Global Journal of Engineering and Technology Advances
eISSN: 2582-5003
Cross Ref DOI: 10.30574/gjeta
Journal homepage: https://gjeta.com/

(RESEARCH ARTICLE)

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# Wastewater Treatment and Reuse as a Strategy for Coastal Water Security: Evidence from the Tetouan Coastal Area, Northern Morocco

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Global Journal of Engineering and Technology Advances, 2026, 28(01), 146–158

Publication history: Received on 14 June 2026; revised on 21 July 2026; accepted on 23 July 2026

Article DOI: https://doi.org/10.30574/gjeta.2026.28.1.0180

## Abstract

Water resources in Morocco, as in many Mediterranean regions, are increasingly affected by climate variability, recurrent drought, demographic growth, urban expansion and tourism-related demand. In this context, treated wastewater represents a strategic non-conventional resource for enhancing local water security, reducing pressure on freshwater resources and limiting coastal pollution. This article examines the contribution of wastewater treatment and reuse to water-resource management in the Tetouan coastal area of northern Morocco. The study adopts a territorial case-study approach based on the analysis of institutional reports, technical data from four wastewater treatment plants and the legal and policy framework governing water reuse in Morocco. The findings show that the four plants studied treated more than 29 million $m^3$ of wastewater in 2024. However, effective reuse remains limited and is mainly concentrated at the Tamuda Bay plant, where treated water is used for irrigating green spaces. In 2024, approximately 1.49 million $m^3$ were reused at this plant, corresponding to about 32% of its treated volume. Since 2016, this practice has helped save approximately 6.7 million $m^3$ of potable water while contributing to the reduction of direct wastewater discharge into coastal environments. Nevertheless, the study identifies several constraints, including limited diversification of reuse sectors, insufficient distribution infrastructure, fragmented institutional coordination, persistent pollution hotspots and the absence of systematic environmental monitoring indicators. The article argues that the contribution of treated wastewater to coastal water security depends not only on treatment capacity, but also on integrated governance, technical efficiency, health and environmental standards and the expansion of reuse toward tourism, agriculture, industry and groundwater recharge.

**Keywords:** Wastewater Treatment; Water Reuse; Water Security; Circular Water Economy; Coastal Management; Tetouan Coast; Morocco

## 1. Introduction

Water security has become a central issue in contemporary debates on sustainable development, climate adaptation and territorial resilience. In many regions of the world, water resources are exposed to combined pressures resulting from climate change, demographic growth, urban expansion, industrial development and increasingly intensive agricultural and tourism uses. These pressures affect not only the quantity of available water, but also its quality, ecological functions and long-term sustainability. Recent scientific and institutional literature emphasizes that water scarcity is no longer a temporary or sectoral challenge; rather, it is a structural constraint that directly affects public health, food security, urban development and ecosystem protection (Abbas et al., 2022; Ciampittiello et al., 2024; UN-Water, 2023; United Nations, 2024).

The Mediterranean basin is particularly exposed to these pressures because of its climatic fragility, recurrent droughts, seasonal tourism demand and strong demographic concentration along coastal areas. Coastal territories are often

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characterized by high spatial competition between urbanization, tourism infrastructures, agricultural perimeters and sensitive ecosystems. In such contexts, the conventional model based mainly on the mobilization of surface water and groundwater is increasingly insufficient. Water policies therefore need to incorporate non-conventional water resources, particularly desalinated seawater and treated wastewater, into broader strategies of integrated water-resource management (OECD, 2024; World Bank, 2023).

Wastewater treatment and reuse have gradually moved from a sanitation-oriented approach to a resource-recovery approach. Treated wastewater is increasingly considered a stable alternative resource that can reduce pressure on potable water supplies, support irrigation, protect aquatic environments and contribute to the circular water economy. This shift is supported by recent studies showing that wastewater treatment plants can be transformed into resource recovery facilities when technical performance, governance arrangements, financing mechanisms and environmental monitoring systems are properly aligned (Angelakis & Snyder, 2022; Kehrein et al., 2020; Silva, 2023).

Morocco is among the countries where water scarcity has become a major development challenge. The decline in rainfall, the recurrence of droughts and the increase in water demand have placed growing pressure on dams, aquifers and drinking-water supply systems. National policies have increasingly emphasized the need to diversify water resources through desalination, wastewater treatment and reuse, and demand-management strategies. Law No. 36-15 on water provides an important legal framework for strengthening integrated water management and promoting the use of non-conventional resources (Royaume du Maroc, 2016; Ministère de l'Equipement et de l'Eau, 2024; CESE, 2024).

The Tetouan coastal area in northern Morocco offers a relevant case for studying the relationship between wastewater treatment, reuse and coastal water security. This territory combines urban growth, tourism development, environmental sensitivity and increasing pressure on water resources. Over the last decade, several wastewater treatment plants have been developed to reduce pollution, improve coastal water quality and create opportunities for treated-water reuse. However, the extent to which these infrastructures actually contribute to local water security remains insufficiently documented.

Although previous institutional reports and technical documents have described sanitation projects in the region, few studies have provided an integrated assessment combining treatment capacity, reuse performance, environmental effects and governance constraints. This article addresses this gap by examining four wastewater treatment plants located along the Tetouan coast: Tetouan, Tamuda Bay, Oued Laou and Amsa. The study focuses on the relationship between treated volumes, reused volumes, potable-water savings and the territorial limits that continue to affect the valorization of treated wastewater.

The objective of this article is to evaluate the contribution of wastewater treatment and reuse to water-resource management and water security in the Tetouan coastal area. More specifically, the study aims to: (1) describe the recent development of wastewater treatment infrastructure; (2) assess the current level of treated-water reuse; (3) identify the main environmental, technical and institutional constraints; and (4) propose policy directions for expanding the contribution of treated wastewater to sustainable territorial development.

## 2. Research Problem and Questions

The research problem addressed in this article stems from the gap between the increasing treatment capacity of wastewater infrastructure on the Tetouan coast and the still limited integration of treated wastewater into local water-security strategies. While large volumes of wastewater are treated annually, actual reuse remains concentrated in a restricted number of uses and places. This raises questions about the technical, institutional and territorial conditions required to transform treated wastewater from a sanitation output into a strategic water resource.

The study is guided by the following research questions:

1. To what extent do wastewater treatment plants on the Tetouan coast contribute to local water security?
2. What are the main volumes treated and reused in the studied wastewater treatment plants?
3. What environmental benefits and remaining pollution problems can be identified?
4. What technical, institutional and governance constraints limit the expansion of treated-water reuse?
5. How can treated wastewater be better integrated into a sustainable coastal water-management strategy?

## 3. Literature Review and Conceptual Framework

This section establishes the conceptual basis of the study by clarifying how water security, non-conventional water resources, wastewater reuse and the circular water economy are interconnected. It also situates the Tetouan case within the broader scientific debate on governance, environmental monitoring and sustainable reuse standards. The objective is not to provide an exhaustive literature review, but to identify the concepts and analytical dimensions that guide the empirical assessment.

### 3.1. Water security and non-conventional water resources

Water security refers to the capacity of societies, territories and institutions to ensure sustainable access to sufficient quantities of acceptable-quality water while protecting ecosystems and reducing water-related risks. This concept goes beyond the physical availability of water and includes governance, equity, resilience, public health and environmental sustainability. In water-stressed regions, water security requires both supply-side and demand-side measures, including the diversification of resources and the optimization of existing systems (UN-Water, 2023; United Nations, 2024; World Bank, 2023).

Non-conventional water resources are increasingly viewed as essential components of water-security strategies. These resources include desalinated seawater, harvested rainwater, brackish-water treatment and treated wastewater. Among them, treated wastewater has specific advantages because it is produced continuously in urban areas, can be reused near its source and can reduce pollution when adequately treated. However, its contribution depends on treatment quality, legal standards, distribution infrastructure, economic feasibility and public acceptance.

### 3.2. Wastewater reuse and the circular water economy

The circular water economy promotes the recovery and reintegration of water and associated resources into productive and ecological cycles. Within this framework, wastewater is no longer considered only as a waste stream requiring disposal, but as a resource that can be recovered, treated and reused according to appropriate quality standards. Resource recovery from municipal wastewater can contribute to water savings, nutrient recovery, energy production and pollution reduction (Kehrein et al., 2020; Silva, 2023).

International experience shows that treated wastewater can be reused for several purposes, including agricultural irrigation, irrigation of urban green spaces, industrial processes, landscape maintenance, aquifer recharge and environmental restoration. Mediterranean countries such as Spain, Cyprus and Israel have developed advanced reuse policies because of their exposure to water scarcity and recurrent droughts. Their experience demonstrates that the success of reuse depends not only on technology, but also on institutional coordination, regulatory clarity, monitoring systems, financing models and social acceptance (Angelakis & Snyder, 2022; Lazarova et al., 2024; OECD, 2024).

### 3.3. Governance, standards and environmental monitoring

The governance of treated-water reuse involves coordination between water agencies, municipalities, sanitation operators, health authorities, agricultural users, tourism actors and environmental institutions. Fragmented responsibilities may limit the efficiency of reuse projects, especially when wastewater treatment, territorial planning and water allocation are managed separately. Effective governance requires clear institutional roles, sustainable financing, transparent monitoring and integration of reuse into local development plans (Evaristo et al., 2023; OECD, 2024).

Environmental monitoring is also essential. Evaluating the performance of wastewater treatment plants should not be limited to measuring treated volumes. It should also include physical, chemical, biological and bacteriological indicators, such as biochemical oxygen demand, chemical oxygen demand, suspended solids, nutrients and microbial contamination. Recent literature also highlights the need to monitor emerging pollutants, including pharmaceutical residues, pesticides, industrial chemicals and microplastics, because they may affect coastal ecosystems and public health even after conventional treatment processes (Abalasei et al., 2025; European Environment Agency, 2024; Sarantuyaa et al., 2025).

## 4. Study Area and Methodology

This section presents the territorial context of the Tetouan coastal area and explains the methodological choices adopted to evaluate the contribution of wastewater treatment and reuse to local water security. It details the study area,

the documentary and technical sources used, the main analytical indicators and the methodological limits that must be considered when interpreting the results.

### 4.1. Study area

The study area is located in the far northwest of Morocco, along the western Mediterranean coast. Administratively, it belongs to the Tangier-Tetouan-Al Hoceima region and includes coastal territories associated with Tetouan province and the M'diq-Fnideq prefecture. The area includes urban and coastal centers such as Martil, M'diq, Fnideq, Oued Laou, Azla and surrounding localities. It is characterized by a Mediterranean climate with humid winters, dry summers and moderate temperatures, while its coastal position gives it major tourism and environmental importance. The location and spatial configuration of the study area are shown in Figure 1.

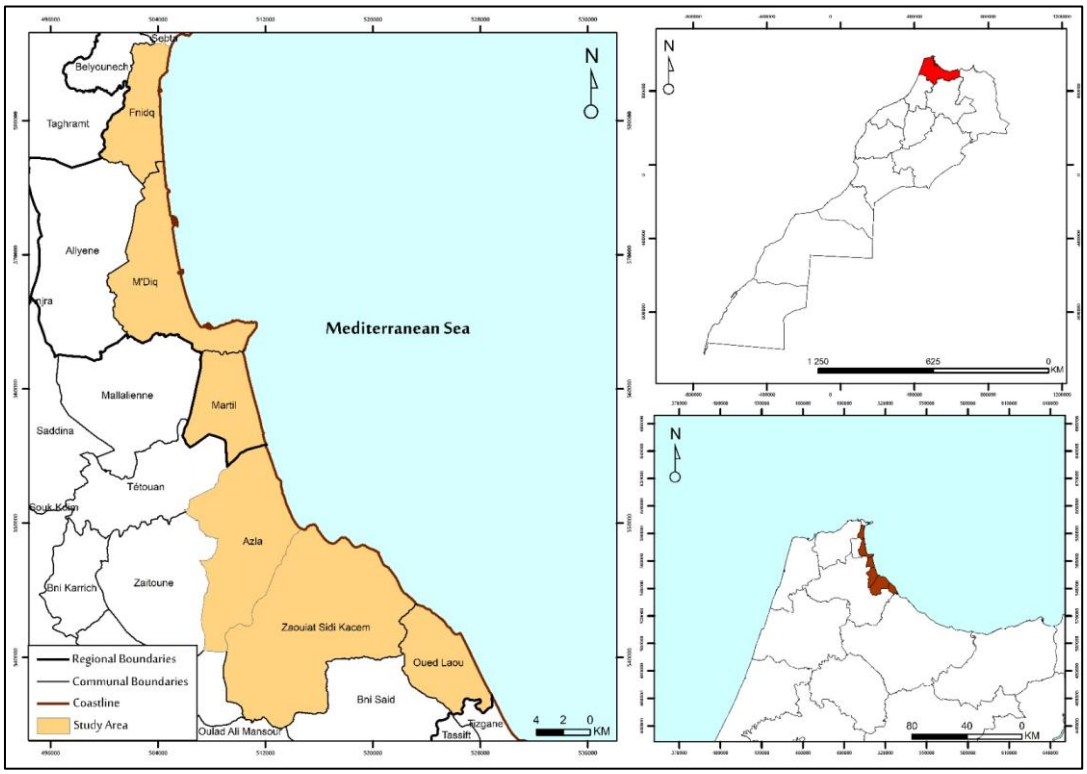


**Figure 1** Location of the Tetouan coastal study area. Source: Author's elaboration based on the Regional Advisory Committee (2015), Proposed Regional Segmentation Atlas.

The Tetouan coast has experienced strong urban and tourism development over recent decades. This development has increased water demand and generated growing wastewater volumes. At the same time, the area includes sensitive coastal ecosystems, beaches, wetlands and valleys that can be affected by untreated discharges and diffuse pollution. These characteristics make the region particularly relevant for analyzing the contribution of wastewater treatment and reuse to coastal water security (Plan Bleu, 2011).

### 4.2. Research design and data sources

This study adopts an analytical case-study approach combining quantitative and qualitative information. The quantitative component focuses on treated wastewater volumes, reused volumes and reuse rates. The qualitative component examines legal, institutional, environmental and territorial constraints affecting the development of reuse. The analysis covers four wastewater treatment plants located in the Tetouan coastal area: Tetouan, Tamuda Bay, Oued Laou and Amsa.

The study relies on institutional and technical sources produced by Amendis, the Loukkos Hydraulic Basin Agency, the Ministry of Equipment and Water, national legal documents and policy reports. These sources were complemented by academic literature on wastewater treatment, water reuse, circular water economy and water governance. The main period of analysis is 2011-2024, with a particular focus on the 2024 treatment and reuse indicators reported by the available technical documents.

**Table 1** Research design and analytical dimensions

| Analytical dimension | Indicators or materials used | Purpose of analysis |
|---|---|---|
| Treatment infrastructure | Number and location of wastewater treatment plants; annual treated volumes; daily production when available | Assess the development of sanitation and treatment capacity on the Tetouan coast |
| Reuse performance | Volume of reused treated water; reuse rate; types of reuse; potable-water substitution | Evaluate the actual contribution of reuse to water security |
| Environmental effects | Reported improvements in coastal water quality; field observations of pollution hotspots | Identify environmental benefits and remaining risks |
| Legal and institutional framework | Law No. 36-15 on water; national water strategies; institutional reports | Analyze the regulatory and governance conditions of reuse |
| Comparative perspective | Mediterranean and international experiences; academic literature | Situate the Tetouan case within broader reuse practices and policy debates |

**Table 2** Main indicators used in the empirical analysis

| Indicator | Calculation or definition | Interpretation |
|---|---|---|
| Annual treated wastewater volume | Total volume of wastewater treated by a plant during a given year | Measures the technical contribution of treatment infrastructure |
| Reused treated-water volume | Volume of treated wastewater used for irrigation or other purposes | Measures the effective valorization of treated water |
| Reuse rate | Reused volume / treated volume x 100 | Shows the proportion of treated water reintegrated into productive or environmental uses |
| Potable-water savings | Volume of treated water substituted for potable water in specific uses | Measures the indirect contribution of reuse to drinking-water conservation |
| Pollution hotspots | Observed or reported areas affected by untreated or insufficiently managed discharges | Identifies environmental limits requiring additional intervention |

### 4.3. Methodological limitations

The study is based mainly on available institutional and technical data. While these data are useful for identifying general trends, they do not provide a complete chronological series for all physical, chemical and biological parameters of treated water. Access to detailed economic data on the cost of treatment, distribution and reuse was also limited. In addition, the environmental assessment relies on available institutional indicators and field observations rather than independent laboratory analyses. Therefore, the results should be interpreted as an integrated territorial assessment rather than a full technical audit of wastewater treatment performance.

These limitations do not reduce the relevance of the case study, but they highlight the need for future research based on continuous monitoring, laboratory measurements and cost-benefit analysis. Such research would make it possible to evaluate more precisely the relationship between treatment efficiency, reuse quality, environmental protection and water-security outcomes.

## 5. Results

The results are organized around four complementary dimensions: the development of wastewater treatment capacity, the level of effective reuse, the environmental improvements and remaining pollution hotspots, and the technical and institutional constraints that limit the wider valorization of treated wastewater. This organization makes it possible to move from descriptive treatment indicators to a more analytical assessment of the contribution of reuse to coastal water security.

### 5.1. Development of wastewater treatment capacity

The results indicate that the Tetouan coastal area has experienced significant development in wastewater treatment infrastructure over the last decade. The establishment and operation of four main wastewater treatment plants, supported by pumping stations and interceptor networks, have contributed to reducing untreated wastewater discharge into the natural environment and to improving sanitation coverage in major coastal localities.

In 2024, the four wastewater treatment plants analyzed in this study treated more than 29 million $m^3$ of wastewater. The Tetouan plant represented the largest share, with more than 24 million $m^3$ treated during the year. The Tamuda Bay plant treated approximately 4.5 million $m^3$, reflecting its role in an area characterized by strong tourism and real-estate development. The remaining plants, including Oued Laou and Amsa, play a more localized role in sanitation and pollution reduction. These figures demonstrate the existence of a substantial technical base for developing treated-water reuse on the Tetouan coast. The distribution of treated wastewater by station and the comparison with selected national stations are presented in Figures 2 and 3.

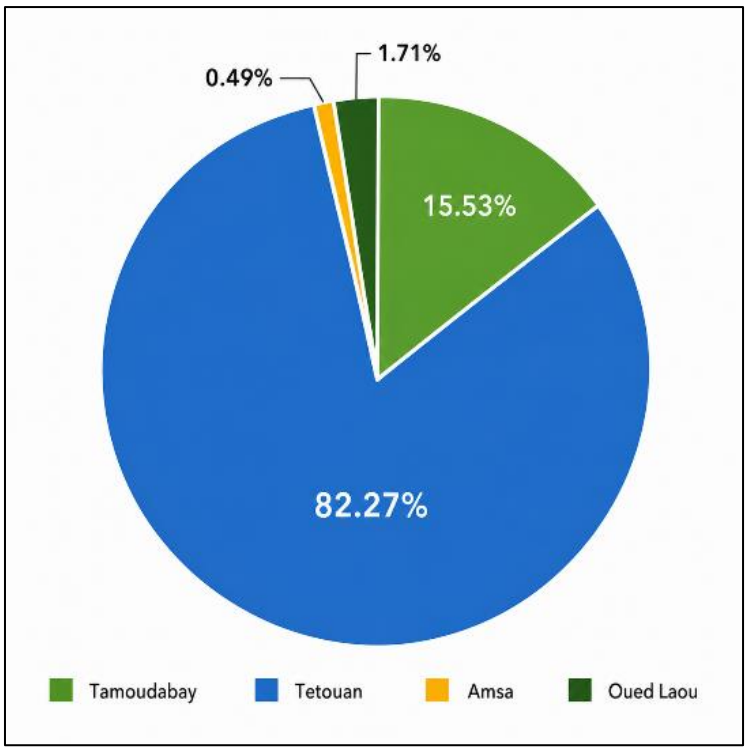


**Figure 2** Distribution of treated wastewater by station in the study area in 2024 (%). Source: Author's elaboration based on Amendis Company data, Directorate of Water and Liquid Sanitation in Tetouan.

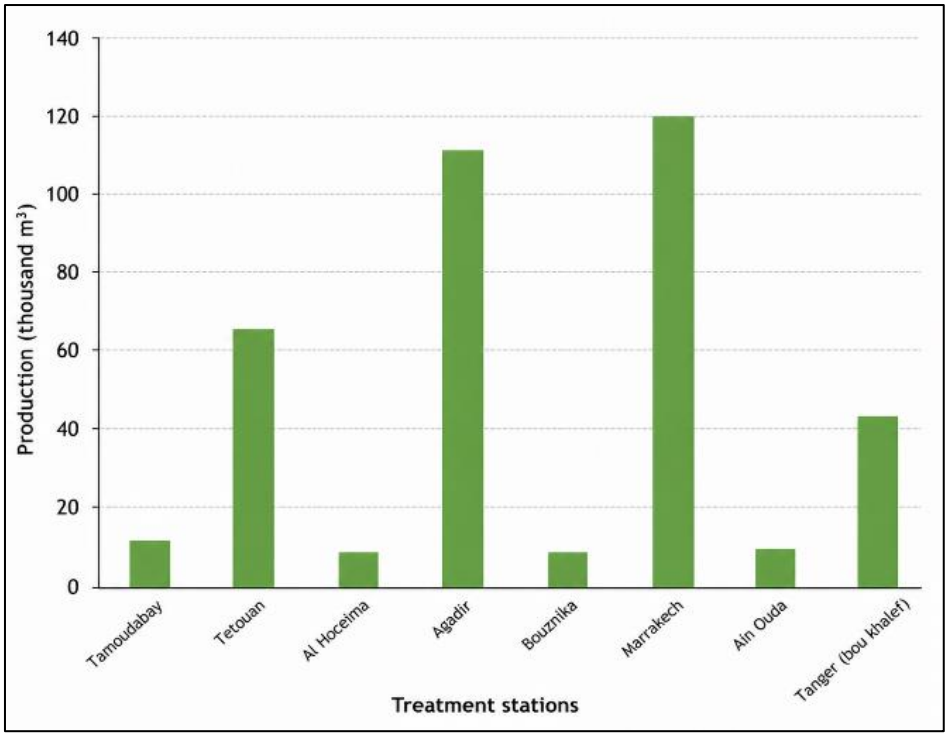


**Figure 3** Daily production of treated water in selected Moroccan wastewater treatment plants in 2024 (thousand $m^3$/day). Source: Author's elaboration based on Amendis Company data and national comparison data.

**Table 3** Key wastewater treatment and reuse indicators reported for the Tetouan coastal area

| Indicator | Reported value | Analytical interpretation |
|---|---|---|
| Total wastewater treated by the four studied plants in 2024 | More than 29 million $m^3$ | Indicates a significant treatment capacity at the coastal-territorial scale |
| Wastewater treated by the Tetouan plant in 2024 | More than 24 million $m^3$ | Confirms the dominant role of the Tetouan plant in regional treatment capacity |
| Wastewater treated by the Tamuda Bay plant in 2024 | Approximately 4.5 million $m^3$ | Represents the main treatment infrastructure linked to tourism and coastal development |
| Treated water reused at Tamuda Bay in 2024 | Approximately 1.49 million $m^3$ | Shows the only clearly operational reuse practice identified in the study |
| Reuse rate at Tamuda Bay in 2024 | Approximately 32% | Indicates partial valorization of treated water, mainly for green-space irrigation |
| Potable water saved through reuse since 2016 | Approximately 6.7 million $m^3$ | Demonstrates the potential contribution of reuse to drinking-water conservation |

### 5.2. Limited reuse despite significant treated volumes

Despite the importance of the treated volumes, the reuse of treated wastewater remains limited. The Tamuda Bay plant represents the main operational example, where treated water is used for the irrigation of green spaces. In 2024, the plant reused approximately 1.49 million $m^3$, corresponding to about 32% of the volume treated at that plant. This reuse has contributed to reducing the use of potable water for irrigation, with cumulative savings estimated at approximately 6.7 million $m^3$ since 2016. The monthly pattern of treated and reused water, together with the temporal evolution of reuse at Tamuda Bay, is presented in Figures 4 and 5.

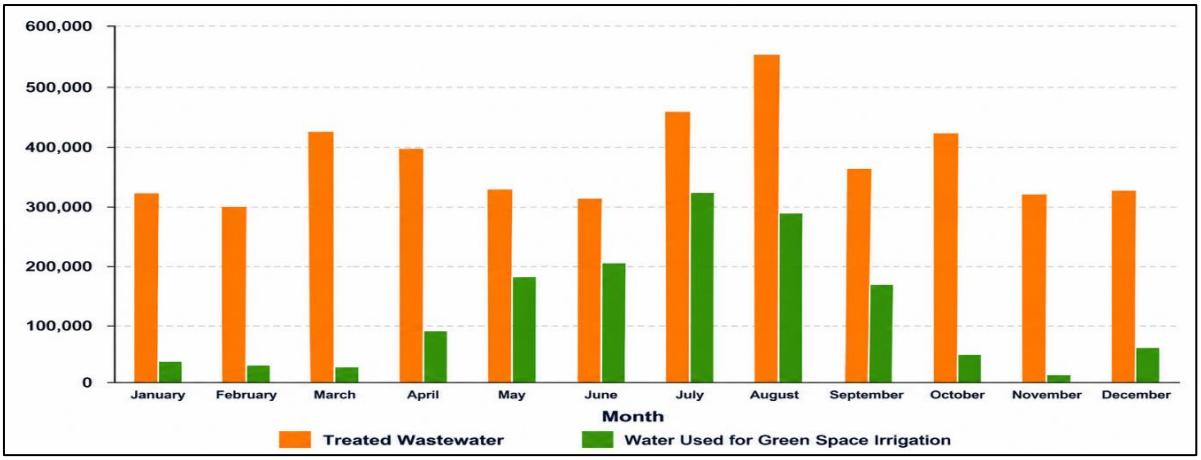


**Figure 4** Monthly distribution of treated and reused water at Tamuda Bay Station in 2024 ($m^3$). Source: Author's elaboration based on Amendis Company data, Directorate of Water and Liquid Sanitation in Tetouan.

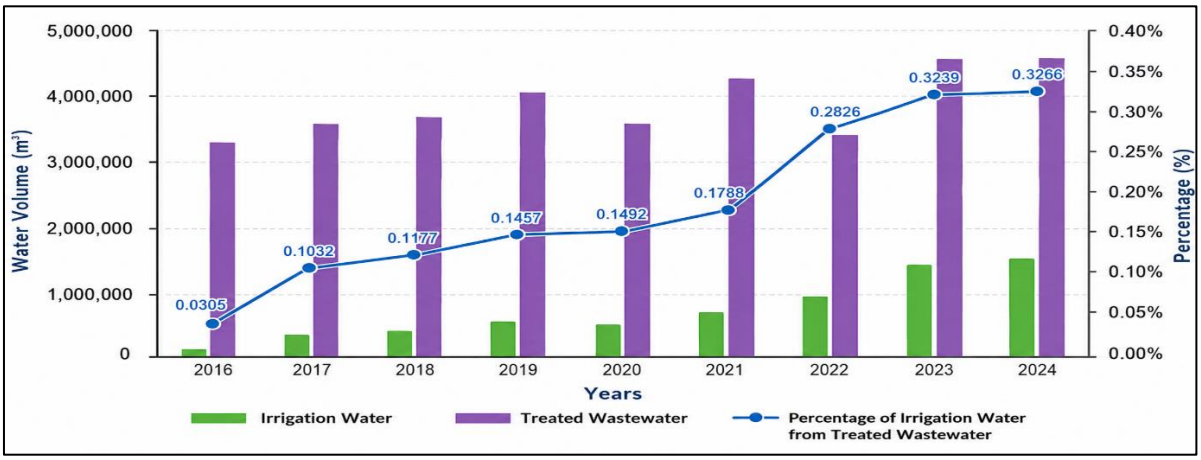


**Figure 5** Evolution of treated and reused water volumes at Tamuda Bay Station between 2016 and 2025 ($m^3$). Source: Amendis Company, Directorate of Water and Liquid Sanitation in Tetouan.

However, this contribution remains below the potential suggested by the overall treatment capacity of the coastal system. The other plants do not appear to be integrated into diversified reuse schemes of comparable scale. As a result, most treated wastewater continues to be managed within a sanitation logic rather than a circular-resource logic. The gap between treated volumes and reused volumes is therefore one of the central findings of this study.

The limited reuse can be explained by several factors. First, the distribution infrastructure required to transport treated water to potential users remains insufficient. Second, reuse is mostly limited to green-space irrigation, while other potential sectors, such as agriculture, tourism facilities, industry and aquifer recharge, remain underdeveloped. Third, coordination between sanitation operators, territorial authorities, water agencies and economic users appears insufficient to transform treated wastewater into a strategic territorial resource.

### 5.3. Environmental improvements and remaining pollution hotspots

Wastewater treatment has contributed to reducing pollution pressures along the Tetouan coast. The development of treatment plants and sanitation networks has helped limit the discharge of untreated wastewater into the marine environment, particularly in areas of tourism importance. These improvements are important for public health, beach quality, coastal ecosystems and the attractiveness of the tourism sector.

Nevertheless, the study also identifies persistent environmental shortcomings. Some coastal valleys, wetlands and local discharge points continue to show signs of pollution. The original field observations associated with the study mention situations in Oued Laou, Lagoon Smir, Oued El Maleh and Oued Amsa where untreated or poorly managed discharges

and stagnant polluted water remain visible. These findings indicate that treatment infrastructure alone is insufficient if it is not accompanied by universal sanitation coverage, regular maintenance, effective network management and systematic environmental monitoring. Examples of these remaining surface-water pollution situations are documented in Figure 6.

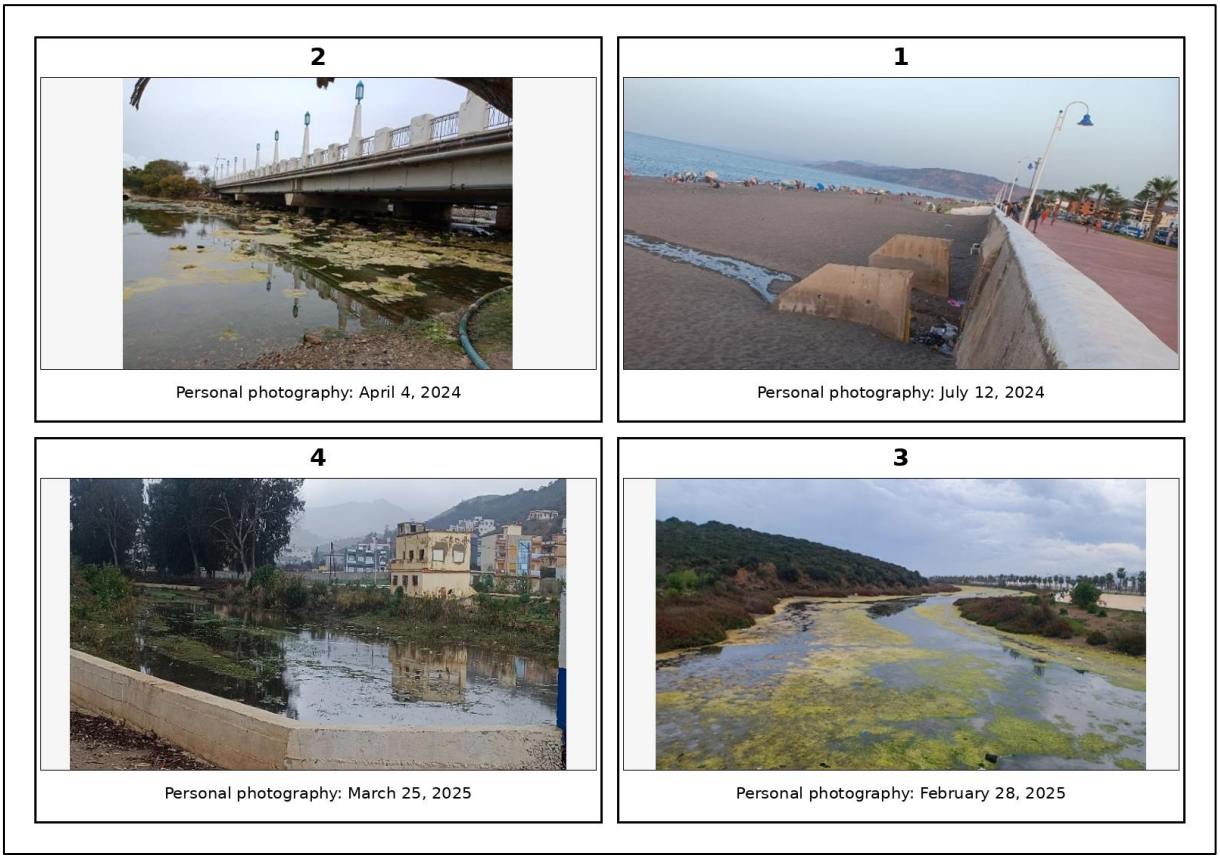


**Figure 6** Examples of surface-water pollution observed in the study area. Source: Author's field photographs, 2024-2025.

Notes: Photo 1 shows direct wastewater discharge onto the beach in the Oued Laou commune. Photo 2 illustrates pollution and stagnation at Smir Lagoon. Similar situations are visible in Oued El Maleh (Photo 3) and Oued Amsa (Photo 4), indicating the persistence of localized pollution hotspots despite the progress achieved in wastewater treatment.

The persistence of pollution hotspots also suggests that coastal water quality should be monitored through a broader set of indicators. Beyond treated volumes, monitoring should include biochemical oxygen demand, chemical oxygen demand, suspended solids, nutrients, bacteriological contamination and emerging pollutants. Such indicators would make it possible to assess the actual environmental effects of wastewater treatment and reuse policies.

### 5.4. Technical and institutional constraints

The effectiveness of treated-water reuse on the Tetouan coast is limited by a combination of technical and institutional constraints. Technically, the absence or insufficiency of independent distribution networks restricts the ability to deliver treated water to agricultural areas, tourism facilities, industrial users or aquifer recharge sites. In addition, the extension of reuse requires continuous quality control to ensure compliance with health and environmental standards.

Institutionally, the reuse of treated wastewater involves several actors whose responsibilities are not always integrated within a single operational strategy. Sanitation operators, water-basin agencies, territorial communities, tourism developers, health authorities and environmental institutions need to coordinate their interventions. Without such coordination, reuse projects risk remaining isolated, limited to demonstration cases or dependent on local initiatives rather than embedded in a coherent regional water-security policy.

Financial constraints also play a role. Treatment, storage and distribution infrastructure require significant investment, while reuse projects must be economically attractive for users. Tariff models, incentives, public-private partnerships

and long-term maintenance mechanisms should therefore be clarified if treated wastewater is to become a stable resource for territorial development.

## 6. Discussion

The discussion interprets the empirical results in light of the conceptual framework and selected Mediterranean experiences. It focuses on the gap between treatment capacity and effective reuse, the governance conditions required for wastewater valorization, and the environmental, health and territorial implications of expanding treated-water reuse in the Tetouan coastal area.

### 6.1. From wastewater treatment to wastewater valorization

The findings show that the Tetouan coast has made important progress in wastewater treatment capacity, but that reuse remains only partially developed. This situation reflects a broader challenge observed in many water-stressed regions: building treatment infrastructure is a necessary condition for reuse, but it is not sufficient. Treated wastewater becomes a strategic resource only when it is supported by distribution networks, quality standards, demand from users, institutional coordination and long-term financing mechanisms.

The Tamuda Bay case demonstrates the practical value of reuse. By substituting treated water for potable water in green-space irrigation, the plant has contributed to potable-water savings and environmental protection. However, the concentration of reuse in a single plant and a limited type of use reveals the need for a broader shift from wastewater treatment to wastewater valorization. This shift requires considering treated wastewater as part of an integrated territorial water cycle rather than as an end product of sanitation.

### 6.2. Lessons from Mediterranean experiences

The comparison with Mediterranean experiences highlights several lessons for the Tetouan coast. In Spain, treated water is widely used in semi-arid regions for agricultural irrigation, urban green spaces and some tourism-related activities. This success is linked to long-term investment, institutional integration and monitoring systems. In Israel, wastewater reuse is a central pillar of national water security, particularly in agriculture, and relies on advanced treatment technologies, separate distribution networks and strong public acceptance (Angelakis & Snyder, 2022; Lazarova et al., 2024; OECD, 2024).

These experiences suggest that the expansion of reuse in the Tetouan coastal area should not be limited to increasing treatment capacity. It should include the creation of reuse networks, the identification of priority users, the development of reuse standards, public communication, cost-recovery mechanisms and scientific monitoring. The objective should be to transform treated wastewater into a planned and regulated resource serving multiple sectors.

### 6.3. Governance as a decisive factor

The results confirm that water governance is a decisive factor in determining the effectiveness of wastewater reuse. Fragmented governance can explain why treated volumes are high while reuse remains limited. Wastewater reuse lies at the intersection of sanitation policy, water-resource management, territorial planning, tourism development, agriculture, environmental protection and public health. If these dimensions are treated separately, reuse projects are unlikely to reach their full potential.

For the Tetouan coastal area, integrated governance should involve the Loukkos Hydraulic Basin Agency, territorial municipalities, sanitation operators, tourism stakeholders, agricultural users, health authorities and environmental agencies. A regional reuse plan could identify potential demand zones, define quality requirements by type of use, prioritize investment in distribution networks and establish monitoring responsibilities. Such a plan would help link infrastructure development to territorial water-security objectives.

### 6.4. Environmental monitoring and health standards

Environmental monitoring must be strengthened if treated wastewater is to be reused safely and sustainably. Conventional treatment indicators are important, but they do not provide a complete picture of environmental quality. The monitoring system should include physical, chemical, biological and bacteriological parameters, as well as emerging pollutants when possible. This is particularly important in coastal zones where wastewater discharge can affect beaches, wetlands, marine biodiversity and tourism activities (Abalasei et al., 2025; European Environment Agency, 2024; Sarantuyaa et al., 2025).

Health standards are also essential for social acceptance. Users and the public are more likely to accept reuse when water quality is transparent, monitored and certified. Communication strategies should therefore explain the treatment process, permitted uses, risk-control measures and benefits of reuse. Public trust is a condition for expanding treated-water use beyond green-space irrigation.

### 6.5. Economic and territorial implications

From an economic perspective, wastewater reuse may require high initial investment, particularly for storage and distribution networks. However, its medium- and long-term benefits can be significant. These benefits include potable-water savings, reduced pressure on dams and aquifers, lower pollution-related costs, improved beach quality, support for tourism attractiveness and new opportunities for green-economy activities. In coastal areas where tourism and urban growth increase water demand, treated wastewater can become a strategic component of territorial resilience.

The agricultural sector may also benefit from treated-water reuse, provided that water quality standards, crop restrictions and monitoring systems are respected. In addition, the possibility of using treated water for aquifer recharge deserves careful assessment, especially in coastal zones exposed to groundwater depletion and saltwater intrusion. Such uses would require advanced treatment, hydrogeological studies and strict monitoring, but they could contribute to long-term water balance.

## 7. Policy Implications and Recommendations

Based on the findings, the study proposes the following policy directions for strengthening the contribution of wastewater treatment and reuse to coastal water security in the Tetouan area.

**Table 4** Recommended actions for expanding treated-water reuse in the Tetouan coastal area

| Priority area | Recommended action | Expected contribution |
|---|---|---|
| Reuse diversification | Expand reuse beyond green-space irrigation toward agriculture, tourism facilities, selected industrial uses and environmental applications | Increase the effective valorization of treated wastewater and reduce pressure on freshwater resources |
| Distribution infrastructure | Develop independent treated-water storage and distribution networks connecting plants to potential users | Transform treatment capacity into operational reuse capacity |
| Governance integration | Establish a regional treated-water reuse plan involving basin agencies, municipalities, operators and sectoral users | Improve coordination, planning and investment efficiency |
| Environmental monitoring | Implement periodic monitoring of physicochemical, bacteriological and emerging-pollutant indicators | Ensure environmental protection, health safety and public trust |
| Economic incentives | Define tariff mechanisms, subsidies or contractual arrangements for users of treated water | Improve the economic feasibility and attractiveness of reuse projects |
| Public awareness | Develop communication and sensitization programs on safe reuse and water-security benefits | Strengthen social acceptance and stakeholder engagement |
| Scientific research | Support laboratory analyses, cost-benefit studies and pilot projects for aquifer recharge | Generate evidence for informed decision-making and innovation |

## 8. Conclusion

This article examined the contribution of wastewater treatment and reuse to water-resource management and coastal water security in the Tetouan coastal area of northern Morocco. The findings show that important progress has been made in wastewater treatment infrastructure, with more than 29 million $m^3$ of wastewater treated by the four studied plants in 2024. This development has contributed to reducing direct pollution pressures and improving the environmental management of a coastal territory exposed to urban, tourism and climatic pressures.

However, the results also reveal a clear gap between treatment capacity and effective reuse. Treated-water reuse remains mainly concentrated at the Tamuda Bay plant, where approximately 1.49 million $m^3$ were reused in 2024 for green-space irrigation, corresponding to about 32% of the plant's treated volume. Although this practice has helped save approximately 6.7 million $m^3$ of potable water since 2016, its limited spatial and sectoral scope prevents treated wastewater from fully contributing to local water security.

The study concludes that expanding the contribution of treated wastewater requires moving from an infrastructure-centered approach to an integrated resource-management approach. This means improving treatment efficiency, developing independent reuse networks, diversifying uses, strengthening environmental monitoring, clarifying institutional responsibilities and involving economic and territorial actors. The experience of the Tetouan coast is promising, but its future impact will depend on the capacity to transform treated wastewater into a regulated, monitored and socially accepted strategic resource.

Future research should complement this territorial assessment with detailed laboratory analyses of treated-water quality, longitudinal monitoring of coastal pollution indicators, cost-benefit analysis of reuse scenarios and hydrogeological studies on the feasibility of aquifer recharge. Such work would provide stronger evidence for decision-makers and support the integration of treated wastewater into Morocco's broader water-security strategy.

### *Highlights*

- The Tetouan coastal area treated more than 29 million $m^3$ of wastewater in 2024.
- Reuse remains spatially and functionally limited, with Tamuda Bay as the main operational example.
- Treated wastewater has helped save potable water and reduce coastal pollution pressures.
- The main constraints are governance fragmentation, limited reuse networks and weak environmental monitoring.
- Expanding reuse toward agriculture, tourism, industry and aquifer recharge could strengthen coastal water security.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

### *Statement of ethical approval*

Not applicable. The study does not involve human participants or animal subjects.

### *Funding*

This research received no external funding.

### *Data availability*

The study is based on institutional reports, technical data and official documents cited in the references. Access to some operational data may be subject to authorization by the relevant institutions.

### *Author contributions*

Rachid Azougagh conceived the study, collected and analyzed the data, prepared the figures, interpreted the results, supervised the study, critically revised the manuscript, and approved the final version for publication. Acherki Abderrafia contributed to the conceptualization of the research, critically revised the manuscript, and approved the final version. Both authors read and approved the final manuscript.

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