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Towards sustainable water management in Morocco: assessing resources, challenges, and adaptation strategies

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Water management in Morocco has become a central challenge at the intersection of climate variability, agricultural modernization, and resource governance. The country is increasingly confronted with extreme hydro-climatic conditions that threaten water security and food production. Recent years have illustrated the severity of this crisis: 2023 was the driest year in at least eight decades, with total rainfall below 100 mm and a deficit of nearly 48% compared to the national average. The six-year period from 2019 to 2024 represents the longest recorded sequence of consecutive drought years, with an average rainfall deficit of 35%. Despite a progressive increase in hydraulic infrastructure, rising from a storage capacity of 1.2 billion m³ in 1960 to more than 19 billion m³ today, reservoirs were only 28.5% full in 2024, storing 4.8 billion m³. This structural water deficit is particularly concerning given that nearly 80% of Morocco's cultivated land relies on rain-fed agriculture, making the agricultural sector vulnerable to fluctuating precipitation and rising temperatures. Morocco has attempted to address these challenges through ambitious policy frameworks, which prioritize efficient irrigation systems, sustainable agricultural practices, and resilience to climatic shocks. Large-scale investments in dams, desalination, and irrigation modernization have been complemented by international partnerships that provide technical expertise and financial support to the country. Simultaneously, agroecological practices, such as agroforestry, crop diversification, and crop rotation, represent underutilized but highly relevant pathways for improving water efficiency, restoring soil fertility, reducing erosion, and enhancing biodiversity. By weaving together climatic evidence, hydrological data, and agricultural strategies, this review highlights the urgency of implementing integrated water governance in Morocco. This underscores the importance of combining technological innovation with ecological practices and policy reforms to secure water and food resources in a context marked by persistent droughts and accelerating climate change.

KEYWORDS

agroecological practices, climate change, drought, Morocco, public policies, integrated water resource management

1 Introduction

Morocco's agricultural sector has faced increasing challenges in recent years due to water scarcity, a phenomenon that has considerable consequences for the country's food security and economic stability (Wang, 2022). Sustainable water management is a major issue, particularly in Morocco's arid and semi-arid regions, where agriculture relies heavily on irrigation. Irrigated areas, which cover roughly 1.6 million hectares (about 16% of the total agricultural land), contribute more than 45% of the country's agricultural value-added, with key productive zones concentrated in the Souss Plain, Gharb, and Saïs regions (Shevah, 2014). The country's water resources are under constant pressure owing to irregular rainfall, a growing population, and limited access to freshwater sources (Vörösmarty et al., 2005). In addition, inefficient water management systems, local government budget deficits, and a lack of public awareness exacerbate this situation (Aimar, 2017). These challenges can lead to social tensions, particularly in rural areas, where agriculture is the backbone of local livelihoods and socio-economic stability. For instance, in the oasis ecosystems of Drâa and Tafilalet, limited water availability directly affects date palm cultivation, cereal production, and associated income sources, thereby influencing food security and community well-being (Kumari et al., 2021).

To address these issues, it is crucial to develop a water resource management strategy that prioritizes sustainable water use, wastewater reuse, and desalination (Velasco-Muñoz et al., 2018; Shevah, 2014). Water management in the agricultural sector is a complex challenge in Morocco, with direct repercussions on food production, farmers' livelihoods, and the environment (Todorovic et al., 2015). Inefficient water use in irrigation leads to reduced production capacity, crop failure, and lower agricultural yields, hampering the country's ability to feed its growing population (Kang et al., 2021). In addition, the overexploitation of groundwater and excessive irrigation contribute to soil degradation, notably through salinization, with salinity levels in some aquifers, such as those in the Saïss and Souss-Massa basins, reaching up to half that of seawater, thereby affecting a significant proportion of irrigated land and threatening agricultural productivity (Said et al., 2022; Sharma et al., 2024). Moreover, water pollution from both point and non-point sources further exacerbates these challenges; for example, nitrate contamination from fertilizers and livestock waste has been widely documented in aquifers in the Souss-Massa, Tadla, and Gharb regions, posing risks to human health and agricultural sustainability (Laftouhia et al., 2003; Sanad et al., 2024).

To ensure a sustainable future, it is imperative to implement water management practices that optimize its use while preserving natural resources and that meet agricultural needs while respecting the environment (Srivastav et al., 2021). In this context, adopting innovative solutions that integrate modern technologies and agroecological approaches offers new prospects for Morocco. The country has developed several strategies to address water management challenges, including the Green Morocco Plan and its successor, Plan Green Generation, which emphasizes the importance of integrating water dimensions into agricultural practices (MAPMDREE, 2024). These initiatives aim to modernize agriculture while strengthening the sustainability and resilience of the sector in the face of climate change. Solutions such as wastewater reuse, desalination, and drip irrigation optimization are also at the heart of the country's water policies (Ait Kadi and Ziyad, 2018).

This manuscript provides a comprehensive overview of Morocco's water resources, integrating information on their availability, spatial and temporal distribution, and key challenges. To better contextualize these issues, it integrates illustrative hydroclimatic indicators (such as precipitation variability, drought patterns assessed through the SPI, and data on dam capacity, dam inflows, and seawater desalination projects). Beyond documenting the status and constraints of water availability, this study also examines agroecological practices that can support sustainable water management in Morocco, as well as the national agricultural policies that shape water governance. Its unique contribution lies in linking hydro-climatic indicators to agroecological water management practices and to national agricultural policies. This integrated approach offers a holistic perspective on the interactions between water, climate, and governance, providing a valuable foundation for future research and policy development in Morocco's arid and semi-arid regions.

2 Methodology

This review synthesizes the current state of water resources in Morocco and identifies the main challenges and opportunities for their sustainable management. A methodological approach was adopted based on the analysis of scientific and institutional literature, supplemented by the integration of illustrative data from various reliable sources. First, a literature search was conducted using international scientific databases such as Scopus, Web of Science, and Google Scholar, as well as institutional reports from the FAO, the Moroccan Ministry of Equipment and Water, and the World Bank. The keywords used were combined terms related to water resources, agriculture, and sustainability, such as Morocco, water resources, drought, precipitation, groundwater, dams, desalination, agroecology, sustainable water management, and agricultural policy. The selected documents had to directly concern the Moroccan context, with a preference for recent publications (from the last 15 years), while incorporating older works if necessary. Only peer-reviewed articles and institutional reports published in English or French were considered, while documents in other languages, conference abstracts, editorials, and non-scientific reports were excluded. Second, to contextualize and illustrate the findings from the literature, hydroclimatic indicators were used for Moroccan conditions. These include spatiotemporal variations in precipitation and drought episodes assessed by the SPI index, temperature trends at the national level, variations in dam storage capacity, changes in reservoir water inflows, and seawater desalination projects in the country. Drought conditions were classified based on the distribution of the Standardized Precipitation Index (SPI), using the methodology described by Bouaziz et al. (2021). Specifically, SPI values greater than +2.0 indicate extremely wet conditions, values between +1.5 and +2.0 correspond to severe wet conditions, and values between +1.0 and +1.5 indicate moderate wet conditions. Values between −1.0 and +1.0 are considered normal. SPI values between −1.0 and −1.5 correspond to moderate drought, between −1.5 and −2.0 to severe drought, and values lower than −2.0 indicate an extreme drought. The Standardized Precipitation Index (SPI) was calculated using the Google Earth Engine platform to ensure a consistent assessment of drought and humidity conditions in time and space. Data processing, spatial analysis, and production of geospatial maps were performed

using ArcGIS Pro software. These maps highlight the spatial variability of hydroclimatic conditions in Morocco and allow tracing the evolution of drought and humidity regimes over the last three decades. These elements are not presented as original results but are used for illustrative and complementary purposes to strengthen the analysis and provide a clearer view of the dynamics affecting water resource availability. Finally, a specific review of the literature on agroecological water management practices (such as efficient irrigation, agroforestry, and rainwater harvesting) was conducted, focusing on their relevance and applicability to the Moroccan context. This analysis was complemented by a study of national agricultural and water policies (Green Morocco Plan, Green Generation, and National Water Strategy) to understand how these strategic orientations are linked to sustainability and water governance. This methodology thus makes it possible to link the state of water resources and constraints with innovative practices and policy frameworks, offering an integrated vision of sustainable water management in Morocco.

3 State of water resources in Morocco

3.1 Water resource potential

3.1.1 Spatial and temporal distribution of water resources

3.1.1.1 Surface water resources

Morocco's surface water resources are highly irregular in both space and time, and are currently estimated at about 18 billion m³ per year (MEWFHR, 2023). Figure 1A illustrates the average annual surface water resources across Morocco's hydrographic regions, estimated at approximately 18 billion m³ per year, although their distribution is highly uneven. The graph reveals a clear hierarchy among the basins: Sebou leads with 5600 mm³/year, accounting for approximately 31% of the total estimated resources. This was followed by Loukkos (3434 mm³/year) and Oum Er Rbia (3315 mm³/year). Together, these three basins constitute over 68% of the country's

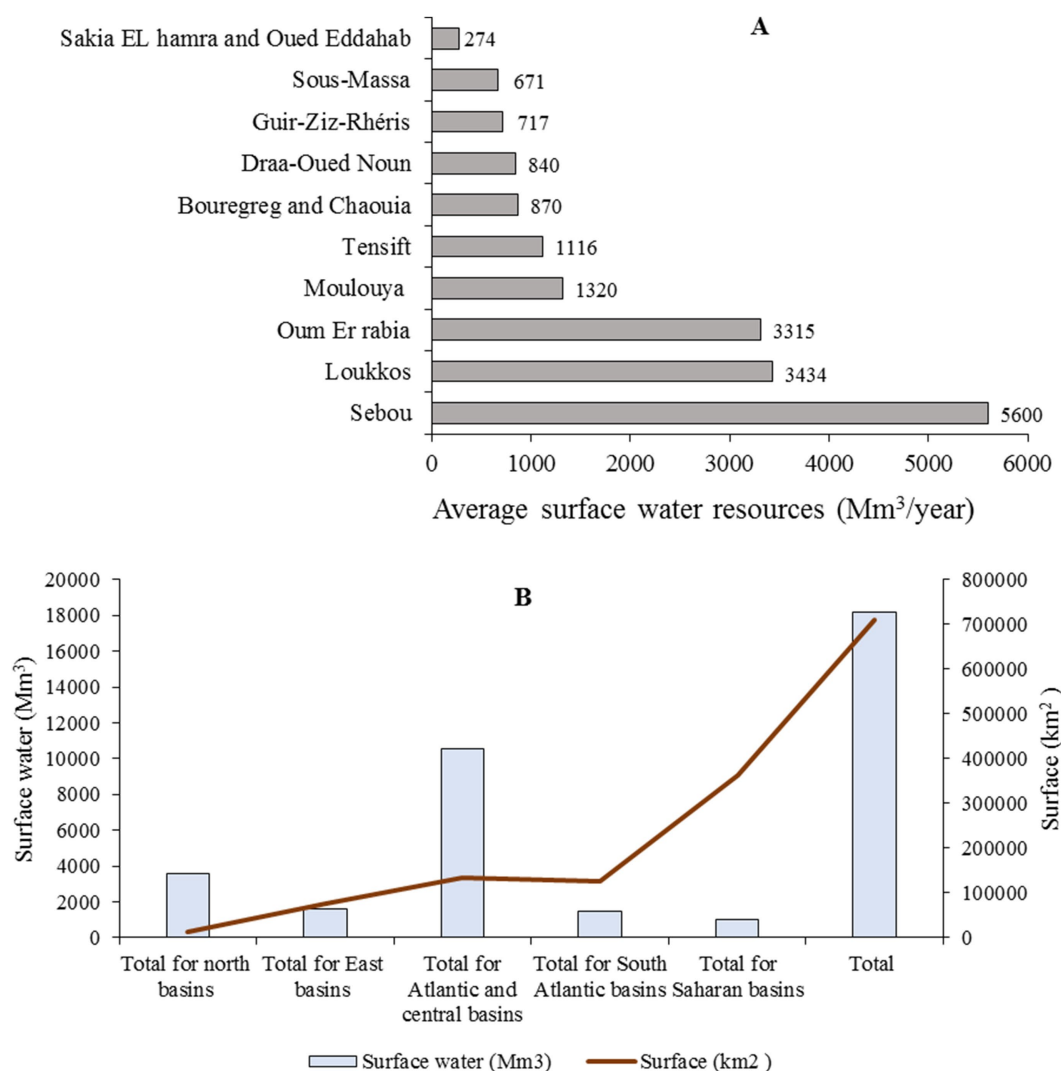


FIGURE 1

Geographic distribution of surface water resources in; (A) the main Moroccan River Basin (mm³) (MEWFHR, 2023); (B) average total surface water by geography (mm³) and total surface area (km²) (adapted from Haddad et al., 2020).

surface water resources. In contrast, basins like Sakia El Hamra and Oued Eddahab (274 mm³/year), Sous-Massa (671 mm³/year), and Guir-Ziz-Rh  ris (717 mm³/year) possess much more limited resources. Figure 1B depicts the distribution of surface water resources in Morocco according to major hydrographic units, comparing them to the surface area of each basin group. There is a noticeable imbalance between water availability and geographical extent. The Atlantic and Central basins concentrate the largest share of resources, at around 11,000 mm³/year, despite occupying only a moderate area relative to other regions. Conversely, the Saharan basins, which cover a vast area, yield very low water resources, roughly around 1000 mm³/year. This trend is similarly observed in the eastern and southern Atlantic basins, where surface area does not correspond to significant water availability. Only the northern basins exhibit a relatively balanced ratio between surface area and resources. This uneven distribution mirrors the climatic contrasts between the wetlands of the north-west and the arid zones of the south and east, creating major challenges for sustainable and equitable water management on a national scale. An analysis of Morocco's surface water resources indicates marked spatial and temporal heterogeneity, highlighting the structural challenges the country faces in water management. Although the average annual volume of surface water resources is estimated at around 18,000 mm³, their distribution remains profoundly unequal among the various water basins. The data indicate a significant concentration of resources in specific basins, notably Sebou, Loukkos, and Oum Er Rbia, which together make up over 68% of the national total, while other basins such as Sakia El Hamra, Oued Eddahab, Sous-Massa, and Guir-Ziz-Rh  ris have very modest supplies (Eau and Hassan II, 2022). This inequality becomes even more pronounced when considering the distribution of resources across major hydrographic units relative to their surface area. Despite their moderate area, the Atlantic and central basins accumulate nearly 11,000 mm³, while the extensive Saharan regions yield only about 1,000 mm³. This contrast between surface area and water availability is largely controlled by the atmospheric circulation and topography. Overall, precipitation in Morocco is strongly influenced by the North Atlantic Oscillation (NAO), which modulates the intensity and frequency of Atlantic frontal systems that deliver rainfall to the western and northwestern basins (Hakam et al., 2025). The High Atlas Mountains act as a major orographic barrier, intercepting moist air masses from the Atlantic and causing high precipitation on their windward slopes, while creating a rain shadow that accentuates aridity in the southern and southeastern basins of the country. These southern and southeastern watersheds are more dependent on summer and early autumn convective storms related to tropical and extra tropical interactions, whereas the western regions receive most of their rainfall from winter frontal systems originating in the North Atlantic (El Garouani et al., 2024). The need for rational redistribution, mobilization of non-conventional resources, and strengthening of water governance thus emerges as a strategic priority for ensuring territorial equity and long-term water resilience (Dinar, 2024).

Table 1 shows the changes in the average water supply in Morocco over different periods, revealing a general downward trend over time. Between 1945 and 1980, the average annual water supply was 22.1 billion m³, indicating a period of relatively abundant water resources. However, when we consider the extended period from 1945 to 2024, this average falls to 18 billion m³ per year, demonstrating a gradual deterioration in water

TABLE 1 Evolution of average annual water supply in Morocco (1945–2024) (www.maadialna.ma website of the Ministry of Equipment and Water).

Period	Average water supply (billions m ³)
1945–1980	22.1
1945–2024	18
1980–2024	13.9

availability. This decline becomes even more pronounced over the recent period from 1980 to 2024, when the average drops to 13.9 billion m³. This negative trend can likely be explained by a combination of factors, including climate variability, lower rainfall, increased demand linked to population growth, and overexploitation of resources. In short, the continued decline in the average water availability per capita in Morocco—from approximately 2,500 m³ per person per year in the 1960s to less than 600 m³ in 2023, well below the water scarcity threshold—is a key indicator of the pressing need to adapt public policies to ensure water security in the medium and long term (Ouhbi and Boudhar, 2025; Wang et al., 2024). This downward trend can be attributed to a combination of anthropogenic and climatic factors. On the one hand, sustained population growth is placing increasing pressure on resources, raising domestic, agricultural, and industrial demand. Additionally, overexploitation of resources, particularly through intensive irrigation and excessive groundwater pumping, is worsening the imbalance between water supply and demand (Pal et al., 2023). These results illustrate the country's growing vulnerability to water-related issues and call for an urgent transformation of management methods.

3.1.1.2 Groundwater resources

Figure 2 illustrates the average annual groundwater resources in various regions of Morocco, measured in millions of cubic meters per year (mm³/year). There is a significant disparity between regions, with Sebou clearly distinguished as having the largest quantity of resources, surpassing 1,100 mm³/year. Other regions such as Moulouya, Tensift, and Oum Er Rbia also possess considerable volumes, nearing or exceeding 600 mm³/year. In contrast, areas like Sakia El Hamra, Oued Eddahab, Bouregreg, Chaouia, and Loukkos have far more limited resources, below 100 mm³/year. At the national level, Morocco's groundwater resources are estimated at approximately 4,000 mm³/year, accounting for roughly 18% of the country's total water potential. However, these resources are unevenly distributed across space and time, with the majority located within only 10% of the national territory. In addition, groundwater quality poses a significant challenge, as only approximately 10% of shallow aquifers have been classified as having good quality, and only 8% are considered true freshwater (Khettouch et al., 2025). This uneven distribution reflects the country's geographical and climatic differences, which heavily influence the availability of groundwater resources. This spatial variability demonstrates the diversity of geological, hydrological, and climatic contexts that impact groundwater recharge and storage capacity. The observed disparities highlight the necessity of considering regional specificities in the planning and management of groundwater resources, especially in areas where resources are scarce and more susceptible to overexploitation (Mo et al., 2025).

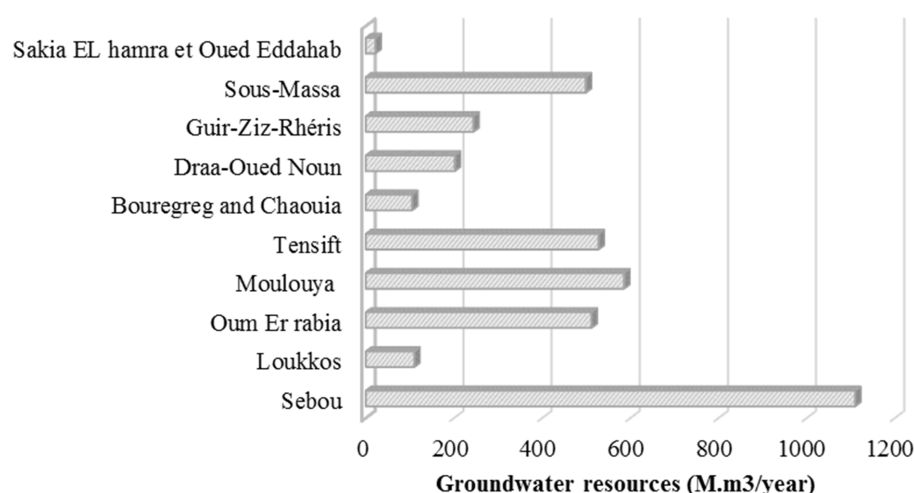


FIGURE 2
Average groundwater inflow in Morocco (MEWFHR, 2023).

3.2 Major challenges

3.2.1 Drought

The data in Figure 3 reports the variation of the national average annual rainfall in Morocco from 1981 to 2023, based on data from the Moroccan Climate Status Report (CSR). The results reveal considerable interannual variability in rainfall over the study period. The highest cumulative annual rainfall was recorded in 1996, exceeding 350 mm, followed by 2010 (>320 mm) and 2018 (>270 mm). In contrast, 2023 stands out as the driest year in at least eight decades, with an annual total of less than 100 mm and a rainfall deficit of approximately 48% compared to the national average. A particularly alarming trend is observed over the last six years (2019–2024), which represents the longest sequence of consecutive dry years ever recorded in the country. During this period, Morocco experienced an average rainfall deficit of about 35%, signaling an unprecedented and persistent drought condition. This prolonged deficit period marks a clear intensification of climate aridity and poses serious challenges to water resource management, agriculture, and ecosystem stability. Three major drought episodes were identified during the studied period, all characterized by annual rainfall values falling below the national average of 185 mm. The first spanned from 1983 to 1986, the second from 1992 to 1995, and the third, by far the most severe, occurred from 2019 to 2024, combining both intensity and duration of rainfall shortage.

Figure 4 presents the geospatial distribution of the Moroccan annual precipitation every five years between 1993 and 2023, based on the Standardized Precipitation Index (SPI). The daily precipitation data used in this analysis were derived from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset, with a spatial resolution of 4.8 km, and have been widely applied in drought and precipitation studies across North Africa and other semi-arid regions (Funk et al., 2015). Nevertheless, this approach has some limitations, particularly in highly irregular areas such as the Drâa Basin, as reported by Khettouch et al. (2023). The Standardized Precipitation Index (SPI) was calculated using the Google Earth Engine platform, allowing for a consistent evaluation of drought and

wetness conditions over time and space. Data processing, spatial analysis, and generation of geospatial maps were performed using ArcGIS Pro software. The maps illustrate the spatial variability of drought and wetness conditions across Morocco, highlighting the evolution of climatic patterns over the past three decades. In 1993, our analysis indicated that most of Morocco was experiencing near-normal climatic conditions, a pattern consistent with observations reported in previous climatological studies (Amouch and Akhssas, 2023; Elair et al., 2023). However, some regions showed signs of slight hydrological anomalies. Generally, areas classified as moderately dry were mainly located in the southern parts of the country, particularly around Dakhla and parts of Laayoune. Simultaneously, small portions of southwestern and central Morocco exhibited moderately wet conditions. No areas were categorized as extremely dry or extremely wet, indicating relatively stable hydrological conditions across the country during this year. However, Morocco displayed a strong spatial contrast in hydrological conditions in 1998. The northern regions, including Tanger, Tetouan, and Al Hoceima, and parts of central Morocco such as the Saïs region, experienced significant drought, with extensive zones categorized from moderately dry to extremely dry. In contrast, the southern regions (Laayoune, Guelmim, and Dakhla) experienced much wetter conditions, ranging from moderately wet to very wet, indicating a highly uneven distribution of rainfall across the country in that year. In 2003, Morocco predominantly experienced near-normal precipitation conditions across most regions. The Oriental and Northern zones, particularly around Nador, Al Hoceima, and Oujda, displayed moderately wet conditions. Overall, this year reflected a relative climatic balance, without extreme drought or excessive wetness dominating the national landscape. The season 2008–2009 stands out as one of the wettest seasons recorded during the study period, with a remarkable spatial distribution of precipitation across Morocco. In particular, the Oriental regions, notably around Oujda and Berkane, and the western zones encompassing Bouarfa and Errachidia recorded precipitation levels ranging between moderately wet and extremely wet classes. The year 2013 was characterized by heterogeneous climatic conditions across Morocco. The northern eastern regions, including the Bouarfa area, showed signs of moderate

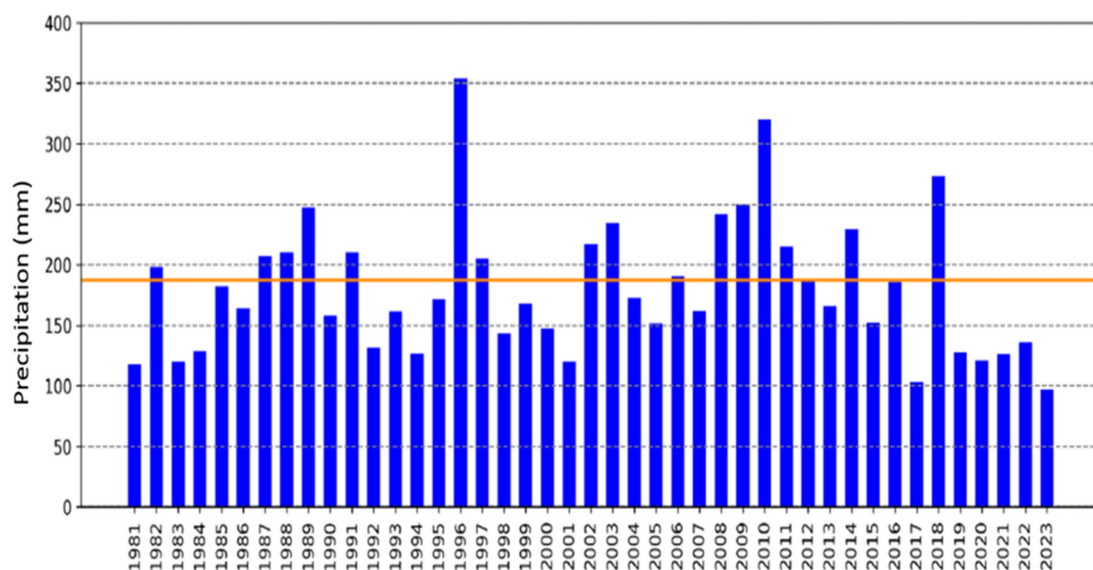


FIGURE 3
National average annual rainfall cumulative total between 1981 and 2023 [DGM, 2023].

to severe drought. The southern zones around Guelmim and Laayoune fluctuated between near-normal and moderately dry conditions. Conversely, certain southern regions, especially around Dakhla, experienced moderately wet to very wet conditions. This spatial divergence highlights the increasing climatic variability observed in the early 2010s.

The year 2018 represented another exceptionally wet season across Morocco, marking one of the most hydrologically favorable years within the study period. In this sense, extensive regions, particularly in the Northern and central parts of the country, experienced conditions ranging from moderately wet to extremely wet. Areas such as Dakhla, Tan Tan, and even parts of the interior regions exhibited notable precipitation surpluses. This widespread increase in rainfall during 2018 reflects favorable atmospheric circulation patterns, contributing to improved water availability and a temporary alleviation of drought stress across large parts of the country. By 2023, Morocco again faced widespread hydric stress, with large areas, especially in the northern and eastern regions (Saïs and Oriental regions), experiencing moderate to severe drought conditions. These patterns reflect the intensified impact of climate change, reinforcing the vulnerability of northern agricultural and urban centers to water scarcity.

The geospatial patterns of precipitation variability observed between 1993 and 2023 in Morocco reflect the profound impact of climate change on regional hydrology and drought dynamics. The increasing frequency and intensity of drought episodes, particularly across northern and central regions, align with broader projections of Mediterranean climate vulnerability, where reduced precipitation and enhanced variability are expected (Lazoglou et al., 2024). The persistence of hydric stress in key agricultural areas such as the Saïs and Oriental regions is particularly concerning, as these zones represent vital agricultural and economic hubs (Adiba et al., 2021b; Hamdani et al., 2021; Achli et al., 2025). Conversely, the intermittent wetter conditions recorded in the southern provinces like Laayoune and Dakhla illustrate the shifting spatial distribution of rainfall

patterns, likely influenced by changes in atmospheric circulation and the northward displacement of subtropical systems (Ouaraini et al., 2025). The pronounced wet seasons, notably in 2008–2009 and 2018, although beneficial for temporary water recharge, also underscore the heightened variability that complicates long-term resource planning (Ouhakki et al., 2024). Overall, the Standardized Precipitation Index (SPI) analysis highlights not only a general trend toward increased drought severity but also an amplification of precipitation extremes, thereby exacerbating Morocco's water management challenges and underscoring the urgent need for adaptive strategies in agriculture and urban planning (El Kenawy, 2024).

Figure 5 illustrates the trend of the national average annual temperature in Morocco over the period from 1981 to 2023. Indeed, the data demonstrate a clear and accelerating increase in the national average annual temperature, consistent with global patterns of climate change. During the period from 1981 to 1987, the national average temperature remained relatively stable, exhibiting modest year-to-year variability without a clear upward or downward trend. Throughout this early period, the recorded temperatures were generally lower than the overall mean temperature for the studied timeframe, which was 18.75 °C. A similar pattern was observed between 1990 and 1994, with temperatures fluctuating slightly but remaining close to or below the long-term average before the onset of more pronounced warming in subsequent years. Starting from the early 2000s, a more pronounced and sustained increase in temperature has been observed. Notably, the last few years consistently surpass earlier averages, suggesting that warming is not only continuing but intensifying. Notably, the year 2023 stands out as a record year for the national average maximum temperature, registering a significant anomaly of +2.5 °C relative to the climatological normal calculated for the 1981–2010 period.

Increased temperature fluctuations in Morocco have had a significant impact on national agricultural production. Rising temperatures, combined with greater variability between seasons, have disrupted crop phenology, reduced yields, and heightened water

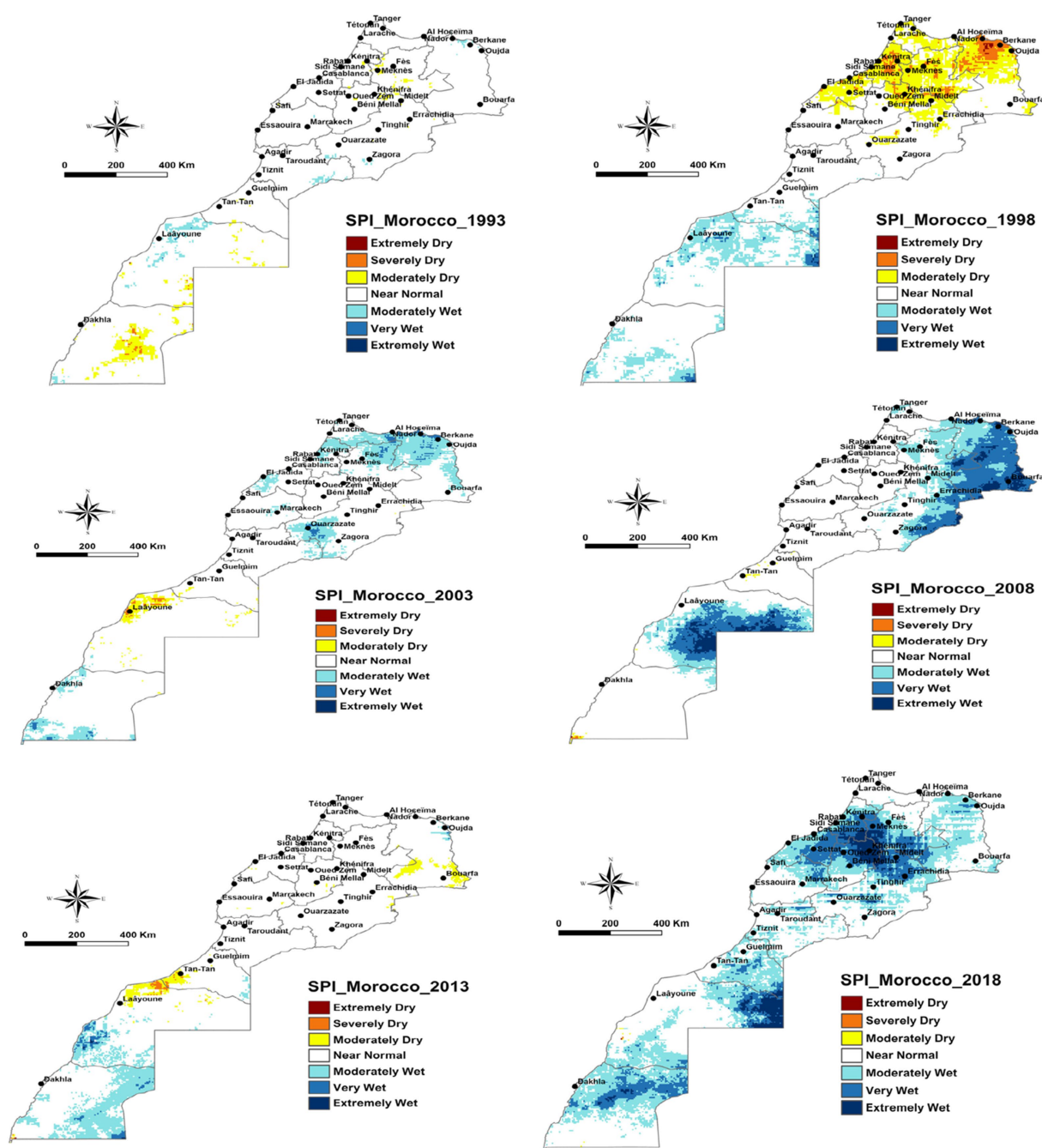


FIGURE 4 (Continued)

demands for irrigation (Adiba et al., 2024a, 2024b; El Amine et al., 2025; Hamdani et al., 2024a, 2024b). In the same way, Bouras et al. (2019), Amiri et al. (2021), and Razouk et al. (2022) reported that crops such as cereals, olives, and citrus fruits that present the key components of Moroccan agriculture are particularly sensitive to extreme heat events and prolonged droughts, which have become more frequent in recent decades. These studies indicate that high-temperature episodes during critical growth stages, such as flowering and grain filling, severely impact crop productivity and quality. In the same way, Adiba et al. (2023, 2024c, 2024d), Hamdani et al. (2024a, 2024b), and Hakam et al. (2024) revealed the effect of the variation of

the environmental factor on the quality of the other fruit trees, including pomegranate, plum, and agram. Furthermore, the increase in evapotranspiration rates, coupled with a reduction in effective precipitation, exacerbates soil moisture deficits, thereby intensifying the vulnerability of both rainfed and irrigated agricultural systems (Ousayd et al., 2024). In this context, the ongoing climatic changes necessitate urgent adaptation measures, including the adoption of drought-tolerant crop varieties, improved irrigation efficiency, and better water resource management strategies to sustain agricultural livelihoods in Morocco (Adiba et al., 2021a; Hamdani et al., 2021; Boudad et al., 2024; Kertolli et al., 2024).

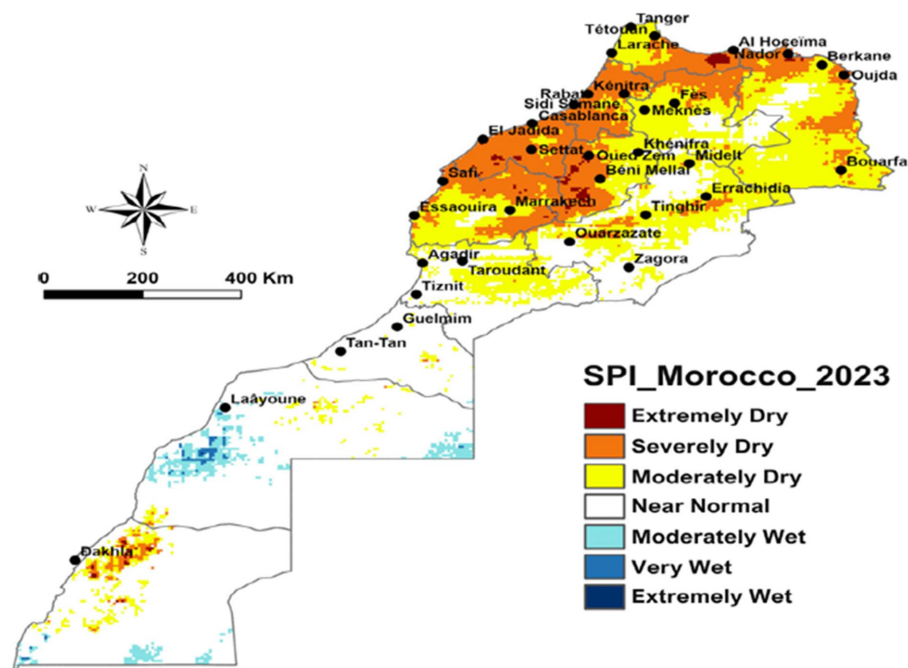


FIGURE 4

Evolution of annual precipitation and drought patterns in Morocco (1993–2023) using the standardized precipitation index (SPI).

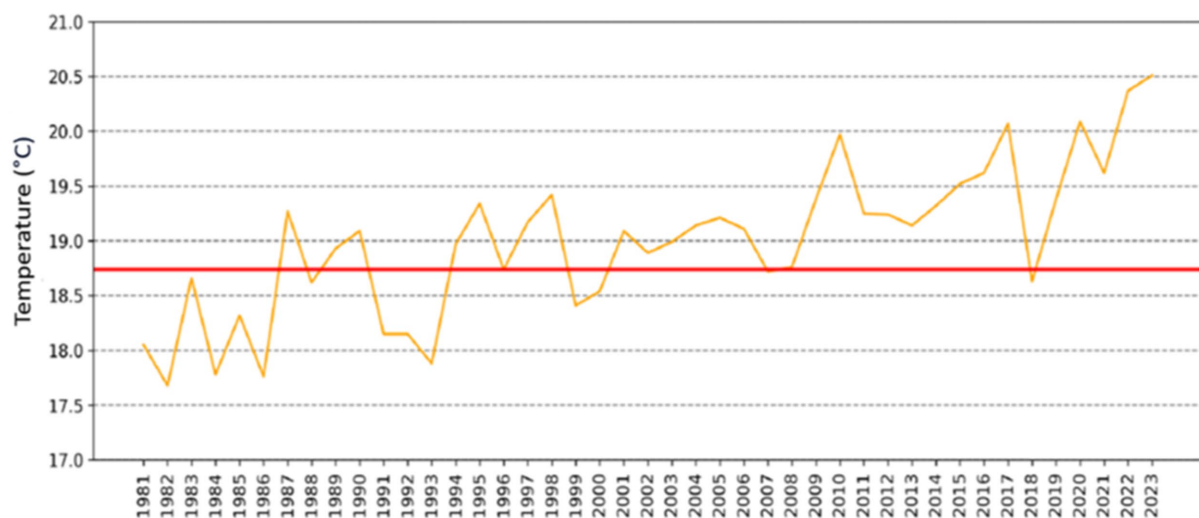


FIGURE 5

Temporal evolution of the Moroccan average annual temperature (DGM, 2023).

3.2.2 Water salinization

Water salinization is a crucial issue threatening Morocco's water resources, especially in arid and semi-arid zones, where water scarcity is already acute. Both groundwater and surface water are affected, reducing their suitability for drinking and irrigation (Hssaisoune et al., 2020). While natural processes, such as evaporation and seawater along coastal zones, contribute to this problem, human activities, including the overexploitation of aquifers and unsustainable irrigation practices, significantly aggravate the situation (Alfarrah and Walraevens, 2018). Beyond soil salinity, coastal regions are

increasingly vulnerable to saltwater intrusion, especially in aquifers along the Atlantic and Mediterranean coasts, where the lowering of groundwater levels has facilitated the intrusion of saline water. For example, in the Laayoune-Sakia El Hamra coastal aquifer, overexploitation has triggered saltwater intrusion, with an average salinity level of 10.5%, confirming the increasing vulnerability of Morocco's coastal groundwater resources (Errich et al., 2023). Recent studies have indicated that salinity levels in some coastal aquifers pose serious risks to agricultural productivity and the supply of drinking water (Ez-zaouy et al., 2022; Bouhout et al., 2024). This dual

phenomenon of soil salinization and saltwater intrusion underscores the urgent need to adopt sustainable groundwater management practices and monitoring programs to mitigate the further degradation of Morocco's water resources (Agbasi et al., 2025).

Groundwater salinization in the Haouz plain has been exacerbated by excessive pumping, which has forced a shift in exploitation from shallow to deeper aquifers from shallow to deeper aquifers characterized by higher salinity levels. This situation is further compounded by nitrate contamination, creating a dual threat to agricultural sustainability and human health (Sahraoui et al., 2025). Comparable issues have been reported in the Rheris watershed in southeastern Morocco, where brackish groundwater severely limits agricultural and household water supply. To address these constraints, recent research has highlighted photovoltaic-powered membrane capacitive deionization (MCDI) systems as a sustainable technological approach for managing salinity in such regions (Ait Lahssaine et al., 2024). In addition, the coastal areas of Morocco face increasing salinity due to seawater intrusion. As a solution to this challenge, several studies based on hydrological and modeling approaches have indicated that reverse osmosis and nanofiltration can effectively reduce salinity levels in local groundwater, providing a promising path for securing potable water in these regions (Abbi et al., 2025).

Regarding public health, rising salinity in drinking water resources contributes to higher concentrations of total dissolved solids, which can pose health risks when combined with other pollutants. Recent studies have emphasized the urgent need to monitor groundwater and surface water salinity and protect vulnerable populations (Rakib et al., 2019; Shaikh and Birajdar, 2024). Similarly, advances in treatment technologies are being investigated. In the Rabat-Kenitra region, electrocoagulation has shown promising results for groundwater treatment, demonstrating efficiency in reducing nitrate and salinity simultaneously, while reverse osmosis plants are being optimized to address scaling issues in brackish-water desalination systems (Addich et al., 2025; Fatni et al., 2025).

3.2.3 Over-exploitation and virtual export of water in Morocco

In Morocco, the overexploitation of water resources has become a growing concern, particularly as the country faces the dual pressures of increasing demand for water and diminishing supplies due to both climate change and population growth (Benaabidate et al., 2021; Ouhakki et al., 2025). Overexploitation of water resources, particularly groundwater, has led to a significant drop in the water table, estimated on average at around 2 meters per year, particularly in regions dependent on irrigated agriculture (Hssaisoune et al., 2020; Ouhakki et al., 2024). This situation is exacerbated by the increasing demand for water for agricultural, industrial, and domestic uses, which often exceeds the natural replenishment rate of groundwater aquifers (Laonamsai et al., 2023). Moreover, Morocco has experienced substantial virtual water exports, which refers to the water embedded in agricultural and industrial products that are traded internationally (Boudhar and Boudhar, 2025). Although intensive cultivation practices, particularly for export-oriented crops like tomatoes in the Agadir region, have led to groundwater overexploitation and significant declines in dam levels, these issues persist even with the use of desalinated water (Molle and Sanchis-Ibor, 2019). The export of water-intensive crops such as fruit trees and cereals has led to an

implicit export of virtual water, contributing to the overall depletion of national water resources (Sebri, 2017). While Morocco benefits economically from such exports, the practice has raised concerns about the sustainability of water use, as the exported water is not returned to the national hydrological system (Hoekstra and Chapagain, 2007).

Studies show that the export of virtual water is exerting significant pressure on Morocco's water balance, with agricultural products accounting for a large proportion of the national water footprint. This dynamic is part of the transformation of the agricultural sector, driven by a government vision aimed at modernizing and developing this strategic sector (Hoekstra and Chapagain, 2007; Boudhar et al., 2023). This phenomenon poses challenges for water resource management, as the country's limited water supply is strained by the simultaneous pressures of consumption and export (Ait Kadi and Ziyad, 2018). Therefore, addressing both overexploitation and virtual water exports requires a comprehensive approach that balances economic development with sustainable water management practices, such as improving water-use efficiency, promoting water-saving technologies, and fostering policies that encourage the responsible use of water resources.

The implications of overexploitation and virtual water exports also extend to the realm of food security, as water resources critical for domestic agricultural production are redirected for export purposes, potentially undermining the country's ability to produce sufficient food for its growing population (Hekmatnia et al., 2023). Thus, a strategic policy shift toward more efficient water use and a reconsideration of the environmental cost of virtual water exports could help mitigate the strain on Morocco's water resources (Brandolini et al., 2021).

3.2.4 Water pollution problems in Morocco

Water pollution in Morocco, whether in groundwater or surface water, is a major environmental concern with multiple consequences. Groundwater, which is essential for drinking water supply and irrigation, is particularly vulnerable. For example, a study in the Tadra region revealed significant nitrate contamination in groundwater, mainly due to the excessive use of nitrogen fertilizers and agro-industrial waste (El Halouani et al., 2017). Diffuse nitrate pollution is exacerbated by urban wastewater, endangering water quality and the health of rural populations, which depend directly on these resources (Laftouhia et al., 2003). In the Khouribga region, intensive phosphate mining has led to fluoride contamination of groundwater. A previous study revealed a high concentration of fluoride in well water, exceeding the standards recommended for human consumption. This poses health risks, particularly in cases of dental and bone fluorosis, affecting the quality of life of residents (Essebbahi et al., 2022). Surface waters are also not spared. The discharge of margins, the liquid residues from olive crushing, into watercourses such as the Oued Sebou causes an increase in biological oxygen demand (BOD) and chemical oxygen demand (COD), leading to a reduction in dissolved oxygen and the death of aquatic fauna. In addition, these margins form an impenetrable film on the surfaces of rivers, preventing the penetration of light and oxygen, which disrupts the ecological balance of aquatic ecosystems (Safaa et al., 2023). The Mediouna Landfill near Casablanca also illustrates the negative impact of human activity on water resources. The leachate produced by this landfill has contaminated the surrounding groundwater, making farmland unsuitable for cultivation

and affecting the health of the local population (Fekri et al., 2006). Faced with these challenges, it is imperative to strengthen the measures to protect water resources. This includes establishing wastewater treatment systems, regulating the use of fertilizers and pesticides, and rigorously monitoring industrial activities. Preserving the quality of groundwater and surface water is essential to guaranteeing public health, food safety, and sustainable development in Morocco (Darwesh et al., 2020).

3.3 Dams in Morocco

3.3.1 Situation of dams in Morocco

Morocco's predominantly semi-arid to arid climate, characterized by irregular rainfall, recurrent droughts, and escalating water scarcity, necessitates robust water resource management strategies (Adiba et al., 2024c, 2024d; Ongoma et al., 2024). Among these strategies, the construction of an extensive network of dams forms the cornerstone of the country's water management framework (Doost et al., 2024). With renewable water resources amounting to only 22,000 mm³ annually and a growing population, dams are essential to securing a stable and reliable water supply (Rachid and Moussaoui, 2025).

The data on the progressive increase in dam capacity in Morocco from 1960 to 2020 reveal a significant upward trend, with dam capacity expanding from approximately 1,200 mm³ in 1960 to 20,000 mm³ in 2020 (Figure 6). Key milestones in capacity expansion are observed around 1980 and 2000, which coincide with the implementation of major national water policies and dam-building programs, such as the National Water Strategy. The consistent growth trend also reflects Morocco's proactive response to mitigate the effects of climate change, particularly the increasing frequency and severity of droughts. These efforts highlight the role of dams in enhancing

water storage and availability, contributing to food security and socio-economic development (MAPMDREE, 2024). Currently, Morocco operates over 152 large dams with a cumulative storage capacity of 19,000 mm³. The ongoing construction of 16 additional dams is projected to increase this capacity by 4,800 mm³, aligning with the national goal of operating 170 dams by 2030 (METLW, 2024). These dams are critical for ensuring water availability for domestic consumption, agricultural irrigation, and industrial use, especially in regions frequently affected by droughts (Hssaisoune et al., 2020).

Notable examples include the Al Massira Dam, with a capacity of 2,760 mm³, which supplies drinking water to urban centers such as Casablanca, Marrakech, and El Jadida. It also supports agricultural irrigation in the Doukkala plain (Bounif et al., 2023). Similarly, reservoirs like Bin El Ouidane, Al Massira, and Ahmed El Hansali ensure water availability for irrigating Morocco's agriculturally significant Tadla and Doukkala plains, which are vital for cereal and horticultural production (Jamali and Namous, 2020; Ainou et al., 2024). Industrial activities also benefit, with the Oued El Makhazine Dam supporting manufacturing in Tangier (Benchbani et al., 2022).

Beyond water supply, Moroccan dams contribute to flood mitigation by regulating water flow and reducing flood risks for downstream communities, as demonstrated by the Mohammed V Dam in northeastern Morocco (Loudyi et al., 2022). They also facilitate groundwater recharge, mitigating aquifer over-extraction, which is a critical issue in drought-prone areas (Ben Salem et al., 2023). Additionally, hydroelectric dams account for approximately 12% of Morocco's energy mix, underscoring their role in the transition to sustainable energy (Boulakhbar et al., 2020).

3.3.2 Agricultural importance and strategic location of dams

The agricultural importance of dams in Morocco is closely tied to their storage capacity and strategic location within key agricultural

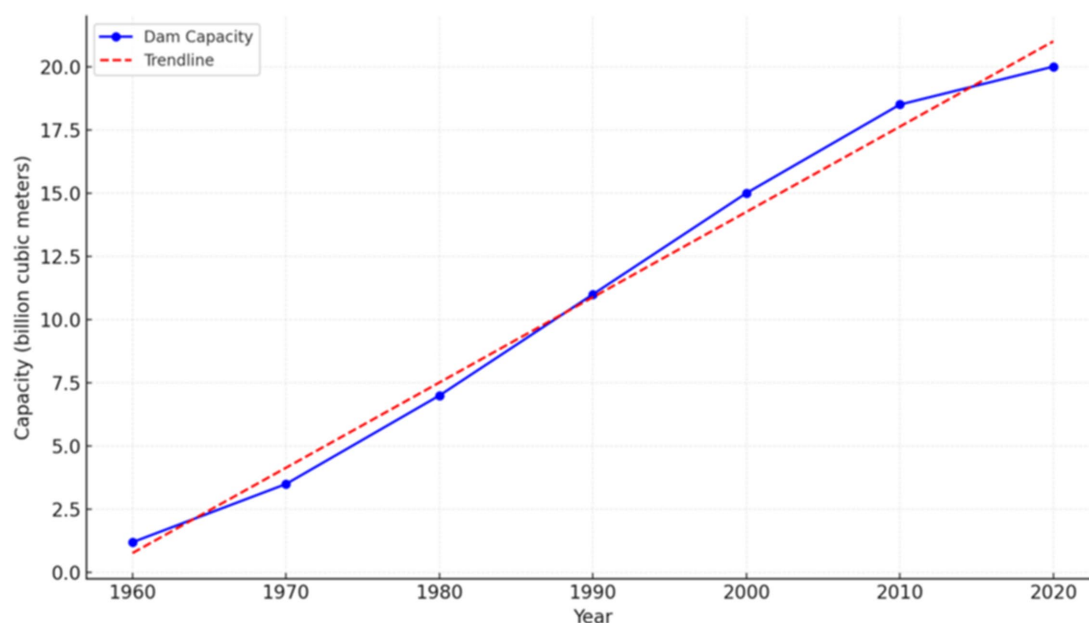


FIGURE 6
Variation of the Moroccan dam's capacity between 1960 and 2020.

regions (Molle and Tanouti, 2017). Dams are predominantly constructed in areas with high agricultural activity to ensure adequate water availability for irrigation (Tatlhego and D'Odorico, 2022). In this sense, the Al Massira Dam, with a 2,600 mm³ storage capacity, plays a vital role in supporting the Doukkala plain, a major irrigated zone covering approximately 100,000 hectares (Bounif et al., 2023). This plain is a significant contributor to national agricultural production, characterized by the cultivation of strategic crops such as sugar beet, durum and soft wheat, maize, and fodder crops, which benefit from an extensive and well-managed irrigation network (Ouraich and Tyner, 2011). As surface water resources in this region are scarce, the Oued Oum Er-Rbia's waters, stored in the Al Massira Dam, serve as the sole surface water source for irrigation in this area (ORMVAD, 2020). Similarly, the Bin El Ouidane Dam, with a capacity of 1,500 mm³, is situated to serve the Tadla Plain agricultural region, which includes the Beni Amir and Beni Moussa perimeters, covering a total area of 105,500 hectares [National Office of Electricity and Drinking Water (ONEE), 2022; Ouhakki et al., 2024]. The Tadla plain is renowned for its diverse crop production, including cereals, forage crops, citrus, and olives, all of which rely heavily on the dam's regulated water supply (Nemmaoui et al., 2014).

In addition, the Idriss I Dam, located near Fes and with a capacity of 1,200 mm³, provides critical irrigation water to the Saïss plain, enabling the production of olives, cereals, and grapes in this high-value agricultural zone (Moumen et al., 2021). The Hassan II Dam, with a storage capacity of 400 million cubic meters, supports agricultural activities in the Tafilalet region, a historically arid area that relies heavily on date palm cultivation and vegetable farming (Chahboune et al., 2013). Meanwhile, the Mansour Eddahbi Dam in southern Morocco, with a capacity of 560 mm³, is vital for the irrigation of the Ouarzazate Basin, where over 20,000 hectares of agricultural land depend on its water (El Qorchi et al., 2023).

The location of these dams is carefully aligned with the agricultural demands of their respective basins, where irrigation accounts for more than 85% of total water usage (FAO, 2022). This strategic placement also mitigates water shortages in arid and semi-arid areas by storing water during the rainy season and releasing it during dry periods (Ragab and Hamdy, 2004). Additionally, their capacities are directly tied to their ability to sustain irrigation and agricultural productivity during prolonged droughts, ensuring the sustainability of Morocco's agricultural sector, which is a significant contributor to the national economy and rural livelihoods (Gouahi et al., 2024).

3.3.3 Prospects and challenges for dams in Morocco

Morocco's extensive network of dams has been crucial in addressing water scarcity and supporting essential sectors such as agriculture, domestic water supply, and energy generation (Ait Kadi and Ziyad, 2018). However, the country faces significant challenges as climate change, population growth, and resource depletion place increasing pressure on these structures. One of the primary issues is the growing sedimentation in reservoirs, which reduces their storage capacity and effectiveness over time. Sedimentation is estimated to reduce the storage capacity of dams by 50 to 75 mm³ annually (METLW, 2024).

The impact of climate change, particularly shifting rainfall patterns, further exacerbates these challenges. Prolonged droughts have become more frequent, and as Morocco enters its seventh

consecutive year of drought, its dams are only 28.47% full, with a total volume of 4800 mm³ as of 2024 (METLW, 2024). While this marks an improvement over 2023, when dams were at just 23.29% (3,800 mm³), the situation remains critical (El Khatri and El Hairech, 2014). Reduced filling rates, combined with aging infrastructure, have made it increasingly difficult to maintain a reliable water supply, particularly for agriculture, which is highly dependent on consistent irrigation (Pereira et al., 2023). Figure 7 shows the development of water inputs to dams in Morocco over a long period (1945–2024), with an alarming downward trend. Figure 7A, covering the period 1945–2021, highlights a high interannual variability of inputs, with several notable peaks in the 1960s, 1996, and 2010. However, this variability is marked by an overall downward trend, particularly from the 1980s onwards, reflecting a progressive scarcity of water resources mobilized by dams. This trend is shown in Figure 7B, which details the annual contributions from 2018 to 2024. After a relatively favorable 2018 (10.8 billion m³), inflows are declining almost continuously, reaching an all-time low in 2022 (2 billion m³). The years 2023 and 2024 remain below the levels required to meet the country's water needs sustainably, confirming a situation of persistent water stress.

The dataset highlights the increasing impact of climate change and recurrent droughts on water resource availability, posing serious challenges for sustainable dam management, national water security, resilience of water-dependent ecosystems, and socio-economic activities. To address these challenges, Morocco is constructing 20 new large dams by 2030, adding 3,200 mm³ of storage capacity (MAPMDREF, 2024). Efforts are also being made to enhance water-use efficiency through modern irrigation systems and digital monitoring technologies for real-time data on water levels and consumption. Additionally, multi-purpose dam projects aim to integrate water storage, energy production, and ecological conservation (Attia and Nasr, 2024).

By combining dams with groundwater recharge systems and community-managed reservoirs, Morocco is adopting a more sustainable approach to water resource management, ensuring resilience against climate change impacts and water scarcity (Bahir et al., 2019).

4 Alternative water management techniques

4.1 Desalination

Desalination is the process of removing salts and other impurities from saline water, primarily seawater or brackish water, to produce freshwater suitable for human consumption, agriculture, or industrial use (Elimelech and Phillip, 2011).

4.1.1 Morocco and seawater desalination

Morocco faces growing water scarcity due to climate change, population growth, and limited natural water resources (Adiba et al., 2021a; Hamdani et al., 2021). To address this challenge, Morocco has adopted strategies such as water recycling, efficient irrigation systems, and desalination (Al-Addous et al., 2024). Desalination has become a cornerstone of Morocco's water management framework, especially in arid and semi-arid regions where conventional water resources are

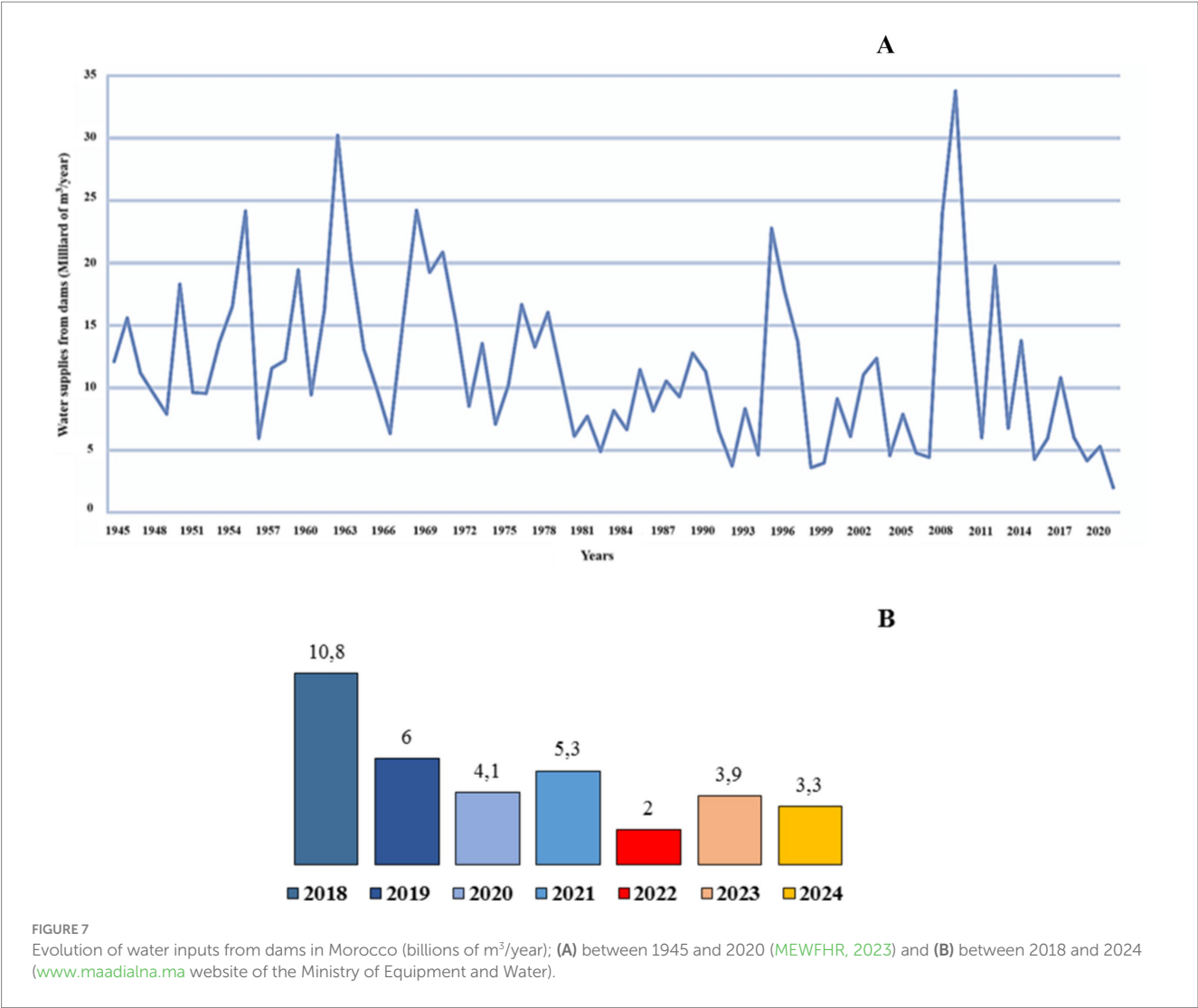


TABLE 2 Overview of seawater desalination projects in Morocco.

Project	Location	Capacity (m ³ /day)	Start year	Targeted beneficiaries	Status
Agadir plant	Agadir	100,000	2020	Urban areas, agriculture	Operational
Jorf Lasfar desalination	Jorf Lasfar	80,000	2017	Industrial, agriculture	Operational
Laayoune desalination plant	Laayoune	50,000	2022	Urban areas	Under construction
Dakhla desalination project	Dakhla	70,000	2021	Urban areas, agriculture	Operational
Tangiers Plant	Tangiers	120,000	2019	Coastal and agricultural regions	Operational
Kenitra seawater desalination	Kenitra	150,000	2023	Urban, industrial sectors	Under construction

insufficient (Zarkik and Ouhnini, 2022) (Table 2). By converting seawater and brackish water into freshwater, desalination offers a viable solution to meet the growing demand for drinking water, agricultural irrigation, and industrial use (Burn et al., 2015). This approach is embedded within Morocco’s National Water Plan, which emphasizes the integration of innovative technologies to mitigate water shortages and ensure long-term water security (Bachegour et al., 2023).

One of the most notable projects is the Agadir Desalination Plant, which began operations in 2021 (Aglagal et al., 2024). This plant,

considered the largest desalination facility in Africa, has a daily production capacity of 275,000 m³ of water (El-Ghizel et al., 2021). The project serves dual purposes: supplying potable water to more than 500,000 people in the Souss-Massa region and providing irrigation water for 15,000 hectares of farmland (Bourziza et al., 2023). Additionally, the Safi Desalination Plant in the coastal Safi province serves as another critical project aimed at providing potable water to local communities (Aroussy et al., 2016b). While smaller in scale compared to other facilities, the Safi plant highlights Morocco’s comprehensive strategy to address water scarcity issues across diverse

urban and rural regions (Aroussy et al., 2016a). Looking to the southern regions, the Dakhla Desalination Plant is a forward-looking initiative that is expected to be operational by 2025. With a planned capacity of 90,000 m³ per day, this facility will be powered by a 40 MW wind farm (MAPMDREE, 2024). The Dakhla plant represents a strategic investment in ensuring water security for the population and the agricultural sector in the southern provinces, while leveraging Morocco's vast wind energy potential to reduce environmental impact (MAPMDREE, 2024).

However, despite these notable advancements, Morocco's water management efforts are not without significant challenges that threaten the sustainability and effectiveness of these initiatives. In this sense, several researchers reported that one of the primary challenges of desalination is the high energy consumption required to desalinate seawater (Al-Karaghoul and Kazmerski, 2013). Seawater desalination is an energy-intensive process, particularly the Reverse Osmosis (RO) technology commonly used in Moroccan plants (El-Ghizel et al., 2021). Morocco is addressing this challenge by integrating renewable energy sources, such as solar and wind power, into desalination projects (Boulakhbar et al., 2020). For instance, the Agadir Desalination Plant is partially powered by solar and wind energy, which helps reduce energy costs and carbon emissions (Tanji and Boutaibi, 2023). On the other hand, the environmental impact and brine disposal are some of the challenges in Morocco (Azdem et al., 2024). The brine contains concentrated salt and chemicals, which can harm marine ecosystems if not properly managed (Omerspahic et al., 2022). Moreover, the high salinity of brine can impact local fisheries and biodiversity, creating a need for improved brine management strategies and innovative technologies to mitigate environmental harm (Sola et al., 2020). Although some desalination plants in Morocco, such as those in Agadir and Chtouka, have implemented systems to reduce the impact of brine discharge, this remains a major concern (Bourziza et al., 2023).

4.1.2 Agricultural importance of desalination in Morocco

Approximately 80% of Morocco's cultivated land relies on rain-fed agriculture, making it particularly vulnerable to fluctuations in precipitation and climate change impacts (Abdelmajid et al., 2021). In this sense, desalination has emerged as a critical solution to address Morocco's water scarcity, particularly in arid and semi-arid regions where agriculture is heavily reliant on irrigation (Migliore, 2024). The integration of desalinated water into agricultural practices has provided a sustainable means to support the country's food security and economic stability (Derouez and Ifa, 2024). Recent studies highlight the significant role desalination plays in meeting the irrigation demands of high-value crops such as citrus, olives, and greenhouse-grown vegetables in regions like Souss-Massa and the Dakhla Oases (Bourziza et al., 2023; Aglagal et al., 2024).

For instance, the Agadir Desalination Plant in Souss-Massa, with a dual-purpose design, supplies irrigation water to 15,000 hectares of farmland. This has notably improved water availability for horticultural production, particularly in areas where groundwater over-extraction and salinization have become critical issues (El-Ghizel et al., 2021). Similarly, the ongoing Dakhla Desalination Plant project is anticipated to boost agricultural productivity by providing 90,000 m³ of desalinated water daily, ensuring water

availability for both irrigation and the region's expanding agricultural exports (MAPMDREE, 2024).

The adoption of desalinated water for irrigation is particularly vital in combating groundwater over-extraction and salinization, issues that threaten the long-term viability of agriculture in semiarid and arid regions (Burn et al., 2015; Bachegour et al., 2023). As Morocco continues to expand its desalination infrastructure, several researchers have reported that the agricultural sector stands to benefit from increased water availability, enhanced crop productivity, and greater resilience against the impacts of climate change (Zarkik and Ouhni, 2022).

4.1.3 Prospects and challenges of desalination in Morocco

Desalination represents a strategic pathway for Morocco to mitigate its intensifying water scarcity, driven by mounting pressures from urban, industrial, and agricultural demands (El-Ghizel et al., 2021). As part of the nation's integrated water management strategy, desalination has been bolstered by the adoption of cutting-edge technologies and renewable energy sources, such as wind and solar power, which significantly reduce both operational costs and environmental impacts (Kettani and Bandelier, 2020). For instance, the Dakhla Desalination Plant exemplifies Morocco's innovative approach by combining desalination with renewable energy, paving the way for sustainable water production in the resource-challenged southern provinces (MAPMDREE, 2024). Similarly, the Agadir Desalination Plant serves as a model of efficiency, simultaneously meeting potable water needs and providing irrigation water, thereby establishing a robust precedent for future projects (Bourziza et al., 2023).

Despite these advancements, the expansion of desalination in Morocco faces several pressing challenges. The high capital and operational costs of desalination plants remains a significant barrier, particularly in areas with limited energy infrastructure (Hafsi and Taky, 2023). Although the integration of renewable energy sources has helped mitigate some expenses, the energy-intensive nature of desalination continues to raise concerns regarding its long-term economic viability (Burn et al., 2015). Furthermore, the disposal of brine, a highly concentrated saline by-product, poses substantial environmental risks, including potential damage to marine ecosystems and biodiversity if not effectively managed (Bachegour et al., 2023).

In agriculture, desalinated water presents significant potential for irrigation; however, its use demands careful management to prevent soil salinization. If insufficiently treated, its mineral content can accumulate over time, undermining soil quality and crop productivity. To ensure sustainability, the integration of advanced irrigation practices and rigorous monitoring is necessary (El-Ghizel et al., 2021). Equitable access to desalinated water is another critical concern. While urban centers and industrial zones often benefit from large-scale desalination projects, rural and economically disadvantaged regions face limited access, exacerbating regional disparities in water availability (Gude, 2017). Addressing this disparity requires targeted investments and policy interventions to ensure that all communities benefit equitably from desalination infrastructure.

The prospects of desalination in Morocco will hinge on its ability to overcome these challenges through strategic investments and innovation. Scaling up the deployment of energy-efficient technologies, reducing the costs of desalinated water, and developing

environmentally sustainable brine management solutions are essential steps forward (Al-Addous et al., 2024). Additionally, fostering partnerships to share best practices and leveraging international expertise can further enhance the efficiency and sustainability of desalination initiatives. By addressing these challenges proactively, Morocco is well-positioned to secure its water resources, support its agricultural and industrial sectors, and emerge as a global leader in sustainable desalination practices (Attar et al., 2022).

4.2 Reuse of treated wastewater

4.2.1 Wastewater treatment and processes

Wastewater treatment refers to all the physical, chemical, and biological processes used to eliminate or reduce the pollutants present in wastewater before it is discharged into the environment or reused (Shojaei and Shojaei, 2021). This treatment helps to protect water resources, improve water quality, and prevent pollution of the natural environment. It generally consists of several stages, such as pre-treatment (elimination of coarse elements), primary treatment (separation of solids), secondary treatment (biodegradation of organic pollutants), and sometimes tertiary treatment (to eliminate specific pollutants such as nitrogen, phosphorus, or pathogens) (Karri et al., 2021).

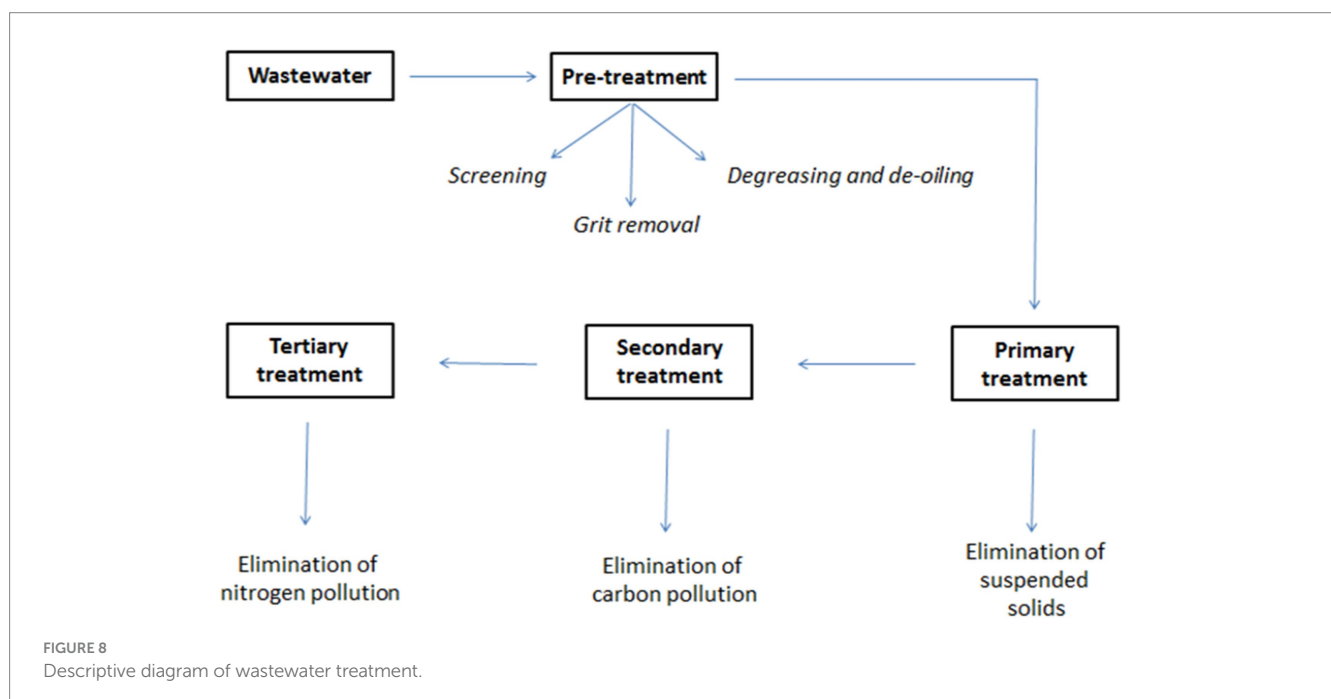
Wastewater can be treated using a variety of processes involving physical, chemical, and biological phenomena. These treatments offer various levels of purification, with costs varying according to the quality required by the receiving environment. Wastewater treatment methods are generally divided into several stages: pre-treatment, primary, secondary, and tertiary treatment (Figure 8) (Ding, 2023).

Pre-treatment is the first stage in the wastewater treatment process. It is based on mechanical or physical methods designed to eliminate the coarsest particles, such as sand, gravel, and grease (Nishat et al., 2023). This treatment is carried out in three phases: (i)

screening: This operation consists of filtering the wastewater through grids, the bars of which are more or less widely spaced, to retain the largest elements. The screens are cleaned manually, mechanically, or automatically to collect the waste, which is then disposed of with household waste (Ye et al., 2021). (ii) Grit removal: This stage targets particles larger than 200 μm , mainly sand and gravel. The water flows through a channel at a speed of between 0.2 and 0.3 m/s, allowing the particles to settle to the bottom through sedimentation under their own weight. The sediment collected is then washed and either disposed of in a landfill or reused, depending on the quality of the washing (Silva, 2023). (iii) Degreasing and de-oiling: This stage aims to remove fats and oils from the wastewater, as they can impair the effectiveness of subsequent biological treatments. The process is based on flotation: air is injected at the bottom of the structure, causing the fats to rise to the surface. The fat is then scraped off, stored, and disposed of at a landfill site or incinerated (Sonawane et al., 2022).

Primary treatment is a physico-chemical process that eliminates more than 50% of suspended solids (SS), both mineral and organic, making it an essential stage in the treatment process. It is based on primary decantation, a gravity-based process that separates solids from liquids (Poleneni, 2020). This operation takes place in a settling tank, generally a large, slow-flowing basin, where the solid particles settle to the bottom in the form of primary sludge, trapping a first part of the pollution. The efficiency of decantation can be improved by adding chemicals such as sulphates, chlorides, or coagulation agents, a technique known as flocculation. This technique captures up to 60% of TSS and reduces biological oxygen demand (BOD) and chemical oxygen demand (COD) by around 30% (Zaharia et al., 2024).

Secondary treatment consists of a series of biological processes that encourage the biodegradation of pollutants by microorganisms. This can include temporary aerobically stabilized water bodies, biological filters, activated sludge treatment processes, aerobic reactors, and stabilization ponds (Chandran et al., 2023). There are different types of biological processes: (i) Activated sludge is an



aerobic purification system in which wastewater, bacteria, and oxygen are mixed in aerated tanks. The bacteria break down the organic matter, producing secondary sludge, which is separated from the treated water in a clarifier (Wang et al., 2020). Some of the sludge is disposed of or used as fertilizer, while the rest is recycled in the tanks to maintain bacterial activity. This process eliminates 85–95% of the BOD5 (Koul et al., 2022). (ii) Bacterial beds are an aerobic treatment where water flows over a solid support, allowing micro-organisms (bacteria or fungi) to develop and break down the organic matter. This process forms a “biological film” that absorbs pollutants. The mixture of wastewater and biofilm is then sent to a secondary decanter to separate the sludge, while the treated water can be discharged into the natural environment. This treatment eliminates up to 90% of BOD5 (Goswami et al., 2022). (iii) Natural lagooning involves treating wastewater in shallow tanks exposed to light, allowing aerobic bacteria to break down organic pollutants, while anaerobic bacteria treat the sediment at the bottom. This process is inexpensive, consumes no energy, and requires few qualified personnel, but it requires large surfaces and partially eliminates nitrogen and phosphates (20 to 30%). Poorly sealed basins can lead to the risk of contaminating groundwater (Singh et al., 2022).

Tertiary treatment, or complementary treatment, is designed to eliminate nitrogen, phosphate, and biological pollution from domestic wastewater. They enable secondary treatment to be refined to improve water quality, making it easier to reuse in industry or for irrigation (Sabrina de Boer et al., 2022). These treatments are implemented when the requirements of the receiving environment make it necessary. They generally include nitrification–denitrification, biological or mixed dephosphatation (biological and physico-chemical), as well as bacterial and viral disinfection (Omar et al., 2024).

4.2.2 Morocco and wastewater treatment

Over the last few decades, Morocco has made significant progress in wastewater treatment. These efforts are part of a national strategy to preserve water resources, meet the growing demand for drinking water, and promote sustainable development. This approach includes the collection of wastewater from domestic and industrial uses and rainwater discharged into the sewer system, which is then directed to a wastewater treatment plant (El Moussaoui et al., 2022). These facilities treat the wastewater to purify it and render it harmless, eliminating harmful elements for reuse and recycling. A wastewater treatment plant is usually located at the end of a wastewater collection network. Its role is to discharge the treated water back into the natural environment or to redirect it to a planned use (Hanae et al., 2024). It is made up of various devices through which the wastewater passes to undergo the treatment process. The configuration of a wastewater treatment plant depends on several factors, including its location, the budget available, the flow rate of water to be treated, the treatment method adopted, the level of purification required, and the final objective of the treatment (El Moussaoui et al., 2019).

According to Benkaroum and Boumadiane (2021), here is an overview of the investments and successes in this sector: The main aim of the National Sanitation Programme (PNA), launched in 2005, is to reduce water pollution, increase access to sanitation services, and modernize wastewater treatment infrastructure. Its ambitions include treating 60% of collected wastewater, covering 80% of urban areas with sewerage networks by 2030, and an overall investment estimated at several billion dirhams. Investments by public companies: ONEE

(National Office for Electricity and Drinking Water): A central player in the implementation of sewerage and wastewater treatment projects, ONEE works closely with local authorities and international partners to develop and optimize the necessary infrastructure. Delegated companies: Companies such as Veolia and Suez, through their local subsidiaries, manage wastewater in large conurbations such as Casablanca, Rabat, and Tangiers, helping to improve sanitation services in these urban areas. International funding: Morocco receives financial support from the World Bank, the European Investment Bank (EIB), and other partners for the construction of modern wastewater treatment plants. In addition, initiatives such as the Clean Development Mechanism (CDM) are helping to attract investment by promoting projects focused on environmental sustainability.

Morocco's efforts in the field of wastewater treatment have borne fruit, achieving significant results at various levels. These advances testify to the country's commitment to the sustainable management of water resources and the fight against pollution. The developments of modern infrastructure, the implementation of innovative projects, and awareness-raising initiatives in Morocco have sought to improve living conditions while managing environmental impacts (GGIREM, 2014). Here is an overview of the main achievements in this field: (i) Modern wastewater treatment plants: Morocco now has more than 150 operational wastewater treatment plants, some of which use advanced technologies such as biological treatment, reverse osmosis, and reuse of treated water (Table 3) (AIDD and EDD, 2020). Example: The Marrakech wastewater treatment plant is one of the largest in the country and reuses treated water to irrigate green spaces. (ii) Reuse of wastewater: Several pioneering projects enable treated wastewater to be reused in agriculture and the irrigation of public spaces. By 2023, around 30 million m³ of wastewater had been reused, with a target of 100 mm³ by 2030. (iii) Improved quality of life: The modernization of sanitation systems has reduced water-related diseases in urban and rural areas. Community initiatives and awareness campaigns have contributed to better wastewater management. (iv) Preservation of ecosystems: Efforts to treat wastewater have limited the pollution of rivers and groundwater, helping to protect sensitive ecosystems (Mishra et al., 2023).

4.2.3 Agricultural importance of wastewater treatment in Morocco

In Morocco, wastewater treatment is essential for agriculture, particularly in the face of water scarcity and climate change (Ortega-Pozo et al., 2022). By providing a sustainable source of irrigation, treated wastewater helps alleviate pressure on natural resources such as groundwater and reservoirs (Ortega-Pozo et al., 2022). This solution is especially critical for ensuring reliable irrigation in arid and semi-arid regions, where water remains scarce and invaluable (Bihadassen et al., 2020). In addition, treated wastewater is rich in essential nutrients such as nitrogen, phosphorus, and potassium, which enrich soil fertility while reducing the need for chemical fertilizers. This helps to increase agricultural yields while reducing costs for farmers (Mishra et al., 2022). Wastewater treatment also eliminates toxic substances and pathogens, protecting soil and crops from harmful contaminants and ensuring their long-term sustainability (Albalasmeh et al., 2020). This approach is part of a circular economy, transforming wastewater, once considered a waste product, into a valuable resource for agriculture. By limiting direct discharges into the environment, water treatment also helps to preserve ecosystems (Braga et al., 2022). In

TABLE 3 Some examples of various wastewater treatment projects in Morocco (AIDD and EDD, 2020).

Project sponsors	Status of the project
The Desert Water Association (DWA)	DWA has launched five community launderette projects in the Tafilalet region, equipped with 10 to 13 semi-automatic washing machines, a multi-purpose room, a solar water heater, and a planted filter to purify grey water (444 716.00 €). The first of these projects, at Ouaklim, was carried out in 2009 in partnership with the Association of Students of the Bridges and Roads of Paris and the Imlil Association.
	The second project was carried out in Izilf between 2011 and 2012. It received a total funding of 700,000 dirhams, provided by the GEF micro-financing program, the POT, INDH, and Desert Water. The construction of the filter was specifically funded by ANDZOA.
	The third project was carried out in Tabesbaste between 2013 and 2014, with funding of 800,000 dirhams provided by the GEF*, the partner association, and Desert Water.
	The fourth project was carried out in Taltfraout between 2014 and 2015, with funding of 1 million dirhams provided by the POT.
	The fifth project was carried out in Magamane between 2014 and 2015, with funding of 1.2 million dirhams provided by the POT.
United States Agency for International Development (USAID)	The total investment of the project amounted to 17 million DH, or about \$1.5 million (2003). Equipment and construction were the main investment costs and represented 76%. Management and maintenance costs are estimated at 800,000 DH per year, or nearly 80,000 \$ per year.
RADEEF/Autonomous intercommunal water and electricity distribution authority of Fes	The objectives of the project, as stated in the Loan Agreement, were to protect the environment, improve hygiene and public health, and preserve water resources through the proper collection, treatment, and disposal of wastewater. It also aimed to strengthen the Borrower's institutional capacity and improve cost recovery in the sanitation subsector. The allocated budget was 626 million dirhams (60 \$ million) in 2005.

addition, access to treated water stimulates agricultural development in rural areas, generating economic opportunities for local communities, curbing the rural exodus, and playing a key role in combating desertification (Bellver-Domingo and Hernández-Sancho, 2022). Morocco is demonstrating a strong commitment to the reuse of wastewater through initiatives such as the National Liquid Sanitation and Wastewater Reuse Programme (PNA) and the installation of wastewater treatment plants in cities such as Marrakech, Agadir, and Ouarzazate (Ortega-Pozo et al., 2022). These projects aim to provide treated water for agricultural irrigation, thereby strengthening food security and the sector's resilience in the face of climate and water resource challenges (Al-Saidi and Dehnavi, 2020). As a result, wastewater treatment is emerging as a sustainable and strategic solution for agriculture in Morocco. It makes it possible to preserve the environment, support food security, and promote balanced rural development while increasing the country's capacity to meet tomorrow's environmental challenges (Abdelmajid et al., 2021).

4.2.4 Prospects and challenges of wastewater treatment

In response to increasing water stress, Morocco has prioritized wastewater management as a key strategy to safeguard its water resources. Since the launch of the National Program for Liquid Sanitation and Wastewater Treatment (PNA) in 2005, the country has made remarkable progress. The wastewater treatment rate, which stood at just 7% in 2006, exceeded 50% by 2020, with a target of 80% by 2050 (Habib, 2022). Nationwide, over 158 treatment plants have been established, processing substantial volumes of wastewater to mitigate pollution in rivers and groundwater. These facilities employ diverse technologies, ranging from biological treatments to advanced systems tailored for water reuse (Bennis, 2023). Reusing treated wastewater plays a crucial role in Morocco's national strategy. This resource is now utilized for agricultural irrigation, maintaining green spaces, and supporting golf courses, alleviating pressure on drinking water supplies (Elamé, 2023). Morocco has set an ambitious target to recycle 100 million m³ of

wastewater annually by 2027. This goal is bolstered by international funding and awareness campaigns designed to garner stronger support from local authorities and the general population (Mbarki et al., 2024). However, many challenges remain. Some wastewater treatment plants fail to meet international quality standards, posing risks to public health and the environment (Ortega-Pozo et al., 2022). Studies have revealed high concentrations of microbial contaminants in some facilities, including helminth eggs, exceeding the recommended thresholds for safe irrigation. Moreover, rural areas remain particularly vulnerable, with a large proportion of wastewater neither collected nor treated, leading to diffuse pollution of groundwater. In addition, the high cost of modern treatment technologies, such as reverse osmosis membranes or activated sludge systems, is a major obstacle for many local authorities (Haldar et al., 2022). To meet these challenges, Morocco is relying on a number of strategic initiatives. The recent opening of the "National Thematic Institute for Scientific Research on Water (INTR-Eau)" in Agadir aims to develop technological solutions tailored to the country's specific characteristics, in particular low-cost treatment systems and techniques for recovering sewage sludge (Taheripour et al., 2020). At the same time, the strengthening of public-private partnerships is playing a key role in the modernization of infrastructure. In addition, the regulatory framework is being revised to introduce more stringent standards for the discharge and reuse of wastewater (Basri et al., 2020). Although the challenges remain numerous, Morocco is clearly determined to transform its wastewater into a valuable resource. Continued investment, scientific research, and awareness-raising efforts will be crucial to ensuring the sustainable and efficient management of this essential resource (Nourredine et al., 2023).

5 Agroecological water management

In Morocco, sustainable water management in agriculture is a major challenge in the face of water scarcity. The agroecological

approach, which combines environmentally friendly farming practices with innovative water management solutions, represents an effective response to the problems encountered in the country's agriculture. These practices are mainly aimed at improving soil health, optimizing water use, and strengthening the resilience of agroecosystems to extreme climatic conditions.

Table 4 summarizes some studies on agroecological water management practices and their impact on agricultural productivity, resilience of cropping systems, and soil quality in Morocco. This illustrates the effectiveness of various techniques, ranging from no-till and mulching to agroforestry, and the use of biofertilizers and biochar. This Moroccan study highlights that integrated approaches, combining soil management, water management, and adapted cultural practices, can significantly improve water-use efficiency, soil fertility, and crop resilience to water stress. However, it is important to note that studies conducted in Morocco, particularly those conducted under open-field conditions, remain limited. Most research has been conducted on a limited number of experimental plots or on specific agroforestry systems, which highlights the need to broaden investigations to better generalize the results and propose recommendations adapted to all semi-arid and arid agricultural zones in the country.

5.1 Soil management practices to improve water retention

Numerous agroecological practices have been used to increase the capacity of the soil to retain water. One of the most common is the application of organic amendments, such as compost or biochar, which enrich the soil with organic matter and improve its structure (Romero et al., 2022). By increasing the organic matter content, these amendments enhance the ability of the soil to retain moisture, reduce the need for frequent watering, and enable more efficient management of the available water. In addition, reducing the mechanical disturbance of the soil, such as plowing, helps maintain its porosity and limits evaporation. In addition, the use of organic mulches, such as straw or leaves, protects the soil surface from erosion and conserves moisture while adding organic matter to the soil as it degrades (Ranjan et al., 2017). Beneficial interactions between plants and microbes, such as arbuscular mycorrhizal fungi (AMF), also play crucial roles in these dynamics. These fungi enhance the uptake of water and nutrients by plants, thereby strengthening their resilience to drought (Daly-Hassen et al., 2019). These agroecological practices not only promote water management but also help to improve soil fertility and structure, making crops more resistant to climatic hazards.

5.1.1 Mulching

Mulching is a key agricultural water management practice. By applying organic or inorganic materials to the soil surface, this technique limits water evaporation, regulates soil temperature, and controls weed growth (El-Beltagi et al., 2022). In Morocco, mulching with cereal straw, leaves, or bark has been demonstrated to be effective in conserving soil moisture and reducing irrigation requirements while improving soil fertility through the natural degradation of these materials (Saha et al., 2018). The use of organic mulch also promotes microbial life in the soil, contributing to improved organic matter degradation and soil enrichment (Iqbal et al., 2020). However, the choice of mulch material is essential to maximize its benefits. For

example, although plastic mulches are effective in controlling weeds and limiting evaporation, their environmental impact is a concern owing to their non-degradability (Zhang et al., 2021). In contrast, organic mulches offer long-term benefits by enriching the soil but can sometimes have allelopathic effects on certain crops, requiring careful selection of materials to be used (Monteiro and Santos, 2022).

5.1.2 Living cover crops

Live cover crops, which are planted to protect the soil and are not harvested, play a central role in water management in Morocco. These crops, often referred to as "green manures," act as living mulch, protecting the soil against erosion, improving soil quality, and promoting moisture retention (Scavo et al., 2020). They also contribute to weed management by limiting weed development and attracting beneficial insects, while repelling certain pests (Scavo et al., 2022). Cover crops are particularly useful for reducing water loss through evaporation during drought periods. By acting as a protective cover, they minimize variations in soil temperature and help maintain stable humidity, enabling the better use of available water (Gabriel et al., 2021). These practices make it possible to diversify cropping systems, increase the resilience of agroecosystems, and optimize the use of water resources.

5.1.3 Tillage management

Tillage management is crucial for optimizing water use, reducing soil erosion and temperature, and enhancing water retention, with conservation tillage being particularly effective. This practice minimizes soil disturbance, retains crop residues on the soil surface, and enriches the soil with organic matter (Shakoor et al., 2022). By limiting erosion and improving the soil structure, conservation tillage promotes better water infiltration and reduces losses due to evaporation. It also encourages better nutrient cycling and prevents nutrient leaching (Zhang et al., 2022). Another key practice, direct seeding, involves sowing seeds directly into unworked soil, thus preserving the natural structure of the soil (Seitz et al., 2020). By avoiding soil disturbance, this technique reduces runoff, increases water infiltration, and preserves soil moisture, which is particularly important in times of drought. Reduced tillage, which consists of limiting plowing operations and maintaining the cover of plant residues, also contributes to water management by reducing evaporation and increasing moisture retention (Du et al., 2022). By improving the soil structure and conserving moisture, these practices optimize water use while preserving soil fertility and durability in the long term.

5.1.4 Biofertilizer

Agroecological fertilization is another crucial aspect of improving water management in sustainable agricultural systems. Organic and biological methods play an essential role in optimizing water use and contribute to soil health. Nutrients, such as nitrogen, phosphorus, and potassium, directly influence water uptake by plants by regulating root physiology and cellular processes (Sardans and Peñuelas, 2021). The use of organic fertilizers, such as manure, compost, or plant residues, which decompose slowly, offers a constant supply of nutrients and improves the water-holding capacity of soils (Shaji et al., 2021). In addition, these practices promote biodiversity by stimulating soil microorganisms and strengthening symbiotic relationships such as those between plant roots and arbuscular mycorrhizal fungi (AMF).

TABLE 4 Summary of some studies concerning agroecological water management used in Morocco.

Water management practices	Cultivated species	Main results observed	Reference
Mulching and No-Till	Wheat	Water use efficiency for wheat cultivation was comparable between direct seeding, deep tillage, and chisel plowing, with values ranging from 6.6 to 7.1 kg mm ⁻¹ ha ⁻¹ .	Mrabet (2000)
Tillage and Fallow Management	Sunflower (<i>Helianthus annuus</i> L.)	No-till and reduced tillage demonstrated better water storage capacity when autumn was wet but spring was dry, thus contributing to maintaining soil moisture.	Aboudrare et al. (2006)
Mulching	Wheat	The use of mulching and cover crops was recommended to optimize land use and limit water losses.	Laouina et al. (2006)
No-till, Minimum Tillage, and Cover Crops	Barley and Wheat	The use of barley residue as cover and the adoption of direct seeding (no-till or reduced tillage) have improved soil moisture retention, particularly on degraded, stony, and sloping land.	Schwilch et al. (2015)
No-till with Cover Crops	Wheat	In semi-arid areas, no-till combined with a soil cover has maintained yields similar to those of conventional tillage, with a slight increase in water use efficiency.	Mrabet (2002)
No-till	Wheat	Direct seeding has helped increase organic matter content, improve soil stability, reduce erosion and promote better moisture retention.	Maher et al. (2020)
Agroforestry: Olive and Annual Crops under Different Water Regimes	Cereals and Legumes Associated with Olive Trees	The evaluation of 42 plots and on-farm experiments showed that olive-based agroforestry systems reduced annual crop yields by more than 50% compared to pure crops, regardless of the water regime. However, tree-crop interactions varied according to seasonality: negative effects in winter/spring (growth) but positive in summer during grain filling, particularly under drought conditions.	Temani (2020)
Agroforestry in Drylands (Argan, Carob, and Fodder Shrub Systems)	Wheat, Barley, Broad Bean (<i>Vicia faba</i>), Alfalfa, Forage Species	The introduction of trees and shrubs into cereal fields improved crop density and biomass, nutritional quality (nitrogen content, total nitrogen content), and soil fertility. Fava bean-carob and barley-atrilex associations showed significant increases in soil organic matter (up to 5.9% in agroforestry versus 2.3% in monoculture). Agroforestry systems have therefore strengthened agricultural productivity, resilience, and sustainability in dry areas of Morocco.	Elkoudrim et al. (2024)
Drip Irrigation with Biofertilizers	Durum Wheat (<i>Triticum durum</i> L.)	The application of biofertilizers (<i>Bacillus</i> sp., arbuscular mycorrhizae, and compost) combined with irrigation improved agrophysiological and biochemical traits, increased grain and straw yields (+130 to +167%), enhanced resistance to water stress, and improved soil quality under semi-arid conditions.	Ikan et al. (2024)
Integrated Soil Fertility Management with Biochar and Biocompost	Alfalfa (<i>Medicago sativa</i>)	The addition of biochar and biocompost, individually or in combination, improved soil water retention capacity (>0.7 g H ₂ O/g dm), supported productivity, enhanced photosynthesis, protein content, and physiological parameters of alfalfa, under normal or deficit irrigation. These results indicate a promising alternative to conventional manuring and chemical fertilization practices.	El Moussaoui et al. (2024)
Adapted crops	Quinoa (<i>Chenopodium quinoa</i> Willd.)	Quinoa has shown tolerance to salinity levels of up to 17 dS·m ⁻¹ , and phosphorus fertilization has significantly improved biomass and seed yields. Under high salinity conditions, 60–70 kg P ₂ O ₅ ·ha ⁻¹ is the optimal rate for maximizing production.	Bouras et al. (2022)
Adapted crops and agroforestry systems	Quinoa (<i>Chenopodium quinoa</i> Willd.) and pomegranate (<i>Punica granatum</i>)	The quinoa-pomegranate agroforestry system mitigated the negative effects of salinity on quinoa dry matter, grain yield, and water productivity compared to monoculture. The high land equivalent ratio (LER) (1.86–2.21) indicates a productivity gain of 86–121%. This innovative system leverages the salt tolerance of quinoa and improves land-use efficiency in semi-arid regions affected by salinity.	Abidi et al. (2024)

These fungi contribute to reduced irrigation requirements and improved soil structure by increasing nutrient uptake and moisture (Bano and Uzair, 2021). Biofertilizers such as *Azotobacter* and *Rhizobium* also play a fundamental role in improving nutrient availability for plants and reducing groundwater pollution from excess nutrients. Through their ability to fix atmospheric nitrogen and solubilize phosphorus, these microorganisms help reduce dependence on chemical fertilizers while increasing water-use efficiency and reducing environmental impacts (Anli et al., 2020). In brief, agroecological fertilization, in addition to improving soil fertility,

contributes directly to optimizing water management, notably by reducing waste and preventing nutrient leaching. These approaches not only improve water use efficiency but also promote more sustainable and resilient agriculture in the face of climate change.

5.2 Contour farming

Contour farming is an ancestral method of land management that involves organizing farming activities, such as plowing, along the

contour lines of the land rather than working in straight lines along slopes (Brempong et al., 2023). This technique aims to reduce the surface runoff and limit erosion, particularly in hilly and sloping areas. By following the natural contours of the soil, contour farming slows down water runoff and promotes infiltration, contributing to more efficient water management in dry, erosion-prone regions (Goyal and Gaur, 2021). There are multiple mechanisms of action of this method. First, contour plowing forms ridges and furrows that slow the flow of water, allowing water to penetrate deeper into the soil instead of flowing quickly, thereby reducing the risk of erosion (Mohamoud, 2012). In addition, these ridges act as natural barriers that retain rainwater, concentrating where it is most needed by plant roots. This method also improves the soil structure and microbial biodiversity, contributing to better soil health and sustainable agriculture (Kumarasinghe, 2021). Another major advantage of contour farming is that it helps reduce the impact of water evaporation. The ridges formed offer shade to crops, limiting direct sun exposure and helping to conserve soil moisture, particularly during dry periods (Patle et al., 2020). This practice is particularly beneficial in arid or semi-arid regions where water conservation is crucial for maintaining agricultural productivity and preserving soil integrity.

5.3 Rainwater harvesting

Rainwater harvesting is an important method of sustainable water management, particularly in areas with limited water supplies. It involves capturing and storing rainwater for later use in various agricultural and domestic activities, thus contributing to more efficient water management (Brempong et al., 2023). This approach offers several environmental and economic advantages. Rainwater harvesting reduces pressure on conventional water resources, such as groundwater and rivers, while minimizing evaporation losses in traditional water distribution networks (Yannopoulos et al., 2019). Rainwater harvesting becomes particularly beneficial during periods of drought. By storing water during periods of heavy rainfall, this method creates a reserve that can be used to irrigate crops during dry periods, thus ensuring continuity of agricultural production and food security in regions prone to extreme weather conditions (Ahmed et al., 2023). Moreover, rainwater, which is naturally soft and chemical-free, is ideal for crops, as it preserves soil quality and reduces erosion (Gupta et al., 2020). These systems consist of small earthen or stone channels called “metfias,” designed to divert and collect rainwater, either into storage basins or directly onto agricultural land. Systems consisting of small earthen or stone channels called “metfias,” are designed to divert and collect rainwater, either into storage basins or directly onto agricultural land. These systems have been used for a long time in rural Morocco to capture and store runoff water. Studies have documented the positive effects of “metfias,” including improved water availability for small-scale farmers, increased local agricultural productivity, and reduced vulnerability to droughts (Laamrani et al., 2000; Van der Hoek et al., 2002).

In economic terms, rainwater harvesting reduces water supply costs, whether for irrigation or domestic use, and offers an alternative to often costly and inefficient municipal water distribution systems (Zabidi et al., 2020). In Mediterranean regions, where winters are wet and summers dry, this technique is particularly suited to maximizing the use of available water resources (Rahim and Nasoher, 2019).

Rainwater harvesting can also be combined with complementary agricultural techniques such as fertigation, which combines irrigation and fertilizer application, to improve the efficiency of nutrient inputs while reducing dependence on conventional water resources (Bafdal et al., 2017). However, the success of this method depends on several factors, including local rainfall patterns, storage capacities, and the proper design of collection systems to ensure water quality and sustainability (Renner and Frasier, 1995). In short, rainwater harvesting offers a robust and adaptable approach to sustainable water management, essential in arid and semi-arid zones, contributing to water security, agricultural productivity, and environmental preservation.

5.4 Crop diversification for water management

Crop diversification, which includes practices such as intercropping, agroforestry, and crop rotation, is an effective strategy for improving water management in agroecosystems (Karray et al., 2008). These approaches optimize the use of water resources, improve soil fertility, reduce erosion, and strengthen the resilience of farming systems to climate change.

5.4.1 Intercropping

Intercropping, which involves growing several types of crops simultaneously in the same field, optimizes water use by minimizing the competition between crops for this precious resource. By choosing complementary crops with different growth habits and water requirements, this practice maximizes the soil moisture uptake. For example, deep-rooted crops can exploit water from deeper soil layers, whereas shallow-rooted crops use moisture from the upper soil layers (Yin et al., 2020). In addition, dense vegetation cover created by intercropping reduces evaporation, conserves soil moisture, and improves water retention. This system also reduces weed pressure, which decreases competition for water and the need for chemical treatments (Bainard et al., 2020; Gu et al., 2021).

5.4.2 Agroforestry

Agroforestry combines trees with crops and/or livestock in the same space, significantly improving water-use efficiency. Deep roots of trees allow better water infiltration and contribute to moisture retention in the soil, whereas the shade provided by the trees reduces heat stress on crops, increasing their ability to use water more efficiently (Pavlidis and Tsihrintzis, 2018). Trees also act as “water pumps,” drawing moisture from deep into the soil and slowly releasing it, while enriching the soil with organic matter via their leaf litter, improving soil fertility and structure. By reducing erosion and runoff, agroforestry helps conserve water and protect soils from degradation (Kaushal et al., 2021). Agroforestry systems, which combine trees and crops, not only capture and store water through the deep roots of trees, but also enhance the biodiversity of agricultural ecosystems (Karray et al., 2008). In Morocco, these diversification systems are commonly used by small-scale farmers. In addition, the oasis ecosystems of Morocco (such as those in the Draa, Tafilalet, and Figuig regions) exemplify the harmonious integration of agriculture, livestock farming, and water management, which are characteristic of traditional agroforestry systems (Santoro, 2023). These systems also

contribute to water regulation on a landscape scale, reducing the risk of erosion and improving water management in cultivated areas. For example, combining leguminous crops with trees can help fix nitrogen, improve soil quality, and optimize the use of water and nutrients in agroecosystems. This approach also supports biodiversity and reduces dependence on chemical inputs, thereby contributing to more sustainable water management (Aminu et al., 2019).

5.4.3 Crop rotation

Crop rotation, which involves alternating different crops in the same plot over time, plays a key role in optimizing water use. This practice promotes soil regeneration, improves soil structure, and reduces erosion, thereby facilitating water infiltration and retention (Cui et al., 2022). By cultivating plants with different water requirements, crop rotation enables better management of water demand while maintaining yields, even during times of drought (Yu et al., 2022). In addition, it limits the spread of diseases and pests, reduces the need to use chemicals, and improves water quality (Fan et al., 2022). Crop rotation also attracts beneficial insects and maintains an ecological balance that is favorable for water management in agroecosystems (Ogilvie et al., 2019).

5.5 Adapted crops to the Moroccan climate

In the face of increasing climatic constraints such as scarce rainfall, desertification, and recurrent droughts, the choice of crops adapted to the agro-climatic conditions of Morocco has become a strategic priority (Table 5). The country has a wide diversity of climate zones, ranging from humid regions in the north to arid and Saharan areas in the south, offering a range of opportunities for resilient crops (Verner et al., 2018).

Among conventional crops, cereals such as barley and durum wheat are historically adapted to semi-arid areas (Boussakouran et al., 2024). Barley, in particular, is notable for its drought tolerance and ability to grow in poor soils (Feroun et al., 2024). Legumes such as lentils, chickpeas, and beans contribute to food security and soil regeneration through their ability to bind nitrogen (Akchaya et al., 2025).

Drought-resistant fruit trees also play a key role in Moroccan agricultural systems. The prickly pear tree (*Opuntia ficus-indica*), an emblematic plant of arid areas, is extremely resilient and provides fruit, fodder, and protection against erosion (Houssni et al., 2022). The argan tree (*Argania spinosa* (L.) Skeels), endemic to southwestern Morocco, is well adapted to extreme conditions and contributes to the preservation of ecosystems while offering high-value products, such as argan oil (Labarca-Rojas et al., 2022). Similarly, the olive tree, which is ubiquitous in the Mediterranean region of Morocco, is a profitable crop that requires little water, especially when cultivated in a rainfed manner (Majikumna et al., 2024).

Quinoa (*Chenopodium quinoa*) is a promising alternative for emerging crops because of its tolerance to salt, drought, and varying temperatures. Originally from the Andes, it has proven particularly well adapted to the arid areas of Morocco, yielding interesting results even under difficult conditions (Nanduri et al., 2019). Another innovative crop is azolla, a fast-growing aquatic fern that can be used as a protein supplement in animal feed and requires little water (Vijayan et al., 2024).

In addition, aromatic and medicinal plants (MAP), such as rosemary, thyme, lavender, mint, and sage, thrive in many regions of

Morocco. They generally require little water and have high economic value, especially in the export sectors and natural cosmetics. Their medicinal properties and the potential for transformation into essential oils or herbal teas enhance their attractiveness (Zira, 2017).

The integration of these crops into Moroccan agricultural systems not only helps to cope with water stress but also diversifies income sources, improves food security, and promotes sustainable agriculture adapted to the country's climatic realities (Kertolli et al., 2024).

One of the key levers to strengthen the resilience of Moroccan agriculture in the face of climate change is to enhance local varieties and cultivars that are often better adapted to water stress conditions. These genotypes, selected naturally or traditionally over generations, possess valuable agronomic characteristics, such as drought tolerance, resistance to local diseases, and better adaptation to poor or saline soils (Kartas et al., 2015; Walters et al., 2021). For example, some wild varieties of barley or durum wheat grown in Moroccan boreal areas demonstrate strong plasticity in response to climatic variations (Nevo and Chen, 2010). Similarly, local cultivars of olive or almond trees can survive long periods of drought while maintaining minimal production. The conservation of these genetic resources and their integration into varietal improvement programs enhances food security while reducing dependence on irrigation. In addition, the use of local seeds contributes to agricultural biodiversity and farmers' seed sovereignty (Aïachi Mezghani et al., 2021; Kodad et al., 2024).

In contrast, some water-intensive crops pose serious challenges in the context of water stress in Morocco. This is particularly true for avocado, which is growing rapidly and can require between 6,000 and 12,000 m³ of water per hectare per year (~400 L/kg), depending on the climatic conditions and soil type (Kourgialas and Dokou, 2021). Although its market value is high, its impact on water is a significant concern in areas already under severe resource pressure (Bossenbroek et al., 2023; Boudhar and Boudhar, 2025). Another emblematic example is the cultivation of watermelon, especially in arid regions such as Zagora, Tata, and Figuig, which has sparked lively debates. Watermelon requires, on average, between 400 and 800 liters of water per fruit (~53 L/kg), totaling approximately 5,000 to 7,000 m³/ha over a production cycle, depending on planting density and the irrigation technique used (Bossenbroek et al., 2023). Although this crop is perceived as rustic, it mobilizes large volumes of water for a fruit that is primarily composed of water (more than 90%) and is often destined for export or mass distribution to the detriment of local water use (Bossenbroek et al., 2023). Moreover, crops such as irrigated rice are not compatible with the arid and semi-arid areas of Morocco because of their high-water demand and low water efficiency (Lage et al., 2003).

In light of these, adopting an agroecological and territorial approach to agricultural planning becomes essential, guiding farmers toward species that are better adapted to local conditions and require less water. It also calls for stricter regulation of hydrophilic crops, particularly in areas with low water resources, to preserve groundwater and ensure sustainable resource management for future generations.

6 Synergy between agroecology and innovative technologies for resilient water management

The integration of advanced technologies into agroecological systems represents a strategic opportunity to improve the efficiency

TABLE 5 Examples of water-efficient and climate-adapted crops in Morocco.

Culture	Type	Climate benefits	Main use	Specific remarks
Barley	Cereal	Very resistant to drought	Food and feed	Ideal for Bour areas
Durum wheat	Cereal	Better suited to dry areas than common wheat	Semolina, pasta	Shorter cycle
Chickpeas, lentils, beans	Pulses	Fix nitrogen, drought-resistant	Feeding/crop rotation	Short cycle, enriches soils
Sorgho	Cereal/Forage	High tolerance to heat and drought	Forage or biomass	Alternative to corn
Alfalfa	Forage	Productive even in arid conditions	Animal feed	Requires controlled water management
Atriplex	Halophyte forage	Supports extreme salinity and aridity	Feed for ruminants	Ideal for pre-war areas
Sunflower	Oilseed	Good yield, low water requirement	Edible oil	Strategic replacement culture
Carthame (Safranier)	Oilseed	Excellent drought tolerance	Oil, biomass	Still underdeveloped but promising
Olivier	Fruit tree	Very resistant to drought	Oil, olives	Essential in Mediterranean agriculture
Almond	Fruit tree	Suitable for arid areas and poor soils	Dried fruits	Early flowering
Grenadier	Fruit tree	Strong resistance to water stress	Fresh fruit/juice	Good added value for export
Figuier	Fruit tree	Very tolerant to drought	Fresh or dried fruit	Undemanding, suitable for rocky areas
Date palm	Fruit tree	Emblematic culture of desert areas	Dates	Pillar of the Moroccan oases
Figuier de Barbarie	Succulent plant/ Cacted	Very high drought tolerance	Fruit, fodder, cosmetics	Important for combating desertification
Argan tree	Endemic arboreal	Excellent adaptation to dryness	Cosmetic oil, food	UNESCO Biosphere Reserve, a major ecological role
Aromatic plants	Aromatic and medicinal	Low water consumption, very adaptable	Herbal, essential oils	Ex: rosemary, thyme, lavender, sage, high market value
Azolla	Emerging Aquatic	Fast growth, low water, nitrogen fixative	Forage, natural fertilization	Ideal for integrated farming and stagnant water areas
Quinoa	Emerging pseudo-cereal	Drought and salinity resistant	Human food, nutrition health	Growing potential, pilot projects in Morocco
Moringa	Emerging plant	Very resistant to drought	Food supplement, forage	Rich in vitamins and antioxidants
Stevia	Natural sugar plant	Moderate tolerance, little water	Natural sweetener	Strong potential for agro-industry

of natural resource management, including that of water. By combining the principles of agroecology with technological solutions, such as soil moisture sensors, localized irrigation, nano-irrigation, or automated irrigation systems, it becomes possible to optimize water inputs while preserving agricultural ecosystems (Boutagayout et al., 2025).

Among the most widespread approaches, drip irrigation has been established as a central tool in Moroccan agricultural policies. This system allows accurate water distribution directly to the root zone, significantly reducing losses through evaporation and infiltration while facilitating fertigation (Van der Kooij et al., 2017). On the other hand, controlled deficit irrigation offers an efficient alternative by adapting water inputs to the physiologically less sensitive stages of crops, thus allowing water conservation without altering yields (Adiba et al., 2024c, 2024d).

Recent developments have offered new opportunities to improve water efficiency. The use of connected sensors allows for the real-time monitoring of soil moisture, plant water needs, and weather conditions (Borrero and Zabalo, 2020). These data, when integrated into automated or remotely controlled systems, enable irrigation to be triggered at the most appropriate time, reduce waste, and improve productivity. Programming irrigation following environmental and agronomic parameters is thus a key lever for intelligent water management.

Among the groundbreaking innovations in culture, technology, and water management, nano-irrigation stands out for its ability to deliver very small volumes of water with high precision, optimizing water efficiency while meeting the physiological needs of plants. This technique is particularly suitable for high-value crops or in areas facing high water stress (El-Sayed et al., 2025). In addition, hydroponic cultivation is another promising approach for producing vegetables and aromatic plants without soil, with almost complete recycling of the water used. It reduces water consumption by up to 90% compared to traditional agriculture, while ensuring regular and controlled production, even in arid or urban environments (Rajaseger et al., 2023). The use of biopolymer-based hydrogels is another promising approach, as these materials can retain several times their weight in water, prolonging the water availability for plants and reducing the frequency of irrigation, especially in horticulture (Tariq et al., 2023). Finally, artificial intelligence opens up new avenues for integrated irrigation management. Through the analysis of large amounts of climate, soil, and crop data, AI systems can model water needs, anticipate periods of water stress, recommend optimized irrigation schedules, reconstruct agricultural yield, and conserve resources (Et-Taïbi et al., 2024).

In addition to technological innovations to improve irrigation efficiency and the adoption of agroecological practices, the

mobilization of alternative water resources is an essential pillar for strengthening the resilience of agriculture to climate change. In addition to seawater desalination and the reuse of treated wastewater for agricultural purposes, other innovative solutions are gaining importance, such as fog harvesting using collection nets. This technique has yielded excellent results in mountainous and semi-arid areas, such as in Sidi Ifni, Morocco, where the average annual collection rate ranges between 1.6 and 6 liters per square meter per day (Bouchaou et al., 2024). This low-cost, low environmental impact technique captures atmospheric moisture and transforms it into a valuable resource for irrigation and livestock watering (Lekouch et al., 2012; Dodson, 2014).

Furthermore, the adoption of a circular approach to agricultural water management, encouraging the internal reuse and recovery of wastewater, appears as a way forward for more sober and sustainable agriculture (Saidani et al., 2022). The success of this transition depends not only on the individual effectiveness of each approach but also on the synergy between all the pillars: agroecological practices, advanced irrigation technologies, research and innovation, appropriate support policies, climate risk management, and mobilization of unconventional water resources (Figure 9).

7 Public policies, local and international water management initiatives

Water management in Morocco is based on a set of actors at the local, national, and international levels, each playing a complementary role in the planning, implementation, and monitoring of water policies. Each plays a crucial role in developing and implementing strategies to ensure sustainable and equitable management of water resources (Table 6).

7.1 Local players

Several departments provide strategic coordination to the sector at the national level (Silva-Novoa Sánchez et al., 2022). The Ministry of Equipment and Water is the central body responsible for planning, building water infrastructure, and implementing national strategies. The Ministry of Agriculture, Maritime Fisheries, Rural Development, and Water and Forestry also integrates water management into its main agricultural policies, particularly through the strategies of the Green Morocco Plan and Generation Green (Benzougagh et al., 2024). Other ministerial departments, such as the Ministry of the Interior or Energy Transition and Sustainable Development, are involved in territorial governance, environmental protection, and adaptation to climate change.

Farmers, who are the main water users, are key players in the transition to more economical agriculture. By adopting techniques such as drip irrigation, mulching, or crops adapted to local climatic conditions, they contribute to reducing the pressure on resources. Rural communities are involved in watershed conservation and collective management initiatives that are often supported by cooperatives or local organizations. NGOs such as the Network of Agroecological Initiatives in Morocco (RIAM) are distinguished by

their awareness-raising activities and the implementation of sustainable development projects (Goetz et al., 2024). An emblematic example is that of the Dar Si Hmad Foundation, which has implemented an innovative system for collecting water from fog in the arid regions of western Morocco, providing a source of drinking water to local populations while promoting the ecological management of resources (Migliore, 2024).

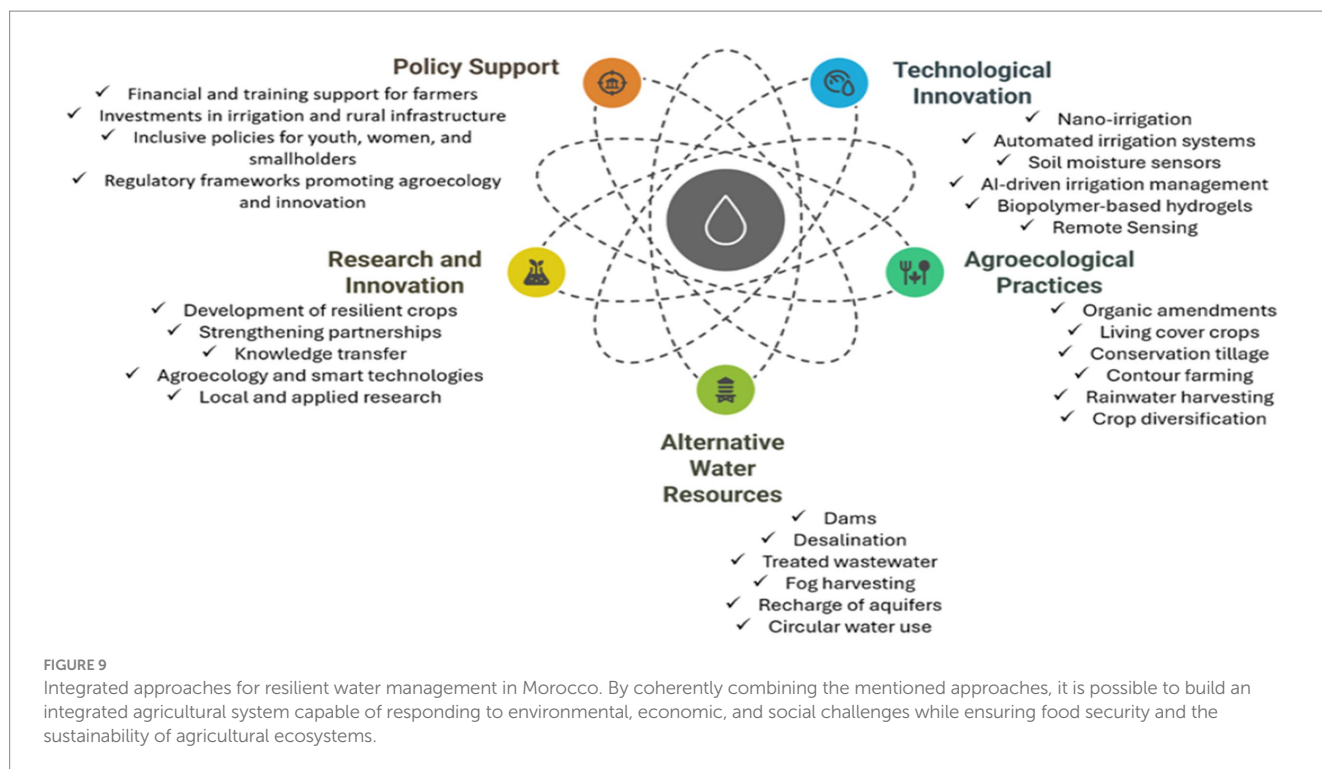
At the regional level, Water Basin Agencies (ABH) play a fundamental role in decentralized governance. They ensure the integrated management of resources at the watershed level, regulate withdrawals, issue permits, and ensure the preservation of groundwater. Local authorities, through regional councils and municipalities, also contribute to local water management, particularly in areas of sanitation and access to drinking water. The public sector is supported by technical institutions, such as the National Office of Electricity and Drinking Water (ONEE), which intervenes in the production, distribution of water, and treatment of wastewater, both in urban and rural areas. Universities, research centers, and specialized institutions, such as INRA, play a crucial role in generating knowledge, training, and innovation to improve water efficiency (Achli et al., 2025).

Finally, civil society and the private sector are becoming increasingly part of the Moroccan water landscape. NGOs and environmental associations raise awareness of the importance of this resource, advocate for equitable access to water, and develop community projects. The private sector is heavily involved in the development of technical solutions and infrastructure, particularly in areas of precision irrigation, seawater desalination, and wastewater treatment.

7.2 International players

At the international level, many bilateral and multilateral partners have supported Morocco in its efforts to ensure sustainable and integrated water management. Among the major players, the World Bank, African Development Bank (AfDB), European Union (EU), and French Development Agency (AFD) provide essential financial and technical support for the modernization of the water sector, adaptation to climate change, and expanding access to safe drinking water (Farnault and Sarr, 2024). German cooperation through GIZ and KfW is actively involved in strengthening decentralized governance, integrated water resources management, and the development of innovative solutions. JICA (Japan International Cooperation Agency) is Japan's international cooperation agency, which supports several countries through sustainable water resource management projects, such as improving agricultural irrigation, groundwater management and strengthening water infrastructure.

United Nations agencies such as UNDP, FAO, UNESCO, and IFAD support projects on water security, scientific research, food security, and sustainable agriculture. These interventions translate into concrete actions, such as aquifer management, improvement of water infrastructure, and introduction of appropriate technologies, especially in arid and semi-arid areas. The EU-supported integrated rural development program, for example, focuses on water resource conservation in vulnerable regions. Bilateral cooperation agreements with countries such as Germany and the Netherlands facilitate the



transfer of expertise in key areas, such as desalination, wastewater reuse, and soil conservation.

Partnerships with international universities and research centers are also encouraging innovation through the development of smart sensors for irrigation, drought early warning systems, and precision agriculture models. These initiatives build local capacity, encourage the adoption of resilient agricultural practices, and promote knowledge-sharing for better water management. In short, international cooperation is a strategic lever for responding to Morocco's water challenges while consolidating the sustainability of agricultural systems and the security of natural resources.

7.3 Public policy

The hydraulic policy in Morocco has undergone a gradual evolution marked by strategic milestones that reflect a transition to integrated and sustainable management of water resources (Ministry of Equipment and Water, 2023) (Figure 10). As early as the 1930s, the Kingdom initiated hydro-agricultural and hydroelectric development, laying the foundation for infrastructure to support irrigated agriculture and generate energy. This movement was reinforced in 1967 with the launch of the Great Dams Policy, the foundation of the national strategy for surface water mobilization to secure the supply of drinking and agricultural water.

From the 1980s onwards, more detailed planning was implemented with the introduction of the Integrated Water Resources Management Master Plans (IPAA), which allowed territorialized management of resources. A major turning point was achieved in 1995 with the adoption of Law 10–95 on water, which established a coherent legal framework for integrated and participatory governance. This dynamic continued with a focus on demand management from

2000 onwards, the diversification of water sources, and the launch of innovative approaches such as groundwater contracts, such as the one signed in the Souss Massa Basin in 2006.

The 2009–2016 period was marked by a consolidation of policies through the development of the National Water Strategy in 2009, the inscription of the right to water in the 2011 Constitution, and the adoption of structuring laws such as Water Law 36–15. These developments have made it possible to strengthen the decentralized and sustainable management of water resources by integrating the environmental, climatic, and socio-economic dimensions.

In recent years, Morocco has continued to update its policies with the National Program for Drinking Water Supply and Irrigation 2020–2027 (PNAEPI), aimed at securing safe drinking water, improving water efficiency in agriculture, and building resilience to drought. 2023 saw the launch of major projects, such as the transfer of water between the Sebou and Bouregreg basins, and the signing of the Boudenib nappe contract.

Simultaneously, water has become a central focus in agricultural strategies, notably through the “Green Generation 2020–2030” strategy, which succeeds the Green Morocco Plan. This strategy aims to develop more resilient and water-efficient agriculture through the modernization of irrigation systems, conversion to less water-consuming crops, and promotion of innovative agricultural entrepreneurship, particularly among the youth. Moroccan public institutions play a strategic role in implementing policies and programs to ensure sustainable water resource management. The Ministry of Agriculture, Marine Fisheries, Rural Development, and Water and Forestry has developed several ambitious plans, such as the Green Morocco Plan (Plan Maroc Vert: 2008–2020) and Green Generation (2020–2030), which integrate water-related issues into agricultural practices. The Green Plan marked a turning point in the modernization of Moroccan agriculture, emphasizing improving

TABLE 6 Local and international actors in water management in Morocco.

Local actors (national and regional)	International players
Ministry of Equipment and Water: planning and management of water resources.	World Bank: financing of water projects, water sector reforms.
Ministry of Agriculture, Marine Fisheries, Rural Development and Water, and Forestry	African Development Bank (AfDB): infrastructure and irrigation support.
Ministry of the Interior: territorial governance, management of water crises.	European Union (EU): technical assistance and institutional support (e.g., EU4Water).
Ministry of Energy Transition and Sustainable Development: climate adaptation, sustainability.	French Development Agency (AFD): financing of water projects.
Water Basin Agencies (ABH): integrated management of resources at the watershed level.	German cooperation (GIZ, KfW): support for local governance and sustainability.
ONEE (National Office of Electricity and Drinking Water): distribution of drinking water, sanitation.	FAO (UN): water management programmes in agriculture, drought resilience.
Local authorities (municipalities, regions): community management, water and sanitation services.	UNESCO-IHP: scientific cooperation and training in the field of water.
Research institutes (INRA, universities): innovation, water efficiency, scientific support.	UNDP & UNEP: projects related to environment, climate and ecosystem management.
NGOs and local associations (e.g., AMCDD): awareness raising, advocacy, community projects.	Various bilateral partners: Spain, the Netherlands, Japan, etc.
National private sector: desalination, irrigation, engineering, infrastructure management.	Enterprises and foreign investors: processing technologies, PPP partnerships.

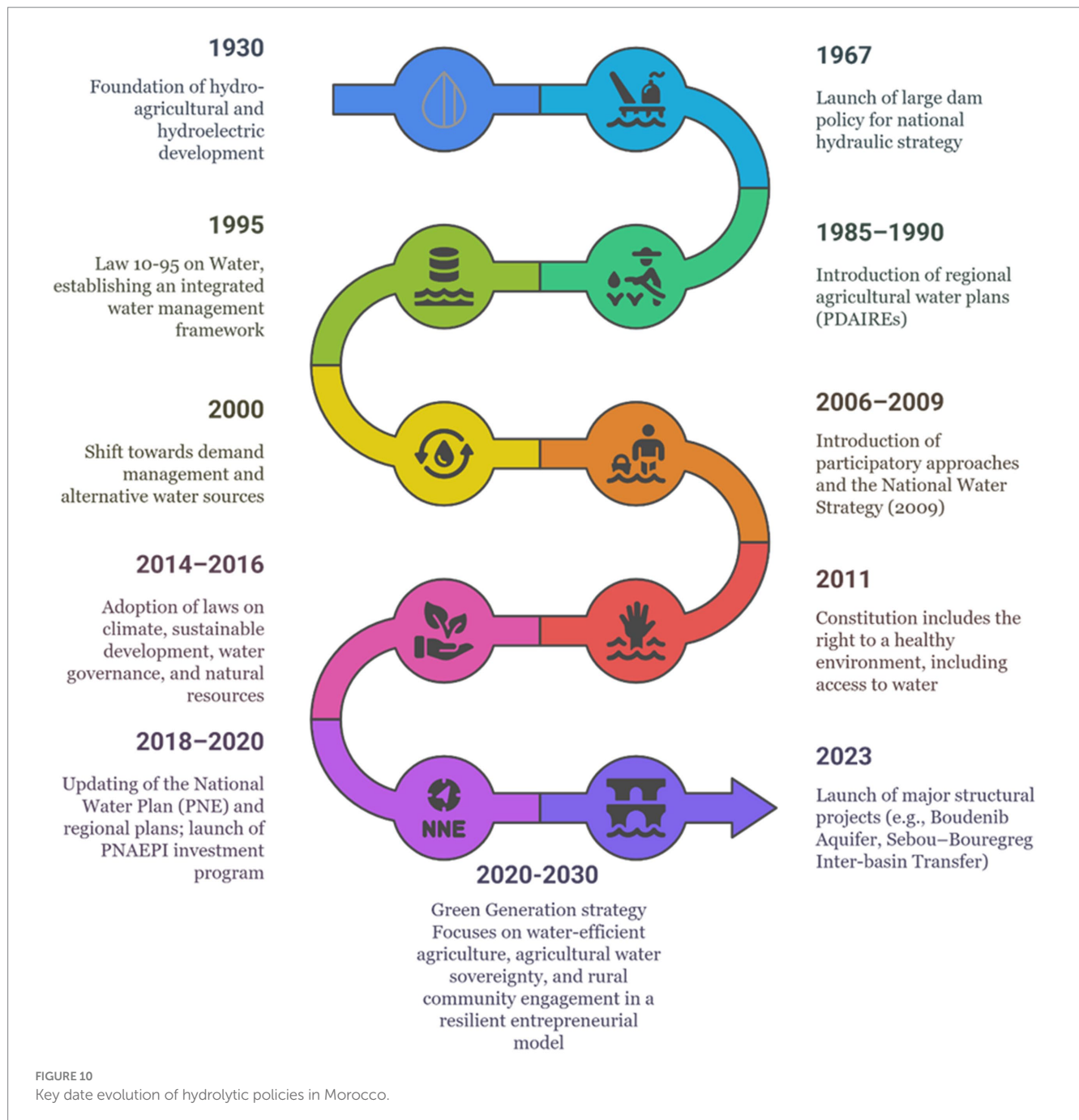
productivity and rational water management. This has encouraged the transition to modern irrigation systems, including drip irrigation, allowing for a more efficient use of water resources in stressed environments. However, the Green Morocco Plan has sparked debate over the promotion of high-value cash and water-intensive crops, which could exacerbate pressure on already scarce water resources in semi-arid regions. This strategy, while economically beneficial, risks intensifying water demand, weakening traditional agroforestry practices, and raising concerns regarding long-term sustainability and water equity in the region. While Moroccan agricultural policies, such as the Green Morocco Plan, have contributed to modernization and productivity gains, they have also raised concerns regarding sustainability. In contrast, the Green Generation Plan focuses on the sustainability and resilience of Morocco's agricultural sector. However, implementing these strategies has faced significant challenges, including limited farmer buy-in, infrastructure constraints, and difficulties in adapting to local socioeconomic and ecological contexts. These critiques highlight the need to reconcile productivity goals with long-term resource conservation and ensure that future strategies

translate more effectively into practice through participatory and context-specific approaches.

This strategy places particular emphasis on water management, conservation of natural resources, and rural development. It aims to double the efficiency of water use by 2030 through measures such as dam construction, reforestation, improved irrigation infrastructure, and exploitation of unconventional water sources such as desalination. Morocco has set an ambitious target of building 20 additional desalination plants by 2030 to produce 1,000 mm³ of desalinated water to meet growing needs. Targeted initiatives have also been launched to modernize water infrastructure and improve watershed management. These projects aim to restore and protect vital ecosystems that are essential for the sustainable regulation of water resources, particularly in vulnerable areas. The Water Basin Agency (ABH) plays a central role in the integrated management of water resources, regulation of withdrawals, and protection of aquifers (Azdem et al., 2025). These efforts are part of a global vision to make Moroccan agriculture more resilient to recurring droughts and climate change challenges while strengthening the effectiveness of agricultural practices for sustainable development. In short, Morocco has gradually built robust water governance, anticipating climate and social pressures. The integration of agricultural, water, and environmental policies, supported by an active institutional framework, demonstrates a clear willingness to adapt to the growing challenges of water security (Lahdili, 2015). This multi-sectoral approach is essential for effective, equitable, and sustainable long-term water management (Silva-Novoa Sánchez, 2024).

8 Conclusion

Morocco faces major water challenges, amplified by extreme climatic conditions and increased pressure on its water resources. Against this backdrop, public policies and agroecological initiatives are essential for sustainable water management, food security, and rural development. Programs such as the Green Morocco Plan and Green Generation integrate water dimensions into global strategies, aiming to improve irrigation efficiency, promote resilient agricultural practices, and develop appropriate infrastructure. Agroecological approaches provide concrete solutions for preserving water resources, restoring soil health, and protecting biodiversity. Techniques such as mulching, cover crops, crop diversification, and crop rotation help optimize water use while strengthening the resilience of farming systems in the face of climate change. Agroforestry and other sustainable practices not only reduce the environmental impact of agriculture but also support the sustainability of ecosystems. There is a major opportunity to change the Moroccan irrigation model by combining technological innovation, integrated water management, and strategic support via public policy. Promoting resilient water management in Morocco requires effective coordination among various stakeholders. Although the new technologies and policies reviewed here offer promising approaches to improving water management and mitigating the effects of drought, several limitations must be considered. Technical challenges, such as infrastructure requirements and data availability, may hinder effective implementation. Economic constraints, including high upfront costs



and limited funding, can hamper adoption, particularly in resource-limited regions. Moreover, social and institutional factors, such as stakeholder acceptance and policy enforcement, can affect the practical effectiveness of these solutions in the real world. Acknowledging these limitations allows for a more balanced perspective and highlights the need for complementary strategies and context-specific adaptation. Local efforts must be supported by robust legislative and financial frameworks, and international expertise must complement these initiatives with proven technological solutions and governance models. This synergy is essential to guarantee equitable access to water and secure the needs of future generations in the face of climate change. Consequently, the success of these initiatives depends on the commitment of local

players, supported by international partnerships. Increased coordination among these stakeholders, accompanied by coherent and inclusive public policies, is essential to guarantee their effectiveness. Therefore, several priorities have emerged to address the challenges of water and sustainability in agriculture:

- 1 Integrated water resource management: Approaches combining dam construction, desalination, and wastewater reuse are essential for diversifying and securing water supplies, while ensuring their sustainability in the context of climate change.
- 2 Local capacity building: Actively involving farmers and local communities in water resource management is crucial. Training and awareness-raising programs are needed to

improve farming practices and to encourage the adoption of sustainable solutions.

- 3 Green investments: Integrating renewable energies, such as solar and wind power, into water infrastructure can reduce the environmental impact and dependence on fossil fuels.
- 4 Research and innovation: It is imperative to develop technologies adapted to Morocco's specific climatic and agroecological conditions. Research must focus on innovative solutions for water management and sustainable agriculture to respond effectively to the challenges of water scarcity and climate change.

Author contributions

AB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AH: Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. IB: Data curation, Formal analysis, Visualization, Writing – review & editing. AA: Data curation, Formal analysis, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer FE declared a shared affiliation with the author AA to the handling editor.

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