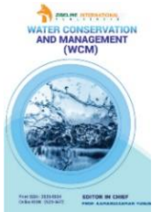
ZIBELINE INTERNATIONAL™ PUBLISHING
ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

**Water Conservation & Management (WCM)**

*DOI: http://doi.org/10.26480/wcm.04.2024.466.474*

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*RESEARCH ARTICLE*

# IMPACTS OF CLIMATE CHANGE ON GROUNDWATER QUALITY AND RECHARGE IN THE TENSIFT BASIN, MOROCCO

**Ghizlane Fahdi[a], Jamal Mabrouki[a], Aziza Lamchaimech[b], Driss Azdem[a], Mounia Benrhanem[c], Souad El hajjaji[a]**

*[a]Laboratory of Spectroscopy, Molecular Modeling, Materials, Nanomaterial, Water and Environment, CERNE2D, Mohammed V University in Rabat, Faculty of Science, Avenue Ibn Battouta, BP1014, Agdal, Rabat, Morocco.*
*[b]Mohammed V University in Rabat, Water and Environment Geosciences Laboratory, Rabat Morocco*
*[c]Tensift Water Basin Agency - Marrakech, Morocco*
*Corresponding Author Email : jamal.mabrouki@um5r.ac.ma*



**ARTICLE DETAILS**

***Article History:***

Received
Revised
Accepted
Available online

**ABSTRACT**

This study examines the impacts of climate change on groundwater quality and recharge in the Tensift Basin, focusing on the Haouz, Bahira, and Essaouira aquifers. Analysis of data collected from 2013 to 2017 reveals significant spatial and temporal variability in water quality, driven by both natural and anthropogenic factors. In the Haouz aquifer, the proportion of water classified as "Excellent" quality dropped from 7% in March 2013 to 0% by July 2017, while "Good" quality water increased from 47% to 60%. The Bahira aquifer consistently showed 45% to 64% of water samples falling under "Average" quality, with occasional increases in "Poor" quality water up to 45%. The Essaouira aquifer exhibited a consistent presence of "Average" quality water at 75%, with "Poor" quality water observed in some instances. These trends indicate a decline in water quality exacerbated by climate change effects such as increased evapotranspiration, altered precipitation patterns, and rising sea levels. The study underscores the urgent need for comprehensive groundwater management strategies, including improved monitoring, sustainable water use practices, and adaptive measures to mitigate the impacts of climate change. These efforts are crucial for ensuring safe drinking water, protecting public health, and sustaining groundwater resources in the region.

**KEYWORDS**

Groundwater quality, Climate change, Water recharge, Groundwater management, Morocco.

## 1. INTRODUCTION

The Tensift Basin, located in central Morocco, is a vital region for both agricultural and urban water supplies. Groundwater resources in this basin are crucial for sustaining agriculture, drinking water, and industrial activities. However, observations indicate that groundwater quality in the basin is under significant pressure due to natural processes, anthropogenic activities, and climate change (Marwan et al., 2022; Mohammed et al., 2020).

Historically, groundwater quality in the Tensift Basin has shown considerable variability, influenced by natural factors such as geological composition and hydrological processes. The basin's diverse aquifers, including the Haouz, Bahira, and Essaouira aquifers, exhibit distinct characteristics and water quality issues. Factors such as salinity, nitrate contamination, and the presence of coliform bacteria have been identified as key concerns, reflecting a complex interplay between natural and human-induced influences. The region's geology may contribute to variations in groundwater quality. High mineral content and salinity are often observed, particularly in coastal and alluvial aquifers, due to natural saline intrusions and mineral dissolution. The presence of chloride and nitrate levels in some aquifers suggests that both natural processes and human activities contribute to water quality degradation (Baccouche et al., 2022).

Furthermore, agricultural practices, particularly the use of nitrogen-based fertilizers, significantly impact groundwater quality by increasing nitrate concentrations. Urbanization and wastewater discharge further exacerbate the issue, leading to contamination from faecal coliforms and other pollutants. In the Haouz aquifer, for instance, the presence of untreated wastewater and industrial discharges has been linked to poor water quality, with elevated levels of salinity, nitrates, and faecal coliforms. Also, the impacts of climate change are increasingly recognized as a major factor affecting groundwater quality. Changes in precipitation patterns, increased frequency and severity of droughts, and altered recharge rates can exacerbate existing water quality issues. Climate change may intensify the salinization of groundwater resources, reduce natural recharge, and increase the concentration of contaminants (Asaad et al., 2016; Arifullah, et al., 2022).

Understanding groundwater conditions about climate change is crucial for several reasons. Groundwater is a primary source of drinking water in many communities, making its quality essential for public health. Contaminants such as nitrates and coliform bacteria pose significant health risks, especially in regions with limited access to clean water. Regular monitoring and management of groundwater quality are vital to safeguard public health and prevent waterborne diseases. Moreover, groundwater plays a critical role in agricultural productivity, particularly in the Tensift Basin. The quality of irrigation water directly impacts crop yields and soil health. High levels of nitrates and salinity can impair agricultural productivity and undermine the sustainability of farming practices. Effective groundwater management is therefore necessary to support agricultural activities and ensure long-term food security. In addition to public health and agriculture, a comprehensive understanding of groundwater quality trends and influencing factors is essential for effective water resource management. This includes evaluating the

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| | **Website:** www.watconman.org | **DOI:** 10.26480/wcm.04.2024.466.474 |

Cite The Article: Ghizlane Fahdi, Jamal Mabrouki, Aziza Lamchaimech, Driss Azdem, Mounia Benrhanem, Souad El hajjaji (2024). Impacts Of Climate Change On Groundwater Quality And Recharge In The Tensift Basin, Morocco. *Water Conservation & Management, 8(4): 466-474.*

impacts of human activities and climate change on water availability and quality. Studying groundwater conditions in the context of climate change also offers valuable insights into how changing climatic patterns affect water resources, which is critical for developing adaptive management strategies and mitigating the impacts of climate change on water availability and quality (Benchrifa et al., 2022; Purnima et al., 2024; Ghizlane et al., 2022 ).

This work aims to assess the conditions of groundwater in the Tensift Basin, focusing on the impact of climate change on water quality. Specifically, it seeks to evaluate the spatial and temporal variability in groundwater quality across the Haouz, Bahira, and Essaouira aquifers; Analyze the influence of natural factors, anthropogenic activities, and climate change on groundwater quality; Identify key contaminants, such as nitrates and coliform bacteria, and their sources and propose recommendations for improving groundwater management and mitigating the impacts of climate change.

Therefore, this study offers significant novelty by integrating a comprehensive assessment of groundwater conditions in the Tensift Basin with a focus on the impacts of climate change by providing a holistic analysis of how shifting climatic patterns interact with both natural and anthropogenic factors to influence groundwater quality. By employing a multi-year dataset and assessing seasonal and spatial variations in key parameters such as conductivity, nitrate levels, and coliform bacteria, the study unveils intricate dynamics between climate variables and groundwater quality. This approach not only highlights the direct impacts of climate change but also examines how these impacts are compounded by local agricultural practices, urban development, and natural processes. Furthermore, the study's emphasis on linking groundwater quality trends with climate-induced changes offers a novel perspective on adaptive management strategies, addressing both current and future challenges in water resource management. This comprehensive and integrated approach provides new insights into the sustainability of groundwater resources in the region and contributes valuable information for developing effective climate adaptation strategies.

## 2. Materials and Methods

### 2.1. Study Area Description

The study area has different types of groundwater resources. The TWBA carried out monitoring of the water quality of these resources between 2013 and 2017. The study area is characterized by significant geographical diversity, ranging from the rugged reliefs of the High Atlas to the vast alluvial plains of the Haouz of Marrakech, passing through the endorheic depressions of the Bahira, and extending to the coastal strip of Essaouira and including also Jbilets and the ancient massif of the High Atlas. This region covers an area of approximately 26,000 km² and includes the following geographical entities: Haouz of Marrakech, Essaouira – Meskala – Korimat, and Western Bahira. Administratively, this area encompasses eight prefectures and provinces. It entirely covers the prefecture of Marrakech, predominantly the provinces of Al Haouz, Chichaoua, Essaouira, and Youssoufia, as well as parts of the provinces of Rehamna, Kelâa des Sraghna, and Safi. Figure 1 illustrates the current boundary of the TWBA's (Tensift Water Basin Agency) area of action.


**Figure 1:** Administrative division of the action area of the Tensift Hydraulic Basin Agency

In the TWBA's action area, surface water resources are very irregular and unevenly distributed. The High Atlas, acting as a reservoir for surface flows, is the source of the main rivers, while the plain serves as a transition and utilization zone for water. The region can be divided into three planning units, each with unevenly distributed surface water resources:

- The Upper Tensift unit (11,900 km²) extends to the confluence of the Tensift River with the Assif Al Mal River and includes the Haouz-Mejjat and western Bahira aquifers. This unit represents the hydrologically active part of the basin, comprising the Tensift River and its tributaries (the N'fis, Rheraya, Ghmat, and R'Dat rivers, as well as the upper part of the river known as the Lahr River).

- The Lower Tensift unit (7,900 km²) stretches from the confluence of the Tensift and Assif Al Mal rivers to the river mouth. It includes the Tensift River and its tributaries (the Assif Al Mal and Chichaoua rivers), the Bousbaâ aquifer, and the alluvial aquifer of Tensift. Its hydrological activity is highly variable.

- The Ksob-Iguezoullen unit (5,000 km²) encompasses the Akermoud aquifer, the Meskala-Kourimat aquifer, and the coastal aquifer of Essaouira.

### 2.2. Water quality assessment system

To assess the state of water quality, the Quality Index (IC) is based on Joint Decree No. 1275-01 of 10 Chaâbane 1423 (October 17, 2002) issued by the Minister of Equipment and the Minister in charge of Territorial Development, Urban Planning, Housing, and Environment. This decree defines a quality scale for surface waters. The system includes a general grid applicable to areas influenced by pollution sources, with quality thresholds for each parameter based on potential water uses, such as drinking, agriculture, aquaculture, and industry. It also includes a simplified grid intended for areas not influenced by pollution sources, allowing for a quick and comprehensive assessment of water quality and pollution status. This simplified grid focuses on a limited number of parameters considered the most critical.

The selected parameters include indicators of organic, nitrogen, phosphorus, and bacterial pollution, such as dissolved oxygen content, BOD5 and COD, $NH_4^+$, and total phosphorus (TP), as well as faecal coliforms. These parameters are essential for evaluating ecological balance, pollution from oxidizable materials, eutrophication of waters, and faecal contamination. The evaluated parameters also include dissolved oxygen, total phosphorus, nitrates ($NO_3^-$), and chlorophyll "a". The overall water quality is determined based on the most unfavorable parameter according to the simplified quality grids (Table 1).

**Table 1**: Simplified groundwater quality grid

| QualityParameter | Conductivity (µS/cm) | $Cl^-$ (mg/l) | $NO_3^-$ (mg/l) | $NH_4^+$ (mg $NH_4^+$/l) | MO (mg/l) | CF (CFU/100ml) |
|---|---|---|---|---|---|---|
| Excellent | <400 | <200 | <5 | <0.1 | <3 | <20 |
| Good | 400-1300 | 200-300 | 5-25 | 0.1-0.5 | 3-5 | 20-200 |
| Average | 1300-2700 | 300-750 | 25-50 | 0.5-2 | 5-8 | 2000-20,000 |
| Poor | 2700-3000 | 750-1000 | 50-100 | 2-8 | >8 | >20,000 |
| Very Poor | >3000 | >1000 | >100 | >8 | - | - |

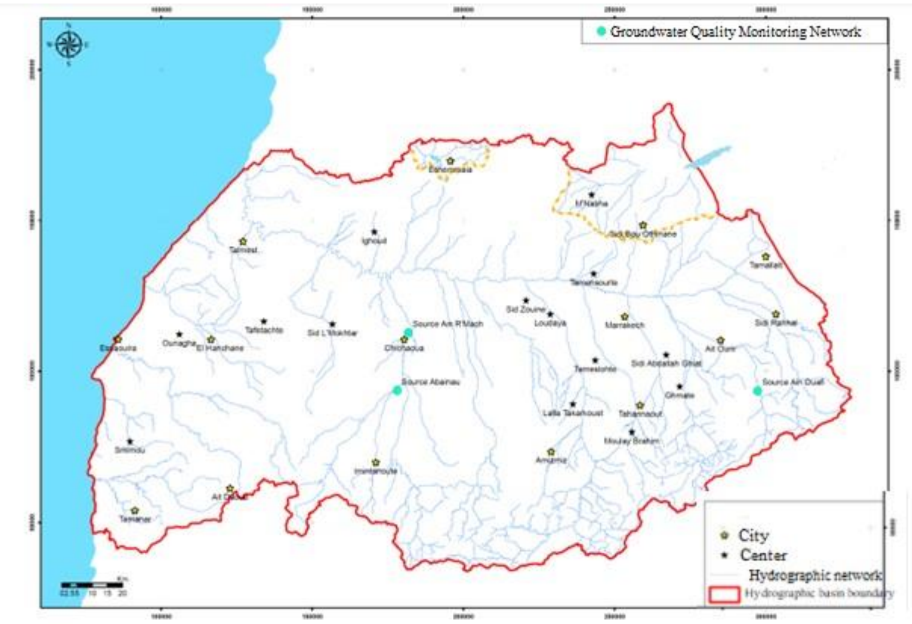


**Figure 2:** Source water quality monitoring network

## 3. Results and Discussions

### 3.1 Status of groundwater quality in the TWBA area of operation

The study area contains various types of groundwater resources. The TWBA conducted monitoring of the water quality of these resources from 2013 to 2017. The findings from this monitoring are presented below.

#### *3.1.1 Quality Of Aquifer Waters*

The following tables present the results of the quality monitoring campaigns for the aquifers tracked by the TWBA. Table 4 represents the results of Haouz aquifer quality. The groundwater quality in the Haouz aquifer, as assessed from various wells and drilling sites over multiple campaigns (March 2013, March 2015, August 2015, July-August 2016, October-November 2016, March 2017, and July 2017), demonstrates notable variability in key water quality parameters. Conductivity values fluctuate significantly, reflecting varying levels of dissolved solids. Some locations, such as Well Douar Laatamna, exhibit high conductivity, indicating elevated mineral content and potential salinity issues (Sarah et al., 2017).

Chloride ($Cl^-$) levels also show a wide range, from as low as 0.252 mg/l at Drilling National Office of Drinking Water Chichaoua to as high as 589 mg/l at Well Douar Laatamna in October-November 2016, suggesting differing degrees of salinity that may affect the water's suitability for agricultural and drinking use. Nitrate ($NO_3^-$) concentrations vary considerably, with some sites like Well Douar Khalifa Brik experiencing extremely high levels, up to 196.4 mg/l, likely due to contamination from agricultural runoff or other human activities. While ammonium ($NH_4^+$) levels are generally low, occasional spikes, such as 0.375 mg/l at Well Douar Laakaritta in March 2017, could indicate localized pollution. Organic matter (MO) and coliform bacteria (CFU/100ml) levels further illustrate the variability in water quality. Organic matter levels are elevated at some sites, suggesting possible organic pollution (Mabrouki et al., 2022). Coliform bacteria counts range from 0 CFU/100ml in several wells to extremely high levels, such as 100,000 CFU/100ml at Well Douar Talberjet in March 2013, highlighting differences in microbiological contamination across the aquifer. The overall water quality classification varies from "Excellent" to "Very Bad," with wells like Well Bidaoui generally showing good to excellent quality, while others, such as Well Douar Khalifa Brik and Well Douar Laatamna, frequently fall into the "Very Bad" category.

**Table 2**: Groundwater quality – Haouz aquifer

| Extraction Point | Campaign | Conductivity (µS/cm) | $Cl^-$ (mg/l) | $NO_3^-$ (mg/l) | $NH_4^+$ (mg $NH_4^+$/l) | MO (mg/l) | CF (CFU/100ml) | OverallQuality |
|---|---|---|---|---|---|---|---|---|
| Well Douar Ben Amen | Mars-13 | - | 72 | 5.600 | 0.132 | 0.630 | 10 | Good |
| Well Boule Houjet | Mars-13 | - | 94 | 16.000 | 0.031 | 0.700 | 20 | Good |
| Well Boujjemaa Razqui | Mars-13 | - | 122 | 83.000 | 0.010 | 1.410 | 250 | Bad |
| ONEP Sidi Rahal | Mars-13 | - | 241 | 15.000 | 0.032 | <0.22 | 0 | Good |
| AEP Boukraker | Mars-13 | - | 120 | 6.270 | 0.076 | 1.510 | 98 | Good |
| Well School of mins | Mars-13 | - | 198 | 43.000 | 0.022 | 0.510 | 44 | Average |
| Well Bidaoui | Mars-13 | - | 112 | 4.490 | 0.037 | 0.460 | 0 | Excellent |
| Well Douar laatamna | Mars-13 | - | 505 | 4.400 | 0.084 | 1.960 | 40 | Average |
| Well Douar Talberjet | Mars-13 | - | 211 | 2.350 | 0.096 | 1.820 | 100000 | Bad |

**Table 2 (Cont.)**: Groundwater quality – Haouz aquifer

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Drilling ONEP Chechaoua | Mars-13 | - | 152 | 21.000 | 0.041 | 0.480 | 0 | Good |
| Well Hacheabd rani | Mars-13 | - | 381 | 16.000 | 0.023 | 0.390 | 135 | Average |
| Drilling ONEP Attaouia | Mars-13 | - | 273 | 25.000 | 0.026 | 0.260 | 1500 | Average |
| Drilling ONEP Sahji | Mars-13 | - | 84 | 6.500 | 0.035 | 2.420 | 5 | Good |
| Well Douar Laakartta | Mars-13 | - | 504 | 21.000 | 0.035 | 0.990 | 1800 | Average |
| Well AEP Asni | Mars-13 | - | 13 | 9.890 | 0.090 | 1.440 | 174 | Good |
| Well Douar Ben Amer | Mars-15 | - | 68 | 6.170 | 0.013 | 0.320 | 0 | Good |
| Well Boulhoujet | Mars-15 | - | 123 | 17.000 | 0.012 | 0.920 | 14 | Good |
| Well Douar Khalifa Brik | Mars-15 | - | 275 | 181.000 | 0.109 | 2.720 | 1200 | Very bad |
| ONEP Sidi Rahal | Mars-15 | - | 243 | 16.400 | 0.013 | 0.580 | 0 | Good |
| AEP Douar Boukraker | Mars-15 | - | 176 | 9.120 | 0.008 | 0.660 | 14 | Good |
| Well School of mins | Mars-15 | - | 300 | 59.000 | 0.015 | 0.520 | 24 | Bad |
| Well Bidaoui | Mars-15 | - | 110 | 3.970 | 0.015 | 0.530 | 0 | Excellent |
| Well Douar Laatamna | Mars-15 | - | 518 | 4.340 | 0.008 | 2.06 | 32 | Average |
| Well douar Nouijji | Mars-15 | - | 270 | 3.145 | 0.009 | 0.510 | 0 | Good |
| Drilling ONEP Chichaoua | Mars-15 | - | 149 | 0.600 | 0.015 | 0.500 | 0 | Excellent |
| Well Harache Abd Rani | Mars-15 | - | 381 | 16.200 | 0.015 | 1.280 | 8 | Average |
| Drilling ONEP Attaouia | Mars-15 | - | 272 | 28.800 | 0.013 | 0.510 | 0 | Average |
| Well Douar Ouled Aakou | Mars-15 | - | 481 | 131.000 | 0.013 | 1.410 | 106 | Very bad |
| Well Laakartta | Mars-15 | - | 564 | 19.100 | 0.008 | 1.530 | 145 | Average |
| Well AEP Asni | Mars-15 | - | 11 | 1.010 | 0.042 | 0.780 | 2 | Excellent |
| Well Douar Ben Amer | Aug-15 | - | 76 | 7.626 | 0.066 | 0.780 | 4 | Goo |
| Well Boulhoujet | Aug-15 | - | 121 | 14.500 | 0.033 | 0.320 | 340 | Good |
| Well Douar Khalifa Brik | Aug-15 | - | 233 | 124.000 | 0.042 | 0.580 | 60 | Very bad |
| ONEP Sidi Rahal | Aug-15 | - | 239 | 17.700 | <0.007 | <0.218 | 0 | Good |
| AEP Douar Boukraker | Aug-15 | - | 184 | 6.000 | 0.015 | 0.320 | 0 | Good |
| Well School of mins | Aug-15 | - | 296 | 42.000 | 0.035 | 0.390 | 195 | Average |
| Well Bidaoui | Aug-15 | - | 110 | 3.090 | 0.009 | <0.218 | 16 | Excellent |
| Well Douar Laatamna | Aug-15 | - | 607 | 3.080 | 0.076 | 1.400 | 0 | Average |
| Well Douar Nouajji | Aug-15 | - | 246 | 2.480 | 0.019 | 0.520 | 360 | Good |
| Drilling ONEP Chichaoua | Aug-15 | - | 135 | 0.252 | 0.013 | 0.260 | 6 | Excellent |
| Well Harache Abd Rani | Aug-15 | - | 422 | 17.140 | 0.046 | <0.218 | 450 | Average |
| Drilling ONEP Attaouia | Aug-15 | - | 266 | 15.780 | 0.059 | <0.218 | 0 | Good |
| Well Douar Oulad Aakou | Aug-15 | - | 216 | 8.160 | 0.045 | <0.218 | 0 | Good |
| Well Douar Laakartta | Aug-15 | - | 146 | 25.200 | 0.049 | 1.890 | 24000 | Bad |
| Well AEP Asni | Aug-15 | - | 12 | 6.500 | 0.008 | <0.218 | 80 | Good |
| Well Douar Ben Amer | Jul-Aug 16 | 690 | 68 | 4.857 | <0.028 | <0.645 | 0 | Good |
| Well Boulhoujet | Jul-Aug 16 | 740 | 84 | 15.000 | <0.028 | <0.645 | 400 | Good |
| Well Douar Khalifa Brik | Jul-Aug 16 | 1756 | 194 | 103.000 | 0.040 | <0.645 | 1300 | Verybad |
| ONEP Sidi Rahal | Jul-Aug 16 | 1038 | 214 | 19.810 | <0.028 | <0.645 | 15 | Good |
| AEP Douar Boukraker | Jul-Aug 16 | 720 | 107 | 8.640 | 0.030 | 1.040 | 3200 | Average |
| Well School of mins | Jul-Aug 16 | 1649 | 271 | 57.000 | 0.025 | <0.645 | 60 | Bad |
| Well Bidaoui | Jul-Aug 16 | 840 | 116 | 2.113 | <0.028 | <0.645 | 90 | Good |
| Well Douar Laatamna | Jul-Aug 16 | 2560 | 566 | 2.858 | 0.46 | 1.200 | 35 | Average |
| Well Talborjt | Jul-Aug 16 | 945 | 192 | 5.488 | <0.028 | <0.645 | 2 | Good |
| Drilling ONEP Chichaoua | Jul-Aug 16 | 1789 | 356 | 1.230 | <0.028 | 0.930 | 0 | Average |
| Well Harache Abd Rani | Jul-Aug 16 | 1880 | 356 | 21.350 | <0.028 | 0.790 | 55 | Average |
| Drilling ONEP Attaouia | Jul-Aug 16 | 1336 | 241 | 35.000 | 0.028 | <0.645 | 70 | Average |
| Well Douar Oulad Aakou | Jul-Aug 16 | 2050 | 425 | 93.000 | 0.071 | 0.920 | 260 | Bad |
| Well Douar Laakaritta | Jul-Aug 16 | 2280 | 453 | 12.970 | 0.041 | 1.60 | 430 | Average |
| Well AEP Asni | Jul-Aug 16 | 438 | 15 | 5.200 | 0.050 | 0.780 | 0 | Good |
| Well Douar Ben Amer | Oct-Nov 16 | 795 | 74 | 8.000 | <0.028 | <0.645 | 6 | Good |
| Well Boulhoujet | Oct-Nov 16 | 707 | 95 | 16.000 | <0.028 | 2.160 | 20 | Good |

**Table 2 (Cont.)**: Groundwater quality – Haouz aquifer

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Well Douar Khalifa Brik | Oct-Nov 16 | 1755 | 205 | 121.000 | <0.028 | 0.930 | 122 | Very bad |
| ONEP Sidi Rahal | Oct-Nov 16 | 1072 | 229 | 17.000 | <0.028 | <0.645 | 2 | Good |
| AEP Douar Boukraker | Oct-Nov 16 | 906 | 176 | 11.000 | <0.028 | 1.370 | 225 | Good |
| Well School of mins | Oct-Nov 16 | 1470 | 226 | 39.000 | <0.028 | 0.660 | 16 | Average |
| Well Bidaoui | Oct-Nov 16 | 810 | 148 | 5.000 | <0.028 | <0.645 | 4 | Good |
| Well Douar Laatamna | Oct-Nov 16 | 2670 | 589 | 6.000 | <0.028 | 1.310 | 5600 | Average |
| Well Talborjt | Oct-Nov 16 | 1220 | 293 | 5.000 | 0.051 | <0.645 | 42 | Good |
| Drilling ONEP Chichaoua | Oct-Nov 16 | 1850 | 115 | 2.360 | <0.028 | 0.710 | 0 | Average |
| Well Harache Abd Rani | Oct-Nov 16 | 1975 | 364 | 20.000 | 0.032 | 0.780 | 35 | Average |
| Drilling ONEP Attaouia | Oct-Nov 16 | 1297 | 248 | 30.000 | 0.033 | <0.645 | 2 | Average |
| Well Douar Oulad Aakou | Oct-Nov 16 | 2047 | 412 | 97.000 | 0.051 | 0.910 | 112 | Bad |
| Well Douar Laakaritta | Oct-Nov 16 | 2290 | 484 | 21.000 | 0.030 | 0.910 | 260 | Average |
| Well AEP Asni | Oct-Nov 16 | 466 | 16 | 6.540 | <0.028 | <0.645 | 4 | Good |
| Well Douar Ben Amer | Mars-17 | 685 | 64 | 5.550 | 0.021 | <0.645 | 0 | Good |
| Well Boulhoujet | Mars-17 | 615 | 78 | 15.000 | 0.021 | <0.645 | 0 | Good |
| Well Douar Khalifa Brik | Mars-17 | 1985 | 227 | 133.000 | 0.021 | 1.300 | 0 | Verybad |
| ONEP Sidi Rahal | Mars-17 | 985 | 204 | 21.000 | 0.021 | <0.645 | 0 | Good |
| AEP Douar Boukraker | Mars-17 | 865 | 167 | 12.000 | 0.021 | <0.645 | 0 | Good |
| Well School of mins | Mars-17 | 1690 | 224 | 40.000 | 0.021 | <0.645 | 148 | Average |
| Well Bidaoui | Mars-17 | 730 | 100 | 7.200 | 0.021 | <0.645 | 0 | Good |
| Well Douar Laatamna | Mars-17 | 2140 | 476 | 22.000 | 0.021 | 1.450 | 0 | Average |
| Well Talborjt | Mars-17 | 1190 | 277 | 1.347 | 0.063 | 1.510 | 30 | Good |
| Drilling ONEP Chichaoua | Mars-17 | 1795 | 118 | 8.000 | 0.021 | <0.645 | 0 | Average |
| Well Harache Abd Rani | Mars-17 | 1930 | 375 | 18.000 | 0.033 | 1.150 | 290 | Average |
| Drilling ONEP Attaouia | Mars-17 | 1365 | 245 | 23.000 | 0.021 | <0.645 | 0 | Average |
| Well Douar Oulad Aakou | Mars-17 | 960 | 149 | 10.000 | 0.021 | <0.645 | 0 | Good |
| Well Douar Laakaritta | Mars-17 | 2400 | 485 | 18.790 | 0.375 | 0.910 | 6 | Average |
| Well AEP Asni | Mars-17 | 330 | 16 | 8.000 | 0.044 | 0.960 | 128 | Good |
| Well Douar Ben Amer | Jul-17 | 730 | 64 | 7.033 | 0.041 | 0.770 | 6 | Good |
| Well Boulhoujet | Jul-17 | 705 | 75 | 13.270 | <0.021 | 0.700 | 0 | Good |
| Well Douar Khalifa Brik | Jul-17 | 2280 | 273 | 196.400 | <0.021 | 1.220 | 150 | Verybad |
| ONEP Sidi Rahal | Jul-17 | 1020 | 204 | 21.000 | 0.022 | <0.645 | 20 | Good |
| AEP Douar Boukraker | Jul-17 | 885 | 172 | 9.840 | <0.021 | <0.645 | 17 | Good |
| Well School of mins | Jul-17 | 1630 | 296 | 67.300 | <0.021 | <0.645 | 0 | Bad |
| Well Bidaoui | Jul-17 | 730 | 93 | 3.680 | <0.021 | <0.645 | 8 | Good |
| Well Douar Laatamna | Jul-17 | 2400 | 440 | 2.930 | <0.021 | 0.860 | 0 | Average |
| Well Talborjt | Jul-17 | 1130 | 237 | 3.783 | <0.021 | <0.645 | 14 | Good |
| Drilling ONEP Chichaoua | Jul-17 | 1730 | 119 | 1.600 | <0.021 | <0.645 | 2 | Average |
| Well Station SOMEP | Jul-17 | 1580 | 302 | 16.300 | 0.021 | <0.645 | 34 | Average |
| Drilling ONEP Attaouia | Jul-17 | 1270 | 245 | 20.300 | <0.021 | <0.645 | 0 | Good |
| Well Douar Oulad Aakou | Jul-17 | 1135 | 177 | 2.850 | <0.021 | <0.645 | 0 | Good |
| Well Douar Laakaritta | Jul-17 | 2200 | 366 | 20.037 | 0.040 | 2.800 | 1100 | Average |
| Well AEP Asni | Jul-17 | 355 | 11 | 3.660 | 0.027 | <0.645 | 80 | Good |

The variations in groundwater quality across the Haouz aquifer underscore the complex interplay of natural and anthropogenic factors. Significant fluctuations in chloride and nitrate levels, along with the presence of coliform bacteria, suggest localized pollution sources. These sources likely include agricultural activities, improper waste disposal, and possibly natural saline intrusions. Natural geology and hydrology contribute to variations in mineral content, as seen in conductivity and chloride levels. High levels of these parameters might result from natural saline water or mineral dissolution from geological formations. Meanwhile, elevated nitrate levels, particularly in certain wells, point to agricultural runoff, likely from fertilizers. The presence of coliform bacteria indicates potential contamination from sewage or animal waste, posing health risks if the water is used for drinking purposes (Al-Aizari et al., 2023).

Temporal variations in water quality, potentially due to seasonal changes, varying human activities, or changing land use patterns, further complicate the situation. Persistent high nitrate and coliform levels at certain sites highlight ongoing pollution issues (Jeerapong et al., 2023).

For the Bahira aquifer, the data from Table 5 provides an overview of the groundwater quality in the Bahira aquifer, based on measurements taken at various extraction points during several campaigns from 2013 to 2017. The parameters analyzed include conductivity, chloride ($Cl^-$), nitrate ($NO_3^-$), ammonium ($NH_4^+$), organic matter (MO), coliform bacteria (CF), and an overall quality assessment.

The data reveals a range of water quality indicators across various sites and periods. Conductivity levels, although not consistently reported, fluctuated, reflecting varying levels of dissolved ions (Ouharba et al., 2024). For instance, Well Dehbi Maloud exhibited very high conductivity (4690 µS/cm) in March 2017, indicating significant mineralization. Chloride ($Cl^-$) concentrations also varied widely, with higher levels often linked to poorer water quality. A notable example is Well Abdelkrim Jikri, which consistently displayed high chloride levels, peaking at 655 mg/l in July 2017 and corresponding with a "Poor" quality rating.

Nitrate ($NO_3^-$) levels were elevated in several locations, such as Well Douar Neouaji, where it reached 80.0 mg/l in August 2015, raising concerns about potential agricultural runoff or contamination. Ammonium ($NH_4^+$) levels were generally low, indicating minimal recent organic pollution, though there were spikes, such as 9.600 mg $NH_4^+$/l in Well Laksir in March 2015. The Organic Matter (MO) content varied, with some samples, like Drilling ONEP Bounaqa (3.970 mg/l in July-August 2015), suggesting either organic pollution or natural organic content in the aquifer (Yulu and Luyao, 2020).

The presence of Coliform Bacteria (CF) in several samples indicated possible contamination, as seen in Well Douar Ouled Sbih with a high count of 1900 CFU/100ml in October-November 2016. The overall water quality assessment ranged from "Good" to "Very Poor," with many samples falling into the "Average" or "Poor" categories. Wells such as Dehbi Maloud and Abdelkrim Jikri consistently showed poor quality, pointing to chronic water quality issues at these sites.

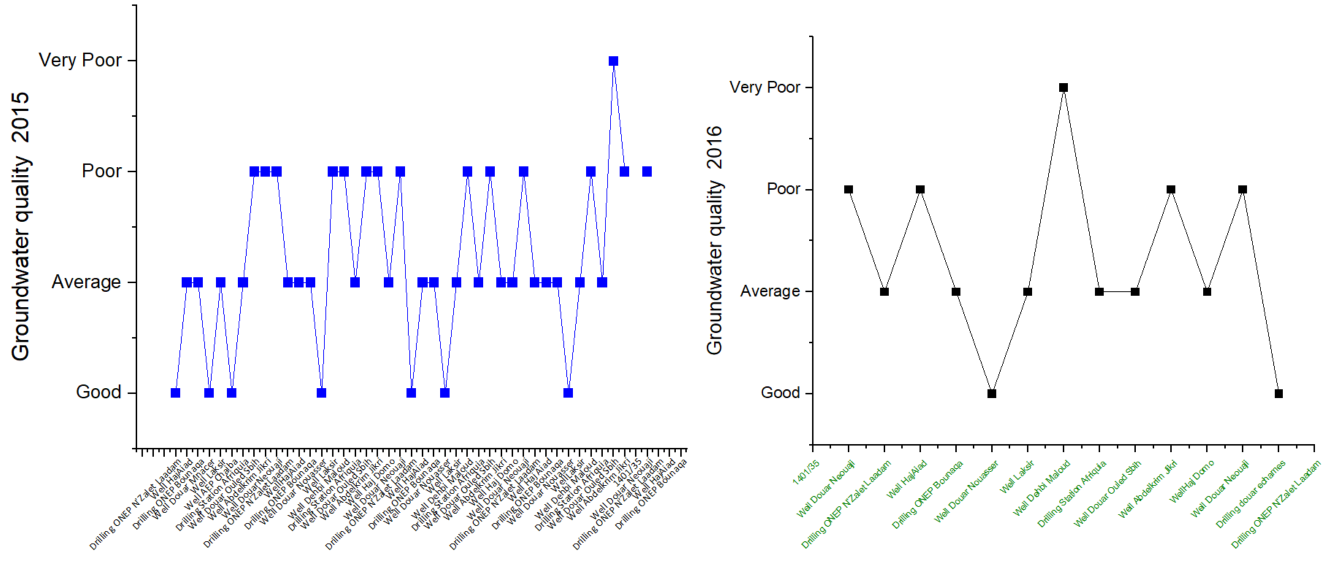


**Figure 3:** Groundwater quality – Bahira aquifer

The variation in groundwater quality parameters across different locations and times within the aquifer reveals a complex interplay of natural and anthropogenic influences. The observed fluctuations in conductivity, chloride, and nitrate levels suggest that both natural geological processes and human activities significantly impact water quality. High levels of chloride and nitrate are often associated with anthropogenic activities, such as the use of fertilizers in agriculture and improper waste disposal.

According to the TWBA report, which cites the 2014 census by the Ministry of Agriculture, the annual consumption of fertilizers in the Tensift watershed is estimated at 30,140 tons per year. Although this amount is relatively high, it remains lower than the quantities used in other watersheds such as Sebou, Oum Er Rabia, and Souss Massa Draa. Regarding nitrogen fertilizers, their consumption amounts to 5,964 tons per year, representing approximately 20% of the total amount of fertilizers consumed in the TWBA's area of action. Nitrates, being highly soluble and mobile in soil solution, are easily leached into groundwater, thus becoming a potential source of pollution for aquifers. The risk of nitrate ion leaching is generally assessed by referring to the potentially leachable nitrogen (PLN). In the Tensift-Ksob-Igouzoulen basin, the PLN was estimated, according to the same census, at 938 tons per year, constituting 16% of the total nitrogen consumed in the TWBA's area of action (ABHT, 2017).

The consumption of phosphate fertilizers in the study area is estimated at 7,836 tons per year. To evaluate the risk of eutrophication of surface waters by phosphorus, the quantities of phosphorus that could be transported by runoff (and erosion) to surface waters are calculated. The delivery rate used, which closely depends on the geomorphological characteristics of the basin, can reach up to 3% of the amount of phosphate fertilizers consumed. The presence of coliform bacteria in some samples further underscores potential contamination from sewage or animal waste, highlighting the influence of human activities on groundwater quality. Seasonal and temporal changes also play a crucial role in shaping groundwater quality. The data indicate fluctuations in water quality parameters over time, which may be linked to variations in groundwater recharge and extraction rates due to seasonal changes. For instance, increased conductivity and pollutant concentrations during certain periods could correspond to dry seasons, where reduced groundwater recharge leads to less dilution of contaminants. This seasonal variability underscores the importance of continuous monitoring to understand the dynamic nature of groundwater quality (Benchrifa et al., 2023). From a management perspective, the consistently poor quality observed in specific wells, such as Dehbi Maloud and Abdelkrim Jikri, indicates the need for targeted interventions. Implementing stricter controls on agricultural runoff, improving waste management practices, and enhancing regular monitoring are critical steps to mitigate contamination sources. Elevated nitrate levels and the presence of coliform bacteria raise significant public health and environmental concerns. Nitrate contamination, for instance, poses a risk of methemoglobinemia ("blue baby syndrome") in infants, while coliform bacteria presence signals potential pathogenic contamination (Gokulan et al., 2023).

Therefore, while some groundwater sources in the Bahira aquifer maintain good quality, others are significantly affected by contamination. A comprehensive groundwater management strategy, incorporating regular monitoring, pollution control measures, and community education, is essential to protect and enhance water quality in the region. Addressing these issues is critical to ensuring safe drinking water for local communities and safeguarding the aquifer's long-term sustainability (Alexandr et al., 2024;Diana et al., 2023; Evangelos et al., 2022).

Concerning the Essaouira aquifer, the data in Table 6 present a comprehensive analysis of the groundwater quality from various wells in the Essaouira aquifer, assessed across multiple sampling campaigns from March 2015 to July 2017. The table includes measurements of key water quality parameters such as conductivity, chloride ($Cl^-$), nitrate ($NO_3^-$), ammonium ($NH_4^+$), organic matter (MO), and coliform bacteria (CF). Out of 28 water quality analyses conducted between 2013 and 2017:71% indicated average quality; 25% indicated poor quality; and 4% were of good quality.

The poor quality was observed at two specific points: IRE n° 261/43 (March 2013) and IRE n° 621/43 (across 6 campaigns). The factors contributing to the degraded water quality are generally high conductivity, nitrates, and chloride. Nitrates are the primary cause of the poor quality observed. Specifically, IRE point n° 261/43 is located in the Meskala-Kourimate aquifer, while IRE point n° 621/43 is situated in the coastal aquifer. The overall water quality is average for the Meskala-Kourimate aquifer, whereas it ranges from average to poor for the coastal aquifer. The quality-degrading elements include nitrates, which are responsible for the poor quality, as well as salinity and chloride.

**Table 3:** Groundwater quality – Essaouira Aquifer

| Extraction Point | Campaign | Conductivity (µS/cm) | $Cl^-$ (mg/l) | $NO_3^-$ (mg/l) | $NH_4^+$ (mg $NH_4^+$/l) | MO (mg/l) | CF (CFU/100ml) | OverallQuality |
|---|---|---|---|---|---|---|---|---|
| Well Laaraich | March-15 | - | 629 | 25.0 | 0.064 | 4.140 | 290 | Average |
| Well Lahyala | March-15 | - | 476 | 52.6 | 0.089 | 1.7 | 36 | Poor |
| Well Ben Said | March-15 | - | 461 | 57.0 | 0.042 | 3.510 | 200 | Poor |
| ONEP Centre Hanchane | March-15 | - | 206 | 35.5 | <0.007 | 0.460 | 124 | Average |
| Well Laaraich | March-15 | - | 367 | 1.6 | 0.067 | 1.560 | 6100 | Average |
| Well Lahyala | March-15 | - | 266 | 24.7 | 0.013 | 0.860 | 20 | Good |
| Well Ben Said | March-15 | - | 507 | 11.2 | 0.023 | 1.820 | 225 | Average |
| ONEP Centre Hanchane | March-15 | - | 264 | 41.7 | 0.014 | 0.790 | 0 | Average |
| Well Laaraich | Aug-15 | - | 307 | 0.7 | 0.018 | <0.218 | 55 | Average |
| Well Lahyala | Aug-15 | - | 270 | 25.7 | 0.045 | 0.640 | 30 | Average |
| Well Ben Said | Aug-15 | - | 879 | 81.2 | 0.159 | 0.980 | 21000 | Poor |
| ONEP Centre Hanchane | Aug-15 | - | 263 | 44.0 | 0.039 | 0.770 | 0 | Average |
| Well Laaraich | Jul-Aug 16 | 1344 | 313 | 12.2 | <0.028 | 1.190 | 45 | Average |
| Well Lahyala | Jul-Aug 16 | 1563 | 242 | 26.6 | 0.068 | <0.645 | 0 | Average |
| Well Ben Said | Jul-Aug 16 | 1922 | 479 | 29.0 | 0.051 | 2.370 | 20 | Poor |
| ONEP Centre Hanchane | Jul-Aug 16 | 2130 | 219 | 33.2 | 0.066 | 1.06 | 0 | Average |
| Well Laaraich | Oct-Nov 16 | 1785 | 425 | 12.0 | <0.028 | 0.720 | 96 | Average |
| Well Lahyala | Oct-Nov 16 | 1640 | 260 | 24.0 | 0.04 | 1.310 | 48 | Average |
| Well Ben Said | Oct-Nov 16 | 1990 | 493 | 54.3 | <0.028 | 1.040 | 215 | Poor |
| ONEP Centre Hanchane | Oct-Nov 16 | 2060 | 210 | 31.0 | 0.04 | <0.645 | 0 | Average |
| WellLaaraich | March-17 | 1570 | 434 | 12.0 | 0.021 | 1.440 | 170 | Average |
| WellLahyala | March-17 | 1360 | 239 | 30.0 | 0.021 | 0.660 | 2 | Average |
| Well Ben Said | March-17 | 1895 | 497 | 57.3 | 0.021 | 1.180 | 108 | Poor |
| ONEP Centre Hanchane | March-17 | 1895 | 110 | 25.0 | 0.021 | <0.645 | 0 | Average |
| Well Laaraich | Jul-17 | 1730 | 421 | 10.8 | <0.021 | 0.780 | 4 | Average |
| Well Lahyala | Jul-17 | 1570 | 240 | 22.7 | <0.021 | 0.770 | 8 | Average |
| Well Ben Said | Jul-17 | 1920 | 369 | 57.8 | 0.046 | 1.3 | 310 | Poor |
| ONEP Centre Hanchane | Jul-17 | 1390 | 164 | 35.5 | <0.021 | 0.580 | 2 | Average |

The data indicate significant spatial and temporal variability in groundwater quality within the Essaouira aquifer, driven by a mix of natural and human-induced factors. Natural processes, such as the inherent salinity of the aquifer, particularly in coastal areas, may account for the high conductivity and chloride levels observed in some wells. This natural salinity could be exacerbated by seawater intrusion a common issue in coastal aquifers where the over-extraction of groundwater reduces the hydraulic head, allowing saline water to migrate inland and mix with freshwater. Seawater intrusion is a significant concern globally, as it can lead to the salinization of freshwater resources, rendering them unsuitable for drinking and irrigation. Agricultural activities also play a crucial role in influencing groundwater quality. Elevated nitrate levels, such as those found in Well Ben Said, are likely linked to the use of nitrogen-based fertilizers in nearby agricultural areas (Ahmed et al., 2024). Nitrates, being highly soluble in water, can easily leach into groundwater, especially in regions with intensive agriculture. The presence of nitrates above recommended limits poses significant health risks, particularly for infants and pregnant women, as it can lead to conditions like methemoglobinemia (blue baby syndrome). This situation underscores the necessity for improved agricultural management practices, such as precision farming and the use of alternative, less harmful fertilizers, to mitigate groundwater contamination. Human impact is further evidenced by the intermittent detection of coliform bacteria, suggesting possible contamination from sewage or animal waste. The presence of coliform bacteria in groundwater is a clear indicator of potential pathways for pathogenic microorganisms, posing serious public health risks. This contamination points to deficiencies in the region's sanitation infrastructure and highlights the need for better waste management practices. In many regions, inadequate sewage treatment and disposal systems can lead to the contamination of groundwater sources, particularly in densely populated or rural areas with limited infrastructure. Temporal trends show a concerning increase in conductivity and certain contaminants over time, indicating a gradual deterioration in water quality (Bencheikh et al., 2020). This decline may be driven by factors such as over-extraction of groundwater, which can reduce natural recharge rates and increase pollutant concentrations in the remaining water. Additionally, the impacts of climate change could exacerbate these trends by altering precipitation patterns, increasing the frequency and severity of droughts, and reducing the availability of water for natural aquifer recharge. These changes could further stress the aquifer system, making it more susceptible to contamination and depletion. Accordingly, the Essaouira aquifer is subjected to multiple pressures from both natural processes and human activities, which collectively impact its water quality. The scientific community and policymakers must address these challenges through comprehensive groundwater management strategies. These strategies should include monitoring and regulating water extraction, improving agricultural and waste management practices, and enhancing the region's infrastructure to ensure the sustainable use and protection of this vital water resource. Such measures are essential for safeguarding the aquifer, which is crucial for the region's economic development and public health (Nadjib et al., 2023; Fattah et al., 2021; Mabrouki et al., 2022; Fattah et al., 2021; Siti et al., 2023).

#### *3.1.2 Seasonal Evolution Of Quality*

The study of the seasonal evolution of groundwater quality is crucial for understanding the dynamic interactions between environmental factors and anthropogenic activities that affect water resources. It provides essential insights into the temporal fluctuations in water quality, which are vital for effective water resource management, public health protection, and sustainable development. By analyzing these seasonal changes, we can better identify and mitigate the impacts of pollution, climate variability, and other stressors on aquifers.

The seasonal evolution of groundwater quality in the Tensift Basin, as presented in Table 7, shows varying conditions across the Haouz, Bahira, and Essaouira aquifers over the period 2013-2017. The Haouz aquifer exhibited a decline in the percentage of wells classified as "Excellent," dropping from 7% in March 2013 to 0% from July-August 2016 onwards. In contrast, the proportion of wells with "Good" quality generally increased, peaking at 60% in July 2017. "Average" and "Poor" quality classifications fluctuated, while "Very Poor" remained relatively low, reaching a maximum of 13%. The Bahira aquifer consistently lacked "Excellent" quality water, with "Good" quality peaking at 27% in March 2013 and declining to 9% in subsequent years. Most wells fell into the "Average" category, with a slight increase to 64% in 2017. The proportion of "Poor" and "Very Poor" quality wells varied, with a notable increase in "Very Poor" classification in March 2017. The Essaouira aquifer showed no "Excellent" quality water throughout the period. The majority of wells were classified as "Average," with a stable 75% across most campaigns. A small proportion was rated "Poor," with the highest at 50% in March 2013 (Rihab et al., 2023; Elouardi, 2023).

The observed seasonal variations in groundwater quality across the Tensift Basin's aquifers underscore the complex interplay between natural and anthropogenic factors, further exacerbated by the impacts of climate change. The Haouz aquifer, which exhibited a decline in "Excellent" quality water and a corresponding increase in "Good" quality, suggests a potential improvement in management practices or natural recharge processes in recent years. However, the persistence of "Average" and "Poor" quality classifications highlights ongoing issues, possibly linked to agricultural runoff, industrial activities, and urbanization. The presence of "Very Poor" quality water, though limited, is concerning and may indicate localized pollution sources or over-extraction leading to a concentration of contaminants. In the Bahira aquifer, the absence of "Excellent" quality water and the predominance of "Average" and "Poor" quality classifications suggest significant water quality challenges. The slight increase in "Very Poor" quality water in March 2017 raises red flags regarding the aquifer's vulnerability to contamination. The consistency of "Average" quality water indicates a baseline level of contamination, potentially from natural mineral dissolution, agricultural practices, or insufficient wastewater treatment. The declining "Good" quality and fluctuating "Poor" classifications point towards variable management and environmental pressures (Fattah et al., 2021). The Essaouira aquifer's lack of "Excellent" quality water and the dominance of "Average" classification across all campaigns reflect a stable but concerning level of water quality. The periodic presence of "Poor" quality water indicates localized issues, possibly related to seawater intrusion, given the aquifer's coastal proximity, and agricultural activities. The lack of significant improvement over time suggests that existing management strategies may be insufficient to address the underlying causes of water quality degradation (Mabrouki et al., 2022). Climate change may play a critical role in these observed patterns by altering precipitation patterns, increasing the frequency and severity of droughts, and reducing natural recharge rates. These changes can exacerbate the stress on groundwater resources, making them more susceptible to contamination from surface activities and reducing the dilution capacity of the aquifers. Moreover, rising temperatures can accelerate the decomposition of organic matter and increase the mobility of certain pollutants, further compromising water quality (Fattah et al., 2021). Consequently, the data reflect a complex and evolving situation in the Tensift Basin's groundwater quality, influenced by a combination of natural factors, human activities, and climate change. Addressing these challenges will require a comprehensive approach, including improved monitoring, sustainable management practices, and adaptive strategies to mitigate the impacts of climate change on water resources (Siti, 2023; Rihab et al., 2023).

### 3.2. Impact of climate change on groundwater recharge the Tensift basin

Climate change is significantly affecting groundwater recharge in the Tensift Basin, with notable impacts on water quality across the Haouz, Bahira, and Essaouira aquifers. According to data collected between 2013 and 2017, there has been a marked decline in groundwater quality, particularly in the Haouz aquifer. The percentage of water classified as "Excellent" dropped from 7% in March 2013 to 0% by July 2017 (table 7). Meanwhile, "Good" quality water saw a gradual increase from 47% to 60%. This shift suggests that while some improvements have been made, the overall quality remains inconsistent, with a persistent presence of "Average" and "Poor" classifications.

In the Bahira aquifer, the water quality data indicate a predominance of "Average" quality, consistently ranging from 45% to 64% (table 7). The "Poor" category showed significant fluctuations, with periods where up to 45% of the water samples were classified as such, highlighting ongoing challenges in maintaining stable water quality. The absence of "Excellent" water quality and minimal "Good" classifications point to a need for improved water management strategies. Meanwhile, the Essaouira aquifer consistently showed a majority of "Average" quality water, with "Poor" water also present, indicating the region's vulnerability to climate-related changes and seawater intrusion.

These trends underscore the broader challenges posed by climate change in the region, including increased evapotranspiration and altered precipitation patterns. The data reflect a general decline in water quality, likely influenced by factors such as rising temperatures and variable rainfall. This scenario stresses the urgency for implementing sustainable water management practices, enhancing monitoring systems, and strengthening policies to mitigate the impacts of climate change on groundwater resources.

## 4. Conclusion

The groundwater quality in the Tensift Basin, encompassing the Haouz, Bahira, and Essaouira aquifers, reveals significant spatial and temporal variability, influenced by both natural and anthropogenic factors. This variability is further compounded by the impacts of climate change, as evidenced by the observed decline in water quality, particularly in the Haouz aquifer, where excellent quality water has vanished, and good quality has only slightly improved. The persistent issues of high salinity, nitrates, and coliform bacteria, especially near urban areas and agricultural zones, underscore the need for urgent intervention.

The Bahira aquifer faces consistent challenges with average to poor water quality, primarily driven by geological factors and agricultural pollution. The situation in the Essaouira aquifer, characterized by average to poor water quality, highlights the region's susceptibility to marine intrusion, which is exacerbated by rising sea levels and reduced recharge rates. These findings indicate that a significant portion of the monitored points report water quality ranging from average to good, with minor seasonal variations. However, the presence of coliform bacteria and fluctuating mineral content raises serious concerns about sanitary conditions and contamination risks. Addressing these challenges requires comprehensive groundwater management, including enhanced monitoring, sustainable practices, and adaptive strategies to mitigate the impacts of climate change. Such measures are essential for ensuring safe drinking water, protecting public health, and maintaining the sustainability of groundwater resources in the Tensift Basin. The data call for a concerted effort to improve wastewater treatment, regulate agricultural practices, and develop resilient infrastructure to safeguard the region's vital water resources.

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