ERASMUS-EDU-2023-CBHE
Project number: 101129032

Duration: 36 months
(01/01/2024 – 31/12/2026)

LESLIE
LAND MANAGEMENT
ENVIRONMENT &
SOLID-WASTE

Co-funded by
the European Union

AKHMET YASSAWI
UNIVERSITY

MICRO-CREDENTIAL

CLIMATE CHANGE FOR SUSTAINABLE LAND MANAGEMENT IN CENTRAL ASIA

4.- Water, Cryosphere and Climate in Central Asia

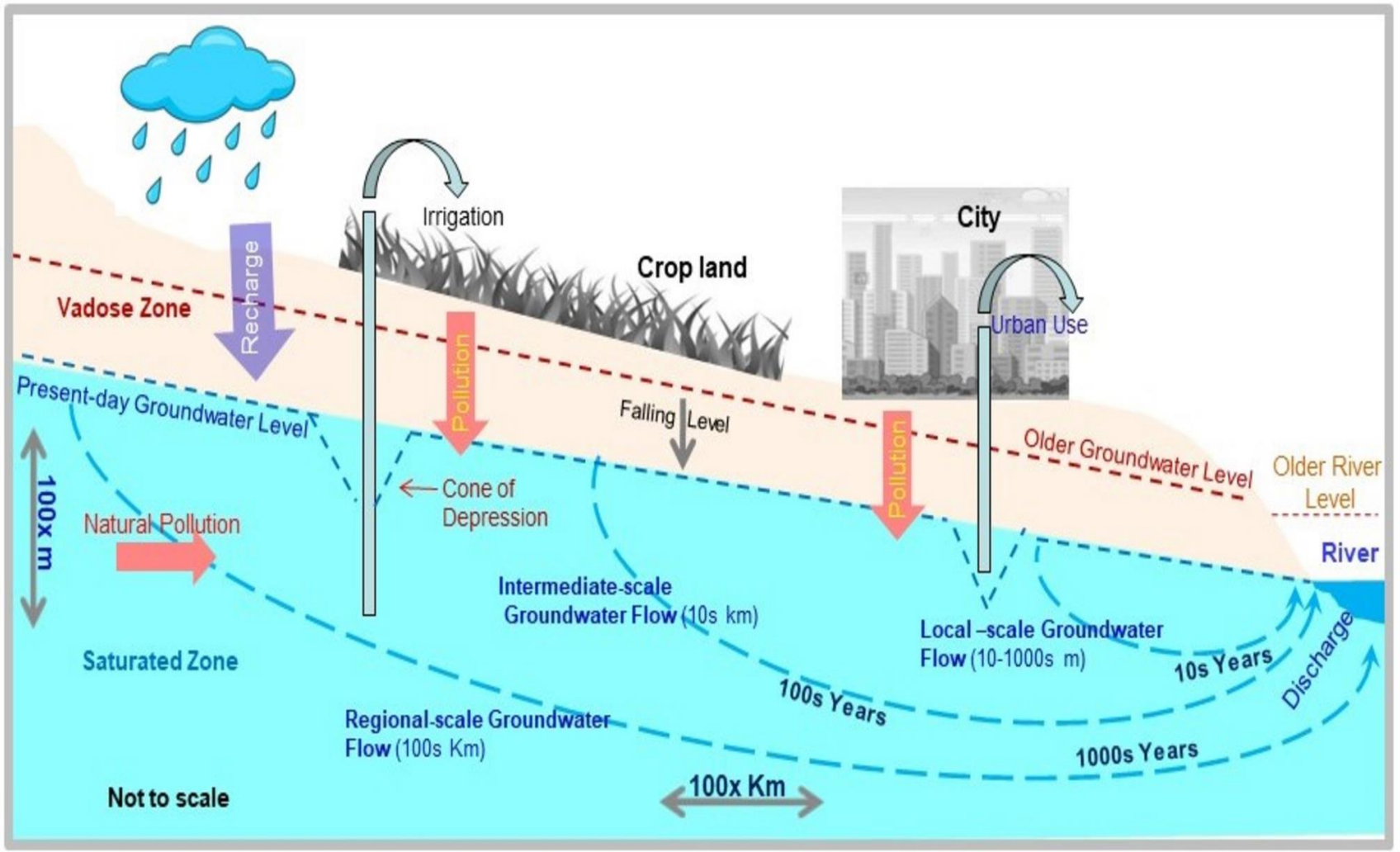
Climate Impacts on Irrigation, Groundwater and Small Transboundary Rivers

CC-W04-V15

Introduction

Water resources are central to agricultural productivity, ecosystem stability, and human livelihoods—especially in arid and semi-arid regions. Climate variability and long-term change are increasingly altering hydrological systems, affecting irrigation practices, groundwater reserves, and the dynamics of small shared rivers. These impacts are best understood within the framework of the Climate Change and its influence on the Hydrologic Cycle.

This lecture explores how changing temperature, precipitation patterns, and extreme events reshape water availability and management at local and transboundary scales.



https://www.nature.com/articles/s41598-024-79936-5

Co-funded by the European Union

Climate Change and Water Availability

a. Temperature Rise

Increasing global and regional temperatures lead to:

Higher evapotranspiration rates

Increased crop water demand

Reduced soil moisture

b. Precipitation Variability

Climate change alters:

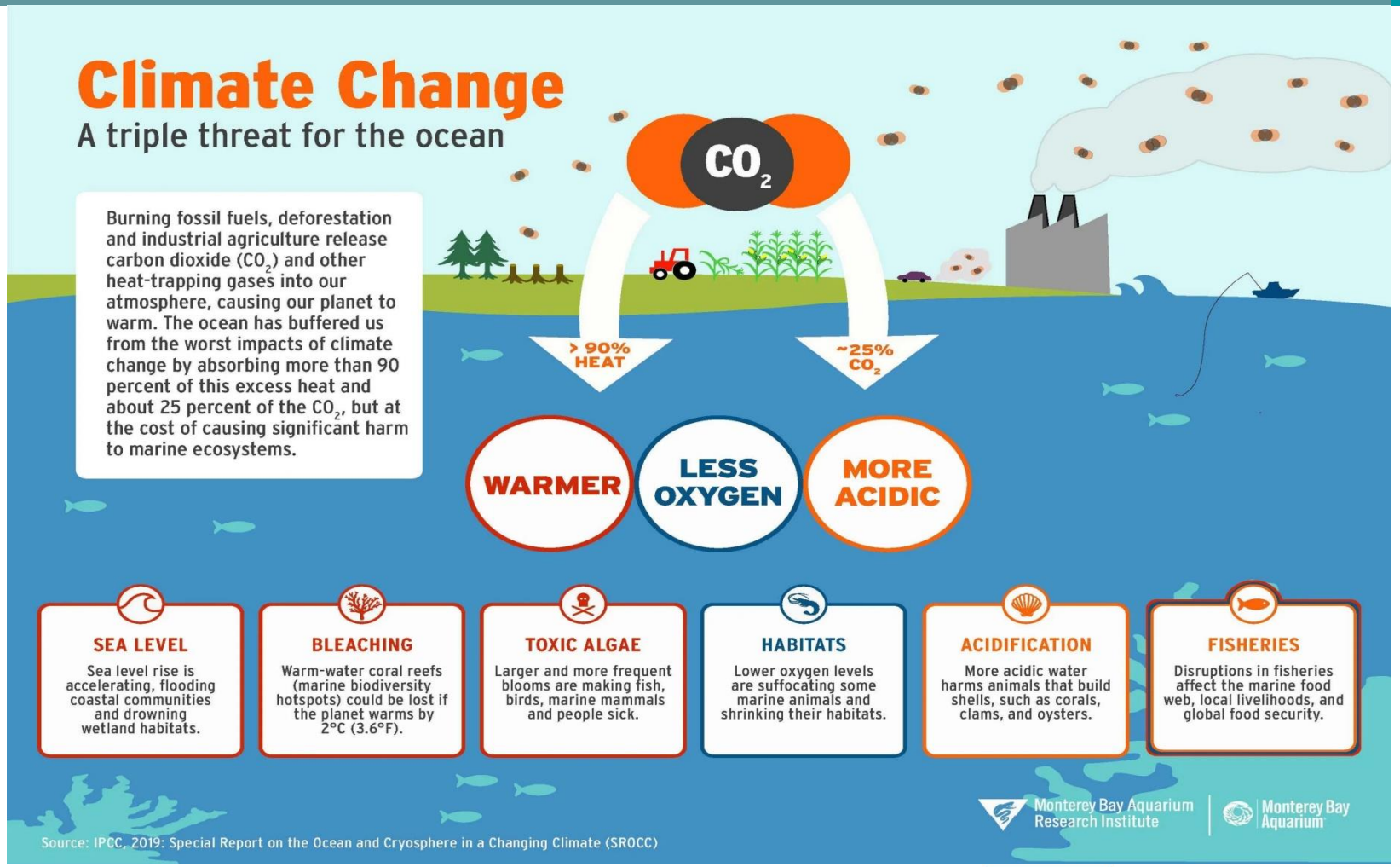
Seasonal distribution of rainfall

Frequency of droughts and intense rainfall events

c. Extreme Events

Droughts reduce water supply for irrigation and recharge

Floods can damage irrigation infrastructure and contaminate groundwater



climatecentral.org

Co-funded by the European Union

Impacts on Irrigation Systems

a. Increased Water Demand

Rising temperatures increase crop water requirements. Irrigated agriculture must compensate for:

Greater evaporation losses

Reduced effective rainfall

This is particularly critical in regions dependent on surface water diversion or groundwater extraction.

b. Reduced Water Supply

Changes in river flow regimes and precipitation reduce water availability during critical growing seasons:

Earlier snowmelt shifts peak flows away from irrigation periods

Declining glacier contributions reduce summer flows

c. Irrigation Efficiency Challenges

Traditional irrigation methods (e.g., flood irrigation) are often inefficient:

High water losses through evaporation and seepage

Vulnerability to climate variability

Modernization (e.g., drip irrigation) can improve resilience but requires investment.

d. Salinization

Climate change exacerbates soil salinity:

Increased evaporation leaves salts behind in soils

Reduced flushing due to lower water availability

This threatens long-term agricultural productivity.

Groundwater Systems Under Climate Stress

- Groundwater plays a critical and often underappreciated role in buffering the impacts of climate variability, particularly in regions where surface water availability is unreliable. As climate change intensifies, groundwater systems are increasingly subjected to multiple, compounding pressures. One of the most significant factors is the alteration of recharge processes. Recharge depends heavily on precipitation patterns and the capacity of water to infiltrate soils and reach aquifers. With rising temperatures and shifting precipitation regimes, many regions are experiencing reduced effective recharge. Even in areas where total rainfall may not decline significantly, increased rainfall intensity often leads to higher surface runoff and reduced infiltration, thereby limiting groundwater replenishment.
- At the same time, groundwater extraction is increasing, especially for irrigation. During drought periods or when river flows decline, farmers and water managers turn to groundwater as a more reliable source. This overdependence leads to declining water tables, which can result in increased pumping costs, reduced accessibility for small-scale users, and in severe cases, permanent aquifer depletion. In certain geological settings, excessive extraction can also cause land subsidence, damaging infrastructure and reducing the aquifer's storage capacity.
- Water quality is another dimension of concern. Climate-induced changes such as prolonged droughts can concentrate contaminants in groundwater, while in coastal regions, rising sea levels may lead to saltwater intrusion into freshwater aquifers. These processes degrade water quality and limit its usability for agriculture and drinking purposes. The interaction between groundwater and surface water systems further complicates the situation, as reduced groundwater levels can diminish baseflow contributions to rivers, exacerbating surface water scarcity.

Co-funded by the European Union

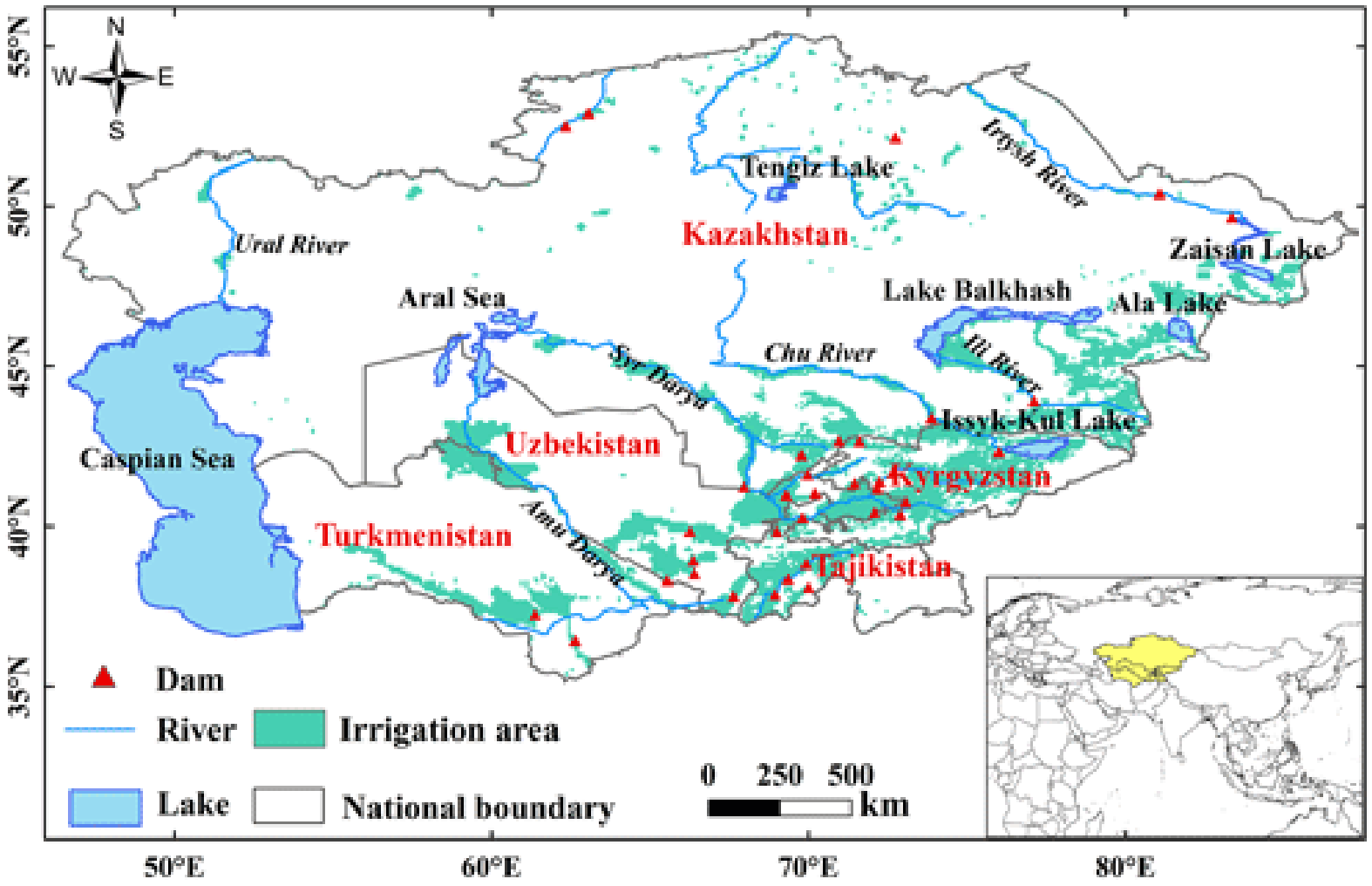
Small Transboundary Rivers: Characteristics and Importanc

- Small transboundary rivers, though often overshadowed by major river systems, are of immense local and regional importance. These rivers cross political boundaries and are typically shared by two or more countries, yet they are frequently under-monitored and under-regulated. Their relatively small size makes them highly sensitive to local climatic variations and anthropogenic pressures. Unlike large rivers, which may have extensive buffering capacity due to large basins and storage systems, small rivers respond quickly to changes in precipitation, temperature, and land use.
- These rivers are vital for rural communities, supporting irrigation, livestock, domestic water supply, and local ecosystems. In many cases, they serve as the primary or sole water source for border regions. Their ecological significance is also notable, as they sustain wetlands, riparian habitats, and biodiversity hotspots. However, the lack of comprehensive data and coordinated management frameworks often leads to fragmented governance, making these systems particularly vulnerable to overuse and environmental degradation.
- In Central Asia, many small tributaries feed into larger systems such as the Syr Darya and Amu Darya, playing a crucial role in maintaining overall basin hydrology. Despite their importance, they are rarely the focus of international agreements, which tend to prioritize major rivers.

Co-funded by the European Union

The accelerating desiccation of small and transboundary rivers

Climate-driven shifts in precipitation, temperature and seasonality are reshaping the planet's freshwater systems. This presentation synthesises contemporary evidence on how drying rivers, irrigation practices and groundwater withdrawal interact - creating cascading risks for agriculture, ecosystems and communities. We focus on three interlinked themes: the accelerating desiccation of small and transboundary rivers, the paradoxes of irrigation efficiency, and the largely hidden crisis of groundwater depletion. Each section pairs scientific insight with practical management implications and design-forward visualisations to guide policy, operational decisions and cross-border cooperation.



https://doi.org/10.5194/hess-25-3281-2021

Co-funded by the European Union

Chapter 1: The Drying Rivers

Small, often overlooked rivers — frequently transboundary and seasonal — act as lifelines for downstream communities and ecosystems. Yet they are among the first systems to show chronic drying: lower baseflows, shortened flow seasons, and increased frequency of disconnected pools. These rivers are sensitive indicators of climate stress and human extraction. This chapter examines the mechanisms driving river drying and documents the ecological, social and geopolitical consequences when flows shrink or vanish.

Local livelihoods at risk

Reduced flow undermines smallholder irrigation, livestock watering and domestic supply. Seasonal crop calendars and pastoral routes become unreliable, increasing vulnerability and migration pressures.

Biodiversity impacts

Aquatic habitats fragment, fish recruitment fails and wetland-dependent species lose refugia. These biodiversity losses are often irreversible on human timescales.

Transboundary tension

Lower flows amplify competition between riparian states. Formal water-sharing agreements are stressed when historic flow regimes change, increasing diplomatic risk and the need for dynamic governance.

Co-funded by the European Union

Murray–Darling Basin: A System Under Stress

The Murray–Darling Basin exemplifies how climate variability and human demand converge. Historically sustaining diverse agriculture and rich ecosystems, the Basin now faces prolonged low flows, more frequent extreme droughts and temperature-driven evaporation increases. Key stressors include: altered rainfall seasonality, reduced autumn–winter recharge, cumulative water extractions and increased wildfire impacts on catchments. Management frameworks developed for a stable historical climate are increasingly inadequate.

Hydrological shifts

Decadal decline in average runoff and shortened flow windows, with more variable peak flows.

Agricultural exposure

Crop yields and irrigation reliability decline; some irrigation relies on opportunistic pumping from drying reaches.

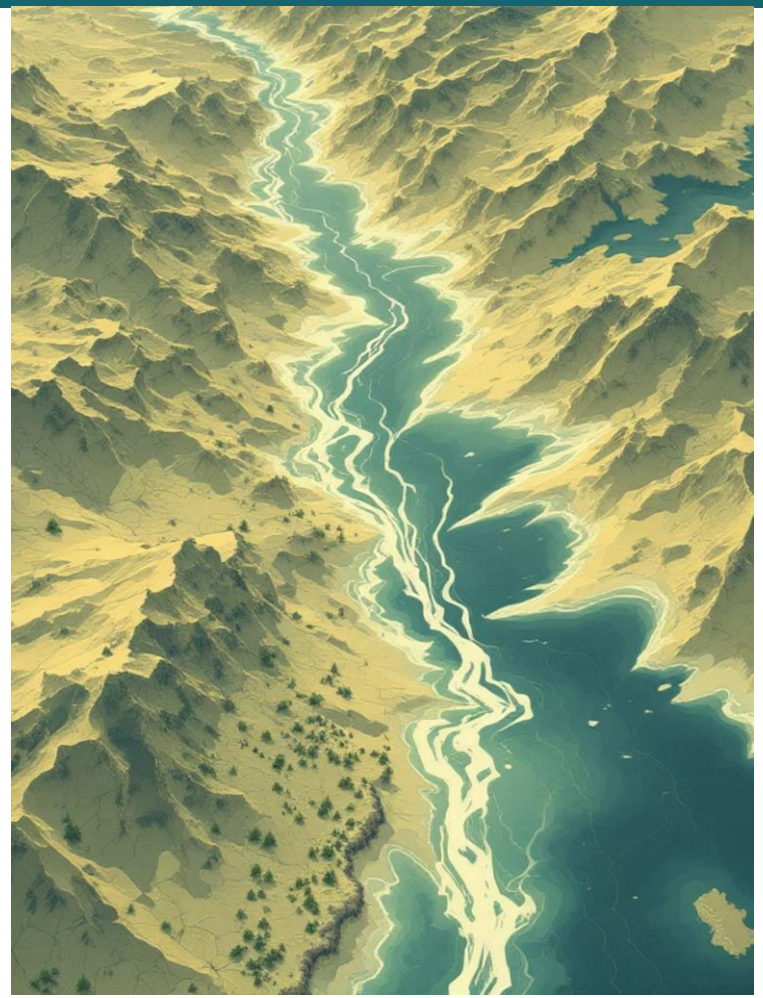
Policy gaps

Existing water allocations and trading mechanisms struggle to reflect non-stationary hydrology and ecological flow needs.

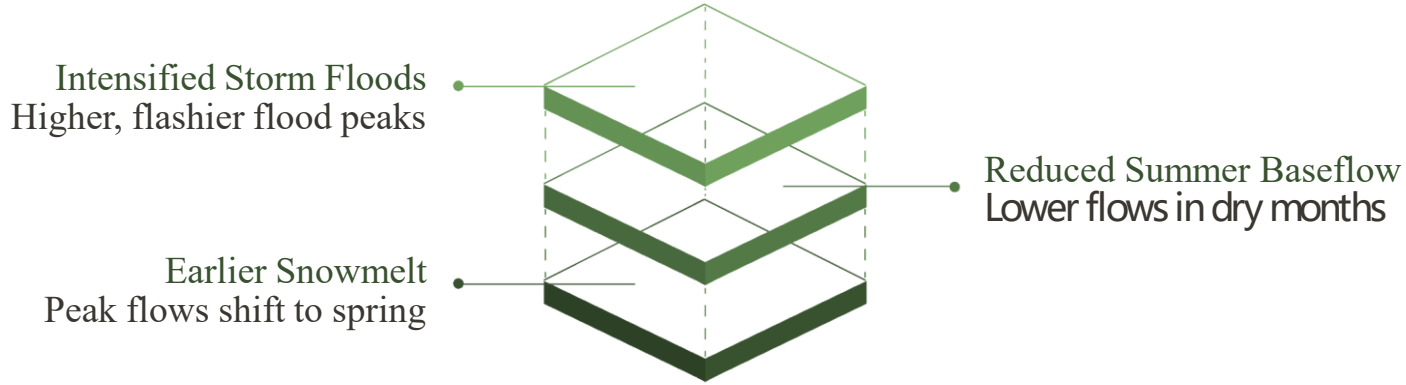
Urgent priorities include updating environmental flow rules, strengthening groundwater–surface water integration, and investing in landscape-scale resilience (catchment restoration, floodplain reconnection and risk-informed allocation systems).

Co-funded by the European Union

Global Rivers Transforming



Rivers worldwide are changing in response to altered precipitation regimes, glacial retreat, and human demand. Patterns vary regionally: snow-melt dependent rivers show earlier peaks and lower summer flows; monsoon-fed systems have more intense but less reliable wet seasons; smaller arid-region rivers shift to ephemeral dynamics. The consequences are universal: threatened food production, compromised hydropower reliability, degraded freshwater ecosystems and rising exposure for urban and rural water users.

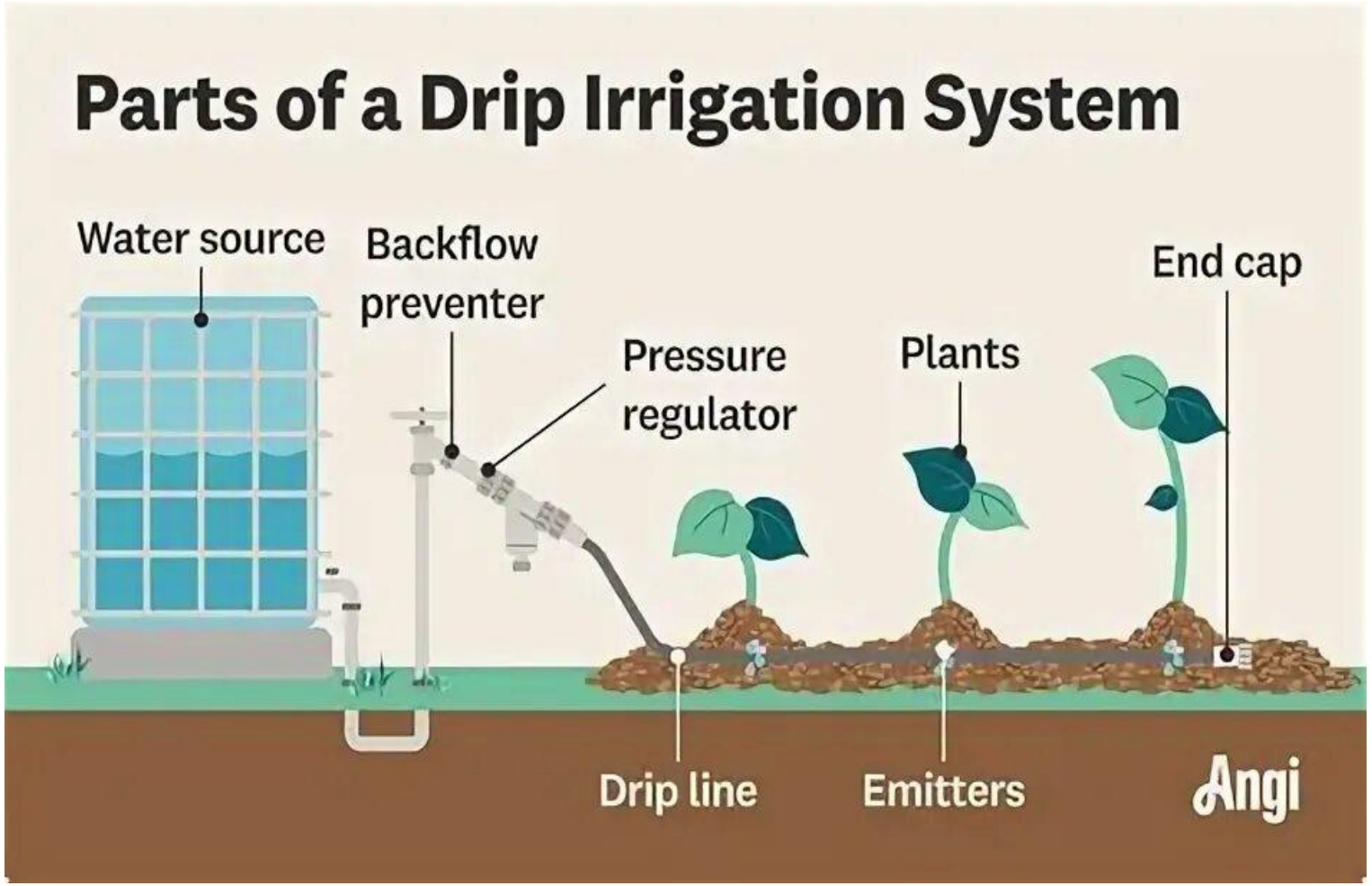


The diagram summarises causal pathways: rising temperatures accelerate snowmelt and evaporation; shifting precipitation increases flood peaks but reduces baseflow persistence; combined with abstraction this produces more frequent low-flow states and intermittent connectivity.

Co-funded by the European Union

Chapter 2: The Irrigation Paradox

Irrigation is essential to global food production, but its interactions with hydrology are complex. Technological improvements - better sprinklers, drip systems, and precision scheduling - reduce on-field losses but can paradoxically increase total consumptive use when crop areas expand or higher-yield varieties demand more water. This chapter explores how irrigation modifies streamflow, groundwater recharge and seasonal water availability, and why efficiency gains do not always equal water savings at the basin scale.



What Is a Drip Irrigation System and How Does It Work? Angi
angi.com

Co-funded by the European Union

Western US: Irrigation's Double-Edged Sword

In the western United States irrigation accounts for nearly 90% of consumptive human water use. It supports high-value crops and rural economies, yet large-scale diversion and consumptive loss substantially reduce streamflow, alter thermal regimes and shrink riparian habitats. Longitudinal studies spanning multiple decades reveal that irrigation-driven streamflow changes can exceed or mask the signal of climate-induced change, complicating attribution and management.

Scale of use

Near-total share of regional consumptive water puts irrigation at the centre of water-resource outcomes.

Streamflow impacts

Reduced summer baseflows, colder winters and warmer water temperatures increase stress on native fish and invertebrates.

Long-term studies

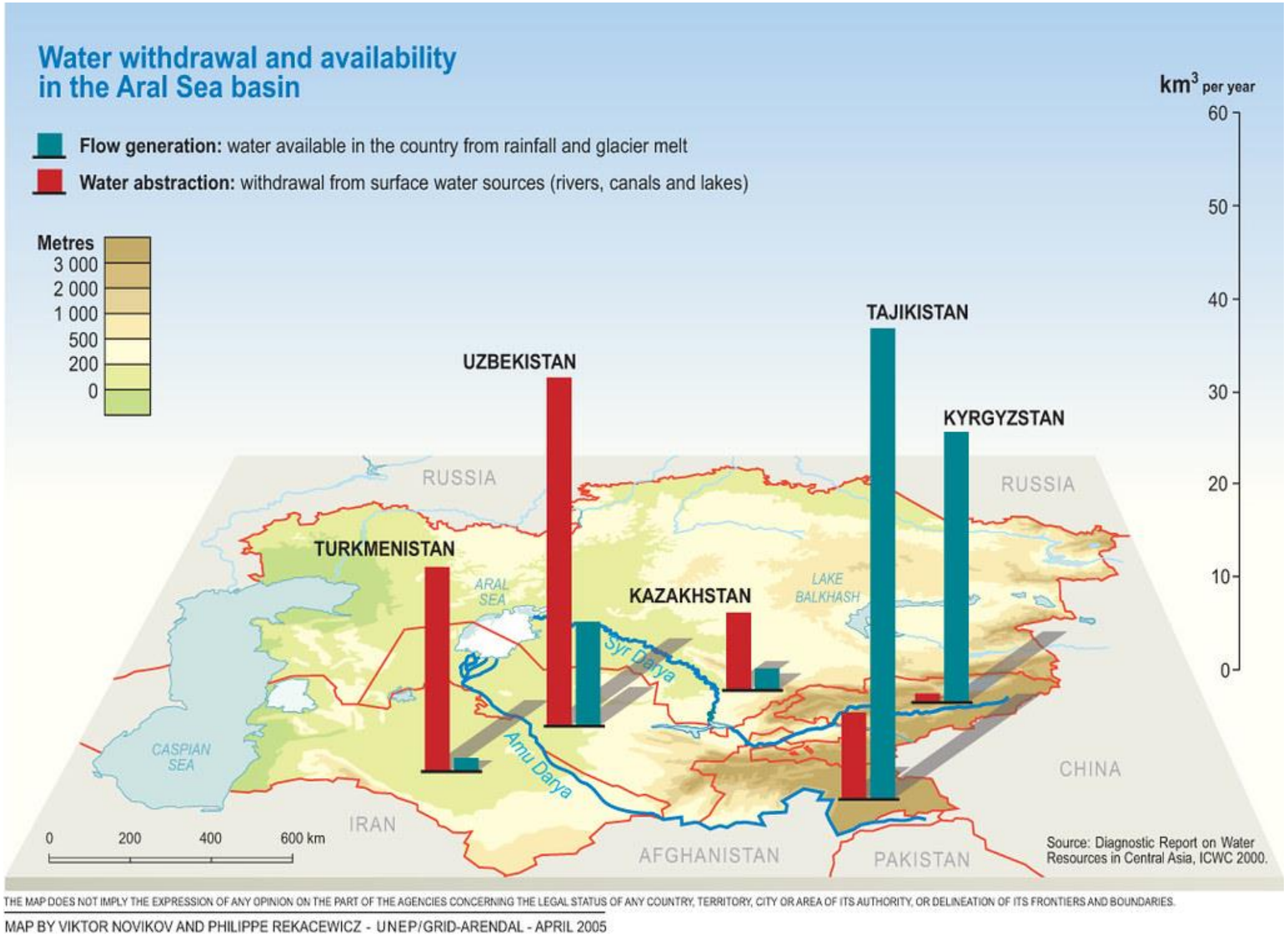
A 35-year analysis demonstrates irrigation changes often exceed observed climate-driven variability in certain catchments, emphasising the need to decouple management actions from climate attribution alone.

Management responses should include conjunctive use planning, demand management via retirement or crop switching, and transparent accounting for return flows and consumptive use.

Co-funded by
the European Union

Chapter 3: Groundwater and Transboundary Challenges

Groundwater buffers seasonal variability and underpins agricultural resilience. However, intensive pumping to offset reduced surface supplies is rapidly drawing down aquifers in many arid and semi-arid basins. Groundwater depletion is not only a local problem: many aquifers and small rivers cross administrative and international borders, creating hidden transboundary exposures that are difficult to govern and costly to reverse.



Co-funded by the European Union

The Efficiency Paradox: More Water Used, Less Water Available

Improving irrigation efficiency at the field scale (for example, through drip systems) reduces local conveyance losses and increases crop water uptake. Paradoxically, this can increase basin-wide consumptive use: higher water-use efficiency often raises crop yields and encourages expansion into marginal lands, while reduced return flows diminish downstream availability. Climate change compounds this effect by increasing evapotranspiration and crop water demand, shifting the timing of peak demand earlier or later in the season depending on crop and region.

Mechanisms

- Lower conveyance losses => less return flow to rivers and aquifers
- Higher yields and cropped area expansion => net increase in total water consumed
- Altered timing of demand intensifies competition during low-flow months

Implications

- Efficiency must be coupled with basin-level limits, allocation reform and incentives to preserve environmental flows
- Monitoring of return flows and seepage is essential for accurate water accounting
- Climate-adaptive crop selection and deficit irrigation can reduce stress when paired with policy measures

Co-funded by the European Union

Groundwater Depletion: The Hidden Crisis

Intensified irrigation increases reliance on groundwater. Over-extraction leads to falling water tables, reduced baseflow contributions to rivers, loss of wetlands, water quality degradation (salinisation and mobilisation of contaminants) and land subsidence. Aquifer recovery can take decades to centuries; in some basins overdraft has already produced irreversible compaction and loss of storage. Because groundwater is often poorly monitored and legally weaker in governance than surface water, effective management lags behind the pace of depletion.

1

1. Monitoring gaps

Insufficient well networks and public data hamper detection of rapid declines and limit evidence-based policy.

2

2. Legal complexity

Fragmented property rights and transboundary legal ambiguities complicate coordinated extraction controls.

3

3. Ecological knock-on effects

Diminished baseflows reduce river resilience, affecting fisheries, wetlands and downstream users across borders.

Solutions must combine expanded monitoring (satellite and in-situ), enforceable allocation limits, recharge enhancement, managed aquifer recharge (MAR) projects and cross-jurisdictional institutions for shared aquifer stewardship.

Co-funded by the European Union

A Call for Integrated Solutions

Co-funded by the European U

Climate change, irrigation practices and groundwater dynamics are tightly coupled. Addressing water security in a non-stationary climate requires integrated, multi-level strategies:

Conjunctive management

Coordinate surface water and groundwter planning, explicitly accounting for return flows, baseflow dependencies and seasonal storage trade-offs.

Transboundary governance

Establish adaptive, data-driven agreements for small cross-border rivers and shared aquifers; include mechanisms for rapid revision as climate signals emerge.

Demand-side reforms

Pair efficiency technology with basin caps, crop choice incentives, seasonal pricing and targeted retirement of water-intensive land where ecological harm is critical.

Enhanced monitoring

Combine Earth observation, groundwater well networks and community reporting to build transparent, near real-time water accounts.

Ecological flows and restoration

Protect minimal flow thresholds, restore floodplain connectivity and invest in riparian buffers that increase resilience to hydrological extremes.

The scale and urgency of these challenges demand coordinated finance, inclusive governance and a willingness to reconfigure agricultural systems where necessary. The choices made today will determine whether rivers remain functioning arteries for both people and nature in a warming world.

Climate Impacts on Small Transboundary Rivers

- Climate change significantly affects the hydrological behavior of small transboundary rivers, often amplifying their inherent variability. One of the primary impacts is increased flow variability. These rivers tend to react rapidly to precipitation events, meaning that periods of drought can quickly reduce flows to critically low levels, while intense rainfall can trigger sudden and potentially destructive floods. This “flashy” hydrological response makes water availability unpredictable and difficult to manage.
- Seasonal shifts are another important consequence. In regions where river flow is influenced by snowmelt, rising temperatures can lead to earlier melting of snowpacks. This shifts peak discharge to earlier in the year, often creating a mismatch between water availability and agricultural demand, which typically peaks later in the growing season. As a result, water shortages during critical irrigation periods become more frequent.
- Moreover, climate change introduces greater uncertainty into hydrological systems. Traditional knowledge and historical data become less reliable for predicting future conditions. This uncertainty complicates planning and allocation, especially in transboundary contexts where multiple stakeholders depend on shared resources. The lack of robust monitoring systems further exacerbates these challenges, leaving decision-makers with limited information.

Co-funded by the European Union

Transboundary Water Governance Challenges

- Managing shared water resources under changing climatic conditions presents complex governance challenges. One of the central issues is the divergence in national priorities. Upstream countries often focus on hydropower generation, which requires storing water in reservoirs and releasing it according to energy demand. Downstream countries, on the other hand, typically depend on consistent water flows for irrigation. Climate change intensifies these competing demands by reducing overall water availability and increasing variability.
- Another major challenge is the lack of reliable data and monitoring infrastructure, particularly for small rivers. Without accurate and timely data on river flows, precipitation, and water use, it becomes difficult to establish equitable and adaptive management strategies. Data sharing between countries is often limited due to political sensitivities or institutional barriers, further hindering cooperation.
- Institutional frameworks governing transboundary water resources are frequently outdated and not designed to accommodate the uncertainties associated with climate change. Many agreements are based on historical flow patterns that no longer reflect current or future conditions. This rigidity reduces the capacity of institutions to respond effectively to new challenges.
- As water scarcity intensifies, the risk of conflict increases. While large-scale conflicts over water are relatively rare, local disputes and tensions are becoming more common, particularly in regions where communities depend directly on shared rivers for their livelihoods. These conflicts can undermine regional stability and hinder cooperative efforts.

Co-funded by the European Union

Case of Central Asia

- Central Asia provides a compelling example of the interconnected challenges facing irrigation, groundwater, and transboundary rivers under climate change. The region's agriculture is heavily dependent on irrigation, with a significant portion of water withdrawals coming from rivers such as the Amu Darya and Syr Darya. As climate change alters the timing and quantity of river flows—partly due to glacier retreat and changing snowmelt patterns—water availability during the growing season becomes increasingly uncertain.
- Groundwater is being used more intensively as a supplementary resource, particularly during periods of low surface water availability. However, this trend raises concerns about long-term sustainability, as recharge rates may not keep pace with extraction. In some areas, declining groundwater levels are already evident.
- Small transboundary rivers and tributaries play a crucial role in local water supply, especially in border regions. These systems are highly vulnerable to climate variability and are often subject to competing demands from neighboring countries. Limited institutional capacity and weak coordination mechanisms further complicate their management.
- The legacy of past water management practices, including large-scale irrigation projects, has also contributed to environmental challenges such as the degradation of the Aral Sea. This highlights the importance of adopting more sustainable and adaptive approaches in the face of ongoing climate change.

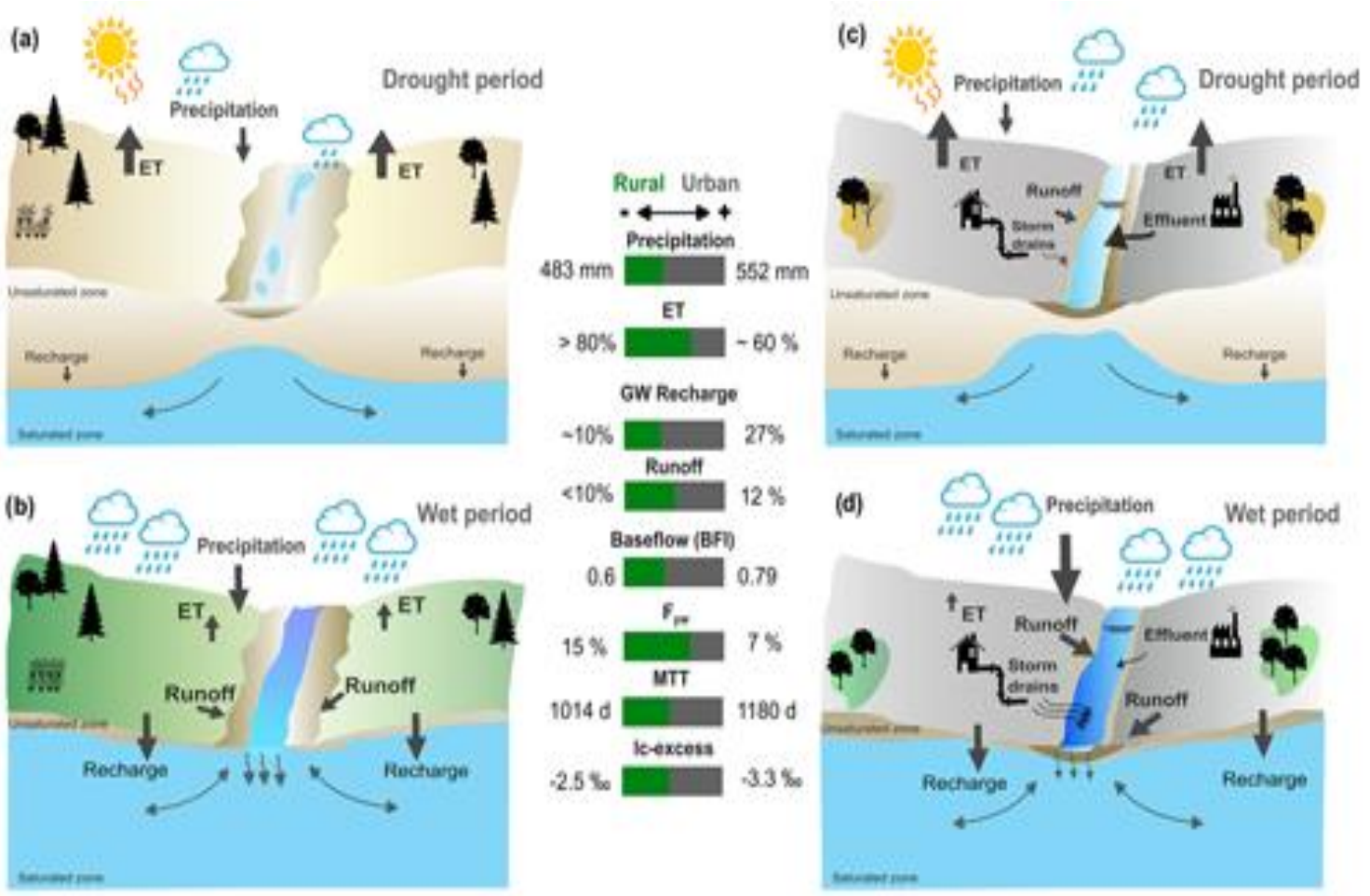
Co-funded by the European Union

Conclusion

The impacts of climate change on irrigation, groundwater, and small transboundary rivers are deeply interconnected and multifaceted. Groundwater systems are under increasing stress from reduced recharge and overextraction, while small rivers exhibit heightened variability and uncertainty. Irrigation systems, which depend on both surface and groundwater, face growing challenges in meeting agricultural demands.

These dynamics are further complicated in transboundary contexts, where multiple stakeholders with differing priorities must share limited and increasingly unpredictable water resources. Effective responses require integrated approaches that combine technological innovation, sustainable management practices, and strong institutional frameworks.

Ultimately, adapting to these changes will depend on the ability to embrace flexibility, improve data and monitoring systems, and foster cooperation at local, national, and international levels. Only through such coordinated efforts can water resources be managed sustainably in a changing climate.



https://doi.org/10.5194/nhess-24-3907-2024

Co-funded by the European Union