IPCC report are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Masson-Delmotte et al., 2021) therefore, we decided on using these scenarios in this study.

The IPCC analyses and assesses the scientific-experimental information and produces unified projections on future sea levels across the world under a variety of potential future scenarios. The NASA Sea Level Projection Tool (Fox-Kemper et al., 2021; Garner et al.,2021) is created to visualize and download the sea level projection data from the IPCC 6th assessment report. Sea-level change for each SSP scenario results in medium confidence (50th percentile) and two low confidence (17th and 83rd percentile range) scenarios adding several other SLR drivers such as ice sheet and thermal expansion (among other parameters). We used the NASA Sea Level Projection Tool to project SLR from 2020 to 2150 under different future climate scenarios for the tide gauge station Cartagena on the Caribbean coast and the station Buenaventura on the Pacific coast. The projected values are presented in Fig. 3 (note that the corresponding tabulated values are reported in Table SM.1).

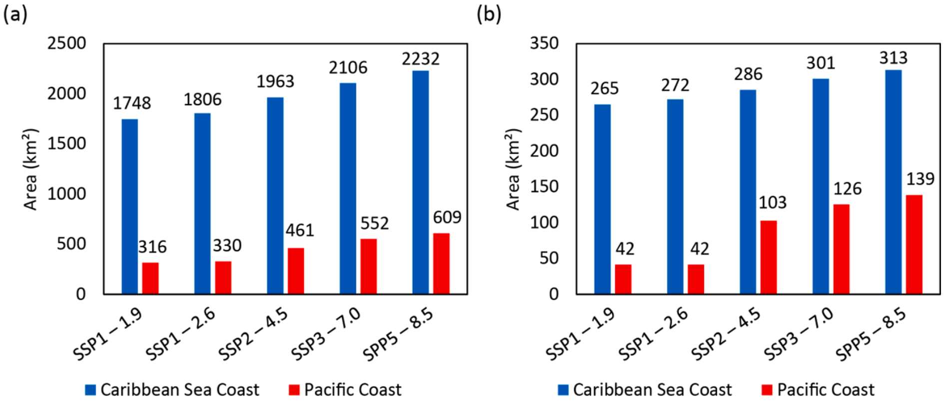


Fig. 4. Potential land loss due to the projected sea level rise for the Caribbean Sea coast and the Pacific coast within the (a) 100 km and (b) 1 km of coastlines.

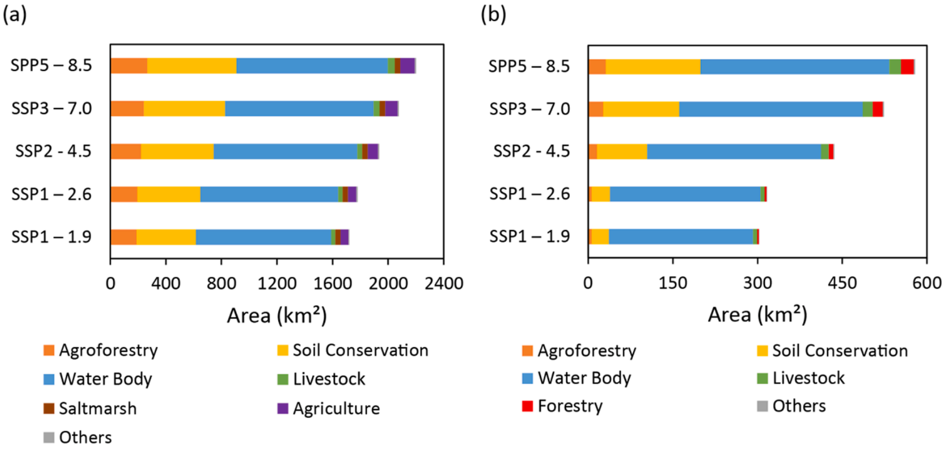


Fig. 5. Land use of the area in potential risk of land loss due to the projected sea level rise on the (a) Caribbean and (b) Pacific coastlines.

3. Results

Over the last few years, a clear SLR is seen in the Caribbean Sea, whereas a slower SLR is observed in the Pacific Ocean.

3.1. Potential land loss due to SLR according to the IPCC scenarios

Based on the previously projected SSP scenarios, the potential land loss on the Pacific and Caribbean Sea coast due to SLR was calculated. Only the area located within the 100 km coastal region (Fig. 1a) was used for the calculation with the data presented in Fig. 4a. Even though the Caribbean coast of Colombia (with around 1600 km length) is only 1.15 times as long as the Pacific coastline (less than 1400 km length), the area at risk is over 5.5 times larger on the Caribbean coast under SSP1-1.9. Under SSP1-2.6. SSP2-4.5, SSP3-7.0 and SSP5-8.5 the area at risk is still 5.5, 4.2, 3.8 and 3.7 times larger on the Caribbean coast. The total area at risk within the 100 km zone (on both Pacific and Caribbean Sea coast) is around 2064 km^2 under SSP1-1.9, 2136 km^2 under SSP1-2.6, 2424 km^2 under SSP2-4.5, 2658 km^2 under SSP3-7.0 and 2841 km^2 under the SSP5-8.5 Scenario.

Our results indicate that the Caribbean Sea coastline will experience a higher SLR than the Pacific Ocean coastline. This could be the result of natural factors such as tectonic activity and sediment compaction (Restrepo-Ángel et al., 2021). As reported in supplementary material, Table SM.1, the Caribbean Sea will undergo a sea level rise between 0.64 m (SSP1-1.9) and 1.04 m (SPP5-8.5) whereas the Pacific Ocean will experience a lesser impact with a sea level rise between 0.35 m (SSP1-1.9) and 0.72 m (SSP5-8.5). An area of 1748 km^2 and 2232 km^2 along the Caribbean Sea coast is at risk of permanent loss under SSP1-1.9 and SSP5-8.5, respectively (Fig. 4a) while these numbers are 316 km^2 and 609 km^2 for the Pacific coast (Fig. 4a). If the SLR would exceed the values of the future projections used

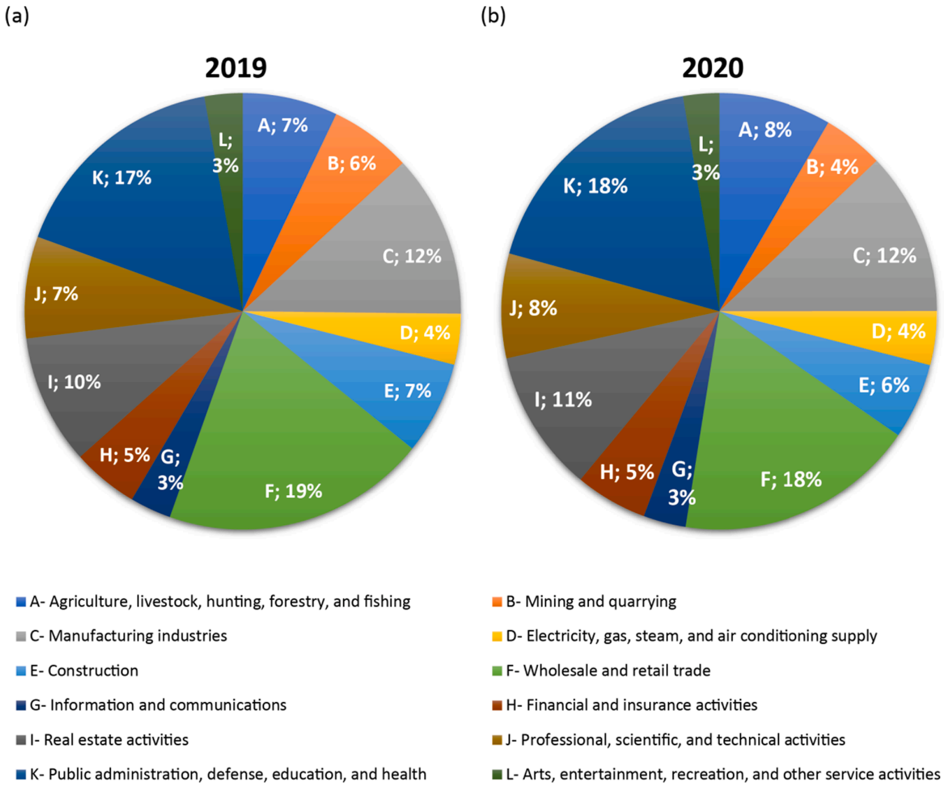


Fig. 6. Gross Domestic Product by branch of economic activity for the year 2019 (a) and 2020 (b) (DANE, 2020b).

Table 1
Department GDP percentage by branch of economy activity (%) presented in Fig. 6 (DANE, 2020b).

Department	Industry code											
	A	B	C	D	E	F	G	H	I	J	K	L
Antioquia	12.97	12.25	19.07	19.50	16.10	14.30	14.70	15.99	14.64	19.86	11.27	14.15
Córdoba	2.83	1.83	1.78	2.05	1.94	1.41	1.77	0.85	0.66	1.76	3.06	1.23
Chocó	1.15	2.26	0.03	0.12	0.33	0.29	0.15	0.17	0.09	0.01	0.98	0.15
Sucre	1.10	0.12	0.52	0.54	1.56	0.79	0.66	0.45	0.51	0.27	1.76	0.94
Atlántico	0.64	0.25	6.15	9.66	4.16	5.40	4.00	4.21	3.72	4.67	4.55	4.44
Bolívar	2.44	2.17	4.76	3.39	5.76	2.91	2.37	1.83	2.59	3.39	4.14	2.09
Magdalena	3.26	0.08	0.48	0.70	1.53	1.53	1.16	0.78	0.92	0.69	2.48	1.14
La Guajira	0.69	3.61	0.06	1.58	1.11	0.71	0.35	0.36	0.49	0.04	1.47	0.66
Cauca	3.37	0.46	2.67	1.49	2.67	1.15	0.75	0.71	0.93	1.93	2.44	0.99
Valle del Cauca	9.31	0.31	14.29	9.78	6.62	10.01	8.79	8.29	13.26	12.95	8.38	8.74
Nariño	3.59	0.33	0.35	0.62	2.38	1.74	0.86	0.99	1.35	0.74	2.77	1.55
San Andrés, Providencia y Santa Catalina (Archipiélago)	0.00	0.00	0.00	0.10	0.10	0.38	0.07	0.10	0.08	0.08	0.16	0.03

in this paper, the calculated numbers reported here would be modified accordingly. Considering that the area within 1 km of the coastline is most affected by changes in mean sea level, this area should be given special consideration by policy makers to adapt to sea level rise and mitigate some impacts. Therefore, we have performed a similar analysis to calculate the area under the risk of permanent land loss due to SLR within 1 km of the coastline of Pacific Ocean and Caribbean Sea with the results presented in Fig. 4b (see supplementary materials, Table SM. 2 and Table SM. 3, for the values used to plot Fig. 4).

Fig. 5a and 5b show the land use of the area that is in potential risk of land loss due to the projected sea level rises (the numerical values used to plot Fig. 5 are presented in the supplementary materials, Table SM. 4). On both coasts, the Caribbean and the Pacific, the land type classified as "water bodies" will be affected most by the SLR under any scenario. The second most affected land type is the

Table 2
Population (2018) in the municipalities that are at potential risk of land loss due to SLR (DANE, 2020a) and GDP per capita by each department that lies within area that is at risks (DANE, 2020b).

Department	Inhabitants	Municipalities	GDP per capita (USD)
Antioquia	371,321	8	5,898
Atlántico	2,001,531	13	4,343
Bolívar	1,081,757	8	4,163
Cauca	60,809	3	3,218
Chocó	210,323	13	2,186
Córdoba	358,124	10	2,614
La Guajira	654,452	7	2,205
Magdalena	822,223	11	2,538
Nariño	355,250	8	2,561
Sucre	109,589	4	2,341
Valle Del Cauca	258,445	1	5,816

land that is dedicated for soil conservation. As is also visible in Fig. 4, the land along the Caribbean coastline is expected to experience greater impacts.

3.2. *Socio-economic considerations and impacts*

Colombia is an emerging economy and an economic power in the South American continent. According to the International Monetary Fund (IMF), Colombia's nominal GDP is the fifth highest in Latin America after Brazil, Mexico, Chile, and Argentina, and ranks 45th in the world. The largest industry sectors in the country are public administration, defense, education and health, wholesale and retail trade and manufacturing industries (Fig. 6: Gross Domestic Product by branch of economic activity for the year 2019 (a) and 2020 (b) (DANE, 2020b). – the numerical values used to plot Fig. 6 are presented in the supplementary material, Table SM. 5).

Our results show that under SSP5-8.5 climate scenario, 12 departments and a total of 86 municipalities are directly affected by the projected SLR via its effects on potential land loss. Table 1 shows those departments and their percentage of the total economic activity of that branch. The departments Antioquia and Valle del Cauca have a great impact on the national GDP, covering a substantial ratio in most of the economic activities.

The population that is affected by the potential land loss due to SLR could vary depending on the country's development and future adaptation policies. Nevertheless, it is possible to estimate the population that currently lives in the potentially endangered area (Table 2). In addition to the affected population, it is crucial to evaluate the economic conditions in which the inhabitants live. The first factor to be evaluated is the GDP per capita. DANE reports the GDP per capita by department, which shows an estimate of the purchasing power per population (Table 2).

4. Discussion

Along the coastline of the Caribbean Sea are many important cities such as Cartagena, Barranquilla, Santa Marta, San Andres and Riohacha, which according to Banco de la Republica de Colombia are the cities that attract a large number of tourists and generate significant employment. Resources that are extracted in this coastal zone, among others, are coal, natural gas, and salts. The region's main crops are cotton, rice, coffee, cacao, cassava, African oil palm, bananas and other fruits. Cattle ranching also plays an important role, especially for dairy products, meat and also the leather industry. The economy of the Pacific region is based on industrial deep-sea fishing and mariculture; in addition, the extraction of forests for the national and international market plays a major role, as well as industrial gold and platinum mining. Livestock is also kept and the agriculture is mainly African oil palm, banana and plantain crops.

In order to determine the impact of sea level rise on the environment and the inhabitants, it is crucial to know the land use of the area that is at risk of inundation. The major land use types on both coasts, that are at risk, are water bodies and soil conservation (Fig. 5). One of the consequences of the SLR is wetland salinization. This salinization modifies the essential physicochemical nature of the soil–water environment, raising ionic concentrations and modifying chemical balances and mineral solubility (Herbert et al., 2015). Wetland ecosystem services are among the most valuable on the planet (Mitsch et al., 2015). The services include water stabilization, flood and drought mitigation, cleaning of polluted water, shoreline protection and recharging of groundwater aquifers. Wetlands also provide a unique habitat for a large variety of flora and fauna and they act as a carbon sink and can stabilize the climate. Therefore, the environmental loss due to sea level rise will have a significant impact on the natural processes of the region. Another consequence of sea level rise is soil salinization, which adversely influences vegetation, food security and environmental health (Shokri-Kuehni et al., 2020; Hassani et al., 2021). In particular, places where groundwater with high levels of salt concentration are being used for irrigation. This poses a threat to the agriculture and food production Funakawa & Kosaki, 2007). Due to the fact that land that is used for agriculture will be affected by the sea level rise under each of the SSP scenarios, and considering that agriculture, livestock, hunting, forestry and fishing represent almost 10 % of the national GDP, sea level rise poses a serious threat to food security and socio-economic activities. The different climate zones, as well as terrains, provide Colombia with a large variety of fauna and flora species making Colombia one of the world's top 5 producers of coffee, avocado, and palm oil, and one of the world's top 10 producers of sugar cane, banana, pineapple and cocoa (Food and Agriculture Organization, 2021). Furthermore, residential zones will also be

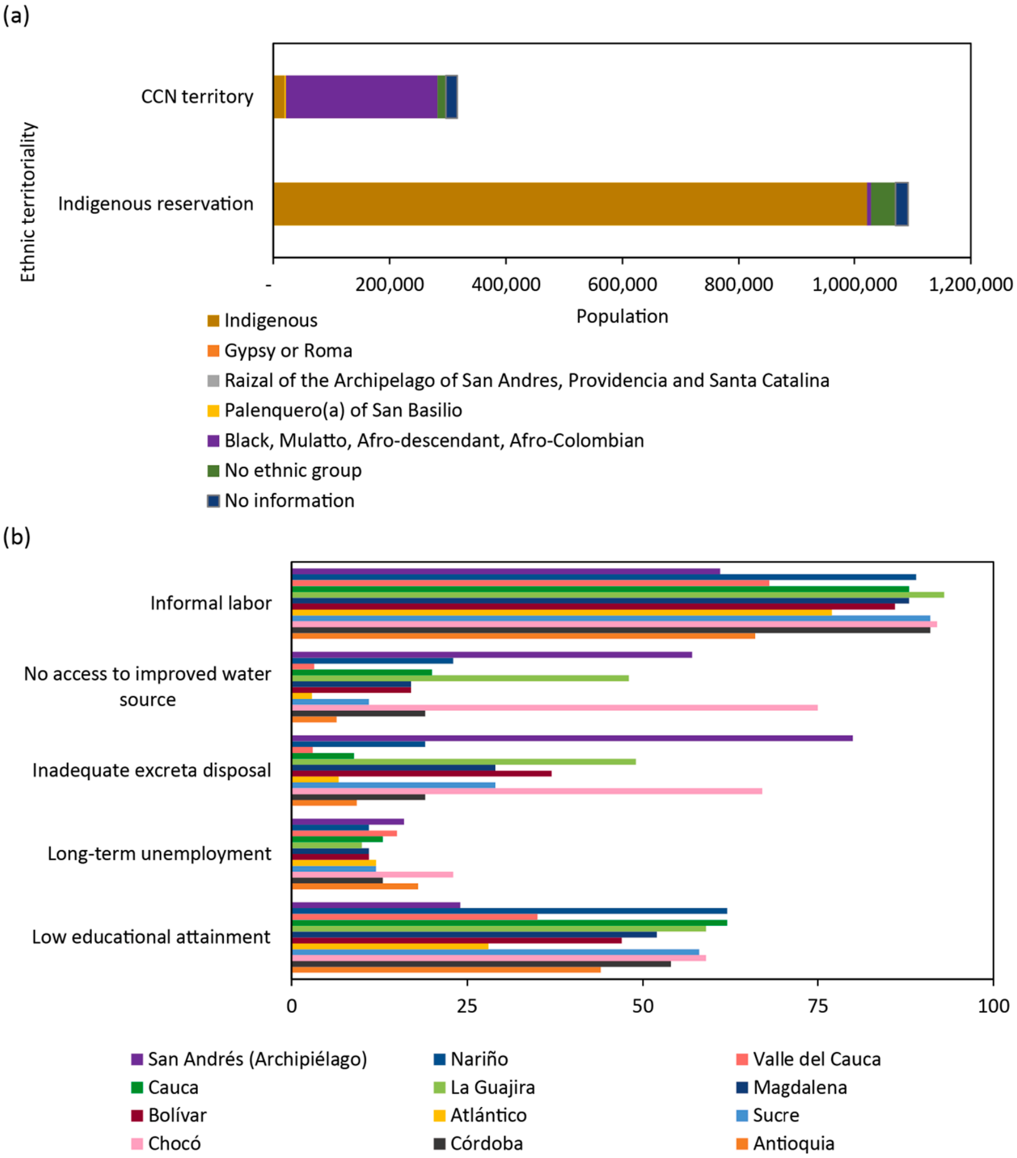


Fig. 7. (a) Population in private households, by ethnic self-recognition and ethnic territoriality. CCN: Collective Territories of Black Communities (Territorios Colectivos de Comunidades Negras) (DANE, 2020c) and (b) Social information Multidimensional Poverty Index 2020 (DANE, 2020d).

affected by the SLR under each of the SSP scenarios, requiring reallocation of families to a secure location in terms of inundation risk. In addition to the financial cost, the social consequences of such a task would be extremely complex.

The population of Colombia contains many different ethnic groups (Fig. 7a) (DANE, 2020a). Given the ethnic territories and the social-cultural value represented, the reallocation of the population in these territories could be more complex and expensive (see Fig. 7b). For example, the departments of Choco and Guajira, which may be affected by sea level rise, have a population of almost 40 % living in indigenous reservations or CCN territory, leading to a special policy in terms of mitigation and adaptation, and reallocation in case this is necessary.

In addition, these departments, and some others, have poverty indicators with values that make the implementation of policies more challenging. The informal labor rate in the departments of Choco and La Guajira are the highest in the country, 92 % and 93 % respectively, and the other affected departments have rates higher than 50 %. This makes tax collection more difficult or non-existing.

Unemployment rates in these departments are also among the highest in the country, which makes it more complicated to adapt to new mitigation and adaptation policies. Moreover, inadequate excreta disposal and no access to treated water sources are also issues that may be worsened by sea level rise.

5. Summary and conclusions

In this study we investigated the economic and social impacts of sea level rise in the coastal zones of Colombia, considering the different SSP scenarios projected by the IPCC report released in 2021. Potential land loss due to the projected sea level rises under different SSP scenarios were delineated. A reconstruction of the sea level rise back to 1870 shows a substantial acceleration in the last century, possibly as a result of global warming which melts land ice and causes ocean expansion (Church & White, 2006). However, the degree of impact on coastal areas depends on the regional and local features such as profile slope, topography, sediment type, wave conditions, tide conditions, meteorological conditions etc. (Orejarena-Rondón et al., 2019). Even though there are severe consequences of sea level rise, in theory, the implementation and success of adaptation policies are fairly uncertain, which leads to a demand for more assessment and consideration (Nicholls & Cazenave, 2010), especially on a regional scale. Therefore, it is essential to conduct local studies that consider all variables to determine the impact of sea level rise on coastal areas, to administer the best mitigation and adaptation measures. The DEM used to analyze the land elevation in our investigation has a resolution of 90 m × 90 m, which leads to uncertainty in the potential land loss assessment. Naturally, the study evaluates the land which would be below sea level with sea level rise and the behavior in an area of 8,100 m^2 could vary significantly. However, our analysis provides a general scope of the area at potential risk of inundation due to the projected sea level rise. Another limitation is that the information used to determine the sea level rise was obtained by the projections performed by the IPCC in the Sixth Assessment Report, released in 2021, which only forecasted the sea level rise for two meteorological stations in Colombia. Fortunately, the two stations are on both Pacific and Caribbean coastlines. The sea level rise projections were extrapolated spatially and temporally to the whole coastline which leads to a substantial assumption when assessing the potential land loss. Certainly, the sea level rise depends on various local and regional meteorological, climatic, geophysical and other factors and therefore, extreme waves, sea level extremes and surges need to be considered when measuring the impact of the sea level rise.

The results showed a clear trend that the Pacific coast will experience a milder increase in sea level than the Caribbean coast. The increased rates in rising sea levels along the Caribbean coast are likely attributable to natural causes such as tectonic activity or sediment compaction resulting in land subsidence (Restrepo-Ángel et al., 2021).

It should be highlighted that the potential risk assessed in this study does not consider any mitigation measures adopted to protect against the impact of the sea level rise. Each SSP scenario represents a specific pathway the society could take, but special measures, such as dykes to prevent inundation, are not considered in this analysis. Hence, the results should be understood as a signal of the consequences of sea level rise if no actions are undertaken. It should also be mentioned that the uncertainties included in the future SLR projections influence the calculated areas that are under risk of being lost.

To the best of our knowledge, the reported results in this paper offer one of the first detailed analyses of the consequences of the projected sea level rises (released by the IPCC in the Sixth Assessment Report in 2021) with the associated socio-economic impacts on the coastline of Colombia under different climate scenarios. This can be a useful tool and a starting point toward a precise calculation of the environmental, ecological and socio-economic consequences in the region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The sources of all data used in this analysis were cited in the paper and the acknowledgement section.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2022.100470.

References

Albright, R., Takeshita, Y., Koweek, D.A., Ninokawa, A., Wolfe, K., Rivlin, T., Nebuchina, Y., Young, J., Caldeira, K., 2018. Carbon dioxide addition to coral reef waters suppresses net community calcification. Nature 555 (7697), Art. 7697. https://doi.org/10.1038/nature25968.

Barbier, E.B., 2015. Climate change impacts on rural poverty in low-elevation coastal zones. Estuar. Coast. Shelf Sci. 165, A1–A13.

Blankespoor, B., Dasgupta, S., Laplante, B., 2014. Sea-Level Rise and Coastal Wetlands. Ambio 43 (8), 996–1005. https://doi.org/10.1007/s13280-014-0500-4.

Borchert, S.M., Osland, M.J., Enwright, N.M., Griffith, K.T., 2018. Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. J. Appl. Ecol. 55 (6), 2876–2887. https://doi.org/10.1111/1365-2664.13169.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. Geophys. Res. Lett. 33 (1).

Coldren, G.A., Langley, J.A., Feller, I.C., Chapman, S.K., 2019. Warming accelerates mangrove expansion and surface elevation gain in a subtropical wetland. J. Ecol. 107 (1), 79–90. https://doi.org/10.1111/1365-2745.13049.

DANE. (2020a). Censo Nacional de Población y Vivienda - CNPV 2018. DANE. http://systema59.dane.gov.co/redcol/CNPV2018/PERSONAS_SOCIAL_Cuadros%20CNPV_2018.htm.

DANE. (2020b). Cuentas Nacionales Anuales. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-anuales.

DANE. (2020c). Gran Encuesta Integrada de Hogares GEIH. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/mercado-laboral/mercado-laboral-por-departamentos.

DANE. (2020d). Indice de Pobreza Multidimensional. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/pobreza-y-condiciones-de-vida/pobreza-multidimensional.

Davtalab, R., Mirchi, A., Harris, R.J., Troilo, M.X., Madani, K., 2020. Sea level rise effect on groundwater rise and stormwater retention pond reliability. Water 12, 1129. https://doi.org/10.3390/w12041129.

Fagherazzi, S., Mariotti, G., Leonardi, N., Canestrelli, A., Nardin, W., Kearney, W.S., 2020. Salt Marsh Dynamics in a Period of Accelerated Sea Level Rise. J. Geophys. Res. - Erath Surf. 125 (8) https://doi.org/10.1029/2019JF005200.

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, A. B. A. Slangen, Y. Yu, 2021, Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In press.

Funakawa, S., Kosaki, T., 2007. Potential risk of soil salinization in different regions of Central Asia with special reference to salt reserves in deep layers of soils. Soil Sci. Plant Nutr. 53 (5), 634–649.

Garner, G. G., T. Hermans, R.E. Kopp, A.B.A. Slangen, T.L. Edwards, A. Levermann, S. Nowikci, M.D. Palmer, C. Smith, B. Fox-Kemper, H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T. L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J-B. Sallée, Y. Yu, L. Hua, T. Palmer, B. Pearson, 2021. IPCC AR6 Sea-Level Rise Projections. Version 20210809. PO.DAAC, CA, USA. Dataset accessed [2021-12-13] at https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report.

Hassani, A., Azapagic, A., Shokri, N., 2021. Global predictions of primary soil salinization under changing climate in the 21st century. Nat. Commun. 12, 6663. https://doi.org/10.1038/s41467-021-26907-3.

Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P., & Gell, P., 2015. A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. Ecosphere, 6, 10, 1–43.

Magnan, A.K., Oppenheimer, M., Garschagen, M., Buchanan, M.K., Duvat, V.K.E., Forbes, D.L., Ford, J.D., Lambert, E., Petzold, J., Renaud, F.G., Sebesvari, Z., van de Wal, R. S. W., Hinkel, J., & Pörtner, H.-O., 2022. Sea level rise risks and societal adaptation benefits in low-lying coastal areas. Sci. Reports, 12, 1, Art. 1. https://doi.org/10.1038/s41598-022-14303-w.

Martyr-Koller, R., Thomas, A., Schleussner, C.F., Nauels, A., Lissner, T., 2021. Loss and damage implications of sea-level rise on Small Island Developing States. Curr. Opin. Environ. Sustain. 50, 245–259.

Masson-Delmotte, V., Zhai, P., Priani, A., Connors, S.L., Péan, C., Berger, S., 2021. IPCC, 2021: Climate Change 2021: The Physical Science Basis. ContrIbutIon of WorkIng Group I to the SIxth Assessment Report of the Intergovernmental Panel on ClImate Change. Cambridge University Press, Cambridge, UK.

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. 19 (1), 17–37. https://doi.org/10.1177/0956247807076960.

Mitsch, W.J., Bernal, B., & Hernandez, M.E., 2015. Ecosystem services of wetlands. In: International Journal of Biodiversity Science, Ecosystem Services & Management (Bd. 11, Nummer 1, S. 1–4). Taylor & Francis.

Moftakhari, H.M., Salvadori, G., AghaKouchak, A., Sanders, B.F., Matthew, R.A., 2017. Compounding Effects of Sea Level Rise and Fluvial Flooding, Proceedings of the National Academy of Sciences, 114 (37), 9785–9790, http://doi.org/10.1073/pnas.1620325114.

Montgomery, M., 2007. United Nations Population Fund: State of World Population 2007: Unleashing the Potential of Urban Growth. Popul. Dev. Rev. 33 (3), 639–641.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science (New York, N.Y.) 328, 1517–1520. https://doi.org/10.1126/science.1185782.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180.

Oppenheimer, M., Alley, R.B., 2016. How high will the seas rise? Science 354 (6318), 1375–1377. https://doi.org/10.1126/science.aak9460.

Orejarena-Rondón, A.F., Sayol, J.M., Marcos, M., Otero, L., Restrepo, J.C., Hernández-Carrasco, I., & Orfila, A., 2019. Coastal impacts driven by sea-level rise in Cartagena de Indias. Front. Marine Sci., 6, 614.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., & Dasgupta, P., 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc.

Perry, C.T., Alvarez-Filip, L., Graham, N.A.J., Mumby, P.J., Wilson, S.K., Kench, P.S., Manzello, D.P., Morgan, K.M., Slangen, A.B.A., Thomson, D.P., Januchowski-Hartley, F., Smithers, S.G., Steneck, R.S., Carlton, R., Edinger, E.N., Enochs, I.C., Estrada-Saldívar, N., Haywood, M.D.E., Kolodziej, G., Macdonald, C., 2018. Loss of coral reef growth capacity to track future increases in sea level. Nature 558 (7710), Art. 7710. https://doi.org/10.1038/s41586-018-0194-z.

Restrepo-Ángel, J.D., Mora-Páez, H., Díaz, F., Govorcin, M., Wdowinski, S., Giraldo-Londoño, L., Tosic, M., Fernández, I., Paniagua-Arroyave, J.F., Duque-Trujillo, J. F., 2021. Coastal subsidence increases vulnerability to sea level rise over twenty first century in Cartagena, Caribbean Colombia. Sci. Rep. 11 (1), Art. 1. https://doi.org/10.1038/s41598-021-98428-4.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O`neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., & Fricko, O., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change, 42, 153–168.

Shokri-Kuehni, S.M.S., Raaijmakers, B., Kurz, T., Or, D., Helmig, R., Shokri, N., 2020. Water table depth and soil salinization: From pore-scale processes to field-scale responses. Water Resour. Res. 56 https://doi.org/10.1029/2019WR026707 e2019WR026707.

The World Bank (2022), Population, total - colombia. (n.d.). Retrieved November 23, 2022, from https://data.worldbank.org/indicator/SP.POP.TOTL?locations=CO.

van den Hurk, B., Bisaro, A., Haasnoot, M., Nicholls, R.J., Rehdanz, K., Stuparu, D., 2022. Living with sea-level rise in North-West Europe: Science-policy challenges across scales. Clim. Risk Manag. 35, 100403 https://doi.org/10.1016/j.crm.2022.100403.

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J.C., Sampson, C.C., Kanae, S., Bates, P.D., 2017. A high-accuracy map of global terrain elevations. Geophys. Res. Lett. 44 (11), 5844–5853. https://doi.org/10.1002/2017GL072874.

Supplementary Materials

Land loss implications of sea level rise along the coastline of Colombia under different climate change scenarios

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Table SM.1: Regional mean sea level projections (in meters) for 5 SSP scenarios, relative to a baseline of 1995-20140.

Climate System	**Station**	**SSP scenario at 2100**				
		SSP1 – 1.9	**SSP1 – 2.6**	**SSP2 4.5**	**SSP3 – 7.0**	**SPP5 – 8.5**
Caribbean Sea	Cartagena	0.64 (0.47, 0.86)	0.69 (0.53, 0.90)	0.82 (0.65, 1.07)	0.94 (0.77, 1.21)	1.04 (0.84, 1.34)
Pacific Ocean	Buenaventura	0.35 (0.19, 0.56)	0.41 (0.25, 0.62)	0.51 (0.35, 0.76)	0.64 (0.46, 0.90)	0.72 (0.53, 1.01)

Table SM.2: Potential land losses due to SLR within 100 km distance of the coastline per Shared Socioeconomic Pathway (SSP), given the regional mean sea level projections (in square kilometers).

Coast	**SSP1 – 1.9**	**SSP1 – 2.6**	**SSP2 – 4.5**	**SSP3 – 7.0**	**SPP5 – 8.5**
Caribbean Sea Coast	1747.68	1805.93	1963.19	2105.56	2231.78
Pacific Coast	316.12	329.68	460.9	552.21	608.89
Total	**2063.8**	**2135.61**	**2424.09**	**2657.77**	**2840.67**

Table SM.3: Potential land losses due to SLR within 1 km distance of the coastline per Shared Socioeconomic Pathway (SSP), given the regional mean sea level projection (in square kilometers).

Coast	**SSP1 – 1.9**	**SSP1 – 2.6**	**SSP2 – 4.5**	**SSP3 – 7.0**	**SPP5 – 8.5**
Caribbean Sea Coast	265.22	272.42	285.68	301.1	313.39
Pacific Coast	41.5	41.63	103.06	125.61	138.78
Total	**306.72**	**314.05**	**388.74**	**426.71**	**452.17**

Table SM.4: Area of land, divided by land use, affected under each of the SSP scenarios in square kilometers.

Coast	**Land Use**	**Shared Socioeconomic Pathway**				
		SSP1 – 1.9	**SSP1 – 2.6**	**SSP2 4.5**	**SSP3 – 7.0**	**SPP5 – 8.5**
Caribbean Sea Coast	Airport	2.91*e-5	2.91*e-5	2.91*e-5	2.91*e-5	2.91*e-5
	Agriculture	56.26	60.39	73.56	88.34	103.16
	Agroforestry	188.54	195.38	222.37	243.22	268.08
	Sandpit	0.004	0.004	0.004	0.006	0.006
	Soil Conservation	428.60	452.75	521.83	583.24	639.90
	Water Body	973.20	993.29	1033.64	1069.26	1090.16
	Forestry	2.66	2.82	3.26	3.59	3.87
	Coal Mine Pit	3.20	3.21	3.21	3.21	3.21

	Livestock	29.89	31.29	36.02	43.52	50.26
	Saltmarsh	37.70	38.56	39.53	39.85	39.96
	Residential Zone	1.35	1.41	1.65	1.98	2.27
Pacific Coast	Agriculture	0.28	0.28	0.93	1.33	1.6
	Agroforestry	6.26	6.55	15.35	26.66	31.11
	Soil Conservation	30.15	32.21	88.81	134.37	167.6
	Water Body	255.7	266.21	308.24	325.29	334.66
	Forestry	2.97	3.13	8.38	17.74	22.26
	Livestock	7.17	7.67	13.42	17.5	20.81
	Residential Zone	0.5	0.53	0.7	0.78	0.87
Total		**2024.44**	**2095.68**	**2370.91**	**2599.89**	**2779.78**
Area in potential risk without a reported land use		**39.36**	**39.93**	**53.18**	**57.88**	**60.89**

SM.5: Gross Domestic Product by branch of economic activity (DANE, 2020b).

Code	**Industry**	**2019**	**2020**
A	Agriculture, livestock, hunting, forestry, and fishing	7.06%	8.39%
B	Mining and quarrying	6.06%	4.50%
C	Manufacturing industries	12.06%	12.09%
D	Electricity, gas, steam, and air conditioning supply	3.76%	3.99%
E	Construction	6.90%	5.65%
F	Wholesale and retail trade	19.60%	17.87%
G	Information and communications	3.07%	3.16%
H	Financial and insurance activities	4.89%	5.35%
I	Real estate activities	9.63%	10.55%
J	Professional, scientific, and technical activities	7.54%	7.73%
K	Public administration, defense, education, and health	16.63%	18.04%
L	Arts, entertainment, recreation, and other service activities	2.82%	2.68%

Paper 3:

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Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions

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ABSTRACT

Dam reservoirs are at the core of local water storage and supply, especially in water-stressed regions of the world with acute water shortage problems. However, evaporative losses from these reservoirs and their storage efficiency are often overlooked in water budgeting. We offer a mechanistic approach that combines physically-based modeling with remote sensing information of reservoir characteristics to reliably predict evaporative losses from dam reservoirs. The developed framework is used to predict evaporative water losses from potential dam reservoirs in different basins worldwide. We apply this framework to 10 of the largest dam reservoirs in the world's water-stressed regions to quantify evaporative water losses. Our analysis, spanning from 2000 to 2020, reveals considerable variations in annual evaporation rates in the reservoirs located in water-deprived regions exceeding 3200 mm/year during the study period with the total evaporative loss reaching 26.5 km^3/year. The evaporative water loss accounts up to 15.8% of the storage capacity in one of the dam reservoirs, posing significant challenges for water allocation and conservation strategies, with notable economic and environmental consequences in regions already suffering from water scarcity.

1. Introduction

Global warming, along with increasing water demands, exacerbates the pressure on limited freshwater resources, particularly in water-stressed regions of the world where demands surpass the available water supply (Boretti and Rosa, 2019; Dolan et al., 2021; Huns, 2020; Wada et al., 2016), leading to a state of 'water bankruptcy' with the corresponding socio-economics implications (Madani et al., 2016; Degefu and He, 2016). Moreover, reservoirs are under increasing stress due to the combined effects of climate change and human activities, further compromising their ability to meet water demands (Cooley et al., 2021; Li et al., 2023). Throughout history, local water storages have been crucial for supplying water during dry periods. However, their numbers have drastically been growing during the past decades reaching to over 76,000 reservoirs around the world that are larger than 0.1 km^2 with total storage capacity of more than 7200 km^3 (Lehner et al., 2011). Dam reservoirs are key components of local water storages not only affecting water management and budgeting across scales, but also regulating global fluvial network and ecosystem functioning. Nevertheless, evaporative losses are often overlooked in water balance of dam reservoirs. This could impact the estimation of their storage efficiency, which could exacerbate water shortage problems, and may even intensify conflicts over shared water resources (Gleick, 2019; Oranye and Aremu, 2021; Pacific Institute, 2023; Schillinger et al., 2020; Sivapragasam et al., 2009).

With some estimates, as much as half of the stored water in small water reservoirs (between 2 and 3 m water depth) may be lost via evaporation (Aminzadeh et al., 2024; Bakhtiar et al., 2022; Craig et al., 2005; Mady et al., 2020; Rost et al., 2008). However, the intricate nature of inflows, seepage, and water releases in dam reservoirs makes it difficult to reliably estimate their evaporative losses (Friedrich et al., 2018; McMahon et al., 2013). Nonetheless, reliable estimation of evaporative fluxes from dam reservoirs are crucial for water resource management, mitigating climate change impact, sustainable development, energy production (hydroelectricity generation), understanding ecological consequences, policy making, planning and international cooperation. In particular, climate change influences evaporative fluxes from land and water reservoirs through changes in temperature, wind, and precipitation (Aminzadeh et al., 2023; Konapala et al., 2020). Dam reservoirs, particularly the ones located in water-stressed regions, could be severely influenced by these changes (Rocha et al., 2020). Furthermore, human activities such as land-use changes, urbanization, and

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increased water withdrawals are compounding the stress on these reservoirs, leading to further depletion of their water resources (Cooley et al., 2021; Li et al., 2023). Strengthening quantitative capabilities to predict and incorporate evaporative losses in the water budget calculations of the dam reservoirs under different climate scenarios enables the development of effective adaptation and mitigation strategies thus protecting people and businesses.

Currently, methods for estimation of evaporative fluxes primarily rely on pan measurements (Sivapragasam et al., 2009), Penman-type estimates with locally calibrated transfer coefficients and heat storage within the water body (Bai and Guo, 2023), eddy covariance (EC) technique (Spank et al., 2020), or measurements of water surface temperature (Zhao et al., 2020, 2022, 2023; Zhao and Gao, 2019). In this study, we seek to provide a mechanistic framework that incorporates physically-based modeling with remote sensing information, utilizing bathymetry and atmospheric data from the MERRA-2 reanalysis (a product based on a combination of models and satellite remote sensing) to reliably predict evaporative losses from dam reservoirs located in different basins worldwide. We thus consider the role of local atmospheric forcing variables and reservoir characteristics including the bathymetry and area to reliably estimate water losses via evaporation. Such mechanistic approach reduces empiricism associated with estimating evaporative losses, which often depends on in situ measurements and local calibrations, and enables trend analysis thus improving local water accounting and management.

To demonstrate the utility of the approach, we focus on the ten largest dam reservoirs in water-stressed regions of the world extended in different climatic zones (Fig. 1a). We opted for dam reservoirs located below 300 m elevation to exclude seasonally frozen reservoirs (primarily limiting the influence of air temperature lapse rate on reservoir's energy balance). High atmospheric evaporative demands in these regions driven by elevated air temperatures and wind speeds, and low humidity levels (as reflected in Fig. 1b), render these reservoirs susceptible to substantial evaporative losses.

2. Materials and methods

2.1. Reservoir characteristics and meteorological data

Water stress was calculated using the WaterGAP model and its indicators (Alcamo et al., 2003; Döll et al., 2003), which estimates runoff and water allocation based on variables such as precipitation, temperature, reservoirs, lakes, and sector-specific water use. The model operates at a spatial resolution of 0.5° (~55 km per grid cell). The water stress index was calculated by aggregating runoff and water use with ecoregion and determining the ratio of water demand to availability.

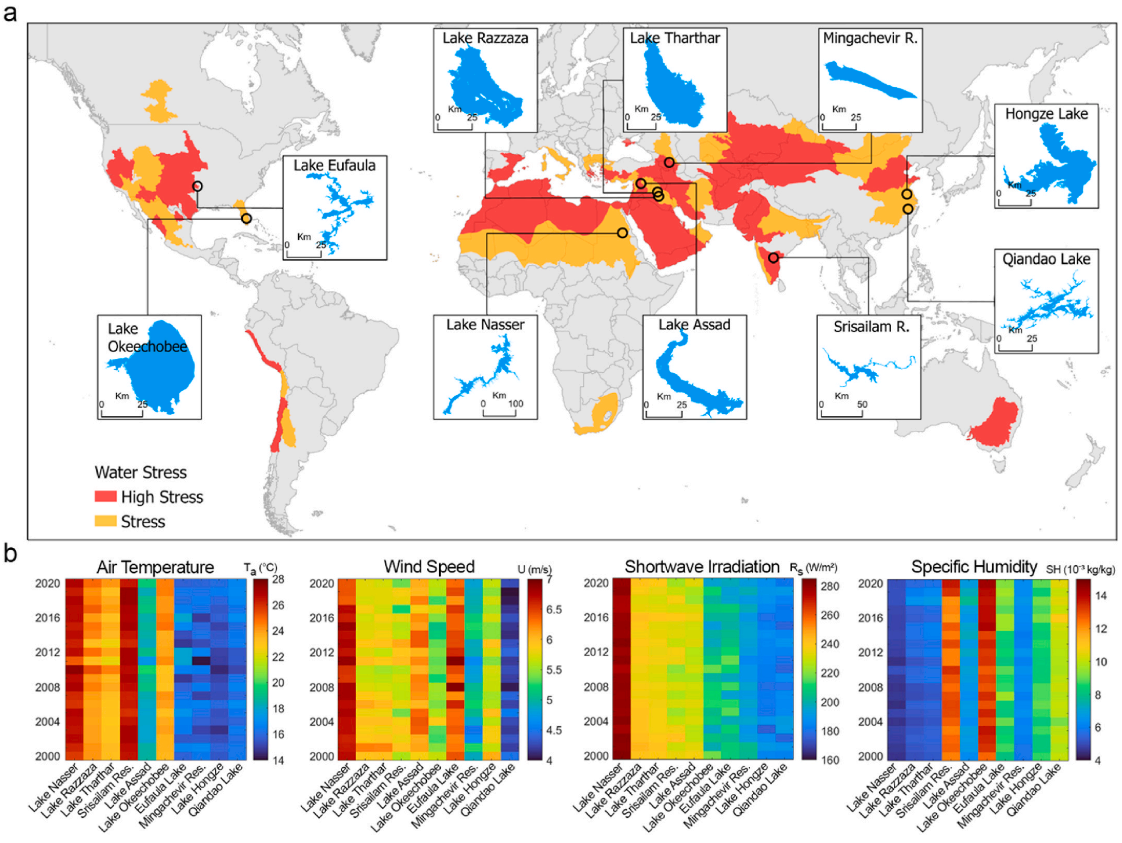

Fig. 1. (a) The largest dam reservoirs in water-stressed regions of the world (Table 1). Water stress is defined as the ratio of water withdrawal to water availability within an ecoregion, where higher values indicate greater stress on water resources (the extent of the water-stressed regions was extracted based on the data provided in the Atlas of Global Conservation (Hoekstra et al., 2010).) (b) Mean annual air temperature, wind speed, shortwave irradiation, and specific humidity of reservoirs from 2000 to 2020 extracted from MERRA-2 reanalysis datasets (Global Modeling And Assimilation Office, 2015a; Global Modeling And Assimilation Office, 2015b).

Reservoir characteristics, encompassing bathymetry, area, capacity, and elevation, were extracted from Global Reservoir and Dam Database (GRanD) and GLOBathy (Khazaei et al., 2022; Lehner et al., 2011). In this analysis, we used information on dams and reservoirs from GRanD version 1.3 consisting of 7320 records of reservoirs and dams. Each dam in the database is geospatially referenced and linked to reservoir outlines at a high spatial resolution. To obtain bathymetry information for the selected dam reservoirs, we utilized the GLOBathy dataset (Khazaei et al., 2022) created using a GIS-based framework, aligning with the widely recognized HydroLAKES global dataset (Messager et al., 2016). GLOBathy covers over 1.4 million waterbodies, including natural lakes and reservoirs. These waterbodies play a crucial role in the ecological and hydrological balance of watersheds, and their morphology and geophysical characteristics, defined by bathymetry, are vital for understanding dynamics of the waterbody. Bathymetric maps were generated based on the maximum depth estimates of waterbodies and the geometric/geophysical attributes from HydroLAKES. The accuracy of maximum depth estimates was validated using data from 1503 waterbodies, incorporating multiple observed sources.

The atmospheric forcing variables required for quantification of evaporative losses were obtained from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalyses dataset (Global Modeling And Assimilation Office, 2015a; 2015b). We thus extracted hourly meteorological data including wind speed, radiation, air temperature, and specific humidity at spatial resolution of 0.5° longitude by 0.625° latitude (approximately 55 km by 70 km).

Reservoirs located at elevations exceeding 300 m were subsequently excluded from our analysis. From the remaining reservoirs, we identified the ten largest reservoirs by surface area for further investigation as these tend to experience higher rates of evaporation (Fig. 1). This approach ensured that our study focused on dam reservoirs within water-stressed areas and prioritized those with substantial potential for water loss due to evaporation.

2.2. *Physically-based modeling of evaporation rate in dam reservoirs*

We used the physically-based model of Aminzadeh et al. (2018) to quantify evaporation rate from water reservoirs. This model solves the 1D energy balance equation considering the radiation adsorption in the depth of the water body to quantify vertical temperature profile in depth of the reservoirs:

$$\frac{\partial T_w}{\partial t} = \frac{\partial}{\partial z}\left(\left(\alpha_{T,w} + D_w\right) \frac{\partial T_w}{\partial z} \right) + \frac{Q(z,t)}{\rho_w c_w} \tag{1}$$

here, T_w [K] is the water temperature at depth z [m], $\alpha_{T,w}$ [m^2/s] is molecular thermal diffusion, D_w [m^2/s] is eddy thermal diffusivity, and ρ_w [kg/m^3] and c_w [J/kgK] are the water density and specific heat, respectively. According to Dake and Harleman (1969), the heat source (Q [W/m^3]) which is responsible for the absorption of radiative flux within the water body, is a function of depth (light attenuation) and time (diurnal or seasonal fluctuation of incoming radiation). The upper boundary condition for Eq. (1) is defined based on sensible, radiative, and latent heat fluxes at the surface, while the bottom boundary condition considers thermal exchanges with the underlying soil layer and radiation interception at the bottom of the water column. This approach allows quantification of surface temperature defining saturated vapor pressure over the surface of the evaporating water body. Hence, evaporative flux can be quantified as:

$$E = 86.4 \times 10^6 \, \frac{0.622\,\kappa^2\,U}{\rho_w\,R_d\,T_a\left[\ln\left(\frac{z}{z_0}\right)\right]^2}\left(e_s(T_{ws}) - e_a\right) \tag{2}$$

where E represents the evaporation rate [mm/day], κ is von Karman's constant, U is the wind speed [m/s], R_d is the gas constant for dry air (~287 [J/kgK]), T_a is the air temperature [K] and T_{ws} is the water surface temperature [K]. The parameter z_0 represents the roughness length [m], and z is the measurement height for wind speed and air temperature [m]. Finally, e_s and e_a [Pa], represent the saturated vapor pressure at the water surface and the vapor pressure within the air, respectively. Through this methodology, we were able to estimate and analyze the evaporation rates in an hourly resolution, providing essential information for our comprehensive assessment of water loss from dam reservoirs in water-stressed regions.

To calculate annual evaporation rates, we adopted a method of averaging the area of MERRA-2 cells that fell entirely or partially within a specific basin. It is important to highlight that the impact of inflows and outflows on changing energy balance of the water body was tacitly ignored. The presence of such detailed information would facilitate a more precise assessment of the water temperature within the reservoir, thereby enhancing the precision of estimates of evaporative losses and the dynamics of the energy balance.

3. Results

3.1. *Model evaluation using Lake Mead data*

Our model predictions of water temperature and evaporation dynamics were primarily evaluated with measurements in Lake Mead, USA, due to the availability of comprehensive, high-quality data for the selected time period (Fig. 2). With more than 640 km^2 surface area and 32 km^3 storage capacity (Ferrari, 2008), it plays a key role in supplying water demands of Nevada, Arizona, and California, which are amongst the driest states in the USA (Bartels et al., 2020; Easterling et al., 2017). The average annual precipitation (based on data from several weather stations around the lake) and temperature (measured at Lake Mead Boulder Basin ET Station, 2011–2021) of 146 mm/year and 23 °C highlight high atmospheric evaporative demands in Lake Mead (Rosen et al., 2012; USGS Surface-Water Daily Data for Nevada, 2023).

Fig. 2 compares model predictions of water temperature and evaporation dynamics with measurements of vertical temperature profile using an array of temperature sensors mounted on a floating platform and surface fluxes obtained from an eddy covariance tower in Lake Mead from March 2010 to March 2011 (Moreo and Swancar, 2013). The required atmospheric forcing variables including radiation, wind, air temperature, and humidity were extracted from a weather station in Lake Mead. The model incorporated the influence of bathymetry and variations in the reservoir's depth, enabling to estimate radiative energy absorption within the water body and subsequent determination of surface fluxes. The results in Fig. 2 indicate that the physically-based model captures dynamics of evaporative losses and temperature variations in the lake. Our model estimates of cumulative annual evaporative loss (1688 mm) is comparable with measurements (~1950 mm). The difference (~15%) between modeled and measured evaporative losses could primarily be attributed to the impact of water inflows with different temperatures affecting energy balance of the water body (currently neglected due to the lack of the reliable data). However, model estimates could be improved wherever reliable temperature data for inflows are available.

3.2. *Evaporative loss from dam reservoirs in water-stressed regions*

Although dam reservoirs play a key role in addressing seasonal water demands in regions with acute water shortages, their impacts can vary depending on local conditions and management practices affecting their storage efficiency. We employed a physically-based model to quantify evaporative losses from the ten largest dam reservoirs in water-stressed regions of the world from 2000 to 2020 (located at elevations below 300 m). The area of the selected largest reservoirs ranged from 354 km^2 (Eufaula Lake, USA) to 5385 km^2 (Lake Nasser, Egypt) with average depths varying from 2.7 m (Lake Okeechobee, USA) to 50.9 m (Qiandao Lake, China) (Table 1). The largest dam reservoir is Lake Nasser in Egypt

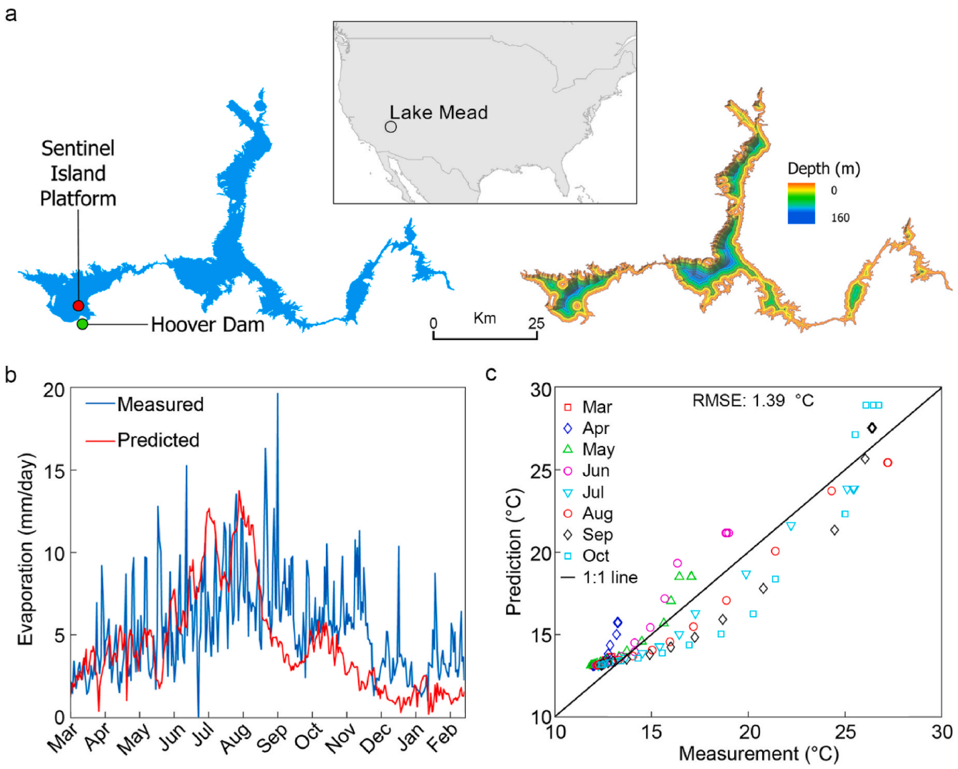

Fig. 2. (a) Lake Mead (USA) with ~640 km^2 surface area and a maximum depth of ~162 m. (b) Comparison between our model predictions of evaporation rate from March 2010 to March 2011 with measurements obtained from an Eddy Covariance (EC) tower at Sentinel Island of the lake. (c) Physically-based modeled water temperature at depths of the reservoir compared with vertical measurements using a multi-parameter water-quality sonde.

with 5385 km^2 surface area, 160 km^3 storage capacity and maximum depth of 130 m, while Eufaula Lake possesses the smallest storage capacity, measuring 4.7 km^3. With only 3.7 m maximum depth, Lake Okeechobee is the shallowest reservoir, while deepest points of Qiandao Lake reach to 176 m. Detailed specifications for each reservoir can be found in Table 1.

Characteristics of the reservoirs including surface area and bathymetry were extracted from GranD (Lehner et al., 2011) and GLOBathy (Khazaei et al., 2022), while local atmospheric forcing variables providing above surface boundary conditions were obtained from MERRA-2 (Global Modeling And Assimilation Office, 2015a; Global Modeling And Assimilation Office, 2015b). The results of our study reveal significant variations in the yearly evaporation rate from the dam reservoirs in water-stressed regions across different climatic conditions (Fig. 3a). Lake Nasser exhibits the highest evaporation rate, ranging from 2350 mm/year to 3200 mm/year, while Qiandao Lake shows the lowest evaporation rate, ranging from 383 mm/year to 692 mm/year. Fig. 3b depicts the evaporation rates for each reservoir during the study period from 2000 to 2020. To gain more profound insights, we explored the relationships between the yearly evaporation rate and first order climatic parameters, including mean annual air temperature, wind speed, shortwave irradiation, and specific humidity (Fig. 3c). Our results demonstrate that the yearly evaporation rate exhibits a positive correlation with air temperature across different climatic zones. The observed increase in the evaporation rate is approximately 122 mm/year per degree rise in temperature. Additionally, an average increase of 1 m/s in wind speed results in a notable rise of over 600 mm/year in evaporation rate. A 1 W/m^2 intensification in average shortwave irradiation causes a

Table 1
Characteristics of dam reservoirs.

Reservoir Name	Dam Name	Country	Area (km^2)	Capacity (mio m^3)	Depth avg. (m)	Depth max. (m)	Elevation ASL (m)
Lake Nasser	High Aswan Dam	Egypt	5385.34	162000	30.1	130	179
Lake Razzaza	Raza Dike	Iraq	1330.22	26000	19.5	45	29
Lake Tharthar	Thartar	Iraq	1698.86	43500	25.6	98	44
Srisailam Res.	Srisailam	India	536.42	8722	16.3	60	263
Lake Assad	Tabqa	Syria	636.77	11600	18.2	48	302
Lake Okeechobee	Structure 193	United States	1418.77	10510	2.7	4	3
Eufaula Lake	Eufaula Lake	United States	354.96	4719	13.3	27	179
Mingachevir Res.	Mingechaur	Azerbaijan	415.51	16000	38.5	130	70
Lake Hongze	Sanhezha	China	1374.36	13500	5.0	6	10
Qiandao Lake	Xinanjiang	China	424.57	21626	50.9	176	100

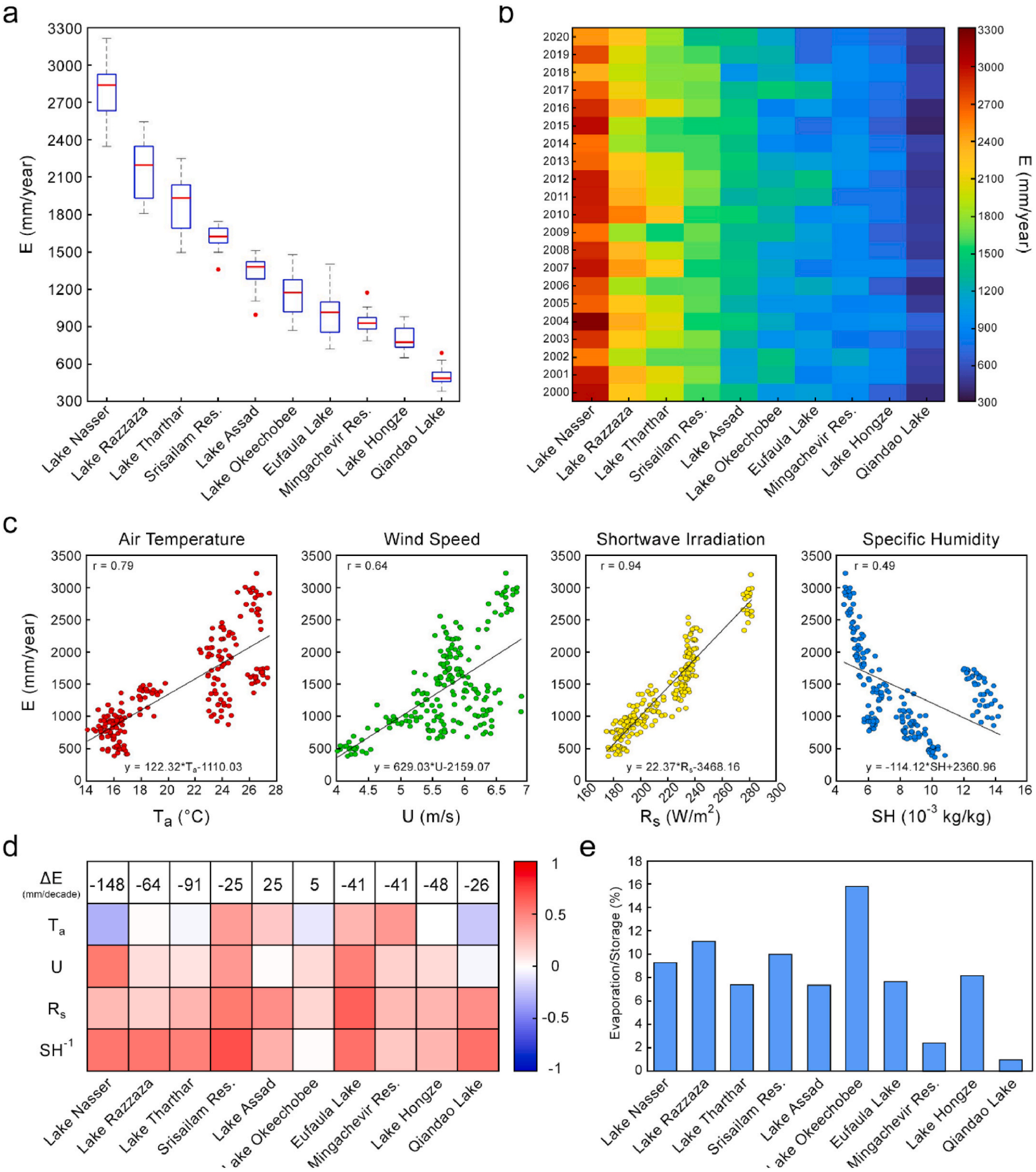

Fig. 3. Analysis of evaporation rates for 10 selected lakes in water stressed-regions of the world marked in Fig. 1. Box plot displaying the evaporation rates (a), and yearly evaporation rate from 2000 to 2020 (b). The relationship between atmospheric forcing variables (i.e., mean annual air temperature, wind speed, shortwave irradiation, and specific humidity), and yearly evaporation rate. Pearson correlation coefficients (r-values) are displayed within each plot, and the p-values are nearly 0 for all plots(c). Model estimates of the variation of evaporation rate and its correlation with local climatological factors (SH^{-1} indicates the inverse of the specific humidity) (d). The relationship between yearly evaporation volume and the total storage volume of the reservoir, expressed as a percentage (e).

rise of 22 mm/year evaporation rate. Evaporation is negatively correlated with atmospheric humidity where an increase of 10^{-3} kg/kg in specific humidity is associated with a decrease of ~115 mm/year in evaporation rate.

As demonstrated in the top row of Fig. 3d, evaporation estimates for eight reservoirs over the 21-year period (2000–2020) reveals a declining trend. This finding may deviate from the prevailing insights into the impact of global warming on heightened evaporative losses from reservoirs (Zhao et al., 2022). Consequently, we conducted additional investigations into the influence of climatic variables to offer a more comprehensive understanding of the intricate relationships governing evaporation rates in these reservoirs. Lake Nasser demonstrated the most notable decrease of ~150 mm/decade. Lake Tharthar experienced a decline of 91 mm/decade, while Lake Razzaza showed a diminishing trend of ~60 mm/decade. Eufaula Lake, Mingachevir Reservoir and Lake Hongze experience comparable decreasing trends of ~40mm/decade. Qiandao lake and Srisailam Reservoir exhibited relatively modest decreases in their evaporation rates, with a reduction of 26 and 25 mm/decade decrease, respectively. In contrast, our analysis showed that Lake Assad and Lake Okeechobee demonstrated increasing trends in their evaporative losses (25 and 5 mm/decade, respectively). Subsequent rows (2 through 5) of Fig. 3d depict the Pearson correlation coefficients between evaporation rate and mean climatic variables in each reservoir, i.e., air temperature, wind speed, shortwave irradiation, and atmospheric humidity. Considering the negative impact of humidity changes on evaporation trends, we opted to calculate the correlation based on the inverse of the specific humidity. A distinct negative correlation between evaporation rates and mean annual air temperature was observed in Lake Nasser, Lake Tharthar, and Qiandao Lake. This suggests that despite increasing air temperatures during the study period, these reservoirs encountered a reduction in evaporation rates. This underscores the complex interplay of local climatological factors influencing evaporation dynamics where the decline in evaporation patterns is primarily attributed to a decrease in wind speed and radiation and an increase in humidity levels.

We elucidated the influence of evaporation on the storage efficiency of these dam reservoirs by calculating the ratio of evaporative loss to total storage for each reservoir. Our results obtained for 2020 suggest that evaporation accounts for up to 15.8% of annual losses in dam reservoirs of water-stressed regions (Fig. 3e). Notably, shallow reservoirs such as Lake Okeechobee, Lake Razzaza, and Srisailam Reservoir exhibit high ratios of evaporative losses to storage capacity, while deep reservoirs like Qiandao Lake and Mingachevir Reservoir appear to be more efficient for water storage purposes.

4. Discussion

4.1. *Implication of evaporative losses from dam reservoirs located in water-stressed regions*

The estimated evaporation rates, surpassing 3000 mm/year in the studied water-stressed regions, underscore the significant water loss taking place in dam reservoirs. These losses amplify overall water stress, exacerbating the challenges faced in water-stressed regions in fulfilling water demands. The cumulative evaporative loss from the top 10 largest dam reservoirs, exceeding 26.5 km^3/year over this 21-year analysis, highlights the significant impact of evaporation on water availability. Considering the global freshwater withdrawal of 3900 km^3 in 2020 (FAO, 2021), the cumulative evaporative losses from the 10 selected dam reservoirs located in the water-stressed regions in this study account for more than 0.68% of the total freshwater demands. To mitigate the evaporative losses, the implementation of effective strategies is essential. Modular floating elements have proven to be a potential solution for reducing evaporation from small water reservoirs (Aminzadeh et al., 2018; Bakhtiar et al., 2022; Jin et al., 2022; Lehmann et al., 2019, Pourmand et al., 2022; Rezazadeh et al., 2020). However, for larger water bodies like dam reservoirs, alternative methods such as chemical monolayers are often used. Laboratory studies have shown that molecularly thin films of compounds like hexadecanol and octadecanol can significantly reduce water evaporation (Barnes, 2008). Despite their potential cost-effectiveness, these monolayers face challenges such as limited lifespans and uneven distribution across large water surfaces (e.g., due to the wind effect), which diminish their efficiency under real environmental conditions (Barnes, 2008; Karimzadeh et al., 2023).

The economic significance of evaporative losses of stored blue water, i.e. liquid water in surface and groundwater reservoirs (Madani and Khatami, 2015), from dam reservoirs can be further assessed by comparing them with the costs of alternative freshwater resources, such as desalination. The cost of desalinated water production could reach to 2 USD/m^3 in some areas of the world depending on the type and capacity of the desalination plants. Accordingly, direct economic cost of 26.5 km^3 evaporative water loss may exceed 53 billion USD/year (Caldera et al., 2018; Pistocchi et al., 2020). This amount of water may alternatively support livestock or additional crop production. Considering the water footprint of wheat, rice, and maize (approximately 1827, 1673, and 1222 l/kg, respectively (Mekonnen and Hoekstra, 2011a; Mekonnen and Hoekstra, 2011b), 26.5 km^3 yearly evaporative losses could provide the necessary water demands for production of ~15 million tons of wheat, 16 million tons of rice, and 21 million tons of maize. These numbers would change if different crops with varying water demands were considered in the calculation. Additionally, since the crops are not produced using only blue water, this also affects the reported values.

4.2. *Global estimates of evaporative loss from dam reservoirs in different basins*

Significant evaporative water losses from dam reservoirs in water-stressed regions highlight the importance of accurately estimating evaporation dynamics from such reservoirs worldwide. Therefore, we used the developed methodology to predict evaporative losses from potential dam reservoirs worldwide with the results presented in Fig. 4 depicting our model predictions for potential dam reservoirs (assuming 30 m average depth, consistent with existing estimates for large dam reservoirs) in different basins worldwide. We tacitly ignored freezing periods and condensation process to provide a conservative estimate for upper bound of potential evaporative losses. Spatially averaged atmospheric forcing variables in each basin were used to obtain the results reported in Fig. 4.

Our approach enables a deeper understanding of the intricate interplay between local environmental factors (air temperature, wind speed, solar irradiation and humidity) and their effects on evaporative losses, fostering a more accurate and reliable assessment of water resources management globally. The results presented in Fig. 4 offer quantitative tools for making informed decisions for the design and construction of water storage infrastructures. In the presence of reliable climate data with high spatial and temporal resolutions (Bauer et al., 2021), one could utilize the methodology proposed here to design and construct more resilient dam reservoirs in the face of projected climate changes. Such efforts contribute to several United Nations Sustainable Development Goals (UN SDGs), The European Green Deal and the Paris Agreement.

4.3. *Model limitations and future improvements*

The proposed mechanistic framework enables the prediction of evaporative losses from dam reservoirs under different climatic and reservoir conditions. However, our modeling approach has some limitations that could be addressed in future investigations. Snowmelt and surface run off with different temperatures (Roberts et al., 2018), water release from the dam reservoirs, and varying water levels throughout the year can affect energy balance and thus water temperature within the

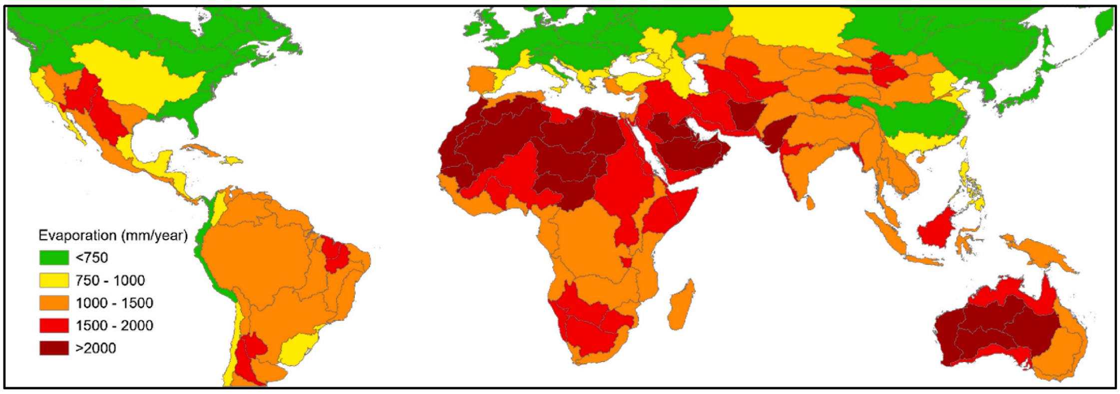

Fig. 4. Modeled yearly evaporation rates from hypothetical representative dam reservoirs (with average depth of 30 m) in 185 basins worldwide. Model results were obtained based on the average meteorological data of 2020 over each basin.

reservoirs (Wright et al., 2009). In the present study, we implicitly neglected the role of water inflows and outflows to the reservoir to maintain the model's applicability for estimating evaporative losses globally. Presence of such detailed information of water flows and their associated temperatures will improve our model estimations. In addition, the relatively coarse resolution of MERRA-2 reanalysis meteorological datasets (0.5° × 0.625°) may not fully represent atmospheric boundary conditions above the reservoirs. Having highly resolved atmospheric forcing variables would enable us to improve our model estimates of water evaporation (Bauer et al., 2021; Shokri et al., 2023).

Uncertainties associated with bathymetric datasets may further influence our model estimations. Current global bathymetry models, including GLOBathy, are known to have relatively large uncertainties, especially when applied at the scale of individual reservoirs (Hao et al., 2024). The lack of high-resolution and accurate bathymetric data for many global reservoirs introduces additional uncertainty into our model's ability to precisely estimate evaporative losses. These inaccuracies can influence water volume estimations, surface area calculations, and, consequently, evaporation predictions. To enhance the model, future studies should consider integrating advanced bathymetric technologies, such as satellite-based altimetry and high-resolution sonar mapping, which are improving the accuracy of bathymetric datasets (Li et al., 2020). The development of these technologies and the refinement of bathymetric data will help to reduce uncertainties in water depth and surface area estimations, leading to more precise predictions of water temperature and evaporation rates.

5. Summary and conclusions

We developed and applied a mechanistic approach to estimate evaporative losses from the largest dam reservoirs in water-stressed regions of the world from 2000 to 2020. The model results revealed that evaporation rates in these regions may exceed 3000 mm/year with cumulative evaporative losses reaching as high as 26.5 km^3/year. Among the studied regions, Lake Nasser, with its hot and dry climate, exhibited the highest evaporation rate (3221 mm/year in 2004), while Qiandao Lake had the lowest rate (383 mm/year in 2015).

Our study highlights the significance of evaporative water losses from large reservoirs, especially in regions with limited water availability and in the state of water bankruptcy. The importance of such losses is better understood when gauged with the cost of conventional water production methods like desalination (with considerable adverse environmental influences (Jones et al., 2019)) or resulting lost opportunities (e.g. crop production with additional water availability) (Caldera et al., 2018). This highlights the urgent need for effective water management strategies to mitigate water loss and ensure the sustainability of water resources around the world, particularly in water-stressed regions. Our analyses unveiled valuable insights into the relationship between evaporation loss from dam reservoirs and meteorological factors. We observed that evaporation increases by 122 mm per 1 °C increase in air temperature, 629 mm per 1 m/s increase in wind speed, and 22 mm per 1 W/m^2 rise in shortwave radiation flux. These identified correlations lay the groundwork for projecting future evaporation rates and devising necessary actions to cope with water shortages in water-stressed regions. The proposed approach further enabled us to delineate potential evaporative losses from typical dam reservoirs across different climatic zones around the world thus highlighted the significance of evaporative losses and their potential implications for improving water management and budgeting.

CRediT authorship contribution statement

Hannes Nevermann: Writing – original draft, Methodology, Formal analysis, Data curation. **Milad Aminzadeh:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Kaveh Madani:** Writing – review & editing, Conceptualization. **Nima Shokri:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data used in this analysis are listed in the acknowledgements and are sourced from publicly available resources.

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References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003. Development and testing of the WaterGAP 2 global model of water use and availability. Hydrol. Sci. J. 48 (3), 317–337.

Aminzadeh, M., Friedrich, N., Narayanaswamy, S.G., Madani, M., Shokri, N., 2024. Evaporation loss from small agricultural reservoirs: an overlooked component of water accounting. Earth's Future 12, e2023EF004050.

Aminzadeh, M., Lehmann, P., Or, D., 2018. Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. Hydrol. Earth Syst. Sci. 22, 4015–4032.

Aminzadeh, M., Or, D., Stevens, B., AghaKouchak, A., Shokri, N., 2023. Upper bounds of maximum land surface temperatures in a warming climate and limits to plant growth. Earth's Future 11, e2023EF003755.

Bai, P., Guo, X., 2023. Development of a 60-year high-resolution water body evaporation dataset in China. Agric. For. Meteorol. 334, 109428.

Bakhtiar, M., Aminzadeh, M., Taheriyoun, M., Or, D., Mashayekh, E., 2022. Effects of floating covers used for evaporation suppression on reservoir physical, chemical and biological water quality parameters. Ecohydrology 15 (8), e2470.

Barnes, G.T., 2008. The potential for monolayers to reduce the evaporation of water from large water storages. Agric. Water Manag. 95 (4), 339–353.

Bartels, R.J., Black, A.W., Keim, B.D., 2020. Trends in precipitation days in the United States. Int. J. Climatol. 40 (2), 1038–1048.

Bauer, P., Stevens, B., Hazeleger, W., 2021. A digital twin of Earth for the green transition. Nat. Clim. Change 11 (2), 80–83.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the world water development report. npj Clean Water 2, 15.

Caldera, U., Bogdanov, D., Breyer, C., 2018. Desalination costs using renewable energy technologies. In: Renewable Energy Powered Desalination Handbook (S. 287–329. Elsevier.

Cooley, S.W., Ryan, J.C., Smith, L.C., 2021. Human alteration of global surface water storage variability. Nature 591, 78.

Craig, I., Green, A., Scobie, M., Schmidt, E., 2005. Controlling evaporation loss from water storages. National Centre for Engineering in Agriculture Publication 1000580/1, USQ, Toowoomba.

Dake, J.M., Harleman, D.R., 1969. Thermal stratification in lakes: analytical and laboratory studies. Water Resour. Res. 5 (2), 484–495.

Degefu, D.M., He, W., 2016. Water bankruptcy in the mighty Nile river basin. Sustainable Water Resources Management 2, 29–37.

Dolan, F., Lamontagne, J., Link, R., et al., 2021. Evaluating the economic impact of water scarcity in a changing world. Nat. Commun. 12, 1915.

Döll, P., Kaspar, F., Lehner, B., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. J. Hydrol. 270 (1–2), 105–134.

Easterling, D.R., Arnold, J.R., Knutson, T., Kunkel, K.E., LeGrande, A.N., Leung, L.R., Vose, R.S., Waliser, D.E., Wehner, M.F., 2017. Ch. 7: precipitation change in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program. https://doi.org/10.7930/J0H993CC.

FAO, 2021. AQUASTAT Database. http://www.fao.org/aquastat/statistics/query/index.html. (Accessed 17 October 2023).

Ferrari, R.L., 2008. 2001 Lake Mead Sedimentation Survey.

Friedrich, K., Grossman, R.L., Huntington, J., Blanken, P.D., Lenters, J., Holman, K.D., Gochis, D., Livneh, B., Prairie, J., Skeie, E., Healey, N.C., Dahm, K., Pearson, C., Finnessey, T., Hook, S.J., Kowalski, T., 2018. Reservoir evaporation in the western United States: current science, challenges, and future needs. Bull. Am. Meteorol. Soc. 99 (1), 167–187.

Gleick, P.H., 2019. Water as a weapon and casualty of conflict: freshwater and international humanitarian law. Water Resour. Manag. 33 (5), 1737–1751.

Global Modeling And Assimilation Office (GMAO), 2015a. MERRA-2 inst1_2d_lfo_Nx: 2d,1-Hourly,Instantaneous,Single-Level,Assimilation,Land Surface Forcings V5.12.4. NASA Goddard Earth Sciences Data and Information Services Center. https://doi.org/10.5067/RCMZA6TL70BG.

Global Modeling And Assimilation Office (GMAO), 2015b. MERRA-2 tavg1_2d_rad_Nx: 2d,1-Hourly,Time-Averaged,Single-Level,Assimilation,Radiation Diagnostics V5.12.4. NASA Goddard Earth Sciences Data and Information Services Center. https://doi.org/10.5067/Q9QMY5PBNV1T.

Hao, Z., Chen, F., Jia, X., Cai, X., Yang, C., Du, Y., Ling, F., 2024. GRDL: a new global reservoir area-storage-depth data set derived through deep learning- based bathymetry reconstruction. Water Resour. Res. 60, e2023WR035781.

Hoekstra, J.M., Molnar, J.L., Jennings, M., Revenga, C., Spalding, M.D., Boucher, T.M., Robertson, J.C., Heibel, T.J., Ellison, K., 2010. The Atlas of Global Conservation: Changes, Challenges, and Opportunities to Make a Difference. University of California Press, Berkeley.

Huns, P., 2020. "Nature-Based solutions" and global water shortages: a political ecology of the united nation's world water development report 2018. http://ruor.uottawa.ca/handle/10393/40102.

Jin, Y., Hu, S., Ziegler, A.D., Gibson, L., Campbell, J.E., Xu, R., Chen, D., Zhu, K., Zheng, Y., Ye, B., Ye, F., 2022. Energy production and water savings from floating solar photovoltaics on global reservoirs. Nat. Sustain. 6 (7), 865–874.

Jones, E., Qadir, M., van Vliet, M.T., Smakhtin, V., Kang, S.M., 2019. The state of desalination and brine production: a global outlook. Sci. Total Environ. 657, 1343–1356.

Khazaei, B., Read, L.K., Casali, M., Sampson, K.M., Yates, D.N., 2022. GLOBathy, the global lakes bathymetry dataset. Sci. Data 9 (1), 36.

Konapala, G., Mishra, A.K., Wada, Y., Mann, M.E., 2020. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nat. Commun. 11 (1), 3044.

Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front. Ecol. Environ. 9 (9), 494–502.

Lehmann, P., Aminzadeh, M., Or, D., Gao, H., 2019. Evaporation suppression from water bodies using floating covers: laboratory studies of cover type, wind, and radiation effects. Water Resour. Res. 55 (6), 4839–4853.

Li, Y., Gao, H., Zhao, G., Tseng, K.-H., 2020. A high-resolution bathymetry dataset for global reservoirs using multi-source satellite imagery and altimetry. Rem. Sens. Environ. 244, 111831.

Li, Y., Zhao, G., Allen, G.H., Gao, H., 2023. Diminishing storage returns of reservoir constructions. Nat. Commun. 14, 3203.

Madani, K., AghaKouchak, A., Mirchi, A., 2016. Iran's socio-economic drought: challenges of a water-bankrupt nation. Iran. Stud. 49 (6), 997–1016.

Madani, K., Khatami, S., 2015. Water for energy: inconsistent assessment standards and inability to judge properly. Current Sustainable/Renewable Energy Reports 2, 10–16.

Mady, B., Lehmann, P., Gorelick, S.M., Or, D., 2020. Distribution of small seasonal reservoirs in semi-arid regions and associated evaporative losses. Environmental Research Communications 2 (6), 061002.

McMahon, T.A., Peel, M.C., Lowe, L., Srikanthan, R., McVicar, T.R., 2013. Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. Hydrol. Earth Syst. Sci. 17 (4), 1331–1363.

Mekonnen, M., Hoekstra, A.Y., 2011a. National water footprint accounts. In: The Green, Blue and Grey Water Footprint of Production and Consumption, vol. 1. Main Report.

Mekonnen, M.M., Hoekstra, A.Y., 2011b. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15 (5), 1577–1600.

Messager, M., Lehner, B., Grill, G., et al., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat. Commun. 7, 13603.

Moreo, M.T., Swancar, A., 2013. Evaporation from Lake Mead, Nevada and Arizona, March 2010 through February 2012, vol. 5229. US Geological Survey Scientific Investigations Report, p. 40.

Oranye, N.P., Aremu, A.W., 2021. The duty to cooperate in state interactions for the sustainable use of international watercourses. Discover Sustainability 2 (1), 45.

Pacific Institute, 2023. Water Conflict – World Water. Water Conflict Chronology. https://www.worldwater.org/water-conflict/.

Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., Millán, M.M., Paton, C., Poullis, D., Herrero, F.S., 2020. Can seawater desalination be a win-win fix to our water cycle? Water Res. 182, 115906.

Pourmand, M., Aminzadeh, M., Eftekhar, M., 2022. Production of evaporation suppression floating covers using ultra-lightweight alkali-activated slag concrete. Mag. Concr. Res. 74 (18), 919–930.

Rezazadeh, A., Akbarzadeh, P., Aminzadeh, M., 2020. The effect of floating balls density on evaporation suppression of water reservoirs in the presence of surface flows. J. Hydrol. 591, 125323. https://doi.org/10.1016/j.jhydrol.2020.125323.

Roberts, D.C., Forrest, A.L., Sahoo, G.B., Hook, S.J., Schladow, S.G., 2018. Snowmelt timing as a determinant of lake inflow mixing. Water Resour. Res. 54 (2), 1237–1251.

Rocha, J., Carvalho-Santos, C., Diogo, P., Beça, P., Keizer, J.J., Nunes, J.P., 2020. Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). Sci. Total Environ. 736, 139477.

Rosen, M.R., Turner, K., Goodbred, S.L., Miller, J.M., 2012. A Synthesis of Aquatic Science for Management of Lakes Mead and Mohave. US Geological Survey.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44 (9).

Schillinger, J., Özerol, G., Güven-Griemert, Ş., Heldeweg, M., 2020. Water in war: understanding the impacts of armed conflict on water resources and their management. WIREs Water 7 (6), e1480.

Shokri, N., Stevens, B., Madani, K., Grabe, J., Schlüter, M., Smirnova, I., 2023. Climate informed Engineering: an Essential pillar of industry 4.0 transformation. ACS Engineering Au 3 (1), 3–6.

Sivapragasam, C., Vasudevan, G., Maran, J., Bose, C., Kaza, S., Ganesh, N., 2009. Modeling evaporation-seepage losses for reservoir water balance in semi-arid regions. Water Resour. Manag. 23 (5), 853–867.

Spank, U., Hehn, M., Keller, P., Koschorreck, M., Bernhofer, C., 2020. A season of eddy-covariance fluxes above an extensive water body based on observations from a floating platform. Boundary-Layer Meteorol. 174, 433–464.

USGS Surface-Water Daily Data for Nevada, 2023. National Water Information System. https://waterdata.usgs.gov/nv/nwis/dv. (Accessed 17 October 2023).

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M.T.H., Yillia, P., Ringler, C., Burek, P., Wiberg, D., 2016. Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. Geosci. Model Dev. (GMD) 9 (1), 175–222.

Wright, S.A., Anderson, C.R., Voichick, N., 2009. A simplified water temperature model for the Colorado River below Glen Canyon Dam. River Res. Appl. 25 (6), 675–686.

Zhao, B., Kao, S.-C., Zhao, G., Gangrade, S., Rastogi, D., Ashfaq, M., Gao, H., 2023. Evaluating enhanced reservoir evaporation losses from CMIP6-based future projections in the contiguous United States. Earth's Future 11 (3), e2022EF002961.

Zhao, G., Gao, H., Cai, X., 2020. Estimating lake temperature profile and evaporation losses by leveraging MODIS LST data. Rem. Sens. Environ. 251, 112104.

Zhao, G., Li, Y., Zhou, L., et al., 2022. Evaporative water loss of 1.42 million global lakes. Nat. Commun. 13, 3686.

Zhao, G., Gao, H., 2019. Estimating reservoir evaporation losses for the United States: fusing remote sensing and modeling approaches. Rem. Sens. Environ. 226, 109–124.

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Research article

Struggling over water, losing it through evaporation: The case of Afghanistan and Iran

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ABSTRACT

Prolonged droughts and rising water demand have worsened water disputes in the transboundary Helmand basin, shared by Afghanistan and Iran. While both countries have built water storage reservoirs to mitigate water shortages, evaporative losses from these reservoirs reduce their effectiveness. This issue intensifies challenges over water shortages in the region without reliable monitoring data. In this study, reanalysis and remote sensing data was used to calculate the rate of water evaporation from the major water reservoirs located in Helmand basin. Additionally, globally available moisture trajectory datasets were used to analyze where the evaporated water from these major storage reservoirs eventually falls as precipitation. Our main focus was on quantifying how much of this water precipitates outside the Helmand Basin. Our results indicate that evaporative losses of blue water from reservoirs in this transboundary river basin have reached to 284 million cubic meters in 2023. Additionally, our results indicate the presence of a teleconnection, whereby a significant portion of the water evaporated from these reservoirs is transported and then precipitates outside the Helmand Basin, reaching up to an annual average of 92%. The largest portion of this evaporated water was received as precipitation by India, Pakistan, Afghanistan and China, accounting for 25%, 19%, 16% and 6%, respectively. This study provides a real-world example of how improved water intelligence and transparency, achieved through remote sensing data and modelling, can support water diplomacy and conflict resolution in transboundary basins.

1. Introduction

Intensifying competition over dwindling freshwater resources is escalating longstanding water conflicts between Iran and Afghanistan, fueling clashes in recent years (Kumar, 2023). The Helmand (Hirmand) river, the main artery of the transboundary Helmand basin (Fig. 1), lies at the heart of the complex challenges in transboundary water management as regional water scarcity worsens. The long-standing water conflict between Iran (downstream nation) and Afghanistan (upstream nation) led to the signing of a Water Treaty in 1973 to ensure Iran's share of the Helmand river. However, prolonged droughts, water diversion and construction of dams in Afghanistan, among other factors, have reduced downstream water availability, escalating water disputes (Loodin et al., 2024; Akbari and Torabi Haghighi, 2022; Mamasani et al., 2024). This has impacted domestic water sectors, and led to the desiccation of the Hamoun wetlands in the past two decades, causing forced migrations, crop failure, livestock loss, desertification, and dust storms stemming from the dry bed of the wetlands arising from "water bankruptcy" (Madani et al., 2016) in Iran's Sistan region (Behrooz et al., 2022). In Afghanistan, water shortage threatens wheat cultivation and previously led to the cultivation of drought-resistant crops.

Over the years, economic development, population growth and increasing water demands have encouraged Afghanistan and Iran to increase their water storage capacity and build water storage infrastructures to alleviate seasonal water stresses (Aminzadeh et al., 2018). The Kajaki, Arghandab, and Kamal-Khan dams, with a total

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capacity of ∼3000 million cubic meters (MCM), satisfy domestic and agricultural water demands in Afghanistan. To cope with water scarcity in the Sistan Plain, the so-called Chah Nimeh reservoirs, comprised of four man-made water storages with capacity of 1440 MCM, were put in use in Iran (Fig. 1). The Kajaki and Arghandab dams, with respective storage capacities of 2500 MCM and 500 MCM, were constructed in 1952 and 1953 to address water demand in Afghanistan. The Kamal-Khan Dam, with a capacity of 52 MCM, was inaugurated in March 2021 after its construction began in 1974. The Chah Nimeh reservoirs consist of four storages: reservoirs 1, 2, and 3, with capacities of 220, 90, and 320 MCM, respectively, were completed in 1983, while reservoir 4, with a capacity of 810 MCM, has been operational since April 2009. In addition to the impact of increased water storage on downstream water availability, the significant evaporative losses from the main storages of the basin with more than 200 km^2 surface area exacerbate water stress in the Helmand basin. Under these circumstances, lack of robust monitoring data with decades of conflicts and political instability in Afghanistan further hindered the dialogue on the water rights and fueled the disputes between the two neighbors as reflected in their reciprocal threats and rhetoric (Dagres, 2023).

Quantifying evaporation from large reservoirs, such as those in the Helmand Basin, is crucial for understanding their storage efficiency because these losses directly impact how much water remains available (Maleki et al., 2024). High rates of evaporation can undermine the intended purpose of water storage, as substantial volumes of water are effectively lost to the atmosphere rather than retained for local use. Additionally, another important aspect is the fate of this evaporated water, specifically where it ultimately precipitates (Rockström et al., 2023) as shown schematically in Fig. 2. Examining the pathways of atmospheric moisture from evaporation to precipitation is essential for understanding climate dynamics at both global and regional levels (Theeuwen et al., 2023). This process, termed atmospheric moisture recycling, tracks the journey of evaporated water through the atmosphere until it falls as precipitation (Tuinenburg et al., 2020). Therefore, a key process connected to the creation of new reservoirs for water storage, which requires careful considerations, is the circulation of additional evaporated moisture through the atmosphere and the subsequent generation of precipitation locally or in distant regions (Lian et al., 2020). This distinction is crucial for regional water sustainability: if evaporated moisture eventually precipitates within the same basin, it contributes back to the local water cycle, potentially mitigating some loss. However, if atmospheric circulation carries this moisture beyond the basin boundaries, leading to precipitation in distant regions, the water is effectively lost from the local hydrological cycle. Understanding the trajectory of evaporated moisture, therefore, becomes essential for accurate water resource management and necessitates careful assessments using atmospheric models or moisture trajectory analyses.

The present analysis aims to leverage Industry 4.0 technologies, including big data analytics, remote sensing, and advanced modeling techniques, to assess the efficiency of major water storage infrastructure (in terms of water evaporation) and enhance water accounting in the ungauged Helmand Basin. Remote sensing data were integrated with physics-based modeling to estimate evaporative losses from the main storage infrastructures in the Helmand Basin. Additionally, spatial precipitation patterns resulting from the evaporative water losses from the major water storage infrastructures in the basin were investigated. By identifying where the evaporated water eventually precipitates, stakeholders can better quantify the true costs of reservoir evaporation and make informed decisions to support sustainable transboundary water governance.

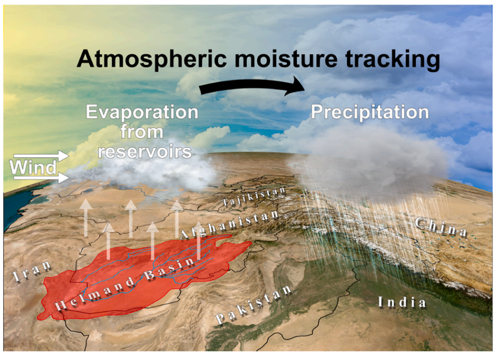

Fig. 2. Schematic of water evaporation from Helmand basin, redistribution of atmospheric water vapor and the subsequent precipitation of the evaporated water locally or in distant regions.

2. Materials and methods

2.1. Evaporation dynamics in water reservoirs

Evaporation dynamics can be quantified by solving the 1D energy equation in depth of a water body considering the radiative energy absorption to obtain the vertical temperature profile (Aminzadeh et al., 2018, 2024) expressed as:

$$\frac{\partial T_w}{\partial t}=\frac{\partial}{\partial z}\left(\left(\alpha_{T,w}+D_w\right)\frac{\partial T_w}{\partial z}\right)+\frac{Q(z,t)}{\rho_w c_w} \tag{1}$$

where T_w is water temperature (K), z is water depth (m), $\alpha_{T,w}$ and D_w are molecular and eddy thermal diffusivity (m^2/s), respectively, ρ_w is water

Fig. 1. The transboundary Helmand Basin shared by Afghanistan and Iran, showing the locations of major dams and reservoirs, including the Kajaki, Arghandab, Kamal-Khan dams, and the Chah Nimeh reservoirs.

density (kg/m^3) and c_w is specific heat of water (J/kg*K). Radiation adsorption in depth of the reservoir is represented by Q (W/m^3) which is a function of shortwave radiation adsorption at water surface, surface albedo, and light attenuation characteristics (Vercauteren et al., 2011). The water body exchanges heat with overlying air via latent, sensible, and radiative fluxes, while heat exchange with the underlying soil and intercepted radiative flux at the bottom of the reservoir govern bottom energy fluxes. Quantification of surface temperature (T_{ws}) through Eq. (1) enables calculation of evaporative flux from the reservoir (Brutsaert, 2023):

$$E = 86.4 \times 10^6 \frac{0.622\,\kappa^2\,U}{\rho_w\,R_d\,T_a\left[\ln\left(\frac{z_m}{z_0}\right)\right]^2}\left(e_s(T_{ws}) - e_a\right) \tag{2}$$

where E is evaporation rate (mm/day), κ is von Karman's constant (−), U is the wind speed (m/s), R_d is the gas constant for dry air (J/kg*K), T_a is the air temperature (K), z_0 is the roughness length (m), z_m is the measurement height for wind speed and air temperature (m), e_s and e_a are saturated vapor pressure at the water surface and vapor pressure within the air mass above the surface (Pa), respectively.

2.2. *Atmospheric circulation reanalysis: from evaporation to precipitation*

The fate of evaporated water can be estimated using either atmospheric numerical models or datasets of atmospheric moisture trajectories (van der Ent et al., 2013). Numerical models offer the advantage of accounting for potential feedbacks from land-use changes on atmospheric circulation, but they come with significant uncertainties due to spatial and temporal discretization of the equations of motion, as well as inaccuracies in representing key physical processes, particularly those influencing precipitation. Additionally, they are computationally intensive. In contrast, using moisture trajectory datasets is more closely tied to observations and is computationally less demanding, especially when focusing on a single point source, though it still requires managing large datasets. This method neglects the effects of land-use changes on atmospheric winds and it allows for faster generation of multiple realizations and scenarios. In other words, this method can be used to quickly generate multiple land-use changes scenarios such as afforestation, cropland and irrigation expansion and the development of new reservoirs by estimating the consequent change of evapotranspiration and using the trajectories dataset to assess the local and distant implications for precipitation. Being derived from the ERA5 reanalysis, the trajectories are accurately representing the current features of atmospheric circulation accounting for the local topography. However, this method assumes that the land-use changes do not affect the atmospheric structure and its circulation. Therefore, it is justified for moderate land-use change scenarios or for real case studies, such as the present one. More drastic land-use change scenarios could result in non-linear feedbacks on the atmospheric flow that should be tested with numerical models such as atmospheric and climate models (Zampieri et al., 2024).

It is worthwhile to note that the considered region in the present analysis is influenced by strong large-scale atmospheric forcing (i.e. pressure gradients), which result in the intense winds observed over the reservoirs. The transition from marches to water surface has a relatively minor impact on surface energy fluxes compared to more significant land-use changes, like afforestation in dry areas, which involve larger modifications to albedo. As such, the addition of the Chah Nimeh reservoirs is not expected to have significantly altered atmospheric winds. This assumption supports the use of atmospheric moisture trajectory climatology in the present analysis to estimate where the evaporated water from the major storage reservoirs eventually falls as precipitation. The trajectories dataset computed by Tuinenburg et al. (2020, hereafter T2020) was used. This dataset was created by applying a Lagrangian moisture-tracking model driven by hourly wind speeds and directions on 25 vertical layers in the atmosphere from the ERA5 reanalysis (Hersbach et al., 2020) over the period 2008–2017, which is well matching the period under consideration in the present study. If the addition of the Chah Nimeh reservoir had altered the atmospheric circulation significantly, this should be mostly accounted for by the reanalysis in that period. This consideration further supports our methodological choice.

The T2020 dataset was used in many studies to quantify the local precipitation recycling (Theeuwen et al., 2023) and the non-local impact of vegetation changes on the water cycle (Baudena et al., 2021; Cui et al., 2022; Hoek van Dijke et al., 2022), the potential of forest management for drought mitigation (Tuinenburg et al., 2022), to define the transboundary atmospheric watersheds for better governance (Rockström et al., 2023), and to assess the local and transboundary impacts of present irrigation and its potential expansion in the Middle East (Zampieri et al., 2024), amongst others. Therefore, T2020 is a well-established and tested source of data for estimating the impact of the evaporation from the reservoirs on large scale precipitation changes.

2.3. *Characteristics of the reservoirs and meteorological data*

To quantify the evaporation from the major reservoirs in Helmand Basin, reservoir bathymetry (Fig. 3) was obtained from GLOBathy (Khazaei et al., 2022).

This dataset was created using a GIS-based framework, aligning with the widely recognized HydroLAKES global dataset (Messager et al., 2016). Monthly variation of the reservoirs' area was extracted from the Global Surface Water (GSW) dataset (Pekel et al., 2016). The dataset makes use of satellite images from Landsat 5, 7, and 8 to identify the extent and spatio-temporal variation of surface water bodies at resolutions of 30 m since 1984 (Vercauteren et al., 2011; Pekel et al., 2016). The evaporation model thus takes into account the influence of bathymetry and variations in the reservoir's depth to estimate radiative energy absorption within the water body (Vercauteren et al., 2011).

Meteorological variables governing heat and vapor exchanges between the reservoirs and overlying air were extracted from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis datasets (Gelaro et al., 2017; Pawson, 2023). Hourly radiation flux, wind speed, air temperature, and specific humidity were obtained from MERRA-2 (with a spatial resolution of 0.625° × 0.5°) to determine associated boundary conditions. Note that above surface meteorological conditions may spatially change considering the extent of the reservoirs. Nevertheless, the model prediction could be improved where detailed meteorological data collected over individual water bodies are available (Hohenegger et al., 2023). Details of annual variations of meteorological parameters are provided in Fig. 4.

The uncertainty associated with climate variables is an important factor to consider for the estimation of the evaporative fluxes. The reanalysis data used in our analysis (ERA5) represents the best available representation of past climate variability in regions characterized by data scarcity. However, we acknowledge its limitations, including the spatial resolution, the assumptions in the model equations, and the availability of assimilated observations in this region. Regarding spatial resolution, it is common practice to apply some form of downscaling when using global datasets, particularly in areas with complex orography or significant land-sea contrasts. This is because surface variables, such as temperature, can vary greatly depending on the resolution and local topography, as reanalysis models often use a horizontally averaged or smoothed orography that differs from reality. Despite these general challenges, ERA5 offers a relatively high resolution compared to its predecessors. In the specific case of our study, while the broader Helmand Basin is geographically complex, the Chah Nimeh reservoir itself is located in a relatively flat area, with the nearest significant mountain ranges more than 50 km away. This reduces the impact of orographic variability on the computed evaporation rates.

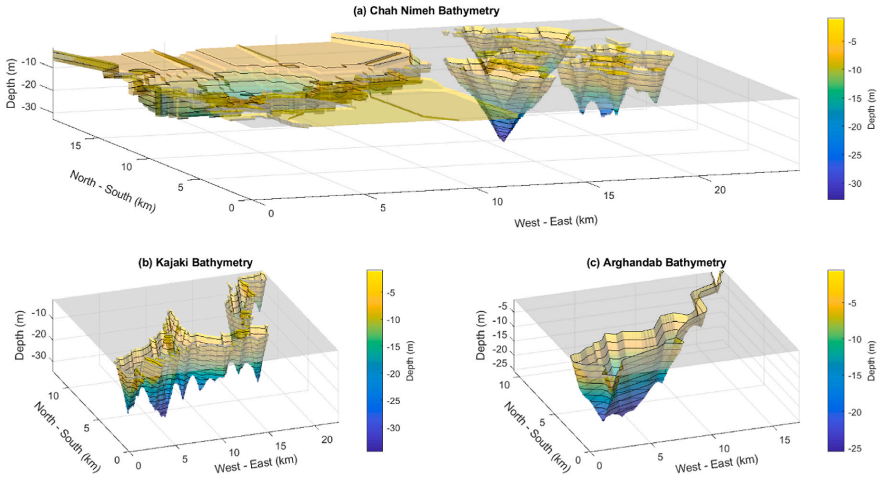

Fig. 3. 3D bathymetric representations of (a) Chah Nimeh, (b) Kajaki, and (c) Arghandab reservoirs. Depth values (in meters) are derived from GLOBathy data, showing the underwater topography and structure of each reservoir.

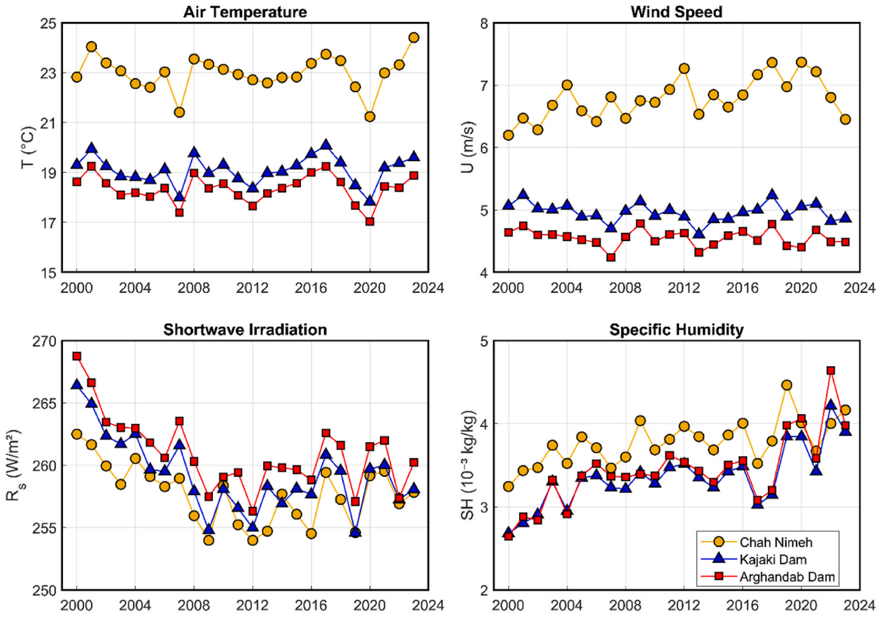

Fig. 4. Mean annual meteorological parameters. Mean annual air temperature, wind speed, shortwave radiation, and specific humidity in the location of storage reservoirs (2000–2023) extracted from MERRA-2 reanalysis datasets (Gelaro et al., 2017).

3. Results

Fig. 5 presents the predicted evaporation from the major water storage reservoirs in the Helmand basin. The results suggest that up to 35.5 and 89.2 MCM/year of water might have been lost via evaporation in the Arghandab and Kajaki reservoirs, respectively, during the study period from 2001 to 2023. On the Iranian side of the basin, the Chah Nimeh reservoirs lose much higher amounts of water through evaporation, peaking in 2020 with approximately 385.7 MCM/year (Fig. 5). The total storage of the Chah Nimeh reservoirs increased from 630 to

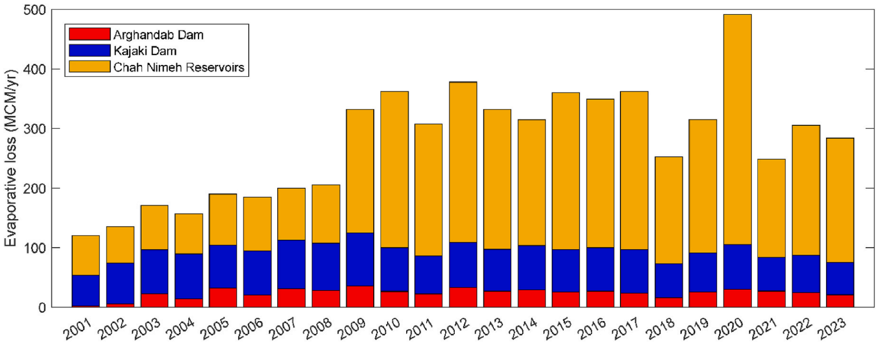

Fig. 5. Evaporative water losses from reservoirs. Water evaporation from storage reservoirs quantified based on the monthly variation of evaporation rate and reservoir area. Note that the total storage of Chah Nimeh reservoirs increased from 630 to 1440 MCM in 2009 with addition of Chah Nimeh reservoir 4. This further increased their cumulative surface area from 47 to 125 km^2.

1440 MCM in 2009 with the addition of Chah Nimeh reservoir 4. This expansion significantly increased their cumulative surface area from 47 to 125 km^2, thereby amplifying their evaporative water losses due to the larger exposed surface area.

Yearly analyses from 2001 to 2023 show increasing evaporative loss ratios relative to reservoir capacity, with the Chah Nimeh reservoirs exceeding 27% loss in 2020 (Fig. 6a). This primarily arises from extremely high wind flows (the so-called 120-day winds) that could easily surpass 100 km/h during summer months in the Sistan region. Additionally, the extent of the Chah Nimeh reservoirs with more than 125 km^2 cumulative surface area facilitates vapor transfer into the overlying airflow. Hot, dry conditions increase atmospheric evaporative demand, reducing water reservoir storage efficiency (Fig. 6b). Modeling results indicate evaporation rates in the Chah Nimeh, Kajaki, and Arghandab reservoirs reached to the maximum rate of 3210, 2032, and 2205 mm/year, respectively over the past two decades, indicating rising vapor demand due to prolonged Helmand basin droughts.

The significant increase in evaporation loss observed in 2020 for the Chah Nimeh reservoirs appears to result from a combination of factors. While annual average wind speeds (Fig. 4) did not show a notable increase, localized strong wind events, lasting up to 120 days, may have disproportionately impacted this reservoir due to its more exposed location. These localized events are not captured effectively by annual averages, underscoring the importance of high-resolution climate data for such analyses. Additionally, evaporation is influenced by multiple factors, including surface water temperature, air temperature, specific humidity, and solar radiation, as described in the methods. Combined variations in these parameters in 2020 may have contributed to the increased evaporation rate.

To analyze where the evaporated water falls as precipitation, the dataset provided by Tuinenburg et al. (2020) was used to study the transport of evaporated water from the large storage water reservoirs located in the Helmand basin through the atmosphere until it precipitates. This dataset enables the identification and quantification of moisture flows to and from any area on Earth, across both local and global scales. Fig. 7 presents the obtained results showing where the water evaporated from the reservoirs (Fig. 1) averaged over the period from 2009 to 2023 ultimately precipitated. Our finding suggests while 8% of the evaporated water is returned to the Helmand basin through precipitation, 92% of the evaporated water from the large water reservoirs in the basin falls in precipitation outside the basin. India, Pakistan, Afghanistan, China, and Nepal receive 25%, 19%, 16%, 6%, and 3% of the evaporated water from the Chah Nimeh reservoirs and the Kajaki and Arghandab dams. To further detail the distribution of evaporation

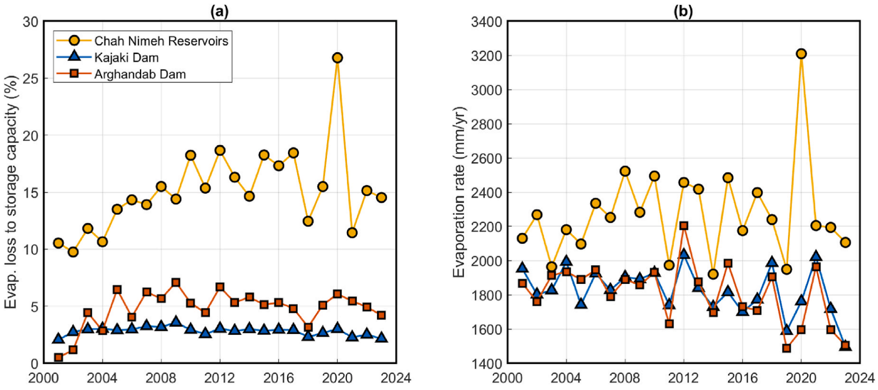

Fig. 6. Evaporative water losses and evaporation rate from reservoirs. (a) The ratio of annual evaporative loss from the reservoirs to their total storage capacity. (b) Annual evaporation rate from water reservoirs.

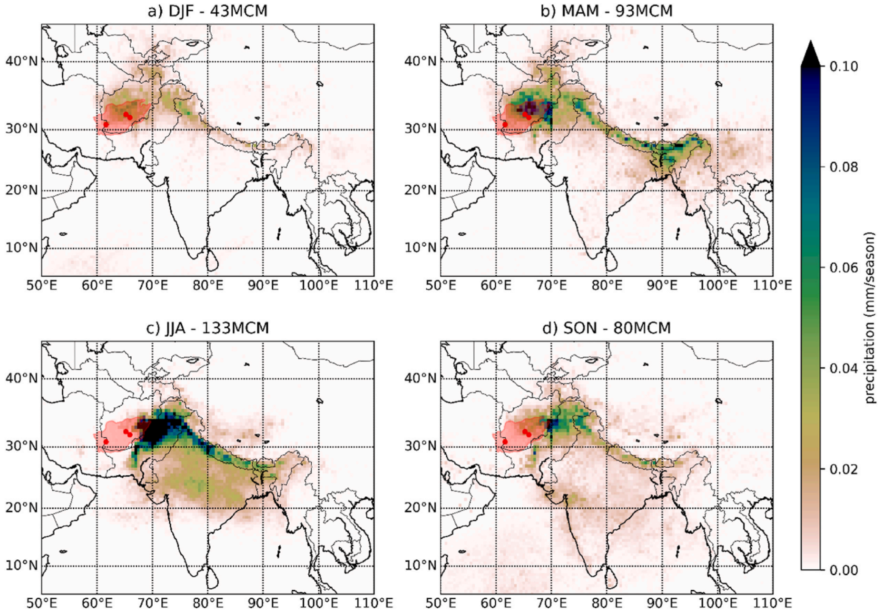

Fig. 7. Fate of evaporated water from the Kajaki and Arghandab dams and Chah Nimeh reservoirs averaged from 2009 to 2023 for a) winter, b) spring, c) summer and d) autumn. The averaged seasonal evaporation amounts are indicated in the panel titles. The precipitation resulting from the atmospheric moisture recycling originated by the evaporation from the dams and reservoirs is given in mm per season. The location of the dams and reservoirs is indicated by the red dots. The red shaded area represents the Helmand basin.

recycling, Table 1 summarizes the main beneficiary countries of evaporated water from the Kajaki and Arghandab dams and the Chah Nimeh reservoirs. Although the majority of the evaporated water comes from the water stored in the Chah Nimeh reservoirs of Iran (Fig. 7), only 0.6% of this evaporated water precipitated in Iran.

3.1. Economic and socio-environmental implications of the evaporative losses

Annual water consumption in the Helmand basin has reached to about 6000 MCM in the past two decades. With ~80% of the basin located in Afghanistan, its agricultural water allocation accounts for more than 90% of the total demands in the basin (Akbari and Torabi Haghighi, 2022). In the Sistan Region, Iran, agricultural and domestic water demands are about 550 MCM/year (Akbari and Torabi Haghighi, 2022), primarily supplied by the Chah Nimeh reservoirs. The estimated cumulative evaporative loss of 284 MCM from the Chah Nimeh, Kajaki, and Arghandab reservoirs in 2023 accounts for 4.73% of the total water demands in the basin. This amount of water is more than a third of Iran's share of the Hirmand river in normal water years, 820 MCM, according to the Water Treaty in 1973. Iran contends that less than 4% of this allocation has been received in 2022 (Iran Daily, 2024), placing water rights currently at the core of disputes between the two neighbors.

The economic value of evaporative losses may be gauged by the planned ~700-km desalinated water transfer from the Sea of Oman to the Sistan Plain with capacity of 200 MCM/year (Financial Tribune,

Table 1
Main beneficiary countries in terms of receiving the evaporated water from the Kajaki and Arghandab dams and Chah Nimeh reservoirs as precipitation, computed for the different seasons over the period 2009–2023, in %. The global evaporation recycling to land areas is reported in the last row.

Ranked beneficiaries	Annual average	Seasonal averages			
		DJF	MAM	JJA	SON
1st	India 25%	Afghanistan 21%	Afghanistan 23%	India 35%	India 26%
2nd	Pakistan 19%	India 10%	India 18%	Pakistan 31%	Pakistan 19%
3rd	Afghanistan 16%	Pakistan 9.4%	Pakistan 13%	Afghanistan 10%	Afghanistan 11%
4th	China 6.0%	China 7.4%	China 9.6%	China 3.0%	China 5.7%
5th	Nepal 2.7%	Kazakhstan 3.7%	Nepal 3.2%	Nepal 2.9%	Nepal 2.2%
…	…	…	…	…	…
Total to land	87%	77%	92%	91%	78%

2022). Considering the cost of desalinated water (often estimated 0.5–2 USD/m^3 (Karagiannis and Soldatos, 2008)), the direct economic value of 385.7 MCM evaporative loss (in 2020) from the Chah Nimeh reservoirs is estimated up to 770 million USD/year (excluding additional transfer costs which could be significant). Evaporative losses can further be gauged by how much profit could have been made with this water following the methodology proposed by D'Odorico et al. (2020). Considering the global value of irrigation water estimated from 0.13 USD/m^3 with the current crop distribution to 0.54 USD/m^3 based on the crops that maximize economic productivity (D'Odorico et al., 2020). In 2020, a year with the highest evaporation rate, the amount of water lost from the Chah-Nimeh could have led to 208 million USD/year in profit for the agriculture sector, in addition to its contributions to food security and unemployment reduction.

It is important to note that these estimates are based on preliminary calculations using specific methodologies and assumptions. Different approaches to valuing evaporative losses could yield different results. A more in-depth economic analysis would be required to accurately estimate the true economic value of the lost water, considering additional factors and uncertainties. Moreover, the true value of evaporated water may extend beyond these economical estimates, encompassing environmental impacts like damaged ecosystems and essential support for regions with poor infrastructures and severe water scarcity (Aminzadeh et al., 2018). Evaporation exacerbates water insecurity in a water-deprived region, impacting families, particularly women and children lacking proper water and sanitation. Additionally, the economy, reliant on agriculture and the health of Hamoun wetlands, faces challenges. Socio-economic instability due to water bankruptcy in the region can fuel extremism and violence, with broader repercussions.

Mitigation of evaporative losses from reservoirs remains a critical challenge, particularly in arid regions like the Helmand Basin. Molecularly thin monolayers, composed of compounds like hexadecanol and octadecanol, have been shown to reduce evaporation rates by up to 40% under controlled conditions (Barnes, 2008; Karimzadeh et al., 2023). However, their limited durability and challenges with uniform application across large water bodies restrict their broader adoption, particularly for reservoirs of significant scale. Floating covers, including modular and self-assembling types, present another promising solution. Laboratory studies by Lehmann et al. (2019) demonstrated that floating covers can reduce evaporation by up to 70–80%, with suppression levels influenced by environmental factors such as wind speed and solar radiation. Similarly, Aminzadeh et al. (2018) explored the impact of floating covers on the energy balance of reservoirs, emphasizing their ability to reduce solar radiation absorption at the surface and enhance water retention. Field studies by Bakhtiar et al. (2022) confirmed the dual benefits of floating covers in mitigating evaporation and maintaining water quality, making them a practical option for arid regions. In addition to these technological interventions, engineering strategies such as increasing the depth-to-surface area ratio during reservoir design can reduce evaporation by minimizing exposed surface areas. Afforestation projects around reservoirs, acting as windbreaks, could potentially provide a complementary approach by mitigating wind-driven evaporation. However, this will have its own challenges. Collectively, these solutions highlight the need for a tailored approach that considers the specific climatic, hydrological, and socioeconomic conditions of regions like the Helmand Basin to ensure both technical feasibility and sustainability.

4. Summary and conclusions

A physics-based approach was utilized to estimate evaporative losses from major water storage reservoirs in the Helmand Basin, shared between Iran and Afghanistan, for the period from 2001 to 2023. Our findings indicate that cumulative evaporative water losses from these reservoirs could reach as high as 491 MCM/year (estimated for the year 2020). Notably, the Chah Nimeh reservoirs show significantly higher evaporative losses compared to the other two dams investigated in this analysis. In particular, annual evaporative losses from Chah Nimeh exceeded 385.7 MCM in the year 2020. The reliability of our approach to estimate water evaporation is further supported by Nevermann et al. (2024), who employed a similar methodology and validated their model using observed data from Lake Mead. This consistency across studies enhances confidence in the robustness of our findings.

Beyond estimating evaporation, the study examined where the evaporated water from these reservoirs eventually falls as precipitation, providing insights into water vapor transport in this water-stressed basin. Our modelling results suggest that 92% of the evaporated water from the reservoirs considered in our investigation falls as precipitation outside the Helmand Basin, with India, Pakistan, Afghanistan, China, and Nepal receiving 25%, 19%, 16%, 6%, and 3%, respectively, of this precipitation (Table 1). In this study, we computed the atmospheric recycling pattern associated to the Kajaki and Arghandab dams and Chah Nimeh reservoirs in the present climate. We acknowledge, however, the possibility that changes in future climate can alter the atmospheric circulation affecting the moisture trajectory and, ultimately, the precipitation patterns associated with the evaporation from the reservoirs. Estimating future atmospheric recycling requires trajectory datasets computed from climate model simulations under different scenarios that are not currently available.

Our findings underscore the often-overlooked impact of inefficient water storage infrastructures and offer a new perspective and set of information to the impacted parties, presenting an overlooked opportunity to the neighboring nations to reduce evaporative losses and improve water-use efficiency through cooperation. Similar to other transboundary water systems experiencing conflicts (e.g., the Nile river), the efficiency of water-use in the Helmand basin is low in the neighboring states, which diminishes water security and quality of life in the region. This inefficiency creates opportunities for cooperation to improve both water efficiency and availability (a win-win outcome). However, such opportunities often remain overlooked in the absence of adequate and transparent monitoring data, as exemplified by the Iran-Afghanistan case.

In terms of future research, investigation of the evaporation from water storage reservoirs is indeed an emerging topic, which is particularly a serious issue for water-stressed regions of the World. Future research could be focused on generalizing the impact of reservoirs in other regions of the world, e.g. the entire Middle East and North Africa region. The non-local impact of irrigation, a closely related topic, is much more studied. Large-scale irrigation is known to alter atmospheric moisture transport and contributing to cloud formation and rainfall (De Hertog et al., 2023; Puma and Cook, 2010). This process can modify local climates and affect regions far from the irrigated areas (Jódar et al., 2010; Sacks et al., 2009). For example, irrigation in the Middle East and South Asia impacts precipitation patterns in the Sahel and Eastern Africa (de Vrese et al., 2016; Zeng et al., 2022; Zampieri et al., 2024). Precipitation in the Sahel also demonstrates significant feedback effects linked to local irrigation activities (Alter et al., 2015b). Similar mechanisms are observed globally (Alter et al., 2015a; Hu and Dominguez, 2015; Lo and Famiglietti, 2013; Shi et al., 2022). We expect that the creation of large reservoirs could cause similar impacts to that of irrigations in the mentioned regions that could be subject of future research.

Furthermore, our analysis demonstrates practical examples of how satellite-based monitoring, big data analytics, and modeling practices can enhance water diplomacy and transboundary cooperation by improving water intelligence, transparency, and data availability. The findings of this study provide practical insights that could help address the ongoing water conflict in the Helmand Basin. By highlighting the scale of evaporative losses and showing where the evaporated water eventually falls as precipitation, we offer valuable information that could support constructive discussions between Iran and Afghanistan. These insights can guide negotiations and cooperation, particularly by showing the mutual benefits of working together to reduce water losses.

Joint efforts, such as investing in better water storage technologies or improving reservoir designs, could potentially ease tensions and foster long-term cooperation. Establishing shared systems to monitor water resources would also help build trust and ensure both sides have access to accurate information. Technological advancements stemming from the Fourth Industrial Revolution (Shokri et al., 2023), particularly in data collection, satellite remote sensing, and processing, provide the scientific community with significant opportunities to support policy-making and conflict resolution by enhancing water and environmental intelligence in transboundary systems. These innovations are especially beneficial in ungauged regions, where the lack of transparent data and effective communications can exacerbate domestic and cross-border tensions. Beyond aiding neighboring parties directly, insights from scientists and impartial organizations using remote sensing and satellite monitoring are invaluable to the United Nations and other international organizations committed to mediating conflicts effectively.

CRediT authorship contribution statement

Hannes Nevermann: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Kaveh Madani:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Matteo Zampieri:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Ibrahim Hoteit:** Writing – review & editing, Visualization, Investigation. **Nima Shokri:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data used for the calculation of evaporative water losses and the ones used to calculate the precipitation patterns are already available with the required references provided in the paper.

References

Akbari, M., Torabi Haghighi, A., 2022. Satellite-based agricultural water consumption assessment in the ungauged and transboundary Helmand Basin between Iran and Afghanistan. Remote Sensing Letters 13 (12), 1236–1248. https://doi.org/10.1080/2150704X.2022.2142074.

Alter, R.E., Fan, Y., Lintner, B.R., Weaver, C.P., 2015a. Observational evidence that Great Plains irrigation has enhanced summer precipitation intensity and totals in the Midwestern United States. J. Hydrometeorol. 16 (4), 1717–1735. https://doi.org/10.1175/JHM-D-14-0115.1.

Alter, R.E., Im, E.-S., Eltahir, E.A.B., 2015b. Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation. Nat. Geosci. 8 (10), 763–767. https://doi.org/10.1038/ngeo2514.

Aminzadeh, M., Lehmann, P., Or, D., 2018. Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. Hydrol. Earth Syst. Sci. 22 (7), 4015–4032. https://doi.org/10.5194/hess-22-4015-2018.

Aminzadeh, M., Friedrich, N., Narayanaswamy, S., Madani, K., Shokri, N., 2024. Evaporation loss from small agricultural reservoirs in a warming climate: an overlooked component of water accounting. Earth's Future 12 (1), e2023EF004050. https://doi.org/10.1029/2023EF004050.

Bakhtiar, M., Aminzadeh, M., Taheriyoun, M., Or, D., Mashayekh, E., 2022. Effects of floating covers used for evaporation suppression on reservoir physical, chemical and biological water quality parameters. Ecohydrology 15 (8), e2470. https://doi.org/10.1002/eco.2470.

Barnes, G.T., 2008. The potential for monolayers to reduce the evaporation of water from large water storages. Agric. Water Manag. 95 (4), 339–353. https://doi.org/10.1016/j.agwat.2007.10.009.

Baudena, M., Tuinenburg, O.A., Ferdinand, P.A., Staal, A., 2021. Effects of land-use change in the Amazon on precipitation are likely underestimated. Global Change Biol. 27 (11), 5580–5587. https://doi.org/10.1111/gcb.15810.

Behrooz, R.D., Mohammadpour, K., Broomandi, P., Kosmopoulos, P.G., Gholami, H., Kaskaoutis, D.G., 2022. Long-term (2012–2020) PM10 concentrations and increasing trends in the Sistan Basin: the role of Levar wind and synoptic meteorology. Atmos. Pollut. Res. 13 (7), 101460. https://doi.org/10.1016/j.apr.2022.101460.

Brutsaert, W., 2023. Hydrology. Cambridge University Press. https://books.google.com/books?id=FV6lEAAAQBAJ.

Cui, J., Lian, X., Huntingford, C., Gimeno, L., Wang, T., et al., 2022. Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. Nat. Geosci. 15, 982–988. https://doi.org/10.1038/s41561-022-01061-7.

Dagres, H., 2023. Iran and Afghanistan Are Feuding over the Helmand River. The Water Wars Have No End in Sight. Atlantic Council.

De Hertog, S.J., Havermann, F., Vanderkelen, I., Guo, S., Luo, F., et al., 2023. The biogeophysical effects of idealized land cover and land management changes in Earth system models. Earth System Dynamics 14, 629–667. https://doi.org/10.5194/esd-15-265-2024.

de Vrese, P., Hagemann, S., Claussen, M., 2016. Asian irrigation, African rain: remote impacts of irrigation. Geophys. Res. Lett. 43 (8), 3737–3745. https://doi.org/10.1002/2016GL068146.

D'Odorico, P., Chiarelli, D.D., Rosa, L., Bini, A., Zilberman, D., Rulli, M.C., 2020. The global value of water in agriculture. Proc. Natl. Acad. Sci. USA 117 (36), 21985–21993. https://doi.org/10.1073/pnas.2005835117.

Financial Tribune, 2022. Project to supply Oman sea desalinated water to sistan-baluchestan underway. https://newspaper.irandaily.ir/7293/1/1887.

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., et al., 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). J. Clim. 30 (14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., et al., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146 (730), 1999–2049. https://doi.org/10.1002/qj.3803.

Hoek van Dijke, A.J., Herold, M., Mallick, K., Benedict, I., et al., 2022. Shifts in regional water availability due to global tree restoration. Nat. Geosci. 15, 363–368. https://doi.org/10.1038/s41561-022-00935-0.

Hohenegger, C., Korn, P., Linardakis, L., et al., 2023. ICON-Sapphire: simulating the components of the Earth system and their interactions at kilometer and subkilometer scales. Geosci. Model Dev. (GMD) 16, 779–811. https://doi.org/10.5194/gmd-16-779-2023.

Hu, H., Dominguez, F., 2015. Evaluation of oceanic and terrestrial sources of moisture for the North American monsoon using numerical models and precipitation stable isotopes. J. Hydrometeorol. 16 (1), 19–35. https://doi.org/10.1175/JHM-D-14-0073.1.

Iran Daily, 2024. Iran received only 4% of water share from Hirmand River last year. https://newspaper.irandaily.ir/7293/1/1887.

Jódar, J., Carrera, J., Cruz, A., 2010. Irrigation enhances precipitation at the mountains downwind. Hydrol. Earth Syst. Sci. 14 (10), 2003–2010. https://doi.org/10.5194/hess-14-2003-2010.

Karagiannis, I.C., Soldatos, P.G., 2008. Water desalination cost literature: review and assessment. Desalination 223 (1–3), 448–456. https://doi.org/10.1016/j.desal.2007.02.071.

Karimzadeh, M., Zahiri, J., Nobakht, V., 2023. Efficiency of monolayers in evaporation suppression from water surface considering meteorological parameters. Environ. Sci. Pollut. Control Ser. 30 (17), 50783–50794. https://doi.org/10.1007/s11356-023-25915-8.

Khazaei, B., Read, L.K., Casali, M., Sampson, K.M., Yates, D.N., 2022. GLOBathy, the global lakes bathymetry dataset. Sci. Data 9 (1), 36. https://doi.org/10.1038/s41597-022-01132-9.

Kumar, R., 2023. On the Afghanistan-Iran border, climate change fuels a fight over water. Science 381, 6658. https://doi.org/10.1126/science.adk2107.

Lehmann, P., Aminzadeh, M., Or, D., 2019. Evaporation suppression from water bodies using floating covers: laboratory studies of cover type, wind, and radiation effects. Water Resour. Res. 55 (6), 4839–4853. https://doi.org/10.1029/2018WR024489.

Lian, X., Piao, S., Li, L.Z.X., Li, Y., Huntingford, C., Ciais, P., 2020. Summer soil drying exacerbated by earlier spring greening of northern vegetation. Sci. Adv. 6 (5), eaax0255. https://doi.org/10.1126/sciadv.aax0255.

Lo, M.-H., Famiglietti, J.S., 2013. Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle. Geophys. Res. Lett. 40 (2), 301–306. https://doi.org/10.1002/grl.50108.

Loodin, N., Eckstein, G., Singh, V.P., Sanchez, R., 2024. The role of data sharing in transboundary waterways: the case of the Helmand River Basin. In: Theorizing Transboundary Waters in International Relations. Springer International Publishing, pp. 165–194. https://doi.org/10.1007/978-3-031-43376-4_10.

Madani, K., AghaKouchak, A., Mirchi, A., 2016. Iran's socio-economic drought: challenges of a water-bankrupt nation. Iran. Stud. 49 (6), 997–1016. https://doi.org/10.1080/00210862.2016.1259286.

Maleki, S., Mohajeri, S.H., Mehraein, M., Sharafati, A., 2024. Lake evaporation in arid zones: leveraging Landsat 8's water temperature retrieval and key meteorological drivers. J. Environ. Manag. 355, 120450. https://doi.org/10.1016/j.jenvman.2023.120450.

Mamasani, P., Jafari, M., Andik, B., Mianabadi, H., Arvin, B., Ghoreishi, S.Z., 2024. Relative deprivation, a silent driver in hydropolitics: evidence from Afghanistan-Iran water diplomacy. Water Altern. (WaA) 17 (2), 2. https://www.water-alternatives.org/index.php/alldoc/articles/vol17/v17issue2/744-a17-2-2/file.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat. Commun. 7 (1), 13603. https://doi.org/10.1038/ncomms13603.

Nevermann, H., Aminzadeh, M., Madani, K., Shokri, N., 2024. Quantifying water evaporation from large reservoirs: implications for water management in water-stressed regions. Environ. Res. 262, 119860. https://doi.org/10.1016/j.envres.2024.119860.

Pawson, S., 2023. Global modeling and assimilation office (GMAO). In: Presented at the 23rd Meeting of the American Geophysical Union (AGU). https://ntrs.nasa.gov/api/citations/20230018433/downloads/20231213-Pawson%20-1.pdf.

Pekel, J.F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540 (7633), 418–422. https://doi.org/10.1038/nature20584.

Puma, M.J., Cook, B.I., 2010. Effects of irrigation on global climate during the 20th century. J. Geophys. Res. Atmos. 115 (D16). https://doi.org/10.1029/2010JD014122.

Rockström, J., Mazzucato, M., Andersen, L.S., Fahrländer, S.F., Gerten, D., 2023. Why we need a new economics of water as a common good. Nature 615, 794–797. https://doi.org/10.1038/d41586-023-00800-z.

Sacks, W.J., Cook, B.I., Buenning, N., Levis, S., Helkowski, J.H., 2009. Effects of global irrigation on the near-surface climate. Clim. Dynam. 33 (2–3), 159–175. https://doi.org/10.1007/s00382-008-0445-z.

Shi, K., Li, T., Zhao, J., Su, Y., Gao, J., et al., 2022. Atmospheric recycling of agricultural evapotranspiration in the Tarim Basin. Front. Earth Sci. 10, 950299. https://doi.org/10.3389/feart.2022.950299.

Shokri, N., Stevens, B., Madani, K., Grabe, J., Schlüter, M., Smirnova, I., 2023. Climate informed engineering: an essential pillar of Industry 4.0 transformation. ACS Engineering Au 3 (1), 3–6. https://doi.org/10.1021/acsengineeringau.2c00037.

Theeuwen, J.J.E., Staal, A., Tuinenburg, O.A., Hamelers, B.V.M., Dekker, S.C., 2023. Local moisture recycling across the globe. Hydrol. Earth Syst. Sci. 27 (6), 1457–1476. https://doi.org/10.5194/hess-27-1457-2023.

Tuinenburg, O.A., Theeuwen, J.J.E., Staal, A., 2020. High-resolution global atmospheric moisture connections from evaporation to precipitation. Earth Syst. Sci. Data 12 (3), 3177–3188. https://doi.org/10.5194/essd-12-3177-2020.

Tuinenburg, O.A., Bosmans, J.H.C., Staal, A., 2022. The global potential of forest restoration for drought mitigation. Environ. Res. Lett. 17 (3), 034045. https://doi.org/10.1088/1748-9326/ac55b8.

van der Ent, R.J., Tuinenburg, O.A., Knoche, H.-R., Kunstmann, H., Savenije, H.H.G., 2013. Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking? Hydrol. Earth Syst. Sci. 17 (12), 4869–4884. https://doi.org/10.5194/hess-17-4869-2013.

Vercauteren, N., Huwald, H., Bou-Zeid, E., Selker, J.S., Lemmin, U., Parlange, M.B., Lunati, I., 2011. Evolution of superficial lake water temperature profile under diurnal radiative forcing. Water Resour. Res. 47 (9), W09522. https://doi.org/10.1029/2011WR010529.

Zampieri, M., Luong, T.M., Ashok, K., Dasari, H.P., Pistocchi, A., Hoteit, I., 2024. Leveraging atmospheric moisture recycling in Saudi Arabia and neighboring countries for irrigation and afforestation planning. Reg. Environ. Change 24 (3). https://doi.org/10.1007/s10113-024-02284-7.

Zeng, Y., Milly, P.C.D., Shevliakova, E., Malyshev, S., van Huijgevoort, M.H.J., et al., 2022. Possible anthropogenic enhancement of precipitation in the Sahel-Sudan Savanna by remote agricultural irrigation. Geophys. Res. Lett. 49 (6), e2021GL096972. https://doi.org/10.1029/2021GL096972.