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Research article

Remote Sensing Assessment of Tourism's Groundwater Consumption: Evapotranspiration Analysis in the Northern Piedmont of the Western High Atlas, Morocco

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Abstract

In semi-arid regions facing escalating water scarcity, tourism development poses critical risks to groundwater sustainability. This study examines the exploitation of groundwater resources by tourism infrastructure in the northern piedmont of Morocco's Western High Atlas, aiming to quantify withdrawals and assess their long-term viability. By integrating satellite-derived evapotranspiration (WaPOR) and precipitation (CHIRPS) data with field surveys of tourism investments, we analyzed irrigation water demand relative to agronomic requirements and mapped spatial exploitation patterns. Results indicate that 65% of tourism establishments exceed sustainable groundwater use for irrigation by 25–30%, with overexploitation concentrated in communes where tourism development is most intensive. These practices threaten local ecosystems, reduce agricultural productivity, and compromise domestic water security. Our findings highlight the urgent need for enforcing groundwater extraction regulations, adopting water-efficient irrigation systems, and developing alternative water sources to reconcile regional economic growth with the preservation of critical groundwater resources in water-stressed environments.

Keywords: Water management; Evapotranspiration; Irrigation; Remote sensing; Tourism investments.

1. Introduction

Tourism has developed into one of the major economic sectors in many countries, especially in areas with distinctive natural and cultural attractions. However, the growth of this industry often poses serious challenges to the availability and sustainability of water resources, especially in arid and semi-arid regions that naturally have limited water supplies (Gössling *et al*., 2012; Gössling, 2015). Water is an important element in supporting various tourism activities, such as the maintenance of parks, golf courses, swimming pools, and sanitation needs in hotels and resorts. This large-scale increase in water demand can lead to overexploitation of water resources, especially groundwater (Afriyani *et al.,* 2024), which is often the only source of water in semi-arid regions. This phenomenon is occurring in various tourism destinations, including in the Northern Piedmont in the High Atlas West of Marrakesh, which is experiencing a surge in water consumption due to the expansion of tourist infrastructure that is not matched by effective water resource management policies (Garcia & Servera, 2003).

In addition, climate change is exacerbating these conditions by increasing rainfall variability, extending drought periods (Elair et al., 2025), and reducing groundwater recharge rates. These conditions further complicate the balance between water demand and availability, especially in areas vulnerable to climate change (Attar et al., 2024). Therefore, without proper management, increasing tourism investment could accelerate the degradation of water resources and cause long-term adverse impacts both ecologically and economically.

One critical aspect of water resource exploitation in the tourism sector is the reliance on groundwater as the main source of water supply. Excessive use of groundwater can lead to various environmental problems, such as declining groundwater levels, seawater intrusion, and degradation of water quality due to contamination by pollutants from tourist and domestic activities (Kent *et al.,* 2002). Previous studies have shown that in tourist destinations with high pressure on water resources, significant environmental degradation occurs, including a significant reduction in the amount of water available for domestic and agricultural use.

Similar issues have been observed globally in tourism-dependent regions. In the Balearic Islands of Spain, groundwater overexploitation for tourism has led to saltwater intrusion, affecting both tourism infrastructure and local agriculture (Garcia & Servera, 2003). In Cyprus, the combination of tourism development and prolonged drought has necessitated strict water rationing and the development of desalination facilities (Gössling *et al.,* 2015). Australian coastal tourism regions have implemented comprehensive water management plans that include rainwater harvesting and wastewater recycling to reduce groundwater dependency (Kent *et al.,* 2002). These global examples demonstrate that sustainable tourism development requires integrated approaches to water resource management that balance economic benefits with environmental protection.

On the island of Mallorca, for example, the exploitation of groundwater to support the tourism sector has led to the depletion of aquifers to alarming levels, threatening the water supply of the local population and other sectors that also depend on these water resources (Lamhour *et al.,* 2024). Similarly, other coastal areas rely on groundwater to support the tourism industry, where increased exploitation has led to significant changes in the hydrological balance, as well as increased competition for water use between the tourist sector and domestic needs (Helal *et al.,* 2024). In some cases, this has even led to social conflict due to limited access to clean water for local communities, especially in areas that rely on groundwater as a primary source. It is therefore important to identify a more sustainable approach to managing water resources in tourist destinations to avoid long-term negative impacts that could be detrimental to local communities as well as the surrounding ecosystem.

The relationship between tourism activities and water consumption is particularly evident in the study area. Tourism establishments require significant water volumes for maintaining aesthetic landscapes, swimming pools, and guest amenities (Ait Zamzami et al., 2024). Our analysis shows that landscaping and irrigation of green spaces account for approximately 60% of water consumption in tourism investments, while swimming pools and guest water usage account for 25% and 15% respectively. This consumption pattern differs markedly from traditional agricultural water use in the region, which typically employs more water-efficient practices adapted to local conditions (SCHMIDT et al., 2024). The expansion of tourism has thus introduced water use patterns that are less aligned with the region's natural water availability, creating additional pressure on groundwater resources (Gössling et al., 2012).

The overexploitation of groundwater resources extends beyond environmental degradation, manifesting profound socio-economic ramifications (Karimi et al., 2022). Empirical evidence from field interviews conducted in Tameslouht a commune included in this study—reveals that local communities face diminishing water availability for domestic and agricultural purposes, directly imperiling livelihoods and exacerbating food insecurity. While tourism development offers economic advantages, these benefits necessitate critical evaluation against the potential destabilization of traditional agricultural sectors, which remain the primary livelihood source for a majority of the local population (Wurl et al., 2018). Furthermore, declining groundwater levels correlate with escalating extraction costs, jeopardizing the long-term viability of both agricultural and tourism-dependent economies. These findings underscore the imperative to reconcile economic development priorities with sustainable resource management. Policymakers and stakeholders must adopt integrated water governance frameworks that prioritize equitable allocation, balancing sectoral demands while safeguarding hydrological resilience for future generations (Achbah et al., 2024).

In this context, this study aims to analyse the impact of tourism investment on groundwater exploitation by applying an approach based on evapotranspiration and rainfall analysis using satellite imagery. This approach allows for a more accurate estimation of the water consumption used for irrigation of tourism infrastructure, as well as quantifying the level of groundwater withdrawals occurring in the study area (Florido-Benítez, 2024). Remote sensing-based approaches have proven to be an effective tool in monitoring changes in water availability as well as the impacts of water use in various sectors, including tourism. In this study, we utilised spatial analysis methods that can identify water use trends and provide data-driven recommendations for more sustainable management strategies (Naeem *et al.,* 2024).

While some previous studies have focussed more on the general impacts of tourism on water resources, this study offers a novel contribution by applying satellite-based quantitative methods that enable more detailed and data-driven monitoring of changes in water use (McCarroll *et al.,* 2024). As such, the results of this study are expected to provide deeper insights for policy makers and stakeholders in crafting water resource conservation policies that consider the balance between tourism economic growth and environmental sustainability.

2. Research Methods

To estimate irrigation water consumption, we adopted an approach based on the evaluation of evapotranspiration using satellite imagery, using the WaPOR platform of the Food and Agriculture Organization of the United Nations (FAO). This method makes it possible to assess groundwater withdrawals using rainfall data obtained from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) satellite images (El Khalki, 2023).

2.1. Study area

The study area, located in the heart of the piedmont of the western High Atlas (piedmont of Marrakech), extends over 1500 km², from the city of Marrakech in the north to the Atlas Mountains in the south (Ait Zamzami, Elaanzouli, Saidi, *et al.,* 2024), covering 12 territorial communes. These include Moulay Brahim, Ourika, Tameslohte, Aghouatim, Sidi Abdellah Ghiat, Ghmat, Tassoultante, Lalla Takarkoust, Ouazguita, Ait Faska, Tamazouzte and Tahannaout.

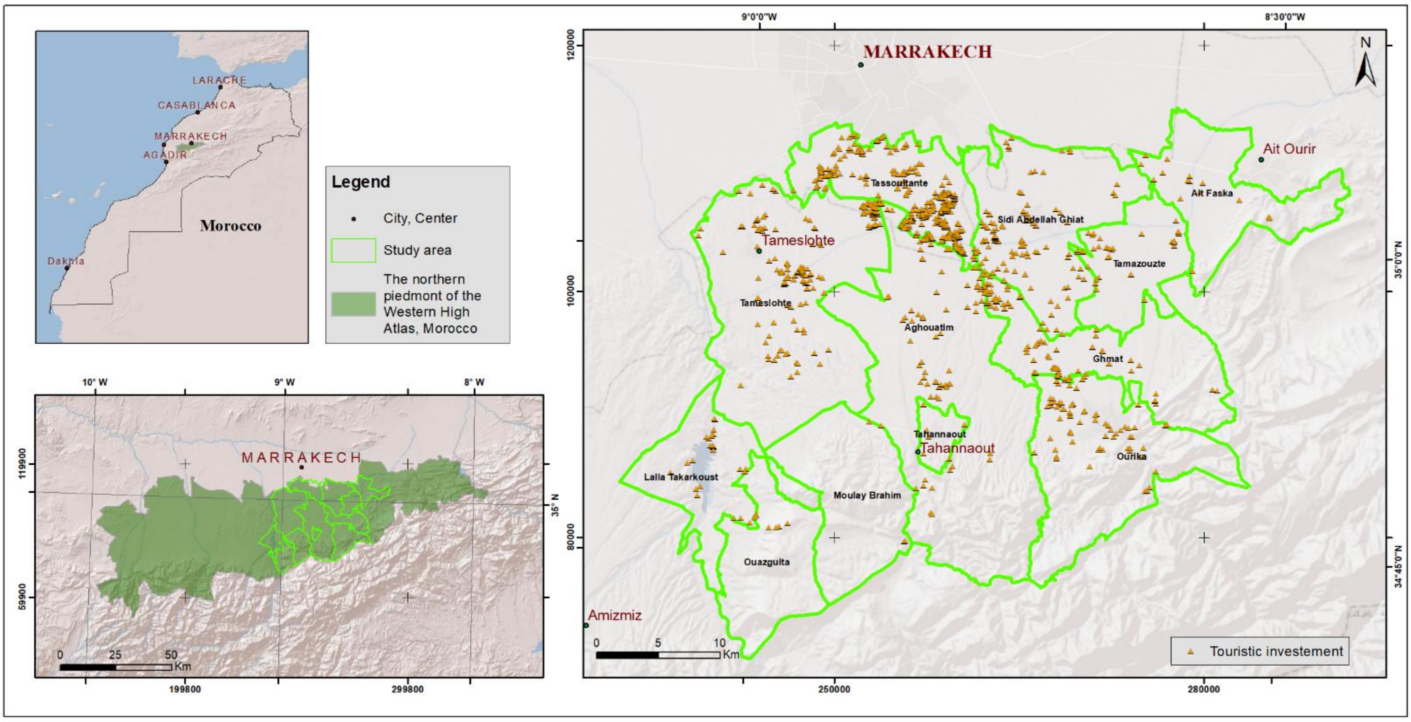

Figure 1. Geographic location of the study area.

2.2. Input data

Vegetation: NDVI

Multispectral images from the Sentinel-2 satellites, operated by the European Space Agency (ESA), provide high-resolution data for analysing vegetation, in particular by calculating the Normalised Difference Vegetation Index (NDVI). NDVI is calculated using the red (Band 4) and near infrared (Band 8) bands, which are fundamental for assessing the health and density of vegetation in a given area (Ait Zamzami, *et al.,* 2024; Hematang *et al.,* 2024). These images, available via the Copernicus Open Access Hub, require prior preparation, including atmospheric correction to eliminate unwanted effects and cropping to focus on the study area (Ma *et al.,* 2025; Patias *et al.,* 2020). Before calculating the NDVI, it is important to prepare the Sentinel-2 images by extracting the relevant spectral bands. The Equation (1) used to calculate the NDVI is.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (1)$$

Where NIR represents the near-infrared band (band 8) and R represents the red band (band 4). Once these bands have been extracted, the formula is applied to create a new NDVI image, where each pixel reflects the value of the index, allowing accurate spatial assessment of the vegetation. Interpretation of the NDVI results allows different vegetation classes to be distinguished. Values close to +1 indicate dense, healthy vegetation, while values close to 0 or negative indicate non-vegetated areas or water surfaces (Alikhanov *et al.,* 2024; Bentahar *et al.,* 2024). To make it easier to analyse the NDVI image, we used a vegetation threshold to map the vegetated area in the tourist investment. This allows vegetated areas to be identified visually.

Evapotranspiration: WaPOR Data

The evapotranspiration images provided by the WaPOR platform, developed by the FAO (FAO., 2019), are essential for estimating evapotranspiration in the tourist investment zone using satellite data . These images can be used to analyse water dynamics in soils (Saloua *et al.,* 2024), crops and vegetation, providing a clear picture of water use in agricultural areas (Allen, 1998). WaPOR data is available online and requires specific preparation, including selecting the appropriate data layers and cropping the images to focus on the study area (Kasihairani *et al.,* 2024).

The preparation of WaPOR data also includes the application of certain adjustments to ensure accurate results. The extracted evapotranspiration values must be multiplied by a transformation factor of 0.1 to obtain consistent units (Safi *et al.,* 2022; Simonet, 2011). Then, a correlation factor of *2 must be applied to align the satellite data with farmers' practices in the field (Etude de modélisation hydrogéologique de la nappe Bahira., 2020). This correlation factor is based on a survey of farmers, who measured their water consumption from meters installed on wells (Harini *et al.,* 2024), thus ensuring a better match with field observations. These adjustments are essential if we are to obtain a reliable estimate of evapotranspiration in the study area (Irmak *et al.,* 2011).

Interpreting evapotranspiration results from WaPOR images, after applying transformation and correlation factors, helps to understand irrigation water use in agricultural areas. Adjusted evapotranspiration values can be visualised using thematic maps, enabling areas of high or low water use to be identified, and thus facilitating informed decision-making on irrigation water management.

Precipitation: CHIRPS Data

The precipitation images provided by the CHIRPS database are invaluable tools for estimating precipitation on a regional scale by combining satellite data and weather stations. These images can be used to analyse precipitation patterns over long periods, providing a clear picture of climate variations in a given area(Alemu *et al.,* 2025). CHIRPS data is available online and requires specific preparation to ensure accurate results, including cropping the images to focus on the study area (Khettouch, 2023).

The preparation of precipitation data from CHIRPS requires certain adjustments to ensure accurate estimates. Once the data have been downloaded, it is essential to crop them and apply a transformation factor of 0.1 to adjust the precipitation units (Laaboudi *et al.,* 2025). This step is important to ensure the consistency and reliability of the results in the precipitation analysis (Salles, 2017).

Interpretation of precipitation results from CHIRPS images, after applying transformation and correlation factors, provides an understanding of climate trends and seasonal variations in the study area. The adjusted data can be displayed in the form of thematic maps, highlighting areas of high or low rainfall. This analysis makes it easier to manage water resources and make informed decisions about agriculture and land-use planning.

Vector Data for Tourism Investments and Authorized Wells

For this analysis, we utilize two shapefiles: one representing tourism investments in the study area, and the other detailing water wells. Initially, a shapefile containing 43 tourism investments was compiled based on a survey of the area conducted by us. This shapefile included detailed information on the location of each facility, its type, its capacity, and its estimated water consumption. However, due to issues encountered during the analysis, a subset of these investments was selected, resulting in the final sample size used in this study. The exact number of tourism investments included in the final analysis is specified in Figure 1.

The well shapefile, obtained from the Hydraulic basin agency of Tensift (ABHT), provides details of the location, depth, flow rate, and type of aquifer exploited by each well. The ABHT is the authorized agency responsible for managing and permitting wells within the Tensift basin. This data is essential for examining the relationship between tourism infrastructures and the use of groundwater resources, in order to check whether these tourist infrastructures are drawing water from the water table and to assess the potential impact on groundwater resources. By superimposing the shapefiles of tourism investments and wells, we aim to identify infrastructures located close to wells, which could indicate direct use of groundwater.

2.2. Irrigation Water Requirements for Green Spaces in Tourism Investments

The annual reference evapotranspiration in Marrakech is estimated, according to the research, at around 1345 mm/year using the Jensen-Haise method, and 1364 mm/year using the Thornthwaite method. These values are close to those obtained using the Penman-Monteith-FAO equation, considered to be the most reliable method for estimating reference evapotranspiration in arid and semi-arid environments (Er-Raki, 2010). It is important to note that these estimates are based on studies carried out in the Haouz region and may vary according to the specific climatic and topographical conditions of the area studied (Kaissi, 2024; Pare, 2006).

Estimation Methods

The methods used to estimate reference evapotranspiration in the northern piedmont of the Western High Atlas include:

• Jensen-Haise method: uses temperature and sunshine data.
• Thornthwaite method: uses temperature and precipitation data.
• Penman-Monteith-FAO method: integrates temperature, relative humidity, sunshine and wind speed data.
These methods have been compared and evaluated in previous studies, showing that the Priestley-Taylor method (a=1) and the Penman-Monteith method are the most efficient for estimating the reference evapotranspiration in Marrakech (Er-Raki, 2010).

Therefore, according to previous studies, the value of 1364 mm/year can be taken as the reference for the basic evapotranspiration needed to avoid vegetation stress. This value will be used to assess whether the water conditions in the study area are sufficient to maintain vegetation without it suffering water stress.

Irrigation Parameters

According to the literature and the recommendations of the Regional Office for the Agricultural Development of Haouz, we have applied an irrigation efficiency factor, defined between 50% and 70% on average for the irrigation methods and tools used (Er-Raki, 2007; Kharrou, 2011).

In a climatic context marked by an increasing trend towards drought over the last five years (Hadri, 2024), we have adopted an irrigation efficiency of 50% (Abou Ali *et al.*, 2024). This estimate is based on in-depth consultations with experts from the Regional Office for Agricultural Development in Haouz (ORMVAH) and irrigation specialists, in particular those from the Moroccan Drip and Pumping Company (CMGP), which are key players in the region's agricultural and irrigation sector.

2.3. Methodology for Estimating and Evaluating Irrigation Water Consumption

Figure 2 shows the diagram illustrating the methodology used in this section.

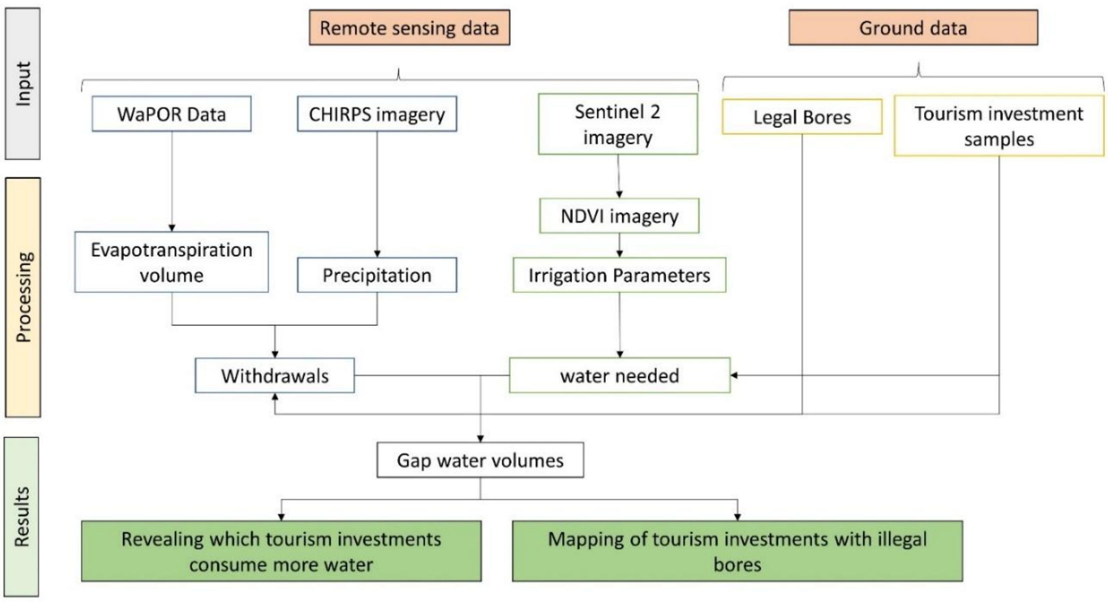

Figure 2. Methodology diagram.

Calculation of Groundwater Extraction and Pumping

We adopted a method based on the calculation of differences between inputs and outputs (water balance) to estimate groundwater abstraction figure 3 (Lima, 2025; Mota *et al.*, 2024). After preparing the input data, we extracted information specific to the areas concerned using shapefiles.

We then applied this method, focusing solely on the vegetated areas within the perimeter of the tourism investments (Vles, 2019), identified using NDVI images. We then extracted evapotranspiration and rainfall values, and applied the irrigation parameters provided by ORMVAH (Office Régional de Mise en Valeur Agricole du Haouz). Finally, we used GIS tools to map the differences observed in the study area (Kanav & Kumar, 2024). Equation (2) shows calculation.

$$\text{Withdrawal} = \text{water pumped} = (\text{Evapotranspiration} * 2) - \text{rainfall} \quad (2)$$

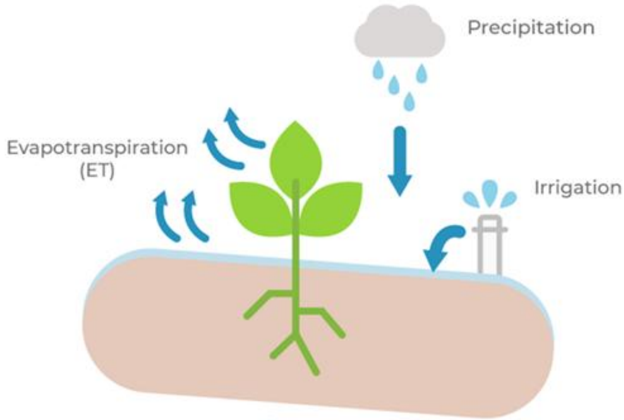

Figure 3. Water Balance Components in Plant Growth: Evapotranspiration, Precipitation, and Irrigation.

3. Results and Discussion

Table 1 shows the results of the samples we examined to assess irrigation water consumption. Analysis of water withdrawals reveals intensive management of water resources in the samples studied. The volumes withdrawn, after correction, vary considerably from one sample to another, illustrating the adaptation of irrigation practices according to climatic conditions and the specific needs of the vegetation. For example, in sample 7, a withdrawal of 18,497 m³ was recorded, indicating a heavy reliance on irrigation to maintain vegetation greenness over a large area. These adjustments, while essential, highlight the need for careful planning to avoid over-consumption of water, especially in a context of increased drought (Miller, 2010).

Table 1. Table of water accounting, (inputs, outputs).

Samples of tourism investments	Surface area in m²		Water output	Water input		Water requirement (m3) ET0	Gap between potential and irrigated water
	Global	Vegetation	Evapotranspiration	Precipitations (m^3)	Withdrawals (m^3)		
1	10101.9	7183.61	3536.68	1595.09	2912.38	9798.44	-2725.09
5	27811.81	15438.7	10361.29	4049.4	9467.84	21058.39	-335.81
6	26457.46	18147.06	14628.33	3852.21	16164.19	24752.58	4504.07
7	29291.37	18357.1	16797.14	4465.47	18497.5	25039.08	8555.19
8	6247.72	2848.98	1925.55	1081.48	1266.1	3886.01	-34.92
10	8271.03	5089.92	2925.88	1431.72	2241.24	6942.64	-1090.89
12	18468.02	43.56	6931.05	4593	3507.08	59.42	13802.68
13	21936.01	16320.25	13208.77	3797.12	14117.47	22260.82	4156.72
14	50323.45	33300.97	19018.91	8982.74	15054.26	45422.52	-7384.7
16	10043.47	5229.74	3297.27	1395.04	2853.35	7133.37	-538.83
17	19039.64	3460.57	5678.26	2878.79	4199.19	4720.21	6636.3
18	7542.11	4927.17	1543.87	1461.66	123.31	6720.67	-3632.93
19	18139.86	12359.54	4802.53	3515.5	1930.53	16858.42	-7253.36
20	10622.08	6916.64	3055.97	1838.68	1825.94	9434.29	-3322.35
22	14865.75	6548.52	3503.86	2653.54	1275.48	8932.18	-1924.47
23	10065.95	6211.3	2690.63	1589.41	1651.82	8472.21	-3090.96
24	16655.98	5738.05	7811.65	3459.45	6528.31	7826.71	7796.6
26	12647.89	7861.51	5008.56	2606.73	3602.75	10723.09	-705.97
29	13448.2	5456.52	2798.57	2123.47	1012.65	7442.7	-1845.55
30	10322.83	5828.54	2508.45	1786.88	1082.35	7950.13	-2933.24
31	21742.79	11628.67	9555.96	3463.63	9138.49	15861.51	3250.4
32	9602.71	2654.57	5817.32	1451.93	6548.09	3620.83	8013.81
33	9635.68	2649.8	1593.74	1528.22	98.28	3614.32	-426.84
34	35038.34	9399.32	6618.74	5557.08	1592.49	12820.67	416.81
35	9845.08	1130.92	1901.08	1554.54	519.82	1542.58	2259.59
38	18160.51	9364.18	6212.71	2892.97	4979.61	12772.75	-347.33
40	31888.18	24280.88	11408	5079.79	9492.31	33119.12	-10303.13
43	17139.69	212.13	3349.95	3321.67	42.42	289.34	6410.57

3.1. Gap Between Water Requirements and Applied Irrigation

The difference between potential water requirements, calculated from evapotranspiration (ET), and the water actually applied by irrigation, highlights imbalances in water management. Positive discrepancies, such as the one observed in sample 31 (+3250.4 m³), suggest over-exploitation of water, where irrigation exceeds the potential needs of green spaces (Bouba-Olga, 2006; Guemouria *et al.,* 2025), which could lead to degradation of groundwater resources. Conversely, significant negative variances, such as in sample 40 (-10,303 m³), indicate under-irrigation, which could reduce crop productivity and increase vulnerability to water stress (Narrada Gamage *et al.,* 2017). Figure 4 shows the Annual irrigation water consumption and the difference between potential and actual irrigation water demand.

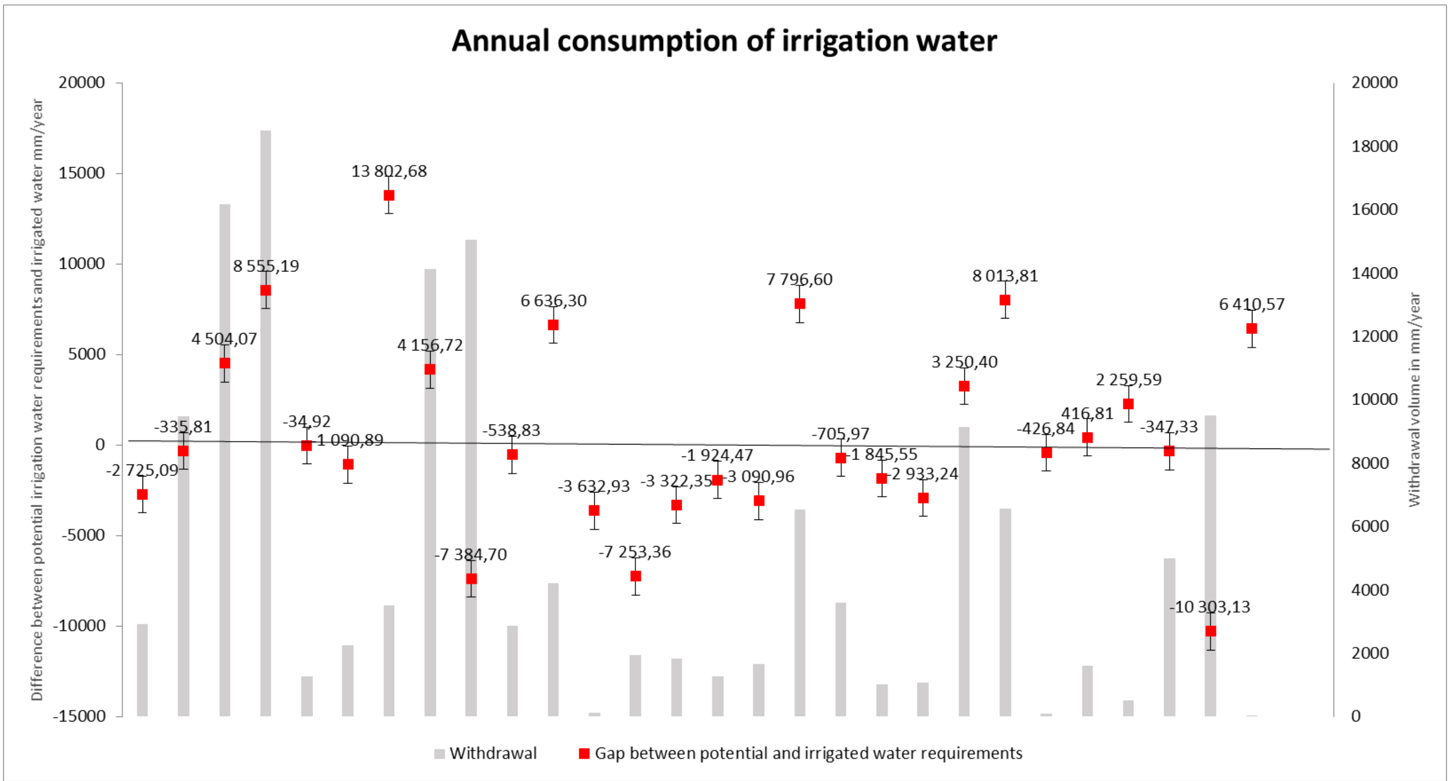

Figure 4. Annual irrigation water consumption and discrepancy between potential water requirements and actual irrigated.

Influence of Surface Area on Irrigation Needs

The surface area of irrigated plots plays a decisive role in the variability of water requirements and the efficiency of irrigation practices. Samples covering large areas, such as sample 40 with 31,888 m², not only show higher water requirements, but also greater discrepancies between calculated requirements and actual irrigation. This trend suggests that large plots may be more difficult to manage optimally, requiring more sophisticated irrigation strategies and continuous monitoring to prevent over- or under-irrigation. The data shows that irrigation practices need to be adjusted not only according to weather conditions, but also according to plot size to ensure sustainable use of water resources (Adger, 2009; Benaly *et al.,* 2025).

Impacts of Precipitation Regimes and Irrigation Practices

The rainfall patterns observed in the samples analyzed indicate a low contribution of rainfall to vegetation water requirements, accentuating dependence on irrigation. For example, sample 18, with an annual rainfall of 193.8 mm, shows an irrigation deficit of -3632.9 m³, which could compromise vegetation productivity. In semi-arid regions such as those studied, efficient irrigation management becomes important to compensate for insufficient rainfall (Miftah *et al.,* 2024). These observations highlight the importance of adopting more efficient irrigation technologies (Lee *et al.,* 2025), and diversifying water sources to meet the growing requirements of sustainable vegetation in these unfavorable climatic conditions (Elsasser, 2001; Faulon, 2020).

3.2. Spatialization of Results

We applied this approach to over 1,000 tourism investments in the study area to assess water consumption. The aim was to compare the volumes of water withdrawn from boreholes with the basic water requirements, defined by the reference evapotranspiration (ET0) (Liu *et al.,* 2025), necessary to avoid water stress for plants. Figure 5 shows the Irrigation water map withdrawn from the water table.

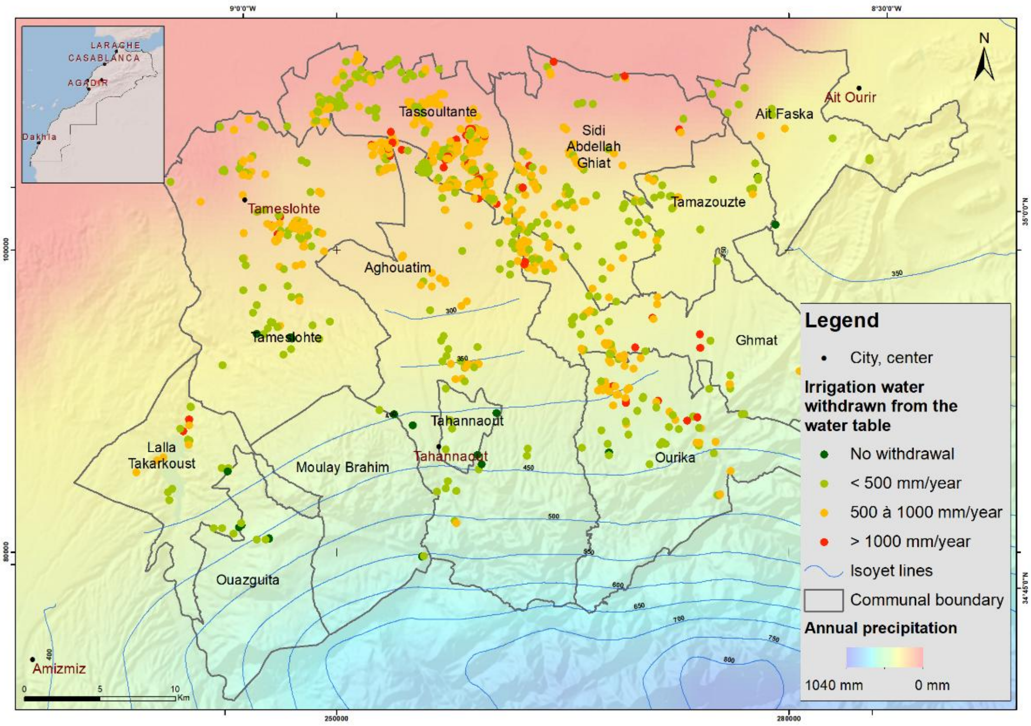

Figure 5. Map of irrigation water withdrawn from the groundwater table.

Water resources are being over-exploited in the communes of Tassoultante, Ghmat, Sidi Abdellah Ghiat and Ourika. This over-exploitation is closely linked to the high concentration of tourist investment in these areas. Because of their tourist appeal, these communes have seen a proliferation of tourist investments, all of which consume a lot of water to maintain gardens, swimming pools and other facilities. This increased pressure on water resources is exacerbated by the drop in rainfall in these regions, making the situation even worse (Boyer *et al.,* 2022).

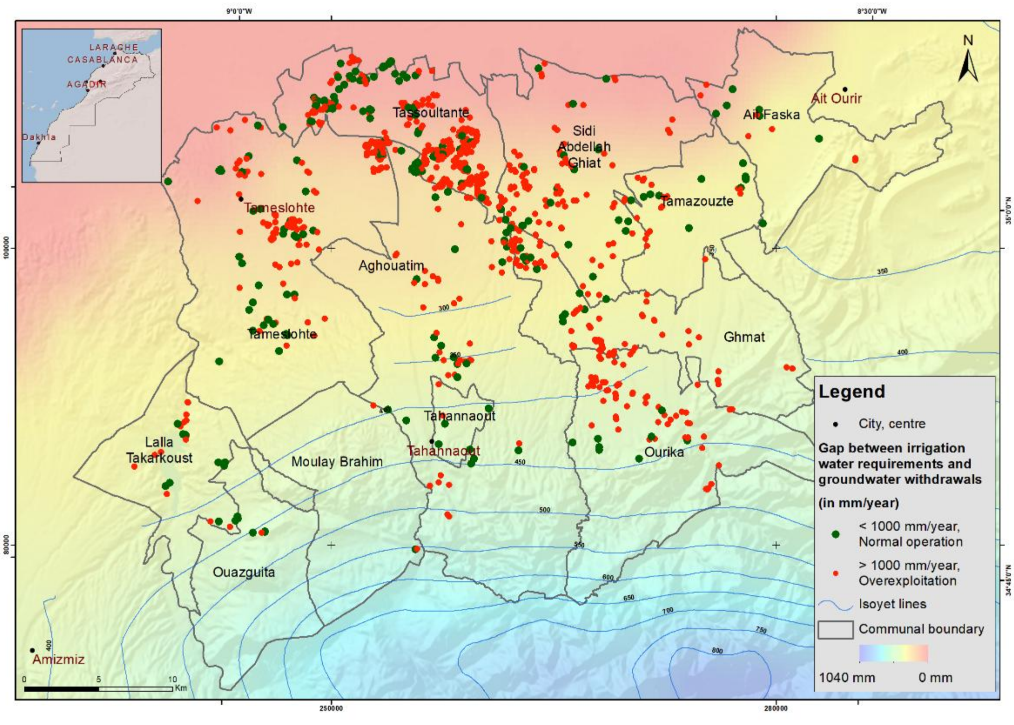

Figure 6. Gap between potential irrigation water requirements and the volume actually irrigated.

Low rainfall is not sufficient to recharge the water table, resulting in almost total dependence on borehole irrigation. This situation jeopardizes the long-term sustainability of groundwater in these communes, requiring urgent action to regulate the exploitation of water resources and encourage the adoption of more efficient irrigation practices. Moreover, this over-exploitation raises concerns not only for the future of local vegetation, but also for the viability of natural ecosystems, which could be seriously affected by the depletion of groundwater reserves. The gap between potential irrigation water demand and the volume of water actually irrigated can be seen in Figure 6.

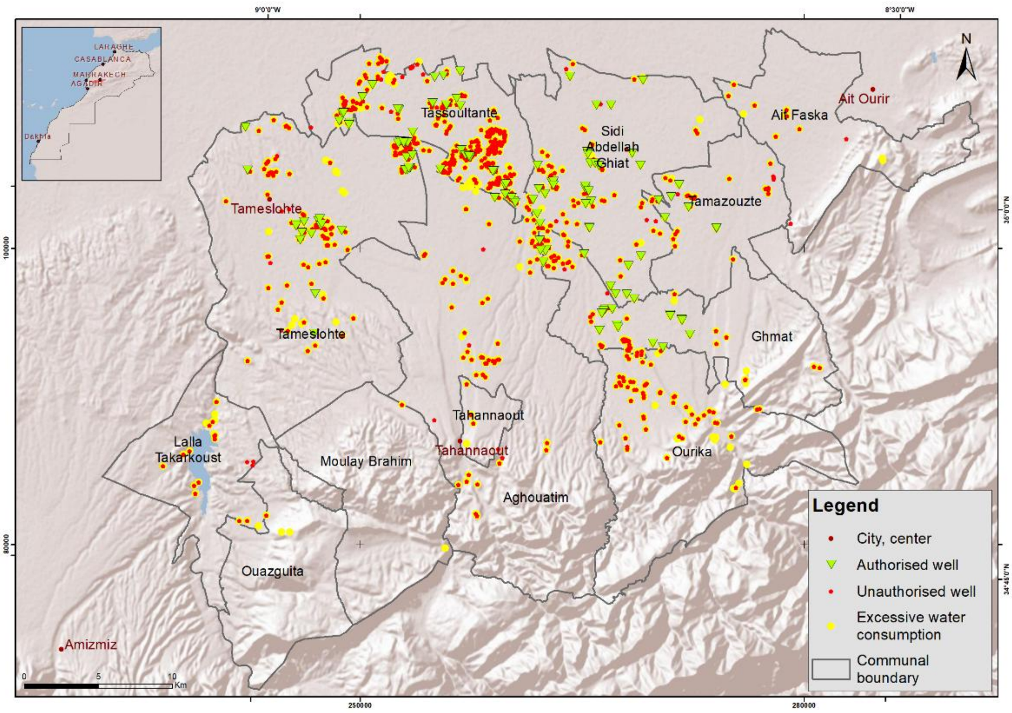

Figure 7. Spatial distribution of authorized and unauthorized wells in the northern piedmont of the western high atlas, Morocco.

Mapping of unauthorised wells, Visual analysis of the map in Figure 7 (Zhang & Marzbali, 2024), reveals a contrasting distribution between authorised and unauthorised wells in the northern foothills of the western High Atlas, highlighting the complex dynamics of water resource exploitation. The concentration of authorised wells in the communes of Tassoultante, Sidi Abdellah Ghiat and Ghmat can be explained by the authorisations granted to farmers in these areas of high agricultural activity, which have shifted agricultural activity towards tourism. On the other hand, the high density of unauthorised wells, particularly in these same areas and in the more remote rural regions, indicates considerable pressure on the water tables (Kadiri, 2008), which are unregulated. This uncontrolled exploitation, visible in the many red dots on the map, poses a serious risk to the sustainability of aquifers and may have long-term environmental and socio-economic repercussions (Gössling, 2001).

This situation highlights the challenges faced by local authorities in effectively managing water resources in this region. If left unchecked, overexploitation of the aquifers could not only reduce water quality, but also disrupt hydrological balances, compromising the resilience of local communities, as is the case for the population of the commune of Tameslouht. These observations call for urgent measures to strictly regulate and monitor water abstraction in order to preserve the ecological integrity of the region while meeting the needs of local populations (Attar *et al.,* 2024; Troin, 1985).

4. Discussion

This study highlights the major impact of tourism development on the depletion of groundwater resources in the northern foothills of the Western High Atlas. By integrating advanced remote sensing analyses with a rigorous assessment of irrigation practices in more than 1,000 tourist establishments (Kustura *et al.,* 2025), it was possible to quantify the overexploitation of aquifers fairly precisely. The results indicate an excessive dependence on groundwater-based irrigation (Ez-Zaouy *et al.,* 2025), accentuated by a reduction in rainfall attributable to prolonged periods of drought (Bertrand, 2015). This situation is all the more critical in that the volumes of water mobilised for irrigation frequently exceed agronomic needs, exacerbating water stress on the aquifers.

Mapping of the results has identified areas of increased vulnerability, particularly in the communes of Tassoultante, Ghmat, Sidi Abdellah Ghiat and Ourika, where the density of tourist investment is highest. These sectors are subject to intensive exploitation of water resources, mainly due to the high demand for water to maintain the landscape infrastructures associated with tourism. Insufficient recharge of aquifers, coupled with sub-optimal management of water resources, could lead to major impacts on local ecosystems, compromising the sustainability of agriculture and access to drinking water (Joyfred *et al.,* 2024; Katircioglu *et al.,* 2014).

The results of this study highlight the urgent need to adopt integrated water resource management strategies that harmonise economic and environmental objectives. It is imperative to promote more efficient irrigation practices, optimise existing irrigation systems, and encourage the adoption of innovative water technologies to reduce water consumption (Hadri *et al.,* 2022). In addition, stricter regulation of unauthorised drilling and active promotion of the use of alternative water sources, such as the reuse of treated wastewater, could ease the pressure on aquifers.

To ensure ecologically sustainable tourism development, cross-sector collaboration between political decision-makers, water resource managers and stakeholders in the tourism sector is essential. This will ensure more rational and sustainable water management (Stoffel, 2002). This study thus provides a solid framework for the development of public policies aimed at protecting water resources (Nkwasa *et al.,* 2025), while supporting sustainable tourism development in the region.

Future works should emphasise integrative approaches to address pressures on groundwater resources due to tourism development, especially in vulnerable semi-arid areas. Firstly, we should develop predictive models that incorporate climate change scenarios to estimate long-term groundwater availability in tourism areas (Jiménez-Navarro *et al.,* 2025; Jiménez-Martínez *et al.,* 2016). Secondly, the effectiveness of alternative water sources such as wastewater reuse and rainwater harvesting needs to be further tested, with studies suggesting that wastewater recycling is more efficient and feasible in tourist resorts than rainwater harvesting, particularly in the dry season when water demand is high and rainfall is low (Cao, 2024). Third, there is a need to explore policy frameworks that promote synergies between groundwater conservation and tourism development (Jhansi & Santosh Kumar Mishra, 2013). Fourth, the socio-economic aspects of water scarcity need to be studied, given the pressures on local communities and traditional agriculture (Han *et al.,* 2025). Finally, future research also needs to develop participatory methodologies based on multi-stakeholder collaboration between investors, local communities, and authorities, as outlined in various studies on collaborative success in water governance and sustainable tourism (Koiwanit & Filimonau, 2023).

5. Conclusion

This study reveals significant impacts of tourism development on groundwater resources in the northern piedmont of the Moroccan Western High Atlas, with profound social and economic implications. Our analysis found that more than 80% of groundwater extraction points linked to tourism infrastructure are unauthorized, exacerbating inequities in water access between tourism facilities and local communities. This unregulated extraction disproportionately affects rural populations reliant on groundwater for agriculture and domestic use, potentially jeopardizing livelihoods in water-scarce regions.

The discrepancy between water required for maintaining green spaces and actual volumes utilized ranges from 25–30% in high-density tourism areas, reflecting inefficiencies that inflate operational costs for businesses while straining communal water supplies. Spatially, communes such as Tassoultante, Ghmat, Sidi Abdellah Ghiat, and Ourika face withdrawal rates exceeding recharge by 40–45% annually, with 91% of all monitored touristic investments (937 of 1,030) operating under overexploitation. These pressures create stark social inequities, as tourism-driven demand prioritizes luxury amenities (e.g., landscaped gardens, pools) over basic needs in adjacent communities. Current rainfall meets only 15–20% of irrigation needs, forcing reliance on unsustainable groundwater extraction. Larger tourism developments (>20,000 m²) exhibit the greatest mismanagement, with inefficient practices increasing water costs by 20–25% compared to smaller, regulated facilities.

These findings underscore the urgent need to align economic incentives with environmental limits. Implementing water-efficient technologies could reduce consumption by 30–35%, lowering operational expenses while preserving aquifers. Stricter enforcement targeting illicit wells and incentives for alternative water sources (e.g., treated wastewater) would mitigate social tensions and stabilize rural economies. Prioritizing equitable water allocation frameworks could prevent conflicts between tourism growth and community needs, ensuring long-term sector viability. Cross-sector collaboration is critical: policymakers must integrate hydrological data into tourism zoning laws, managers adopt participatory governance models with local communities, and businesses transition to sustainability-certified operations. Only through such harmonized action can the region balance economic prosperity with environmental and social equity.

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Conceptualization: Ait Zamzami, H., Aachrine, B., Saidi, J., & Boumeaza, T; **Methodology**: Ait Zamzami, H., Aachrine, B., Boumeaza, T; **Investigation**: Ait Zamzami, H., Elaanzouli, M., Zahrani, A., and Boumeaza, O.; **Writing—original draft preparation**: Ait Zamzami, H., Elaanzouli, M., Aachrine, B., and Boumeaza, T.; **Writing—review and editing**: Ait Zamzami, H., Elaanzouli, M., Aachrine, B., Saidi, J., Musiyam, M., Boumeaza, T.; **Visualization**: Ait Zamzami, H., Elaanzouli, M., Aachrine, B., Boumeaza, O. and Boumeaza, T.. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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