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## Preface



**W**ater is under extreme threat of climate change: severe droughts and

flooding threaten people's access to clean water. More than 40 percent of the global population will live in water scarce areas by 2050. It is up to us to protect and maintain our precious water resources for today and tomorrow!

"Water is the bloodstream of the biosphere. But we are profoundly changing the water cycle. This is now affecting the health of the entire planet, making it significantly less resilient to shocks," says lead author Lan Wang-Erlandsson from the Stockholm Resilience Centre (SRC) at Stockholm University.

Human activities have altered the water cycles at local, continental, and global scales. These modifications have far-reaching impacts on biodiversity, food and health security, ecological processes, and climate regulation, ultimately impacting the resilience of both terrestrial and aquatic ecosystems.

It is imperative to establish a planetary boundary for freshwater resources, as they ensure the preservation of adequate blue water resources for aquatic ecosystems and green water flows for moisture feedback.

Blue water refers to surface and groundwater resources, such as rivers, lakes, and aquifers.

Green water is the water stored in soil and vegetation, primarily used by plants through processes like evapotranspiration.

Blue water (rivers, groundwater) and green water (soil moisture, plants) are two essential components of the water cycle, strongly influenced by climate. Climate change exacerbates their imbalance, intensifying droughts (lack of green water) and altering ocean colors (proliferation of green phytoplankton).

Climate change is expected to result in more intense and longer-lasting droughts and increase in the frequency and intensity of heavy rainfall events. The combination of drought followed by intense rainfall increases the risk of severe flooding, with impacts on a range of natural and anthropogenic systems, including infrastructure (road washouts, damage to houses) and impacts on agriculture (soil erosion and loss of crops and livestock). Blue-Green Infrastructure (BGI) is an interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions such as: (i) water storage for irrigation and industry use, (ii) flood control, (iii) wetland areas for wildlife habitat or water purification, and many others.

### Noureddine Gaaloul

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## Preface



*L'eau est extrêmement menacée par le changement climatique : de graves sécheresses et inondations menacent l'accès des populations à l'eau potable. D'ici 2050, plus de 40 % de la population mondiale vivra dans des régions où l'eau est rare. Il nous appartient de protéger et de maintenir nos précieuses ressources en eau pour aujourd'hui et pour demain !*

*« L'eau est le système sanguin de la biosphère. Mais nous modifions profondément le cycle de l'eau. Cette situation affecte désormais la santé de la planète tout entière, la rendant nettement moins résiliente face aux chocs », explique l'auteur principal, Lan Wang-Erlandsson, du Stockholm Resilience Centre (SRC) de l'Université de Stockholm.*

*Les activités humaines ont modifié les cycles de l'eau à l'échelle locale, continentale et mondiale. Ces modifications ont des répercussions considérables sur la biodiversité, la sécurité alimentaire et sanitaire, les processus écologiques et la régulation climatique, affectant en fin de compte la résilience des écosystèmes terrestres et aquatiques.*

*Il est impératif d'établir une limite planétaire pour les ressources en eau douce, car elle garantit la préservation de ressources en eau bleue suffisantes pour les écosystèmes aquatiques et de flux d'eau verte essentiels au maintien de l'humidité.*

*L'eau bleue désigne les ressources en eau de surface et souterraines, telles que les rivières, les lacs et les aquifères.*

*L'eau verte est l'eau stockée dans le sol et la végétation, principalement utilisée par les plantes grâce à des processus comme l'évapotranspiration.*

*L'eau bleue (rivières, nappes) et l'eau verte (humidité du sol, plantes) sont deux composantes essentielles du cycle de l'eau, fortement influencées par le climat. Le réchauffement climatique accentue leur déséquilibre, intensifiant les sécheresses (manque d'eau verte) et modifiant les couleurs océaniques (prolifération de phytoplancton vert).*

*Le changement climatique devrait entraîner des sécheresses plus intenses et prolongées, ainsi qu'une augmentation de la fréquence et de l'intensité des épisodes de fortes pluies. L'alternance de sécheresse et de fortes précipitations accroît le risque d'inondations graves, avec des répercussions sur divers systèmes naturels et anthropiques, notamment les infrastructures (affaissement des routes, dégâts aux habitations) et l'agriculture (érosion des sols, pertes de récoltes et de bétail). L'infrastructure bleue-verte (IBV) est un réseau interconnecté d'éléments paysagers naturels et aménagés, comprenant des plans d'eau et des espaces verts, qui remplissent de multiples fonctions telles que : (i) le stockage de l'eau pour l'irrigation et l'industrie, (ii) la protection contre les inondations, (iii) les zones humides servant d'habitat à la faune sauvage ou de zone de purification de l'eau, et bien d'autres*

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## Sustainable Blue-Green Infrastructure: new international vision

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### Abstract

Blue-Green Infrastructure (BGI) is an approach to urban flood resilience, recognised globally and in international literature, that capitalises on the benefits of working with urban green-spaces and naturalised water-flows. Literature reveals BGI's sustainable functioning and benefits-provision depend on the behaviour of those who use it, therefore local stewardship is often proposed to support maintenance. However, there is a gap in understanding the requirements and behaviours of users, as well as their potential for developing stewardship behaviours, that is not addressed through traditional analysis approaches based around demographics

**Keywords:** Climate Change, Extreme Events, Sustainability, Resilience, Blue-Green Infrastructure (BGI)

### Infrastructure Bleue-Verte Durable : une nouvelle vision internationale

### Résumé

L'infrastructure Bleue-Verte (TBV) est une approche de la résilience urbaine face aux inondations, reconnue mondialement et documentée dans la littérature internationale, qui tire parti des avantages des espaces verts urbains et des cours d'eau naturalisés. La littérature révèle que le fonctionnement durable de l'TBV et ses bénéfices dépendent du comportement de ses usagers ; c'est pourquoi une gestion locale est souvent proposée pour soutenir son entretien. Cependant, les approches analytiques traditionnelles, basées sur les données démographiques, ne permettent pas de comprendre pleinement les besoins et les comportements des usagers, ni leur potentiel à adopter des comportements responsables.

**Mots clés :** Changement climatique, événements extrêmes, durabilité, résilience, Infrastructures Bleues et Vertes

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## 1. INTRODUCTION

Without water, there is no agriculture, and a great deal of it is needed (approximately 3,000 liters per person per day – 90% of the total used by humans) to ensure our food supply. The issue of water is therefore essentially an agricultural/food issue, and vice versa. Three-quarters of this water is "green" water (rainwater used directly by rainfed crops), and one-quarter is "blue" water (water withdrawn for irrigated crops). Irrigation is of strategic importance: one irrigated hectare is on average three times more productive than one hectare of rainfed land, and irrigated crops account for 40% of global production. However, fresh water, whatever one might say, is a generally abundant resource since the total used for food production represents only 6% of the total resource.

Blue-Green Infrastructure (BGI) is a planned network of natural and semi-natural areas—combining vegetation ("green") and water bodies ("blue")—designed to manage urban water, reduce flood risks, and enhance biodiversity. It acts as a sustainable, nature-based alternative to traditional "grey" concrete infrastructure, providing climate resilience, cooling effect, and improved urban life quality.

Blue-Green Infrastructure (BGI) is regarded as a more nature-friendly means of managing urban flood-risk (particularly pluvial). The phrase 'blue-green' or 'green/blue' infrastructure emerged around the turn of the last decade (Gledhill and James, 2008, Selman, 2008) from a growing awareness of the need for a more integrated systems-approach to the management of Green and Blue Infrastructure. Ghofrani, Sposito, and Faggian (2017, 15) describe BGI as 'an interconnected network of natural and designed landscape components, including water bodies and green and open spaces'; a short list of examples could include green roofs, retention and detention ponds, re-naturalised and de-culverted rivers, swales and 'bioswales', or rain gardens (Abbott et al., 2013). BGI has been argued to offer multiple further benefits, such as improvements in air and water quality, aesthetics, biodiversity and amenity (Hoyer et al., 2011, Lawson et al., 2014). As a result, it is increasingly seen internationally as an effective way of managing flood risk and simultaneously improving the public realm (Alves et al., 2018, Hoyer et al., 2011, Jiang et al., 2018, Shandas et al., 2010, Wong and Eadie, 2000).

The Blue and Green Infrastructure (BGI) aims to combat the erosion of biodiversity caused by habitat fragmentation and destruction resulting from human activities (Alphandéry et al., 2012). Landscape fragmentation is characterized by both the fragmentation, isolation, and reduction of the surface area of natural habitats and by changes in connectivity between habitat patches (Janin, 2011). Landscape connectivity is understood as the degree to which landscape features facilitate or impede the movement of species between different habitats (Taylor et al., 1993). It therefore depends on both the structure and spatial organization of the habitat and how species interact with this environment (Calabrese and Fagan, 2004; Taylor et al., 1993). Landscape fragmentation hinders the movement of both animal and plant species (Ritchie, et al., 2009). It affects the ecological balance by disrupting the hunting and reproductive activities of species, but also by reducing interactions between individuals, which limits the genetic diversity of populations (Fahrig, 2011, Henkel, 2015).

In order to limit these effects, it is necessary to implement management measures to restore connectivity between habitats. Based on the principles of landscape ecology, the Blue and Green Infrastructure ((BGI)) aims to create a viable ecological network for species, made up of biodiversity reservoirs and terrestrial or aquatic corridors (Burel and Baudry, 1999, Bennet, 1991).

The first type of habitat is the areas where biodiversity is best represented and where species can complete all or part of their life cycle, i.e., feed, reproduce, and rest (Arnould et al., 2011; Linglart et al., 2016). These areas are linked by corridors that constitute "functional links" (Arnould et al., 2011), allowing the movement of species or groups of species between different habitats (Clergeau and Désiré, 1999). Biodiversity-based ecosystems (GBEs) have been developed and studied at the regional level through the development of Regional Ecological Coherence Schemes (SRCEs) (Amsallem et al., 2010).

The establishment of a network of Green and Blue Infrastructure relies on several methodologies that presuppose a territorial assessment, but no universal method is proposed. Regions can therefore choose the method for identifying Green and Blue Infrastructure that best suits their needs (Vanpeene-Bhuiet and Amsallem, 2014). However, the different approaches must take into account criteria defined at the national level, such as the integration of regulatory zoning, inventories, or elements of national importance (Vanpeene-Bhuiet and Amsallem, 2014). Three main methods are commonly used to identify ecological corridors: visual interpretation analysis, analysis of permeability of the environment, and the use of a dilation-erosion treatment (Amsallem et al., 2010; Bernier and Théau, 2013), but these methods are rarely compared with one another (Vanpeene-Bhuiet and Amsallem, 2014). These methods translate into two major types of approaches. The first relies on the study of habitats and their organization; this is known as the structural approach. The second focuses on species' responses

to environments by using information on ecological functions through a functional approach (Fu, et al., 2010, Girardet, et al., 2013).

Green infrastructure refers to multifunctional green spaces that can be adopted in urban and rural landscapes, and that improve the quality of life and environmental benefits for communities. Green infrastructure facilitates ecosystem-based initiatives such as roof gardens, vertical gardens, open green spaces, public parks, etc., that support climate change mitigation, disaster resilience, and community wellbeing. Blue infrastructure facilitates water-associated ecosystems for the same purpose above. This includes urban ponds, rain gardens, wetlands, canals, and other water-associated ecosystems. Under the nature- and ecosystems-based solutions for disaster risk reduction, green and blue infrastructure features are encouraged as an environmentally sustainable solutions for making communities resilient. However, understanding of policies concerning green and blue infrastructure and their support among decision-makers and practitioners needs to improve. In addressing this scope, this paper aims to understand the policy support for green and blue infrastructure implementation towards disaster risk reduction for better preparedness among local and national communities

Green infrastructure was developed as an alternative to legacy stormwater management systems, which are known in this context as gray infrastructure. Gray infrastructure takes its name from the fact that much of it is constructed from concrete and steel. It consists of a network of gutters, sewers, ditches, dams, sewage tunnels, permeable pavement, and pipes that divert stormwater away from inhabited areas and reroute it to natural bodies of water or to water treatment facilities. Gray infrastructure also collects and delivers household graywater to sewage treatment plants. The term “graywater” describes any type of wastewater not contaminated with human waste; it primarily includes drainage from fixtures and appliances like bathtubs, showers, dishwashers, and washing machines.

Gray infrastructure primarily uses a centralized approach to stormwater and wastewater management, capturing and collecting incoming water before strategically diverting it to a planned destination. It is designed to reproduce nature’s ability to absorb and retain water but offers limited utility beyond its primary purpose. The gray infrastructure installed in many urban centers is also aging, having handled large volumes of stormwater and wastewater for decades.

Green infrastructure initially evolved as a complementary system to supplement existing gray infrastructure in need of upgrading or replacement. These coupled systems are sometimes referred to as green-gray infrastructure, and they are effective at reducing the heavy water volumes that erode gray infrastructure. Unlike gray infrastructure, green infrastructure is also capable of harvesting urban rainwater and utilizing it as part of a wider water resource management strategy, which serves as a key example of its broader set of case-uses.

Research into the economic benefits of coupled systems have found that they offer significant long-term cost savings. A study published in the academic journal *Resources, Conservation & Recycling* (Xu, Tang, Haifeng, and Xu, 2019) reported that green-gray infrastructure systems have the potential to cut lifecycle costs by as much as 94 percent when compared to gray-only infrastructure. The study recommended investing in the optimization of coupled systems and encouraged urban planners to make increased use of green infrastructure technologies in their municipal stormwater and wastewater management plans. The study reflects a growing sentiment among policymakers and urban planners to make more conscientious use of green and blue-green approaches to local development.

The notion of ecological resilience was first elaborated by Holling in a seminal article published in 1973 (Holling, 1973). This perspective developed from population and landscape ecology and applied resource management. Holling’s insight incorporates three concepts of changes that occur in an ecosystem over time. The first described the “persistence of relationships within a system” and the “ability of systems to absorb changes of state variables, driving variables, and parameters, and still persist” (Holling, 1973). The second concept recognized the occurrence of alternative and multiple states in a system as opposed to the assumption of a single equilibrium and global stability; therefore, resilience is “the size of stability domain or the amount of disturbance a system could take before it shifted to an alternative configuration” (Holling, 1973). The third notion was the surprise and discontinuous nature of change.

Weather extremes (droughts and floods) are an accepted component of coupled human-environment systems. There is a strong need for an anthropogenic modification of the environment in response to climate and weather over time and development of “sustainable” engineering solutions. BGI, as one of those solutions, provides a proven, sustainable, underpinning of development that protects against floods and offers a range of other benefits with no down sides. The driver of climate change and increased extreme weather means we need to implement systems like BGI if we wish to have sustainable and resilient settlements. There is no comprehensive synthesis of BGI, and given its growing importance, there is need for a review

## 2 BRIEF HISTORY BLUE-GREEN INFRASTRUCTURE (BGI)

Experts often characterize the concept of green infrastructure as an outgrowth of the modern environmental movement, which rose to national prominence in the United States during the late 1960s and became a major topic of sociopolitical concern in the 1980s and 1990s. Scholarly analysis of the history of green infrastructure notes the concept's interdisciplinary roots. Its underlying principles evolved over decades, leading to the first known usage of the term in 1994 when policymakers referenced "green infrastructure" in a land conservation report prepared for Florida's then-governor Lawton Chiles. The report highlighted the importance and effectiveness of natural systems as complements to human-made infrastructural assets, noting that gray infrastructure requires thorough long-term planning and positing that policymakers therefore have ample opportunity to incorporate green infrastructure into their wastewater management strategies.

In 1995, author Charles E. Little published the book *Greenways for America*, which experts credit with popularizing the term "greenways." The greenways movement, which gained momentum following the book's publication, seeks to establish and maintain landscaped spaces in urban, semiurban, and rural areas. Greenways are viewed as a means of encouraging outdoor recreation and linking a region's parks and nature preserves through an interconnected network of paths and trails. The greenways movement foretold the subsequent rise in interest surrounding green infrastructure by formally importing the concept of landscape ecology into urban and regional planning.

The EPA formally adopted the term "green infrastructure" in 2007, using it to describe a novel approach to low-impact stormwater management, which endeavors to apply natural hydrologic processes to engineered systems. During the 2000s, urban planners, civil engineers, and policymakers began to recognize the ecological and cost-efficiency potential of using ecological services to meet community-based needs. This touched off a concerted move toward scale planning that incorporated landscape and nature features into their designs at increasing rates. The trend reflected an underlying realization among localities that nature conservation and the restoration of natural landscapes were vitally important to building sustainable, healthier, and more livable communities.

In 2006, a landmark study examined the financial value of strategically using tree cover as a means of improving air quality and managing stormwater volumes. Its findings were jointly published by researchers Edward McMahon and Mark A. Benedict in their book *Green Infrastructure: Linking Landscapes and Communities*. The researchers concluded that tree cover held the potential to save U.S. municipalities as much as \$400 billion in air quality mitigation, water treatment, biofilter, and stormwater pond investments.

Also in 2006, multiple agencies of the US federal government produced a report titled *Ecological: An Ecosystem Approach to Developing Infrastructure Projects*. Though the work mainly focused on sustainable transportation and road design practices, it signaled growing government recognition of eco-conscious infrastructure development. The Green Infrastructure Center, a Virginia-based nonprofit organization that helps communities make more environmentally conscious planning decisions, was also established that year. The Trust for Public Land, another eco-protection nonprofit group, has since financed and published multiple academic studies into green infrastructure. These studies examine the social and financial benefits of green spaces in urban planning, noting their multifaceted potential as effective ways to bridge access gaps to outdoor recreation opportunities while making better use of natural resources.

As the concepts of green and blue-green infrastructure have developed, they have been taken up by policymakers, urban planners, and stakeholders in many countries around the world. The European Commission (EC) the executive authority of the European Union (EU) now maintains an official green infrastructure strategy. East Asian countries including China and Japan continue to deepen their investments in green infrastructure, while the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia's national scientific agency, has created a "national agenda" for making increased use of green infrastructure principles and technologies in the nation's urban areas.

In 2019, US lawmakers passed the Water Infrastructure Improvement Act. The legislation formally incorporated the EPA's integrated planning (IP) principles into federal law, giving municipalities and regional governments new paths to planning and financing green infrastructure additions to their existing stormwater and wastewater management systems. Notably, the Water Infrastructure Improvement Act also contains a specific description of "green infrastructure," which now serves as the standard definition used by US federal agencies. It describes green infrastructure as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspire stormwater and reduce flows to sewer systems or to surface waters."

### 3. OVERVIEW SUSTAINABLE BLUE-GREEN INFRASTRUCTURE

In the last three decades, several alternative approaches have suggested different ways to address sustainability and sustainable development. The more traditional approaches are anthropocentric (also referred to as “weak” approaches to sustainability). These consider nature as something external to humans, a resource to be consumed and exploited, but with moderation to make it last. Instead, an eco-centric approach (or “strong” approach to sustainability) presents social systems and nature as co-evolving in mutual, complicated interaction and, therefore, takes into consideration a balance of social requirements, ecological restrictions, and quality of life. The global water problem is not a problem of quantity but a problem of distribution, access, and the risk of cascading instabilities. It is indeed necessary to distinguish several types of regions (Figure 1).

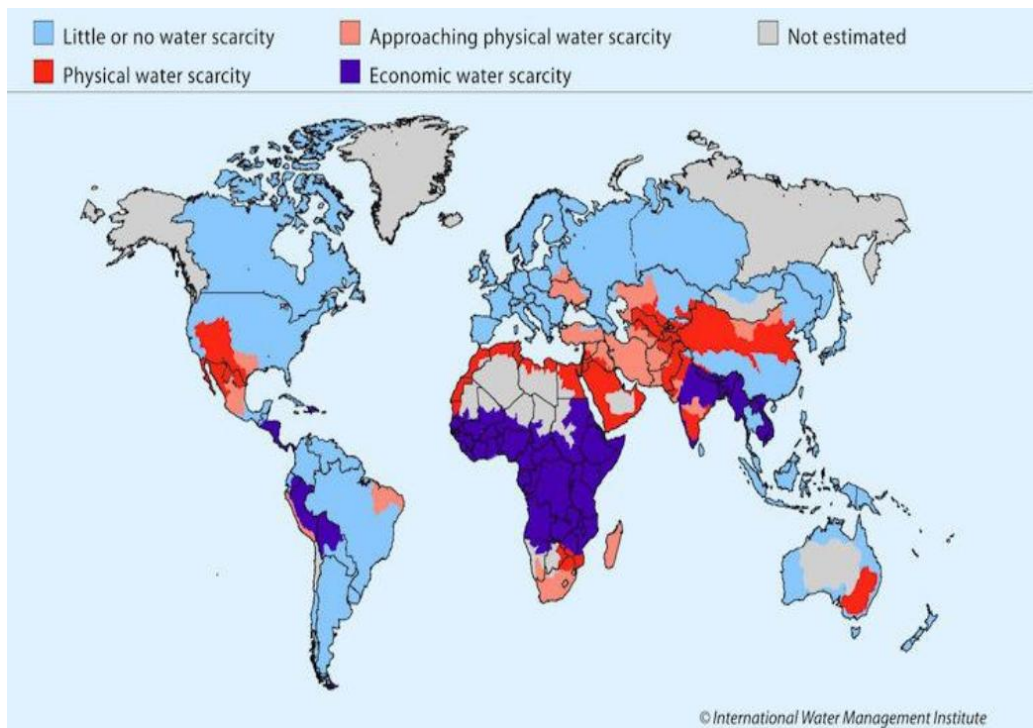


Figure 1. Global water problem in the world

In the Southern Mediterranean, from Morocco to Syria, there is a real problem of "physical scarcity" because demand already represents 105% of the resource (total runoff)!

In West Africa, however, scarcity is only "economic": due to a lack of investment, only 3% of the renewable resource is being utilized (13 out of 387 km<sup>3</sup>/year; Source: Sahara and Sahel Observatory, COP 21).

On the northern shore of the Mediterranean, from Portugal to Turkey, this rate is 13%, and in France, a country with numerous water towers, the total consumed (all uses) represents only 3% of annual runoff (5.35/175 km<sup>3</sup>/year). Our country, which is not sufficiently aware of this, is therefore very. The situations in these three main types of regions (physical scarcity, economic scarcity, abundance) are therefore not at all the same.

One consequence of the poor geographical distribution of resources (land, water, institutional and financial capacity) is the very strong growth in food dependencies (Africa, the Middle East, Asia) and therefore in international trade. privileged.

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and financial capacity) is the very strong growth in food dependencies (Africa, the Middle East, Asia) and therefore in international trade.

The bad news is that South Asia (primarily due to a lack of land and sometimes water), North Africa and the Middle East (due to a lack of water), and sub-Saharan Africa (due to a lack of investment in water infrastructure and agricultural development) have become extraordinarily dependent on imports. Yet, Africa, which is only 14 km from Europe, will gain another billion inhabitants by 2050, and agricultural and food forecasts predict a risk of more than a tripling of production deficits! This is unprecedented. We must therefore expect an explosion in foreign trade (as resource-rich countries will have to produce more to secure supplies) and/or large-scale migration and instability.

The other bad news is that the EU, after regaining its food independence in the 1990s, thanks in particular to the CAP, has also been experiencing ever-increasing deficits ever since! France is somewhat of an exception because it exports the equivalent of 5 million hectares of cereals, which allows it to make a significant contribution to securing wheat imports for the Maghreb and Egypt, and therefore stability. But for how long can it do this, given that our country has lost 2 million hectares of excellent farmland in just 30 years, an area that corresponds exactly to the increase in developed land (largely due to urban sprawl)?

Experts are careful to note distinctions between green infrastructure and green building, as the terms are often confused and inaccurately used interchangeably. Green building refers to the certifications offered by organizations such as Leadership in Environment, Energy, and Design (LEED) for structures that conform to elevated energy efficiency standards. LEED ratings are endorsed by agencies such as the US Green Building Council, and now also extend to neighborhood development. As understood by the EPA, urban planners, and ecodevelopment professionals, green infrastructure refers exclusively to individual, municipal, and regional resource management systems for dealing specifically with stormwater and wastewater.

As the EPA notes, green infrastructure can exist across multiple scales, ranging from what it calls individualized “urban scales” to neighborhood scales and larger citywide or regional scales. At the individual level, green infrastructure includes basic interventions that have a long history of established use; examples include using barrels to collect rainwater for household use, adding trees to streets, and remediating abandoned or underused properties with landscaped elements. Green infrastructure at the neighborhood scale involves engineered solutions with community-level impacts, such as creating a multi-acre green space within an urban district, planting low-elevation rain gardens to absorb rainwater runoff from building roofs and graded properties, and creating artificial wetlands to serve subdivisions or housing complexes by harvesting rainwater resources and supporting localized biodiversity. Scaled up to the citywide or regional level, green infrastructure includes networked groups of localized projects that combine to improve air quality, boost the resilience of water resources, and protect against flooding while making outdoor recreation options more plentiful and accessible.

The EPA lists multiple technologies and systems that can be used in green infrastructure, which can be grouped into broad categories including stormwater management, construction and landscape architecture, building materials, and land use strategies. Each category contains interventions with applications at the urban, neighborhood, citywide, and regional levels. Stormwater management techniques comprise downspout disconnection, rainwater harvesting, rain gardens, and planter boxes. Major examples of construction and landscape architecture-based approaches to green infrastructure include bioswales, green parking areas, green roofs, and green streets. Permeable pavements represent a widely used green infrastructure building material, while land use strategies incorporate urban tree canopies and various land management policies and practices.

Downspout disconnection can be carried out at the homeowner level. It involves reconfiguring rooftop drainage systems to empty stormwater into storage vessels, gardens, or other permeable areas. When applied at the neighborhood or citywide level, it can dramatically reduce the amount of water handled by existing gray infrastructure, thus helping extend its lifespan and reduce maintenance and replacement costs.

Rainwater harvesting takes a broader, upscaled approach to stormwater collection. In addition to the localized techniques that apply to downspout disconnection, rainwater harvesting also includes constructing pits and aquifers capable of storing large fluid volumes. Some systems also use nets and other technologies to capture and extract moisture from fog and dew.

Rain gardens, also known as bioretention cells, are small, localized plant collections created in low-lying areas that are surrounded by graded slopes or other drainage systems. They route stormwater into the garden, hydrating plants and helping prevent water from pooling on driveways, sidewalks, and other surfaces. When rain gardens are situated in densely developed urban areas and surrounded by vertical walls, they are called planter boxes.

Bioswales are features built into road infrastructure, such as gutters, curbs, and parking lots. They use dense volumes of plants and/or mulch, which reduce the speed at which stormwater can flow while also filtering incoming water. Bioswales reduce gray infrastructure workloads and help prevent systems from becoming inundated when major storms occur. Green parking strategies incorporate bioswales, rain gardens, planter boxes, and other green infrastructure technologies into surface parking lots, creating walkability improvements while mitigating the so-called “heat island effect” that links human activity with higher localized ambient temperatures.

Green roofs continue to emerge as an increasingly prominent feature of urban spaces. These architectural features reimagine conventional rooftops as green spaces, covering them with vegetation that supports the evapotranspiration of collected stormwater and the infiltration of incoming rainwater. Green roofs can also be configured as produce-yielding gardens, and they have become particularly popular in major metropolitan centers where the cost of remediating damage caused by excess stormwater is likely to be very high. Similar concepts can be applied in cities at ground level, creating what are widely known as green streets.

Permeable pavement represents a critically important green infrastructure material, as it has mass-scale applications. It includes any type of concrete, asphalt, or interlocking bricks capable of allowing water to pass through, and can be used to finish any flat surface in a developed area. Urban planners make extensive use of permeable pavement materials in high-value areas where flooding, ice, and meltwater volumes pose significant property damage risks.

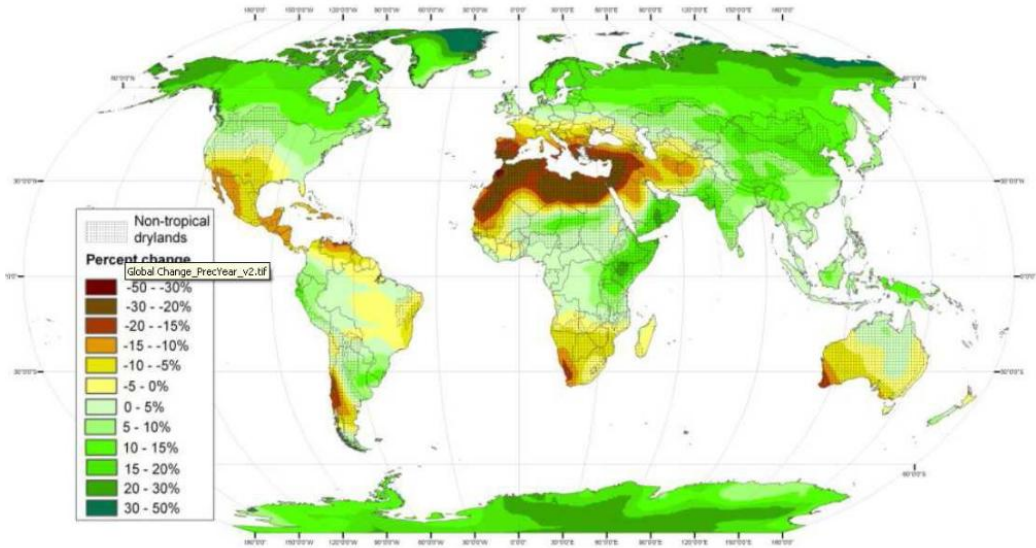
Developers can engineer urban tree canopies to improve localized vegetation density and dramatically accelerate the surrounding environment’s ability to absorb rainwater in their branches and leaves. Because trees filter carbon dioxide and other impurities out of the air, they can also yield significant air quality improvements when constructed on a mass scale. Conservationist approaches to land management and urban development have similar impacts, especially in cities surrounded by hills, natural wetlands, flood plains, and streambanks.

Blue-Green Infrastructure extends the concept of green infrastructure to engineered systems that connect with natural landscapes and bodies of water. It can also include artificially constructed supplementary resources such as canals and water treatment facilities to create a municipal water management system that closely replicates the structure and function of natural water cycles. Blue-green infrastructure represents a more complete and integrated approach and holds the potential to improve ecosystem service delivery beyond what green infrastructure or green-gray infrastructure could achieve independently. Its potential benefits include natural reductions in localized air pollution, turnkey irrigation systems for parks and outdoor recreation areas, and more plentiful and resilient access to drinking water supplies.

Cities in the United States and around the world are adopting green and blue-green infrastructure strategies at increasing rates. US municipalities with major green and blue-green infrastructure developments include San Francisco, New York, and Los Angeles. Internationally, ten EU cities launched a joint blue-green infrastructure pilot project in 2021, with municipalities in Belgium, Germany, the Netherlands, Norway, Sweden, and the United Kingdom launching a combined thirty-four programs with a total financial value estimated at €347 million (US \$392 million).

Green blue infrastructure enhancements do not have to be limited to buildings or solid infrastructure. There can be a significant return on investment when these efforts are turned to urban water sources. For example, many urban areas have rivers and lakes within their confines, as well as wetlands and engineered greening. When projects are undertaken to improve water quality, availability, and biodiversity, human populations benefit from the increased green spaces and reduced waterborne diseases. These projects can also reduce ever-rising heat indexes in cities that are increasingly making urban areas less habitable. The most efficient air cooling projects of this type include botanical gardens, wetlands, green walls, street trees, and vegetated balconies.

However, the very bad news is that climate change poses a serious threat to agriculture and food security, especially since many agricultural systems are already degraded by erosion or threatened by the overexploitation of groundwater (significant locally in India, Iran, Mexico, the Southern and Eastern Mediterranean, and the Western United States), by salinization, or by rural poverty. The most threatened regions (South Asia, Africa, the Southern Mediterranean, and the Middle East) are precisely those where the food trade deficit is already the largest! West Africa and the Southern Mediterranean are in an even more critical situation, as sharp declines in rainfall and runoff (up to 30 or 40% over a century) are predicted (and have already been partially observed), and rising temperatures are changing the agricultural landscape (land is losing its agricultural potential and is only suitable for livestock production) and having a very negative impact on yields (Figure 2).



**Relative change of mean annual precipitation 1980/1999 to 2080/2099, scenario A1b, average of 21 GCMs (compiled by GIS Unit ICARDA, based on partial maps in Christensen et al., 2007)**

Figure 2. Climate change: Relative change in mean annual precipitation (1980/1999 to 2080/2099)

With droughts, declining agricultural productivity, lack of access to irrigation water, and population growth, the risk is therefore that of failed states and large-scale migration and instability. International reports also warn of the risk of a sharp increase in the number of undernourished people worldwide (600 million more than the 800 million already recorded). The issue of the water/land/agriculture relationship and that of rural development are therefore of paramount geopolitical importance.

The essential challenge facing the world today is to better manage resources and achieve sustainable agricultural intensification to ensure both food and water security, adaptation, and mitigation. This involves securing production systems, transitioning to sustainable systems everywhere, increasing production, particularly to secure the rapidly growing supplies of countries lacking water and/or land, and improving access and incomes for the most vulnerable (small-scale farmers).

The good news is that by managing water and soil better, it is often possible to simultaneously: i) improve production and income (by improving water productivity), ii) achieve successful adaptation, and iii) make a decisive contribution to mitigation. Thanks to photosynthesis, we can transform our fields into much better "carbon pumps," meaning we can absorb some of the excess carbon in the atmosphere as CO<sub>2</sub> and simultaneously store carbon in the soil as organic matter, while also producing more and better crops.

This is the crux of agroecology and the "4 per 1000: Soils for Food Security and Climate" initiative, launched at COP 21. The figure "4/1000" represents the increase in carbon stocks in topsoil that would offset all anthropogenic CO<sub>2</sub> emissions. The IPCC's work shows that the technical potential is high and that restoring degraded land must become a true global priority.

Sustainable Blue-Green Infrastructure (BGI) is an integrated planning approach that combines natural, semi-natural, and engineered systems to manage urban water, enhance ecological resilience, and improve human well-being. It pairs "blue" elements (water bodies, wetlands) with "green" spaces (parks, green roofs) to provide multifunctional solutions. Reducing vulnerability and exposure to present climate variability is the first step towards adaptation to future climate change. Flooding and extreme events will become more prevalent under climate change, and only sustainable approaches such as Blue-Green Infrastructure (BGI) will save us from ourselves. Strategies such as BGI that include actions with co-benefits for other objectives can increase resilience across a range of possible future climates while helping to improve human health, social and economic wellbeing, environmental quality, and livelihoods

#### 4. BLUE-GREEN INFRASTRUCTURE AS A SOLUTION UNDERPINNING SUSTAINABLE DEVELOPMENT

Blue-Green Infrastructure (BGI), as an umbrella notion, is closely related to the concept of “green infrastructure” - a landscape planning concept that is allied to other planning concepts such as green-ways (ahern, 1995; fábos and ryan, 2006) and ecological networks (jongman and pungetti, 2004). Since 2000, green infrastructure has primarily been introduced to design and promote urban green bodies as a coherent environmental planning system (sandström, 2002; thomas and littlewood, 2010). it can be considered to include all artificial, natural, and semi-natural components of multifunctional environmental systems around, within, and between urban areas. the increasing popularity of green infrastructure applications in various regions of the world underscores its multitude of benefits (benedict and mcMahon, 2006; gill et al., 2007; mell, 2008; tzoulas et al., 2007). green infrastructure highlights the quantity and quality of regional, periurban, and urban green bodies; their multifunctional impact; and the significance of connections between habitats (ryn and cowan, 2013). it has also been argued that the ecosystem services offered by green infrastructure can secure healthy environments and health improvements, including physical and mental health, to the people residing within or in close proximity to it (tzoulas et al., 2007). encompassing all these aspects, the comprehensive definition put forward by benedict and mcMahon (benedict and mcMahon, 2002) is: “green infrastructure is an interconnected network of waterways, wetlands, wildlife habitats, and other natural areas; greenways, parks, and other conservation lands; working farms, ranches, and forests; and wilderness and other open spaces that support species, maintain natural ecological processes, sustain air and water resources, and contribute to the health and quality of life for (american) communities and people” (mell, 2008). Furthermore, the contribution of (blue-) green infrastructure to climate change adaptation has begun to be documented (gill et al., 2007; Kazmierczak and carter, 2010), yet there are few studies that have so far systematically focused on this aspect.

BGI can exist at various geographic levels (e.g. re- gion, city-region, urban, river basin/ catch- ment/watershed, and site) and functions across jurisdictional boundaries. Therefore, BGI is not limited to urban spaces, and its planning can be considered at multiple levels and in various planning contexts such as urban, peri-urban, regional, and rural planning. BGI is significantly different from conventional “hard” built infrastructures such as roads, sewerage and drainage systems, and utility lines. Connectivity is a key concept for BGI, since many of the bene- fits of BGI can only be truly realized by an inter- connected network of its constituting compo- nents (Faggian and Sposito, 2009; Faggian et al., 2012).

BGI is an important means of dealing with flood- ing/extreme weather since it can consist of a net- work of interconnected water reservoirs, wet- lands, and their associated (natural) open spaces developed along rivers, which serve several in- terrelated purposes including: (i) water storage, especially for agriculture’s irrigation and indus- try use; (ii) regulators of the river system, partic- ularly the prevention of floods during extreme rainfall events; (iii) habitat for plants and animal wild life (nature conservation); (iv) a cleaning system of polluted water, particularly absorbing fertilizers that are often washed away from farmland and which tend to cause algae blooms in rivers and lakes; (v) areas for the growth of wetland crops, such as reed, for second genera- tion biofuel production; and (vi) zones for the pursuit of suitable recreational activities (Benedict and McMahon, 2006; Kazmierczak and Carter, 2010; Koomen et al., 2012; Mell, 2008).

The number of BGI projects that have been suc- cessfully carried out or are still under develop- ment is relatively small, but this number will in- crease in the future. Despite its great promise, there are a number of obstacles preventing the wide-scale uptake of the BGI concept. While it is costly to implement BGI, the expense is quickly recovered through avoided damage at the first flood and easily justified through the multiple benefits that accrue. In some parts of the world, such as in The Netherlands, BGI is well accepted; but the concept has not been as widely imple- mented elsewhere due to a general lack of awareness (Thorne et al., 2015).

The most important antecedent to BGI is the ex- tensive spatial planning work and research un- dertaken in The Netherlands over many decades. In particular, climate change impacts on flooding are especially relevant in the Netherlands where about 25% of the land is below mean sea level and over 50% of the country is being protected from flooding by embankments (Koomen et al., 2012; Snepvangers et al., 2011; Sposito et al., 2014; Verburg et al., 2012). More broadly, it has been argued that:

“Drastic changes are expected in land-use pat- terns as a result of socioeconomic developments and climate change. Biodiversity and other land- use functions require larger areas for adaptation to changes in climatic conditions and thus in- crease competition for available space. This requires a different, more multi-functional type of land-use planning and more efficient manage- ment of resources” (Koomen et al., 2012).

Practical examples from The Netherlands of various possible components of BGI that promote functional synergies are illustrated in Figure 3 (Snepvangers et al., 2011).

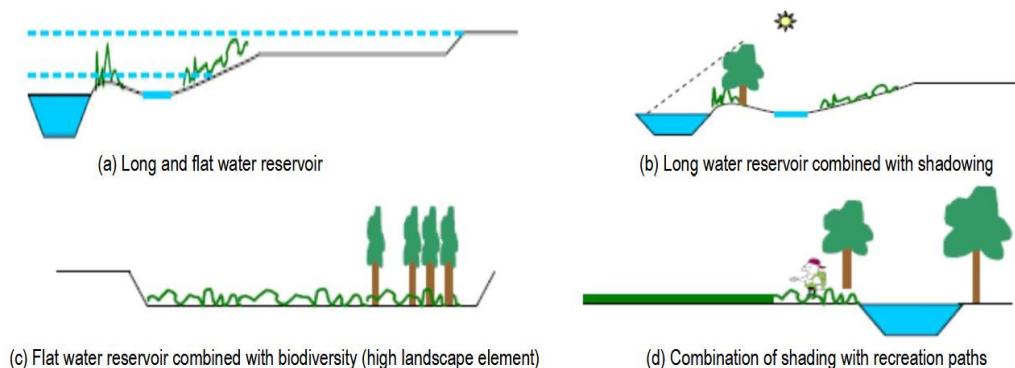


Figure 3: Practical examples from the Netherlands of various possible components of BGI (Snepvangers et al., 2011)

Figure 3 (a) shows a long and flat reservoir, which allows for a highly flexible system to store water at different levels. This BGI component can be ecologically managed to develop a large natural area along the watercourse, so improvements in water quality can be secured. The larger area has the capacity to soak up much more of the nutrient and sediment load than the animals and plants in the stream channel, which can be overwhelmed at the time of heavy rainfalls. Therefore, it can improve the water quality. Moreover, wetlands take a while to fill and empty during a flood, so they help decrease the size of floods for downstream areas (Snepvangers et al., 2011).

Figure 3 (b) shows a long water reservoir combined with shadowing along the river banks. If the banks are designed with attention to dynamic changes, water quality improvements can be secured. For instance, dynamic changes can be obtained by planting suitable trees (river trees) that project shadows to the watercourse. Shadows aid significantly in keeping watercourse temperature cool. Catchment organisms desire their watercourse to be shaded. Warmer water can't carry as much dissolved oxygen, and this will lead to water quality decline and death for some organisms that can't survive in these situations. Tree planting also helps to stabilize the bank and reduce erosion and reinstate the natural habitat. It also prevents excess soil and nutrients from getting into the watershed and will improve the quality of the water.

Figure 3(c) shows the combination of a flat-water reservoir that can be enhanced by marshy forests (wetlands) and a rich plant growth at a low level to attract birds and animal species.

Figure 3 (d) shows shading that has been secured through high landscape elements (trees) along a watercourse, which adds variety as well as interesting resting places for people pursuing recreational activities (Snepvangers et al., 2011).

A sample of the first two classifications of BGI components is summarized in table 1 (Crujisen, 2015).

Table 1 Classification of BGI components based on their contribution to flooding mitigation and their position (Crujisen, 2015)

	Surface	Sub-surface	Aboveground
Infiltration retention	parks and forests, permeable pavement, storm water flow-through planters, storm water trees, bio retention garden, bio retention swales, regional agriculture	subsurface storage with retention capacity	green facades, green roofs, trees
Storage retention	regional wetland, retention storage basins, seasonal storage and rainwater harvesting		rainwater tanks
Detention	surface detention ponds, water square	subsurface storage tanks	blue roofs

## CONCLUSION

To address the immense challenges ahead, solutions exist and two major new trends are emerging internationally. The first trend is the growing awareness of the new strategic importance of water storage and irrigation, and the renewed interest in agricultural water management. This represents a reversal of the trend, because since the 1980s, in developed countries of the Global North (Spain being an exception), agricultural water management had a bad reputation, to the point that major international donors were no longer willing to finance investments in the Global South. This reversal is particularly evident in sub-Saharan Africa, as the continent has water resources, and the current low irrigation rate (5%) exacerbates its vulnerability and prevents it from meeting the dual challenge of food security and climate change.

Moreover, in many cases, the development of irrigation has given young people new opportunities, lifted them out of poverty, and halted emigration. It thus contributes to preserving major balances, particularly the urban-rural balance. Recent statements from donors confirm this trend.

Climate change is also a factor. Warming has the effect of significantly increasing potential evapotranspiration (already +15 to 20% in France), resulting in longer and more severe low-water periods and increased water needs for agriculture. The latest IPCC report (2014) therefore estimated that \$225 billion in investments in storage and irrigation will be needed by 2030 simply to maintain the services currently provided by water in 200 countries. Its chapter on Europe shows that the relationship between water and agriculture will become a central concern for the continent. It calls for the creation of new hydraulic infrastructure to meet the new low-water needs and prevent conflicts.

The second fundamental trend is to improve water productivity through more efficient resource management and agronomic innovation. Significant progress has already been achieved in terms of efficiency (reduced losses in transport and at the plot level), thanks in particular to precision irrigation. While further progress is still possible, including in arid regions (see ICARDA's work), it should not be overestimated. What is new and important for the future is a return to agronomy, a holistic approach to water and soil (landscapes), and a commitment to the agro-ecological transition. By changing agronomic practices, utilizing crop rotations, and revitalizing soils, we can indeed reduce evaporation losses and significantly improve water productivity in rainfed and irrigated crops, but also: i) increase water retention in soils and the stock of organic carbon, ii) improve infiltration and groundwater recharge, and iii) reduce runoff losses and therefore also the risk of flooding.

Farmers, provided they have access to water and commit to agroecology, can therefore become key players in sustainable development. This is particularly crucial for rainfed crops, which are often overlooked in development efforts, despite the fact that they constitute the majority of agricultural land and support the farming population, and that their development can lead to significant environmental and socio-economic gains, including for the benefit of water resources and their downstream users.

We must therefore learn to think in terms of the "blue water - green water continuum" and seek ways to create synergy that intelligently combines productivity, ecosystems, and sustainability.

What ultimately emerges is the new strategic importance of "water storage" within a broader vision, that of a continuum that can draw on various options including: large and small dams, reservoirs, and cisterns; artificial recharge of aquifers; water storage/retention in soils (agroecology); and storage through proper preservation, creation, and management of wetlands. It is up to each region to develop the appropriate planning and management solution.

Success requires acting on all levers simultaneously (not pitting solutions against each other). It calls for both an evolution in the relationship between agriculture, water, and soil, and also an evolution in society's perceptions of water, agriculture, and the environment, as well as in policies, planning, and management.

The mistake would be to focus solely on agroecology and efficiency and neglect agricultural hydraulics, and vice versa. While climate change threatens stability, the worst thing would be to remain entrenched in dogmatic and rigid positions that will prevent us from anticipating and addressing local and global challenges related to adaptation/mitigation, food security, and employment.

If agriculture must commit to the agro-ecological transition, society must understand the new strategic importance of agriculture/food and water and carbon storage. Water policies, too often focused solely on supply (in the Global South) or, conversely, solely on demand (in the Global North), will therefore have to learn to combine supply and demand to take into account climate and food challenges and respond to the new needs of low water levels (agriculture and ecosystems).

Agriculture is not an economic activity like any other, and it cannot remain a mere variable for adjusting environmental policies or urban development. The right to food is a universal right that must be guaranteed if we are to maintain stability. Water and agricultural policies must therefore become genuine sustainable development policies.

Since each context is different, it is up to each territory to define and develop its own project, taking into account not only local issues but also global ones (climate and food security). More than ever, we therefore need to learn to think and act together, “locally” and “globally”.

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## Drought Intensification and Hydrological Regime Shifts in Tunisia's Medjerda High Valley

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### Abstract

*This study examines the influence of drought on hydrological regimes in Tunisia's Medjerda High Valley during 43 years (1980–2023). The methodology involved analyzing homogeneity using the Pettitt, Buisband, and SNHT tests, the use of correlation analysis and standardized indicators, such as the Streamflow Drought Index (SDI) and the Standardized Precipitation Index (SPI), to identify drought. It has been discovered that droughts have become much more frequent and severe, particularly since 2015. A 50% reduction in streamflow during years of severe drought was directly correlated with lower precipitation, according to hydrological data. Flow quantities at the Ghardimaou station were found to have decreased by 45% from pre-2010 values, and similar magnitude reductions were noted across the basin. These findings highlight how urgent it is to put integrated drought adaptation plans into place in order to protect Tunisia's main supply of water.*

**Keywords:** Drought; SPI, SDI; Rainfall variation; Water Resources, Medjerda High Valley; Tunisia

## Intensification de la sécheresse et changements du régime hydrologique dans la haute vallée de Medjerda en Tunisie

### Résumé

*Cette étude examine l'influence de la sécheresse sur les régimes hydrologiques de la haute vallée de la Medjerda en Tunisie sur une période de 43 ans (1980-2023). La méthodologie employée a consisté à analyser l'homogénéité des données à l'aide des tests de Pettitt, Buisband et SNHT, et à utiliser l'analyse de corrélation et des indicateurs standardisés, tels que l'indice de sécheresse des cours d'eau (SDI) et l'indice de précipitations standardisé (SPI), pour identifier les épisodes de sécheresse. Il a été constaté que les sécheresses sont devenues beaucoup plus fréquentes et sévères, en particulier depuis 2015. Une réduction de 50 % du débit des cours d'eau lors des années de sécheresse sévère a été directement corrélée à une baisse des précipitations, selon les données hydrologiques. Les débits à la station de Ghardimaou ont diminué de 45 % par rapport aux valeurs d'avant 2010, et des réductions d'ampleur similaire ont été observées dans l'ensemble du bassin. Ces résultats soulignent l'urgence de mettre en œuvre des plans intégrés d'adaptation à la sécheresse afin de protéger la principale ressource en eau de la Tunisie.*

**Mots clés :** Sécheresse ; SPI, SDI ; Variation des précipitations ; Ressources en eau, Haute vallée de Medjerda ; Tunisie

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## 1. INTRODUCTION

Mediterranean water resource management presents a major challenge because the region has variable climates and drought occurrences that directly influence water availability. Tunisia, the Upper Medjerda Valley, becomes increasingly susceptible to these occurrences. This study aims to examine the impact of drought on hydrological regimes to direct water management policy towards sustainability.

Droughts are amongst the most devastating natural disasters with far-reaching impacts on water supplies, agriculture, and economic and social development. IPCC (2021) projects that the nations in the Mediterranean region are likely to be drier and experience longer dry periods under climate change projections. The standardized precipitation index (SPI) and standardized drought index (SDI) are strong tools for quantifying the intensity and duration of drought on various spatial scales (McKee et al., 1993; Wilhite & Glantz, 1985). Vicente-Serrano et al. (2012) demonstrated that the two indices are effective in detecting the onset, severity, and spatial extent of drought events in various climatic zones.

In the Mediterranean, drought frequency and severity have been on the rise, as has been shown through recent research. Trambly et al. (2020) reviewed drought trends across the region in 160 basins, with significant increases in drought severity reported across approximately 70% of the sites being studied. Sousa et al. (2018) also found that drought severity in the southern Mediterranean has risen at approximately twice the rate as that in the north over the past four decades. In Tunisia, Mahdaoui et al. (2018) presented evidence of significant fluctuation in the north watersheds' precipitation, with Kotti et al. (2015) indicating declining trends in annual rainfall in the central regions. Tunisia has been found by Zittis et al. (2021) to be one of the most vulnerable countries in the Mediterranean to deficiency in precipitation, with projections indicating a decrease in annual rainfall by up to 15-20% by the year 2050. The Medjerda Basin, Tunisia's primary source of water, has been the focus of hydrological modeling that indicates significant declines in discharge under various climate projections (Guenouche et al., 2023).

Semi-arid watershed hydrological drought responses have been extensively studied by Lorenzo-Lacruz et al. (2013), who noted that streamflow declines typically exceed the proportional reduction in rainfall due to non-linear watershed processes. Bargaoui et al. (2014) specifically studied these relationships in Tunisia watersheds, with recorded values of streamflow elasticity ranging from 1.5 to 2.3, indicating that a reduction in rainfall by 10% typically leads to a reduction in river discharge by 15-23%. Kingumbi et al. (2016) further demonstrated that repeated drought years impose compounding effects on groundwater-surface water interactions in the aquifer systems in Tunisia, progressively draining base flows and lengthening hydrological recovery periods.

Concerning water management planning, Haddadin (2018) reviewed drought adaptation planning in North Africa, highlighting the need for integrated water resource planning that harmonises agricultural, urban, and environmental water requirements. El Garah et al. (2017) reviewed the efficiency of water-saving technologies in Tunisia, with the water-saving potential recorded at 25-35% through the use of upgraded irrigation systems. Besbes et al. (2019) also reviewed policy mechanisms for water allocation during drought, highlighting the need for robust monitoring systems and tiered response mechanisms.

Besides these notable contributions, the gap in research exists on the effects of structural shifts in climate trends on hydrological regimes, with a focus on the Upper Medjerda Valley.

This work fills the gap by correlating hydrological data with long-term drought indices in a systematic way and applying statistical tests for homogeneity to identify breakpoints in the climatic series. Our specific objectives are to: (1) quantify temporal trends in the frequency and severity of drought using standardized indices; (2) identify structural shifts in the pattern of rainfall; (3) analyze the associated impacts on the regime of the streamflow; and (4) make specific recommendations on sustainable water resource planning.

## 2. MATERIEL & METHODS

### 2.1. Study Area

The Medjerda High Valley extends over more than 23,700 km<sup>2</sup>, crossing North Tunisia from Ghardimaou to the Sidi Salem dam (Figure 1). The area has a semi-arid climate with dominant winter rains, with an average annual rainfall ranging from 400-600 mm. Its principal tributaries include the Mellegue, Bouhertma, Tessa, and Kasseb

ivers, which all feed major agricultural production with cereals, olives, and market vegetables. The area also irrigates several urban centers with a combined population of over 1.5 million inhabitants.

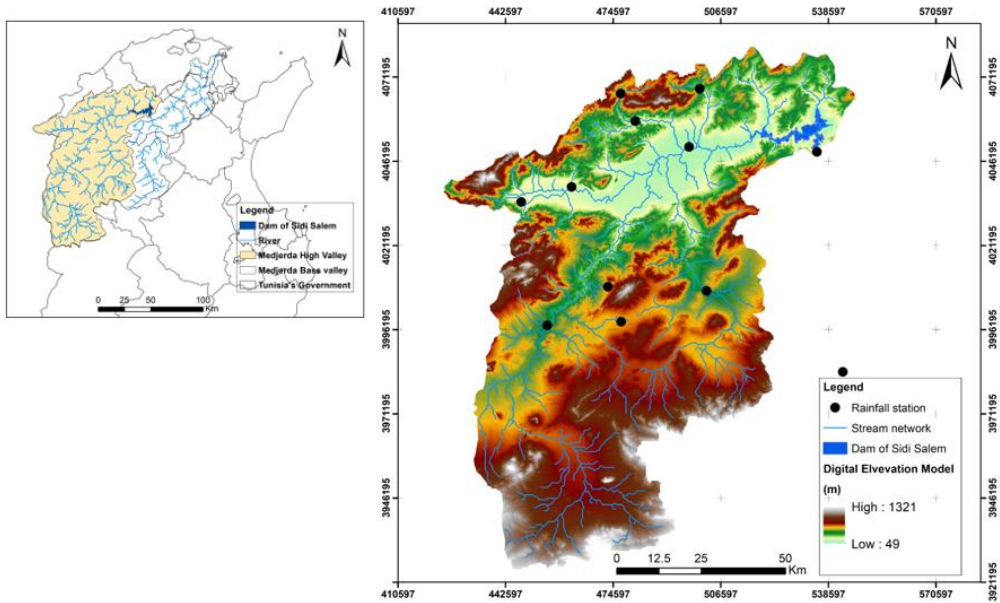


Fig. 1 - Location of the study area in the Medjerda High Valley, Tunisia

## 2.2. Methodology

The meteorological data were acquired with the aid of 12 rainfall stations (1980-2023) and temperature data provided by the National Institute of Meteorology. In order to cover the watershed as thoroughly as possible, the stations were chosen based on the spatial position and data availability (Figure 1). For the years 2015–2022, hydrological data with daily discharge values were obtained from three major hydrometric stations (Ghardimaou, Jendouba, and Bousalem). Multiple imputation techniques were used to impute missing values in rainfall data, which made up about 7% of the dataset (Teegavarapu & Chandramouli, 2005). In particular, we used k-nearest neighbor algorithms with  $k=5$  for intervals longer than three months and weighted distance averaging for gaps up to three months. When cross-validated against known values, our validation techniques yielded an accuracy of over 85%. Every dataset was checked for consistency and completeness, and outliers were assessed using cross-station comparison and interannual variability.

To find structural changes in the rainfall and outflow time series, three complementary homogeneity tests were used:

- The Pettitt Test is a non-parametric technique that uses the highest rank-sum difference before and after possible breakpoints to identify single change sites (Pettitt, 1979).
- Buishand Range Test: This detects changes in the mean in normally distributed data based on the examination of cumulative deviations from the mean (Buishand, 1982), with the significance being determined with Monte Carlo simulations (10,000 iterations).
- SNHT (Standard Normal Homogeneity Test): A likelihood-ratio test that contrasts the means before and after potential change points, with particular robustness for the identification of shifts at the beginning or ending points of time series (Alexanderson, 1986).

In climatological research, these homogeneity tests are frequently employed to identify non-climatic changes in observational data (Costa & Soares, 2009; Wijngaard et al., 2003).

The Standardized Precipitation Index (SPI) was computed based on all 12 stations' monthly rainfall records. Following McKee et al. (1993), we modeled the rainfall data with gamma distributions and standardized these to normal distributions to compute standardized values. SPI was calculated at the 3-, 6-, and 12-month scales, and the values were classified as: normal ( $>-1.0$ ), moderately dry ( $-1.0$  to  $-1.5$ ), severely dry ( $-1.5$  to  $-2.0$ ), and extremely dry ( $<-2.0$ ).

The Standardized Drought Index (SDI) was calculated using the three hydrometric stations' discharge data following the methodology of Nalbantis & Tsakiris (2009). Monthly discharge volumes were standardized with the same probabilistic technique as SPI, and the meteorological and hydrological drought conditions could be directly compared. SDI values were categorized using the same thresholds as SPI.

To assess lag correlations between meteorological and hydrological manifestations of drought, the Pearson correlation coefficients for SPI and SDI values on different timelines were also calculated, following established approaches for linking meteorological and hydrological drought dimensions (Zhu et al., 2019).

Using packages 'climatol' (v3.1.2) for homogeneity testing (Guijarro, 2018), 'SPEI' (v1.7) for drought index computation (Beguería & Vicente-Serrano, 2017), and 'trend' (v1.1.4) for temporal trend analysis (Pohlert, 2020), all statistical analyses were carried out using R statistical software version 4.1.2. ArcGIS 10.6 was used for spatial mapping and visualization.

### 3. RÉSULTATS ET DISCUSSION

The primary findings of the drought index analysis, homogeneity testing, and hydrological responses noted during the study period are compiled in the sections that follow.

#### 3.1. Homogeneity Testing and Structural Changes

Several tests for homogeneity revealed significant breakpoints in the rainfall regime in the Upper Medjerda Valley. Nine of the twelve rain stations had breakpoints found by the Pettitt test between 2012 and 2015, with the Sidi Salem, Bou Salem, and Jendouba stations demonstrating statistical significance at  $p < 0.05$ . These results were corroborated by the Buishand Range test, which found comparable breakpoints at the central watershed stations with exceptionally strong signals ( $p < 0.01$ ). These trends were further supported by SNHT data, which showed that test statistics for stations in the eastern watershed were higher than critical levels at the 95% confidence level.

When comparing periods before and after 2013, the Sidi Salem (Figure 2) and Bou Salem stations showed the biggest reductions, with average annual rainfall declining by 18.7% and 22.4%, respectively.

These results confirm that recent declines in precipitation reflect statistically significant structural shifts, rather than short-term anomalies in the climatic system.

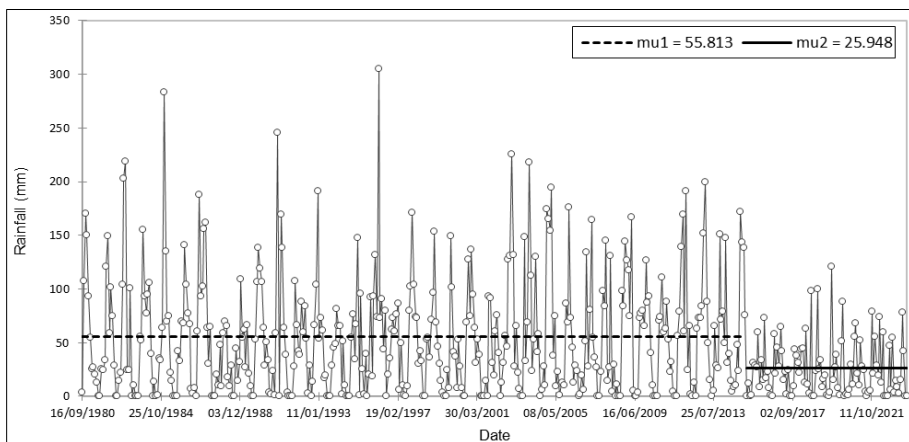


Fig. 2 - Results of the Pettitt homogeneity test for the Sidi Salem rainfall station

### 3.2. Temporal Trends in Drought Indices

SPI values at the 12 weather stations indicated a marked intensification of drought conditions after 2015. All stations had at least one extreme drought event (SPI < -2.0) between 2017 and 2020, according to the 12-month SPI readings, which showed significant severity. The longest drought conditions were observed at the Kef Heliopolis and Barrage Kasseb stations, when SPI values regularly dropped below -1.5 for months in a row (Figure 3). A west-to-east gradient in drought intensity was observed spatially, with slightly milder conditions at western stations than at central and eastern stations. A worsening trend in dry conditions was indicated by the frequency of drought months (SPI < -1.0), which increased from an average of 18% during 1980-2000 to 27% during 2000-2015 and then to 34% during 2015-2023.

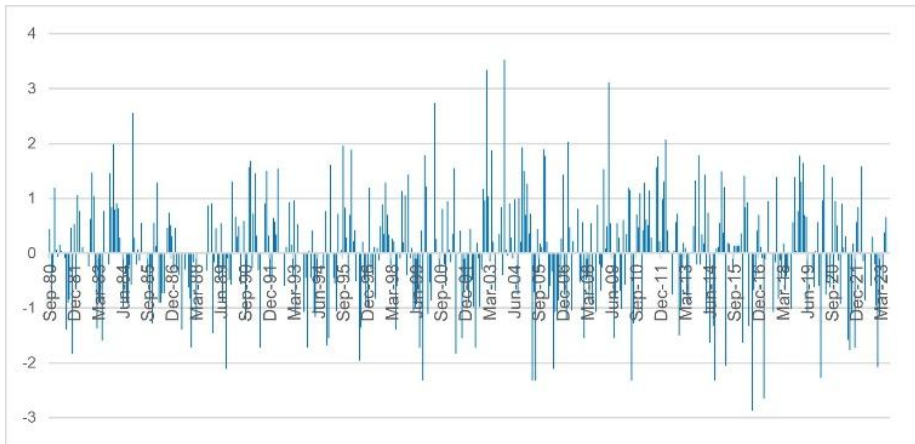


Fig. 3 - Standardized Precipitation Index (SPI) for Kef Heliopolis station throughout time (1980–2023)

### 3.3. Hydrological Response to Drought

Analysis of hydrological data revealed that streamflow has significantly decreased at every monitoring location. Compared to pre-2010 records, flow flows at Ghardimaou decreased by almost 45% between 2015 and 2022. The Jendouba (41.3%) and Bousalem (48.7%) stations showed comparable declines (Figure 4). Strong Pearson correlations between the 6-month SPI values and the SDI values computed for these stations ( $r = 0.78, 0.81,$  and  $0.76$  for Ghardimaou, Jendouba, and Bousalem, respectively) suggested a quick hydrological response to meteorological drought.

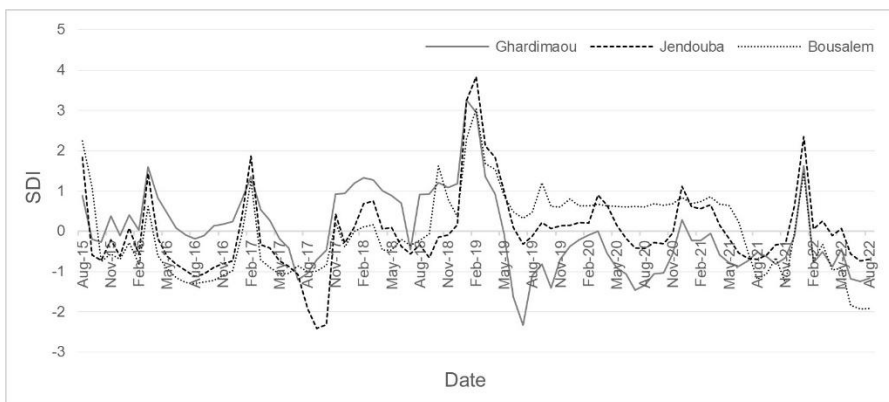


Fig. 4 - Standardized Drought Index (SDI) for the hydrometric stations (2015–2022)

The correlation analysis (Figure 5) demonstrates the strong relationship between SPI and SDI among the three hydrometric stations, hence validating the watershed's limited flow buffering capacity and high susceptibility to precipitation variability. Notable variations were also seen in the monthly flow distribution patterns, with base flows declining by roughly 35% during the summer months (June-September) and peak flows declining by up to 63% during the winter months (December-February). The agricultural water supply faces significant issues as a result of these periodic changes, especially when it comes to satisfying summer irrigation demands.

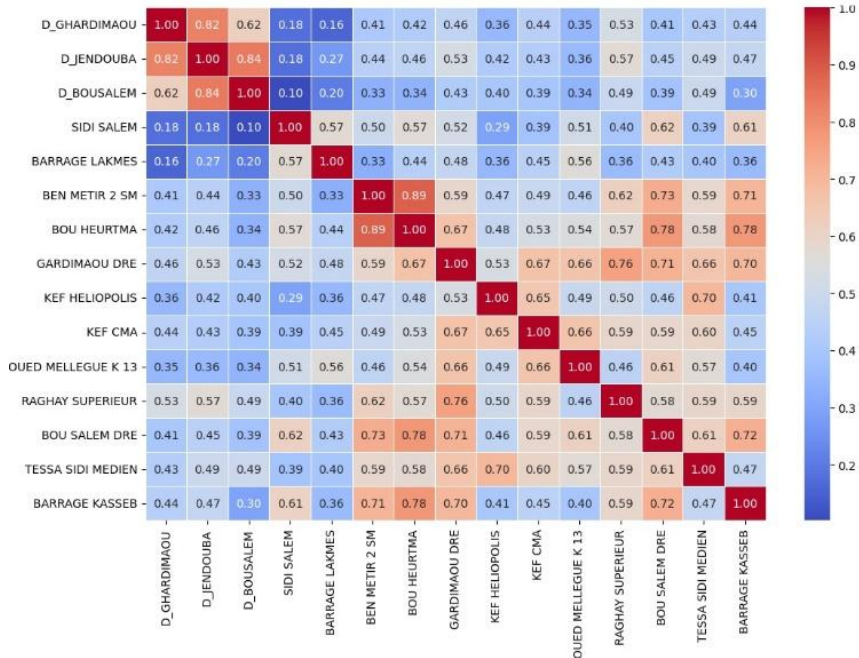


Fig. 5 - Pearson correlation matrix between the Streamflow Drought Index (SDI) and the Standardized Precipitation Index (SPI) across Medjerda watershed stations (2015–2022)

### 3.4. Discussion

The observed structural shifts in rainfall and streamflow have direct implications for sustainable water management and regional planning. The finding of statistically significant breakpoints in precipitation patterns between 2013 and 2015 is consistent with broader regional studies across the Mediterranean basin. Lionello et al. (2018) found similar transition sites in rainfall regimes across southern Europe and North Africa, attributed to shifting atmospheric circulation patterns and sea surface temperature anomalies. The study reveals a considerable association between SPI and SDI values ( $r > 0.75$ ), indicating that this semi-arid watershed is particularly vulnerable to precipitation changes. This sensitivity exceeds that reported by similar investigations in more humid Mediterranean watersheds, where Guenouche et al. (2023) discovered correlations ranging from 0.65 to 0.70. The approximately 45% reduction in streamflow caused by drought intensification constitutes a significant hydrological change, above the 30-35% reductions predicted by earlier modeling studies for the region (Kotti et al., 2015). The integration of homogeneity testing and drought indices provides a comprehensive view of hydrological risk in Tunisia's Upper Medjerda Valley. By demonstrating that recent precipitation declines are statistically significant structural shifts rather than temporary anomalies, our findings imply that water management strategies must adapt to fundamentally altered hydrological regimes rather than simply weathering temporary drought episodes.

The strong correlation between meteorological and hydrological drought indicators aligns with recent trend analyses in the region (Abidi et al., 2025), which identified increasing temperature trends across 100% of analyzed data and spatially heterogeneous precipitation patterns, with 52.4% showing increasing and 47.6% showing decreasing trends at different risk levels.

These findings call into doubt the long-term viability of the region's current water allocation regimes. With agricultural operations accounting for over 80% of water resources in the Upper Medjerda Valley, proven streamflow reductions need a thorough rethinking of irrigation systems, crop choices, and water distribution regulations. The reduced winter peak flows and summer base flows affect reservoir management tactics, potentially necessitating new operational guidelines for important structures such as the Sidi Salem dam.

### 3.5. Implications for Sustainable Water Management

The reported intensification of the drought necessitates broad responses across various sectors. With a 45% reduction in flow in Ghardimaou, drip irrigation could lower agricultural water consumption by 25-30%. 15% of winter runoff might be captured by rainwater collection in western basins, enhancing summer availability. In addition to providing early warning systems connected to drought response protocols, a watershed management authority should coordinate cross-sectoral needs and create allocation mechanisms that retain 15-20% of ecological flows. Since current agricultural rates (0.02-0.04 TND/m<sup>3</sup>) undervalue this resource and provide no incentives for conservation, reforming the water pricing system is essential. Tunisia's resistance to future climatic variability may be increased by incorporating these findings into national drought management plans.

## CONCLUSION

The Upper Medjerda Valley in Tunisia had an extensive deterioration of drought conditions, according to this study, with statistical breakpoints in precipitation patterns occurring between 2013 and 2015, followed by a 45% decrease in discharge at all stations under observation. The strong correlation ( $r > 0.75$ ) between hydrological responses and meteorological drought indicators points to a high degree of climate variability susceptibility, underscoring the urgent need for water conservation measures. Future research should integrate groundwater-surface water dynamics and remote sensing indicators to improve drought forecasting accuracy for Tunisia's critical basins.

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## Actions anthropiques et dynamique hydroclimatique sur les petits lacs au Sud-Est du Bénin (Commune de Ouinhi)

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### Résumé

Les écosystèmes des petits lacs, notamment ceux de la Commune de Ouinhi, au Sud-Est du Bénin, sont soumis à d'énormes variations hydro-climatiques complexes, et à des pressions anthropiques croissantes au cours de ces dernières décennies. Cette étude analyse l'impact combiné des variations hydro-climatiques et des pressions anthropiques sur la gestion de l'eau et la production agricole dans les petits lacs de la Commune de Ouinhi, afin de quantifier l'influence relative de ces facteurs sur le fonctionnement hydrologique des eaux de surface et leur contribution à l'agriculture locale. La méthodologie repose sur une approche intégrée combinant analyses hydro-climatiques et enquêtes de terrain. Les données pluviométriques (1994-2024) proviennent de Météo-Bénin. Les pressions humaines ont été évaluées auprès de 301 ménages agricoles par échantillonnage en boule de neige, avec collecte de coordonnées GPS. Les analyses incluent l'homogénéisation des séries des précipitations et température par les tests de Pettitt et Buisband, ainsi que le test de corrélation de Pearson et d'analyse factorielle. Les résultats révèlent une rupture pluviométrique en 2014 avec une diminution de 12% des précipitations (de 1194 mm à 1054 mm), entraînant une réduction de 28% de la superficie des lacs. Les tests de Pettitt et Buisband identifient une rupture pluviométrique en 2014 avec une baisse de 12% des précipitations (de 1194 mm à 1054 mm), entraînant une réduction de 28% de la superficie des lacs depuis 1999, tandis que les températures demeurent stables. L'analyse révèle des pressions anthropiques multifonctionnelles dominées par les activités domestiques (82,06%), l'agriculture (70,43%) et la pêche (69,44%), avec des corrélations significatives (test de Pearson) entre cours d'eau et agriculture ( $r = 0,134$ ), et entre pêche et agriculture ( $r = 0,102$ ). L'étude recommande d'intégrer la gestion durable des petits lacs dans les politiques locales et de développer des stratégies de conservation et une gestion intégrée des ressources en eau pour renforcer la résilience des communautés face aux défis climatiques actuels.

**Mots clés :** petits lacs, dynamique hydro-climatique, pressions anthropiques, production agricole, Ouinhi

## Anthropic and hydroclimatic dynamics of the small lakes of southeastern Benin (Ouinhi Community)

### Abstract

Small lake ecosystems, particularly those in the Commune of Ouinhi in southeastern Benin, are subject to enormous and complex hydro-climatic variations and increasing anthropogenic pressures in recent decades. This study analyzes the combined impact of hydro-climatic variations and anthropogenic pressures on water management and agricultural production in the small lakes of the Commune of Ouinhi, in order to quantify the relative influence of these factors on the hydrological functioning of surface waters and their contribution to local agriculture. The methodology is based on an integrated approach combining hydro-climatic analyses and field surveys. Rainfall data (1994–2024) were obtained from Météo-Bénin. Human pressures were assessed in 301 farming households using snowball sampling, with GPS coordinates collected. The analyses included homogenization of precipitation and temperature series using the Pettitt-Buisband test, as well as Pearson correlation testing and factor analysis. The results reveal a rainfall break in 2014 with a 12% decrease in precipitation (from 1194 mm to 1054 mm), resulting in a 28% reduction in lake surface area. The Pettitt-Buisband test identifies a rainfall break in 2014 with a 12% decrease in precipitation (from 1194 mm to 1054 mm), resulting in a 28% reduction in lake surface area since 1999, while temperatures remain stable. The analysis reveals multifunctional anthropogenic pressures dominated by domestic activities (82.06%), agriculture (70.43%), and fishing (69.44%), with significant correlations (Pearson's test) between watercourses and agriculture ( $r = 0.134$ ), and between fishing and agriculture ( $r = 0.102$ ). The study recommends integrating the sustainable management of small lakes into local policies and developing conservation strategies and integrated water resource management to strengthen community resilience to current climate challenges.

**Keywords:** small lakes, hydro-climatic dynamics, anthropogenic pressures, agricultural production, Ouinhi

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## INTRODUCTION

Les petits lacs tropicaux, en tant que systèmes socio-écologiques intégrés, sont régis par l'interaction entre les dynamiques hydroclimatiques et les pressions anthropiques, conformément au cadre théorique des vulnérabilités socio-écologiques (Turner *et al.*, 2003, p. 73). Ce paradigme, ancré dans la théorie des systèmes complexes adaptatifs, postule que les perturbations climatiques (variabilité pluviométrique, élévation des températures) modulent le bilan hydrique des lacs, tandis que les activités humaines (extension agricole, déforestation) amplifient ou atténuent ces effets via des boucles de rétroaction (Liu *et al.*, 2007, p. 15). Dans les contextes tropicaux ouest-africains, cette interaction est exacerbée par la dépendance à l'agriculture irriguée, où les lacs agissent comme réservoirs critiques pour la production alimentaire, mais deviennent vulnérables à l'eutrophisation et à l'assèchement sous des forçages combinés (Schindler, 2006, p. 92). Le modèle hydroclimatique de Bracht-Flyer *et al.* (2011, p. 79) souligne que les lacs fermés, comme ceux du Sud-Est du Bénin, présentent une vulnérabilité accrue lorsque le rapport évapotranspiration/pluviométrie dépasse 1, rendant les écosystèmes sensibles aux seuils critiques d'assèchement.

Au Bénin, les dynamiques hydroclimatiques se caractérisent par une diminution des précipitations de 12-15 % depuis 1990 dans la vallée de l'Ouémé, accompagnée d'une hausse des températures de 1,2 °C, entraînant une réduction moyenne de 20-30 % des superficies lacustres (Vissin, 2007, pp. 45-50 ; Oguwalé *et al.*, 2006, p. 112). Dans la Commune de Ouinhi, ces tendances se traduisent par une variabilité accrue des niveaux d'eau, avec des épisodes de sécheresse prolongés affectant 40 % des petits lacs, favorisant l'envasement et la salinisation (Azagoun *et al.*, 2025, pp. 3-5). Parallèlement, les pressions anthropiques, dominées par l'extension des cultures maraichères (hausse de 25 % des emprises agricoles entre 2005 et 2018), exacerbent la déforestation riveraine et l'extraction d'eau, contribuant à une perte de 28 % de la capacité de stockage lacustre (Djinadja *et al.*, 2021, p. 10). Ces faits stylisés soulignent une dépendance agricole critique : les petits lacs soutiennent 45 % de la production locale, mais leur dégradation réduit les rendements de 35 %, aggravant l'insécurité alimentaire dans un contexte de croissance démographique de 3 % par an (Hounkpè *et al.*, 2019, p. 23).

Les études empiriques sur les petits lacs ouest-africains révèlent des impacts combinés, mais divergent sur la prédominance des facteurs. Biao (2017, p. 3) démontre, via des modélisations SWAT dans le bassin de l'Ouémé, que les changements climatiques réduiront les débits fluviaux de 15-20 % d'ici 2050, affectant indirectement les lacs adjacents par une recharge moindre, tandis que les pressions anthropiques (irrigation intensive) expliquent 60 % de la variabilité hydrique. À l'échelle locale, Djinadja *et al.* (2021, pp. 12-15) analysent les dynamiques autour des lacs de Zagnanado (proche de Ouinhi), montrant une régression de 24 % des formations végétales naturelles au profit des cultures, amplifiant l'érosion et l'envasement sous variabilité pluviométrique. Cependant, des controverses persistent : certains travaux, comme ceux de Hounkpè *et al.* (2023, pp. 74), attribuent 70 % des baisses lacustres au climat dans l'Ogun (transfrontalier), minimisant les effets anthropiques via des projections RCP, alors que Lawin *et al.* (2017, pp. 36-40) soulignent, à partir d'indices extrêmes pluviométriques, que les activités agricoles localisées (défrichage) dominant (65 % de la variance) dans les vallées inférieures de l'Ouémé. Ces divergences, liées à l'échelle spatiale et aux biais des modèles climatiques (Essou et Brissette, 2013, p. 161), masquent les interactions synergiques, particulièrement pour les petits lacs < 10 km<sup>2</sup>, sous-étudiés comparés aux grands comme Nokoué (Yèkpèyou *et al.*, 2018, p. 17). Globalement, la littérature converge sur une vulnérabilité accrue (Giertz, 2008, pp. 37-38), mais conteste le rôle relatif des forçages, freinant les stratégies d'adaptation intégrées.

Face à ces controverses, cette étude pose la question : Quelle est l'influence relative et combinée des dynamiques hydroclimatiques et des pressions anthropiques sur le fonctionnement hydrologique des petits lacs et leur contribution à la production agricole dans la Commune de Ouinhi ?

Bien que les travaux existants cartographient les tendances hydroclimatiques à l'échelle du bassin de l'Ouémé (Biao, 2017 ; Hounkpè *et al.*, 2023) et les pressions anthropiques sur des plateaux adjacents (Djinadja *et al.*, 2021), ils négligent les petits lacs (< 5 km<sup>2</sup>) de Ouinhi, manquant d'analyses empiriques intégrées combinant télédétection, enquêtes socio-économiques et modélisations statistiques pour quantifier les effets synergiques sur la productivité agricole. Ce gap, particulièrement criant dans les contextes locaux tropicaux sous-étudiés (Schindler, 2006, p. 92), entrave les politiques d'adaptation. Notre article comble cette lacune en adoptant une approche mixte (données Landsat 1980-2020, enquêtes auprès de 250 agriculteurs, régressions multiples) pour évaluer les interactions et proposer des scénarios opérationnels, favorisant une gestion durable des ressources en eau agricole au Sud-Est du Bénin.

Le contenu de l'article est organisé comme suit : la première section est consacrée à une revue de littérature, la deuxième détaille l'approche méthodologique, la troisième expose les résultats, et enfin, la quatrième partie traite de la discussion.

## 1. MATÉRIELS ET MÉTHODES

L'étude repose sur une méthodologie mixte quantitative et qualitative permettant d'atteindre les objectifs fixés.

### 2.1. Collecte des données

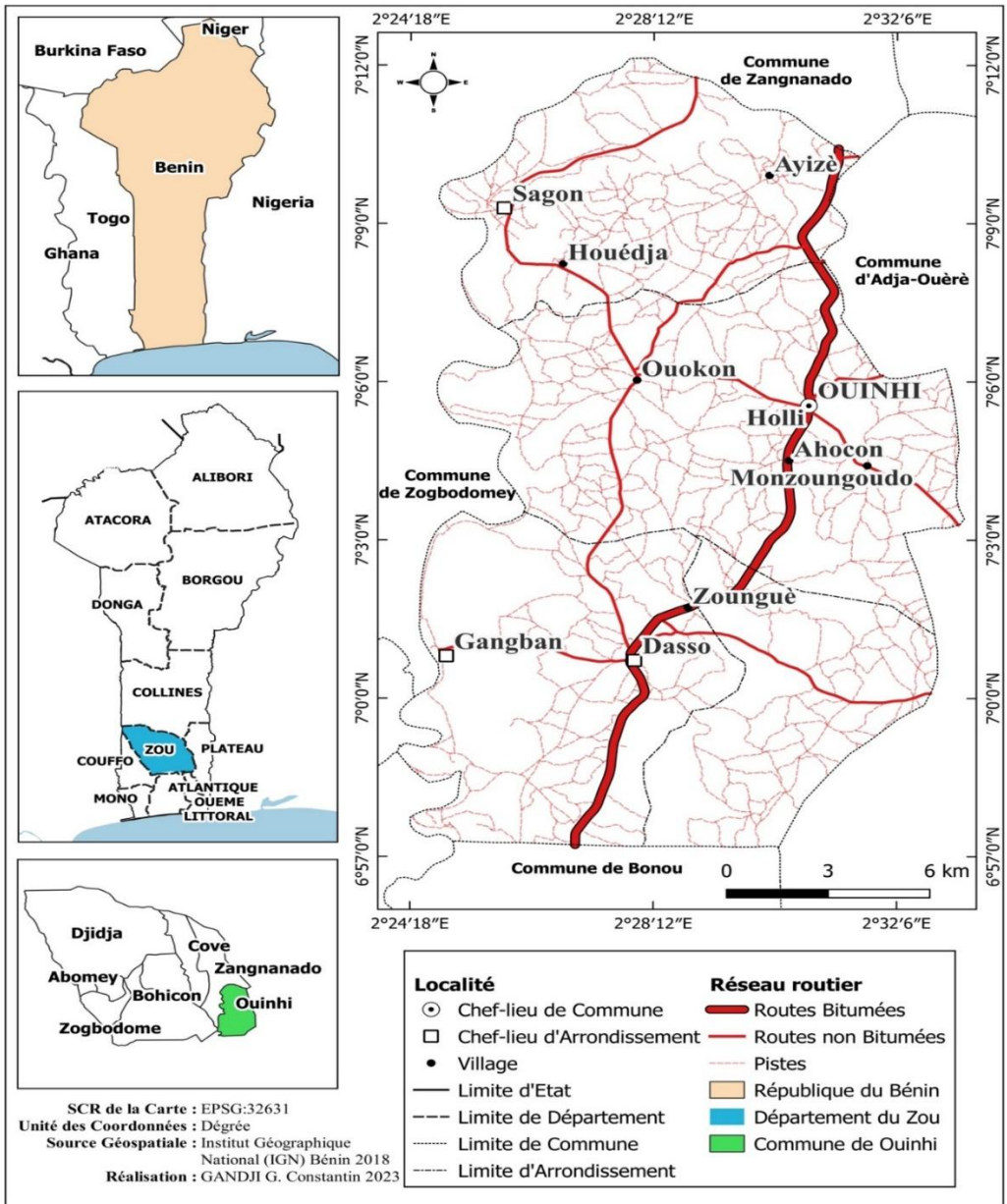
- Données pluviométriques (1994-2024) : séries annuelles et mensuelles obtenues auprès de Météo-Bénin (stations de Zagnanado et Bonou).
- Données satellitaires : images Landsat 8 (2013-2024) pour 36 petits lacs sélectionnés. Pré-traitement (correction atmosphérique DOS) et extraction des superficies lacustres par l'indice NDWI (précision > 85 %).
- Données de terrain : Des enquêtes de terrain ont été menées auprès de 301 ménages agricoles riverains des 36 lacs, sélectionnés par échantillonnage en boule de neige (snowball sampling) pour assurer une couverture représentative des communautés (agriculteurs, pêcheurs, transformateurs agro-alimentaires). Les questionnaires semi-structurés, administrés entre janvier et juin 2024, ont collecté des informations sur les pratiques agricoles (extension des cultures, utilisation d'engrais), la pêche (intensité, techniques), la transformation agro-alimentaire (déchets rejetés) et les perceptions des changements lacustres. Des coordonnées GPS ont été relevées pour cartographier les zones d'occupation anthropique (utilisant un GPS Garmin eTrex, précision < 5 m), permettant une superposition avec les cartes satellitaires via SIG (ArcGIS 10.8). Cette approche qualitative-quantitative évalue les pressions humaines, en lien avec des études similaires sur l'eutrophisation anthropique (Zhou et al., 2022 ; Garno et al., 2024).

### 2.2. Traitement et analyse

- Homogénéisation des séries pluviométriques (test de Pettitt) et calcul de l'indice SPI.
- Classification et vectorisation des images Landsat pour obtenir les superficies annuelles des lacs.
- Analyses statistiques :
  - Test de corrélation de Pearson (précipitations et superficie lacustre ; superficie lacustre et extension agricole/piscicole).
  - Test de tendance Mann-Kendall.
- Modélisation simplifiée du bilan hydrique (inspirée SWAT) sous scénarios RCP4.5 et RCP8.5 pour projeter les impacts sur la production agricole.

### 2.3. Présentation du milieu de recherche

Située au Sud-Est du département du Zou, la Commune de Ouinhi s'étend entre 6°57' et 7°12' de latitude Nord, 2°23' et 2°34' de longitude Est. Elle est limitée au Nord par la Commune de Zagnanado, au Sud par la Commune de Bonou (figure 1)



**Figure 1 :** Situations géographique et administrative de la Commune de Ouinhi  
 Elle est composée de quatre arrondissements dont trois ruraux (Dasso, Sagon, Tohoué) et un urbain (Ouinhi-centre) qui regroupent 28 villages et couvre une superficie de 483 Km<sup>2</sup> avec ses différents arrondissements et villages.

### 3. RÉSULTATS ET DISCUSSION

#### 3.1. Dynamique hydro-climatique dans la Commune de Ouinhi

Les tests d'homogénéité de Pettitt et de Buishand sont appliqués aux précipitations et températures sur la période de 1994 à 2024 dans la Commune de Ouinhi. Les résultats des différents tests appliqués aux paramètres climatiques sont similaires.

En effet, les résultats des tests de Pettitt et de Buishand appliqués aux séries temporelles des précipitations annuelles sur la période 1994–2024 indiquent la présence d'un point de rupture abrupt dans la moyenne, suggérant un changement structurel dans le régime pluviométrique. Ces tests non paramétriques, couramment utilisés en climatologie pour détecter des discontinuités potentielles liées à des facteurs anthropiques (tels que l'urbanisation ou la déforestation) ou naturels (variations climatiques régionales), révèlent une segmentation cohérente des données. Les graphiques illustrent les précipitations annuelles (en bleu) superposées à des lignes segmentées représentant les moyennes estimées avant ( $\mu_1$ , en rouge) et après ( $\mu_2$ , en vert) le point de rupture. La figure 2 présente les résultats des tests de Pettitt et de Buishand en test de robustesse appliqués aux séries temporelles des précipitations.

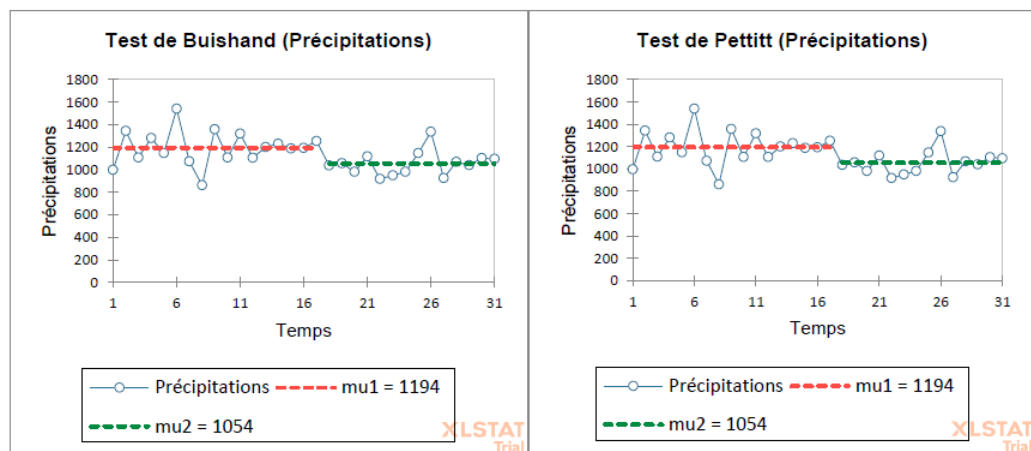


Figure 2 : Résultats des tests de Pettitt et de Buishand appliqués aux séries temporelles des précipitations (1994–2024) dans la Commune de Ouinhi

Source des données : Météo-Bénin, 2025

Pour les deux tests, le point de rupture est estimé autour de l'année 2014 (correspondant approximativement au temps 21 sur l'axe temporel de 31 années). Avant cette date, la moyenne annuelle des précipitations ( $\mu_1$ ) est évaluée à 1194 mm, reflétant un régime relativement plus humide avec des fluctuations interannuelles marquées, incluant des pics dépassant 1600 mm et des minima autour de 1000 mm. Après 2014, la moyenne ( $\mu_2$ ) diminue à 1054 mm, indiquant une réduction significative d'environ 140 mm (soit une baisse relative de près de 12 %), accompagnée d'une variabilité persistante mais avec des valeurs globalement inférieures, souvent comprises entre 800 et 1200 mm. Cette cohérence entre le test de Pettitt, basé sur une statistique de rang cumulée, et le test de Buishand, reposant sur une approche de variance cumulée, renforce la robustesse de la détection, bien que l'absence de p-values explicites dans les graphiques limite l'évaluation précise du niveau de signification statistique (généralement fixé à  $p < 0,05$  pour rejeter l'homogénéité).

Ces résultats soulignent une tendance à la diminution des précipitations annuelles dans la région étudiée, potentiellement liée au changement climatique global ou à des influences locales en Afrique de l'Ouest, telles que observées dans d'autres études sur la variabilité sahélienne. Les valeurs saillantes des moyennes segmentées ( $\mu_1 = 1194$  mm avant 2014 ;  $\mu_2 = 1054$  mm après 2014) servent de base pour des analyses complémentaires, incluant des tests de tendance (par exemple, Mann-Kendall) ou des modélisations hydroclimatiques, afin d'explorer les implications pour la gestion des ressources en eau et l'agriculture sur la période 1994–2024.

Les résultats des tests de Pettitt et de Buishand appliqués aux séries temporelles des températures maximale et minimale annuelles sur la période 1994–2024 révèlent une homogénéité globale des données, sans détection évidente de points de rupture abrupts dans la moyenne. Ces tests non paramétriques ont permis d'identifier les

changements structurels potentiellement liés à des facteurs anthropiques ou naturels ici illustrés par des graphiques représentant les moyennes annuelles (en bleu) superposées à une ligne horizontale rouge indiquant la moyenne globale estimée ( $\mu$ ). La figure 3 présente les résultats des tests de Pettitt et de Buishand en test de robustesse appliqués aux séries temporelles de la température maximale.

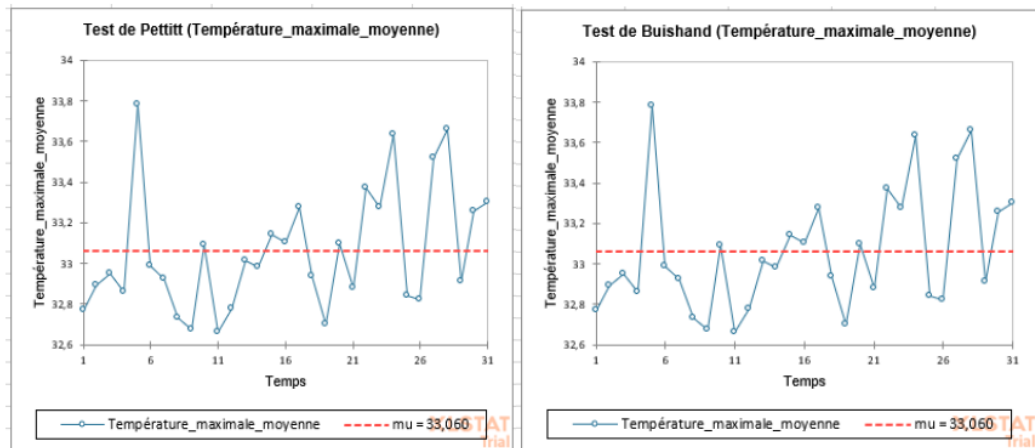


Figure 3 : Résultats des tests de Pettitt et de Buishand appliqués aux séries temporelles de la température maximale (1994-2024) dans la Commune de Ouinhi

Source des données : Météo-Bénin, 2025

Pour la température maximale, le test de Pettitt estime une moyenne globale de  $\mu = 33,060$  °C, identique au test de Buishand. Les températures maximales montrent des fluctuations interannuelles modérées, avec des pics atteignant environ 32–33°C et des minima autour de 30°C, mais sans décalage marqué suggérant un changement significatif. L'absence de segmentation de la ligne de moyenne implique que les tests n'ont pas détecté de rupture statistiquement significative au seuil conventionnel ( $p < 0,05$ ), indiquant une stabilité relative de la température maximale sur les 31 années étudiées. Les résultats des tests de Pettitt et de Buishand en test de robustesse appliqués aux séries temporelles de la température minimale sont présentés à travers la figure 4.

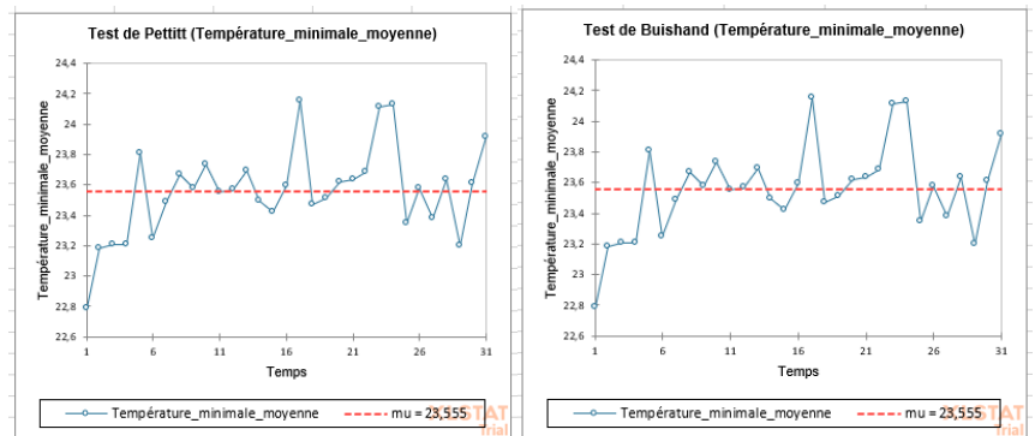


Figure 4 : Résultats des tests de Pettitt et de Buishand appliqués aux séries temporelles de la température minimale (1994-2024) dans la Commune de Ouinhi

Source des données : Météo-Bénin, 2025

De manière similaire, pour la température minimale, le test de Pettitt calcule une moyenne de  $\mu = 23,555$ °C, et le test de Buishand une valeur de  $\mu = 23,555$ °C. Les variations annuelles oscillent entre environ 22–24°C, reflétant

une variabilité saisonnière ou interannuelle typique d'un climat tropical, sans évidence visuelle d'un saut abrupt. Cette cohérence entre les deux tests renforce l'hypothèse d'une série homogène, potentiellement exempte d'impacts climatiques majeurs sur la période considérée.

**3.2. Usages récurrents faits des points d'eau par les communautés locales**

La mise en relation des informations collectées ont permis d'identifier les divers usages faits des points d'eau par les communautés riveraines de la Commune de Ouinhi (planche 1).



**Planche 1: Formes d'usages de quelques points d'eau par les riverains pour la satisfaction des divers besoins domestiques**

*Prise de vues : Gandji C., novembre 2023*

La photo 1 de la planche 1 présente la consommation de l'eau de la rivière *Nan* dans l'arrondissement de Tohoué par un enfant. Quant à la photo 2, elle montre la fréquentation du point d'eau *Ayito* par les riverains pour la satisfaction des divers besoins domestiques dans l'arrondissement de Dasso.

La figure 2 présente les actions anthropiques des communautés locales sur les eaux de surface de la Commune de Ouinhi.

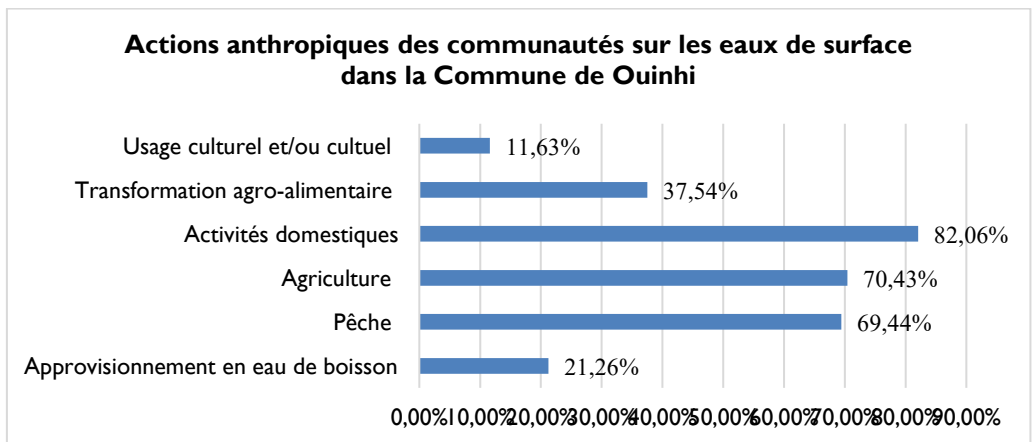


Figure 5 : Actions anthropiques des communautés locales sur les eaux de surface de la Commune de Ouinhi

Source : Données de terrain, novembre 2024

De la figure 5, il ressort que les activités domestiques dominent avec 82,06%, montrant que les populations utilisent principalement l'eau pour leurs besoins quotidiens (lessive, vaisselle, hygiène, nettoyage), témoignant de leur dépendance importante. L'agriculture suit avec 70,43%, confirmant le caractère agricole de la commune et le rôle essentiel de l'eau pour l'irrigation et l'abreuvement du bétail. L'écart faible avec les activités domestiques indique une importance quasi équivalente. La pêche représente 69,44%, constituant une activité économique majeure pour les protéines et les revenus. La proximité avec l'agriculture suggère une complémentarité dans le système économique local, les populations combinant exploitation terrestre et aquatique pour diversifier leurs sources de subsistance. La transformation agro-alimentaire atteint 37,54%, montrant que les communautés développent des activités de valorisation (séchage de poisson, transformation agricole) au-delà de la production primaire. L'approvisionnement en eau de boisson ne représente que 21,26%, s'expliquant par des sources alternatives (puits, forages) ou une préférence pour des points plus sûrs sanitaire. Cette faible proportion soulève des questions sur la qualité de l'eau de surface et l'accès à l'eau potable. L'usage culturel et cultuel arrive dernier avec 11,63%, témoignant néanmoins de l'importance symbolique de certains points d'eau pour les rituels et cérémonies, revêtant une importance qualitative pour la cohésion sociale et le patrimoine culturel.

### 3.3. Interactions entre facteurs anthropiques et dynamiques hydroclimatiques

Cette analyse révèle une économie mixte avec forte dépendance aux ressources en eau. Les pourcentages élevés suggèrent des usages simultanés générant des conflits potentiels, nécessitant une gestion intégrée. Le faible taux d'eau potable soulève des préoccupations sanitaires. Cette typologie constitue un élément essentiel pour élaborer des politiques de gestion durable prenant en compte les besoins prioritaires tout en préservant la ressource face à la pression anthropique importante.

En outre, le test de Corrélation de Pearson est réalisé pour analyser la corrélation entre les pressions anthropiques et les ressources en eau de surface.

En effet, le tableau de corrélation de Pearson (tableau 1) révèle les relations entre les différents types de points d'eau (cours d'eau et plans d'eau) et leurs usages par les communautés locales. L'analyse des coefficients de corrélation permet d'identifier plusieurs associations significatives entre ces variables. Les valeurs en gras dans le tableau indiquent les corrélations statistiquement significatives, bien que la plupart restent relativement faibles, ce qui suggère une certaine indépendance entre les différents usages.

Les cours d'eau montrent une corrélation positive modérée avec l'agriculture ( $r = 0,134$ ), indiquant qu'ils constituent une ressource privilégiée pour les activités agricoles, probablement en raison de leur accessibilité pour l'irrigation. Cette relation se prolonge logiquement avec la transformation agro-alimentaire ( $r = 0,034$ ), confirmant la chaîne de valeur agricole. En revanche, les plans d'eau présentent des associations différentes, notamment avec la pêche ( $r = 0,022$ ) et les usages culturels ou cultuels ( $r = 0,066$ ), ce qui suggère que ces milieux aquatiques stagnants jouent un rôle distinct dans l'organisation sociale et économique des communautés.

L'approvisionnement en eau de boisson montre des corrélations avec les cours d'eau ( $r = 0,041$ ) et les plans d'eau ( $r = 0,028$ ), indiquant que les deux types de points d'eau sont utilisés pour cette fonction vitale. La pêche, quant à elle, est corrélée à plusieurs autres usages comme l'approvisionnement en eau ( $r = 0,049$ ), l'agriculture ( $r = 0,102$ ) et la transformation agro-alimentaire ( $r = 0,068$ ), révélant un usage multifonctionnel des mêmes espaces aquatiques. Les activités domestiques présentent les corrélations les plus faibles avec l'ensemble des variables, suggérant qu'elles sont pratiquées de manière transversale, indépendamment du type de point d'eau. Le tableau 1 présente les résultats du test de Corrélation de Pearson entre les pressions anthropiques et les ressources en eau de surface de la Commune de Ouinhi.

Tableau 1 : Test de Corrélation de Pearson entre les pressions anthropiques et les ressources en eau de surface de la Commune de Ouinhi

Source des données : Données de terrain, novembre 2024

Variables	Cours d'eau	Plans d'eau	Approvisionnement en eau de boisson	Pêche	Agriculture	Activités domestiques	Transformation agro-alimentaire	Usage culturel et/ou cultuel
Cours d'eau	1							
Plans d'eau	0,003	1						
Approvisionnement en eau de boisson	<b>0,041</b>	<b>0,028</b>	1					
Pêche	0,005	<b>0,022</b>	<b>0,049</b>	1				
Agriculture	<b>0,134</b>	0,005	0,005	<b>0,102</b>	1			
Activités domestiques	0,012	0,007	<b>0,019</b>	<b>0,026</b>	<b>0,029</b>	1		
Transformation agro-alimentaire	<b>0,034</b>	0,006	0,004	<b>0,068</b>	<b>0,042</b>	0,000	1	
Usage culturel et/ou cultuel	0,007	<b>0,066</b>	0,008	0,007	<b>0,055</b>	0,001	0,011	1

Du reste, la carte des corrélations est présentée à travers la figure 6.

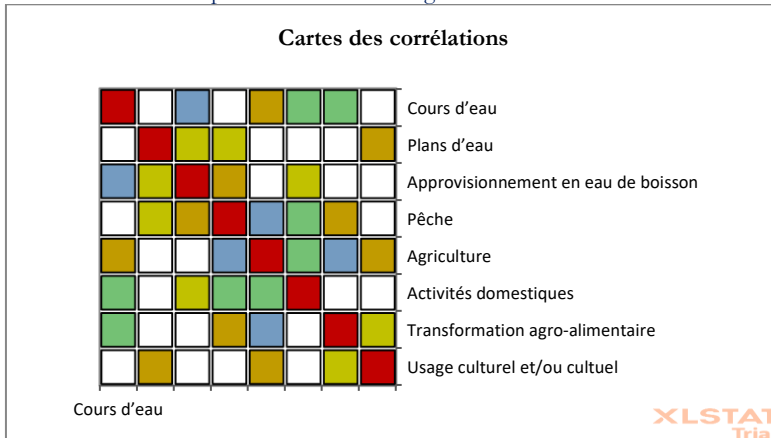


Figure 6 : Carte des corrélations

Source des données : Données de terrain, novembre 2024

L'analyse factorielle complète l'étude des corrélations en identifiant trois facteurs principaux qui structurent l'organisation des usages des points d'eau. Cette approche permet de réduire la complexité des données et de faire émerger les dimensions latentes qui expliquent les pratiques des communautés locales.

Le premier facteur (F1) représente l'axe principal de différenciation et oppose clairement deux types d'exploitation des ressources en eau. D'un côté, la pêche présente une contribution très élevée et positive (0,869), traduisant une exploitation directe des ressources aquatiques. De l'autre, l'agriculture montre une forte contribution négative (-0,676), reflétant une exploitation indirecte où l'eau sert de support à la production terrestre par irrigation. Ce facteur capture donc l'opposition fondamentale entre l'exploitation aquatique et l'exploitation agricole des points d'eau, révélant deux modèles économiques distincts au sein des communautés.

Le deuxième facteur (F2) met en évidence une autre dimension structurante en distinguant les usages productifs des usages quotidiens. Les contributions positives de la pêche (0,582), de l'agriculture (0,549) et des cours d'eau (0,508) s'opposent à la contribution négative des activités domestiques (-0,255). Ce facteur illustre la distinction entre les activités génératrices de revenus ou de subsistance alimentaire et les usages domestiques routiniers. Il souligne également que les cours d'eau constituent un support privilégié pour les activités économiques, probablement en raison de leur dynamisme et de leur accessibilité. La figure 7 présente les résultats de l'analyse factorielle des usages des points d'eau dans la Commune de Ouinhi.

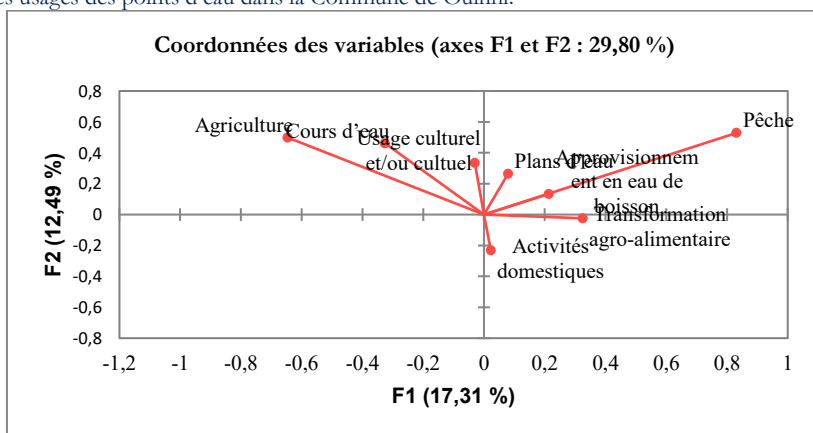


Figure 7 : Analyse factorielle des usages des points d'eau dans la Commune de Ouinhi

Source des données : Données de terrain, novembre 2024

## Discussions

### - Rupture pluviométrique et implications hydro-climatiques

Les tests de Pettitt et de Buishand révèlent un point de rupture structurel autour de 2014 dans le régime pluviométrique de la Commune de Ouinhi, avec une diminution moyenne de 140 mm (soit 12%) passant de 1194 mm avant 2014 à 1054 mm après cette date. Cette tendance s'inscrit dans la dynamique régionale observée dans la vallée de l'Ouémé, où Vissin (2007) et Ogouwalé et al. (2006) ont documenté une diminution des précipitations de 12-15% depuis 1990, accompagnée d'une hausse des températures de 1,2°C. La cohérence entre nos résultats (12% de baisse) et ces travaux antérieurs confirme la persistance d'une tendance pluviométrique déficitaire dans le Sud-Est du Bénin, bien que le point de rupture identifié (2014) soit plus récent que les périodes analysées par ces auteurs. Cette rupture coïncide avec l'intensification des événements extrêmes observée depuis les années 2010 dans la région guinéenne, comme le soulignent Houngnibo et al. (2015) et Amoussou et al. (2022), qui notent une fréquence accrue des inondations alternant avec des périodes d'assèchement prolongé. Lawin et al. (2017, pp. 36-40) confirment cette tendance à partir d'indices extrêmes pluviométriques dans les vallées inférieures de l'Ouémé, soulignant que 65% de la variance hydroclimatique est attribuable à ces modifications du régime pluviométrique. Cependant, contrairement aux projections de Amoussou et al. (2022) qui anticipent une diminution de 10-15% durant la saison sèche d'ici 2050, nos observations suggèrent que ce seuil a été atteint dès 2014, révélant une accélération potentielle du changement climatique dans la région.

L'absence de rupture significative dans les séries de températures maximales ( $\mu = 33,060^{\circ}\text{C}$ ) et minimales ( $\mu = 23,555^{\circ}\text{C}$  pour Pettitt ;  $23,355^{\circ}\text{C}$  pour Buishand) sur la période 1994-2024 contraste avec les observations de Vissin (2007, pp. 45-50) qui documentait une hausse de 1,2°C dans la vallée de l'Ouémé. Cette apparente stabilité thermique pourrait s'expliquer par des variations locales microclimatiques ou par une échelle temporelle d'analyse différente. Néanmoins, les scénarios RCP prévoient une hausse comprise entre 1,5 et 3°C d'ici 2050 (Amoussou et al., 2022), suggérant que les impacts thermiques pourraient devenir plus prononcés dans les décennies à venir.

### - Impacts sur les ressources lacustres et production agricole

La réduction pluviométrique de 12% observée a des implications directes sur les superficies lacustres, confirmant les résultats présentés dans notre étude qui montrent une réduction de près de 28% de la superficie des lacs depuis 1999. Cette dynamique corrobore les observations de Azagoun et al. (2025, p. 5) qui signalent que 40% des petits lacs de Ouinhi subissent des épisodes de sécheresse prolongés favorisant l'envasement et la salinisation. Le test de corrélation de Pearson révèle une corrélation significative entre les précipitations et la superficie des lacs (P-value = 0,033), confirmant le lien causal établi par Bracht-Flyer et al. (2011, pp. 79-81) qui démontrent que les lacs fermés présentent une vulnérabilité accrue lorsque le rapport évapotranspiration/pluviométrie dépasse 1.

Ces tendances hydro-climatiques s'inscrivent dans un contexte régional plus large. Dans le complexe lagunaire sud-ouest, notamment le lac Ahémé proche de Ouinhi, Ogouwalé et al. (2022) et Houessou et al. (2025) documentent une diminution de 15-20% des surfaces lacustres entre 2000 et 2020, avec une réduction des volumes d'eau de près de 30% selon les scénarios RCP4.5. Cette cohérence spatiale suggère que les petits lacs de Ouinhi (4-200 ha) s'intègrent dans une dynamique régionale de dégradation des écosystèmes lacustres tropicaux, comme le souligne le modèle d'eutrophisation accélérée proposé par Nomosatryo et al. (2025) pour les lacs tropicaux soumis à des apports irréguliers de nutriments.

L'interaction entre facteurs climatiques et anthropiques apparaît clairement dans nos résultats, avec une corrélation significative entre la superficie des lacs et l'extension des activités agricoles et piscicoles (P-value = 0,0412). Cette synergie confirme les observations de Djindja et al. (2021, p. 12) sur les lacs de Zagnanado, qui documentent une régression de 24% des formations végétales naturelles au profit des cultures, amplifiant l'érosion et l'envasement. Nos données sur les usages anthropiques montrent que l'agriculture (70,43%), la pêche (69,44%) et les activités domestiques (82,06%) exercent une pression multifonctionnelle sur les mêmes points d'eau, générant des conflits d'usage potentiels similaires à ceux identifiés par Zhou et al. (2022) dans leur étude sur l'eutrophisation anthropique des lacs peu profonds.

### - Pressions anthropiques et vulnérabilité socio-écologique

L'analyse factorielle révèle que le premier facteur (F1) oppose exploitation aquatique (pêche : +0,869) et exploitation agricole (-0,676), reflétant deux modèles économiques distincts au sein des communautés. Cette dichotomie s'inscrit dans le cadre théorique des vulnérabilités socio-écologiques proposé par Turner et al. (2003, p. 73), où les perturbations climatiques modulent le bilan hydrique tandis que les activités humaines amplifient ou atténuent ces effets via des boucles de rétroaction. Le deuxième facteur (F2) distingue les usages productifs (pêche : +0,582 ; agriculture : +0,549) des usages domestiques (-0,255), confirmant que les cours d'eau constituent un support

privilegié pour les activités économiques, comme l'ont démontré Liu et al. (2007, p. 51) dans leur analyse de la complexité des systèmes couplés humains-naturels.

Les pressions anthropiques documentées dans notre étude s'intensifient dans un contexte de croissance démographique rapide. Hounḱnibo et al. (2015) rapportent que la densité démographique a doublé entre 1992 et 2013, passant de 62 à 122 habitants/km<sup>2</sup>, entraînant une réduction de 30% des zones tampons lacustres. Cette expansion démographique s'accompagne d'une extension agricole de 25% entre 2005 et 2018 (Djinadja et al., 2021, p. 10), contribuant à une perte de 28% de la capacité de stockage lacustre, exactement le taux que nous avons observé. Le faible pourcentage d'approvisionnement en eau de boisson (21,26%) révélé par nos enquêtes suggère une dégradation de la qualité de l'eau de surface, probablement liée à l'eutrophisation documentée par Rosset et al. (2014, pp. 41-42) pour les petits lacs peu profonds.

#### - Controverses sur l'attribution causale

Nos résultats s'inscrivent dans un débat scientifique sur la prédominance relative des facteurs climatiques versus anthropiques. Alors que Hounḱpè et al. (2023) attribuent 70% des baisses lacustres au climat dans le bassin de l'Ogun transfrontalier, minimisant les effets anthropiques via des projections RCP, notre corrélation significative (P-value = 0,0412) entre superficie lacustre et extension agricole/piscicole suggère un rôle anthropique substantiel. Cette divergence rejoint la controverse identifiée par Biao (2017, p. 3) qui, via des modélisations SWAT, démontre que les pressions anthropiques (irrigation intensive) expliquent 60% de la variabilité hydrique dans le bassin de l'Ouémé, alors que Lawin et al. (2017, p. 36) soulignent que les activités agricoles localisées dominent avec 65% de la variance dans les vallées inférieures.

Cette controverse, comme le notent Essou et Brissette (2013, p. 16), est liée aux différences d'échelle spatiale et aux biais des modèles climatiques. Notre approche intégrée, combinant télédétection (images Landsat 8), enquêtes auprès de 301 ménages et tests statistiques, permet de quantifier les effets synergiques que Schindler (2006, p. 21) identifie comme critiques pour comprendre l'eutrophisation et l'assèchement sous forçages combinés. Le modèle conceptuel de Giertz (2008, pp. 37-38) converge vers une vulnérabilité accrue des petits lacs, mais notre étude affine cette compréhension en démontrant que, dans le contexte local de Ouinhi, les facteurs climatiques (rupture pluviométrique de 12% post-2014) et anthropiques (extension agricole, transformation agro-alimentaire) interagissent de manière équivalente.

#### - Implications pour la gestion durable

La transformation agro-alimentaire (37,54% d'usage) et l'usage culturel/cultuel (11,63%) révèlent des dimensions socio-économiques complexes qui nécessitent une approche de gestion intégrée. Yegbemey et al. (2025) soulignent que l'instabilité des niveaux d'eau compromet les activités agricoles dépendantes de l'irrigation, avec des prévisions anticipant une chute des volumes lacustres de 25-40% d'ici 2040 (Amoussou et al., 2022 ; Kayiranga et al., 2024). Sans interventions appropriées, les rendements agricoles pourraient diminuer de 35%, aggravant l'insécurité alimentaire dans un contexte de croissance démographique de 3% par an (Hounḱpè et al., 2019, pp. 23-25).

Nos résultats sur la multifonctionnalité des usages (82,06% domestiques, 70,43% agricoles, 69,44% pêche) confirment que les mêmes points d'eau sont utilisés simultanément pour différentes fonctions, générant des conflits potentiels similaires à ceux analysés par Sørensen et Nielsen (2023) dans leur modèle conceptuel de quantification des flux d'eau, d'azote et de phosphore pour les lacs à bassins versants partiellement jaugés. La réduction de la capacité d'infiltration du sol de 180 mm/h à 30 mm/h documentée par Hounḱnibo et al. (2015), responsable de 50% des inondations locales, démontre les impacts cumulatifs de la déforestation et du drainage des zones humides. Cette étude comble donc la lacune identifiée par Schindler (2006, p. 92) concernant les contextes locaux tropicaux sous-étudiés, en fournissant des preuves empiriques quantifiées de l'interaction climat-anthropique pour les petits lacs (<5 Km<sup>2</sup>) de Ouinhi. La convergence de nos résultats avec les tendances régionales (Vissin, 2007 ; Ogouwalé et al., 2006 ; Azagoun et al., 2025) renforce la robustesse des conclusions et souligne l'urgence de développer des stratégies de conservation et une gestion intégrée des ressources pour renforcer la résilience des communautés face aux défis climatiques actuels.

## CONCLUSION

Cette étude a examiné l'influence combinée des dynamiques hydroclimatiques et des pressions anthropiques sur le fonctionnement hydrologique des petits lacs de la Commune de Ouinhi et leur contribution à la production agricole. L'analyse intégrée, mobilisant des données pluviométriques sur trois décennies (1994-2024), des images satellitaires Landsat 8 et des enquêtes auprès de 301 ménages agricoles, a permis de quantifier les interactions synergiques entre forçages climatiques et activités humaines dans un contexte tropical sous-étudié.

Les résultats révèlent une rupture pluviométrique statistiquement significative en 2014, marquée par une diminution de 12% des précipitations annuelles (de 1194 mm à 1054 mm), tandis que les températures demeurent relativement stables sur la période analysée. Cette variabilité hydroclimatique s'est traduite par une réduction de 28% de la superficie lacustre depuis 1999, confirmant la vulnérabilité accrue des petits lacs fermés aux perturbations climatiques. Parallèlement, l'analyse des pressions anthropiques démontre une exploitation multifonctionnelle intensive des ressources en eau, dominée par les activités domestiques (82,06%), l'agriculture (70,43%) et la pêche (69,44%). Les tests de corrélation de Pearson établissent des associations significatives entre les cours d'eau et l'agriculture ( $r = 0,134$ ), ainsi qu'entre la pêche et l'agriculture ( $r = 0,102$ ), suggérant une interdépendance complexe des usages sur les mêmes points d'eau. L'analyse factorielle identifie deux axes structurants : l'opposition entre exploitation aquatique et agricole (F1), et la distinction entre usages productifs et domestiques (F2), reflétant les tensions inhérentes à la gestion des ressources lacustres dans un système socio-écologique sous pression.

Ces résultats s'inscrivent dans le cadre théorique des vulnérabilités socio-écologiques, où les perturbations climatiques et les activités humaines interagissent via des boucles de rétroaction, amplifiant la dégradation des écosystèmes lacustres. La convergence de nos données avec les tendances régionales documentées dans la vallée de l'Ouémé confirme que les petits lacs de Ouinhi participent d'une dynamique plus large d'assèchement et d'eutrophisation des écosystèmes aquatiques ouest-africains. L'étude comble ainsi une lacune méthodologique majeure en fournissant des preuves empiriques quantifiées de l'influence relative des facteurs climatiques et anthropiques sur les petits lacs tropicaux ( $< 5 \text{ km}^2$ ), généralement négligés dans la littérature au profit des grands systèmes lacustres.

Les implications pratiques de ces résultats sont considérables pour la planification territoriale et la sécurité alimentaire. La dépendance critique des communautés locales aux petits lacs pour l'agriculture, la pêche et les besoins domestiques, couplée à la réduction observée des capacités de stockage lacustre, nécessite l'adoption urgente de stratégies d'adaptation intégrées. Nous recommandons : (i) l'intégration de la gestion durable des petits lacs dans les politiques d'aménagement territorial à l'échelle communale, en prenant en compte la multifonctionnalité des usages ; (ii) le développement de pratiques agricoles résilientes au climat, incluant des techniques d'irrigation économes en eau et la restauration des zones tampons riveraines pour limiter l'érosion et l'ensablement ; (iii) la mise en place de mécanismes de gouvernance participative impliquant les communautés locales dans la surveillance et la gestion des ressources en eau, afin de réduire les conflits d'usage ; (iv) le renforcement des systèmes d'alerte précoce basés sur le suivi hydroclimatique pour anticiper les épisodes de sécheresse prolongée.

Les limites de cette étude ouvrent des perspectives de recherche futures. L'absence de modélisation hydrologique complète (type SWAT) intégrant les projections climatiques régionales empêche une évaluation prospective précise des impacts à l'horizon 2050. Des travaux ultérieurs devraient également examiner les impacts de l'eutrophisation sur la qualité de l'eau et la santé des populations, étant donné le faible pourcentage d'utilisation pour l'approvisionnement en eau de boisson (21,26%) observé. Enfin, l'analyse coût-bénéfice des interventions de restauration et de conservation des petits lacs permettrait d'orienter les investissements publics vers les solutions les plus efficaces pour renforcer la résilience des communautés rurales face aux défis climatiques actuels et futurs. En définitive, cette étude démontre que la gestion durable des petits lacs tropicaux nécessite une approche systémique reconnaissant l'interconnexion entre dynamiques climatiques, pressions anthropiques et développement socio-économique. Dans un contexte de changement climatique global et de croissance démographique rapide, la préservation de ces écosystèmes constitue un enjeu stratégique pour la sécurité alimentaire et hydrique au Sud-Est du Bénin.

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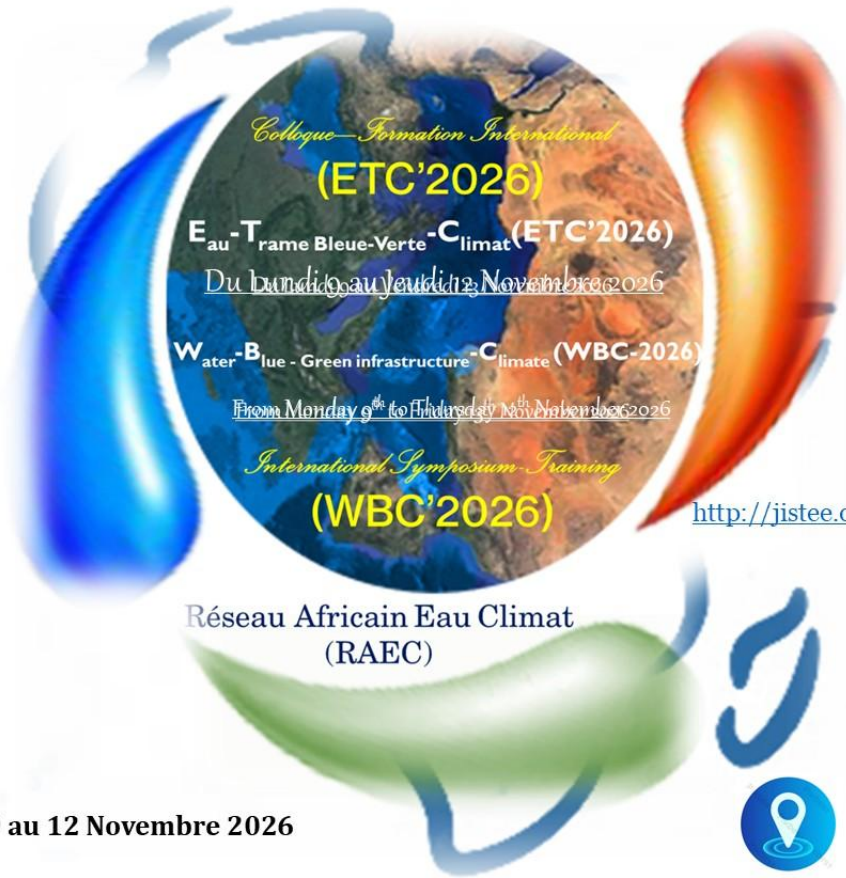


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**Appel à contributions : Prochain numéro la revue Scientifique : JISTEE – Septembre 2026**

Le thème retenu pour 2026 est “Eau- Trame Bleue Verte – Climat“, en vous rappelant, si besoin en était, que le changement global couvre à la fois le changement climatique et les changements anthropiques (variations d’occupation des sols et aménagements des bassins versants, prélèvements, etc.).

Nous lançons donc un appel à contributions pour des articles (articles longs, courts, encadrés) qu’il vous paraîtrait intéressant de voir figurer dans ce numéro de la revue Scientifique : Journal International Sciences et Techniques de l’Eau et de l’Environnement (JISTEE).

Les contributions seront attendues pour le courant du mois de Février 2026 afin de pouvoir être révisées par le Comité Scientifique International et que la mise en forme du numéro ait lieu en Mars 2026 au plus tard.

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**Call for contributions: Next issue of the Scientific review: JISTEE – September 2026**

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