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1 **Multi-decadal analysis of water resources and agricultural change in a Mediterranean**  
2 **semiarid irrigated piedmont under water scarcity and human interaction**

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15 **Abstract**

16 Mediterranean piedmonts are an important hydro-agricultural systems. They constitute the junction  
17 between the mountains, where the streamflow is generated, and the surrounding plains, where the water  
18 is used. In Morocco, these traditional systems extend largely along the High Atlas Mountains. Yet,  
19 changing conditions in the Mediterranean basin as well as recurrent droughts in recent decades remain  
20 poorly understood in terms of hydrological and agricultural impacts, particularly in traditional hydro-  
21 agro-systems. The combined effects of climate variability and ineffective management of water resource  
22 dynamics may lead to increased water scarcity in these regions. The present work aims to assess the  
23 effects of climate variability and associated agricultural changes on water resources in a traditional  
24 irrigated piedmont of the Moroccan High Atlas. To that end, a trend analysis, together with change  
25 points detection, was carried out on annual and monthly precipitation, and streamflow from 1965 to  
26 2018. Then, the standardized precipitation index (SPI) was employed to identify meteorological

27 droughts. Also, groundwater, and spring discharge data were analyzed and discussed from 1973 to 2021.  
28 SPI outcomes revealed three major droughts, in 1981-1988, 1999-2008, and 2013-2018. Although the  
29 precipitation data showed no significant trend, except for Tahannaout station, the average annual  
30 precipitation over the piedmont area decreased by 28%. Similarly, streamflow decreased significantly  
31 by almost 40% for all stations, as did the Abainou spring's discharge. Consistent with that, groundwater  
32 level has declined dramatically over the past decades in the downstream piedmont. These decreases in  
33 water cycle components were tightly aligned with droughts. Yet, irrigation diversions were maintained  
34 in both dry and wet periods. Paradoxically, this decrease in water resources was associated with an  
35 agricultural transition from seasonal crops (cereals) to perennial crops (olive trees). This conversion is  
36 likely to amplify the water shortage, leading to groundwater resources overexploitation to satisfy the  
37 growing agricultural demand.

38 **Keywords:** Mediterranean region, precipitation, streamflow, groundwater, agriculture, trends  
39 analysis.

## 40 **1 Introduction**

41 The world's population has almost doubled from 1990 to the present, from 4.9 to 7.8 billion  
42 people ([U.S.Census Bureau, 2019](#)). Representing roughly 6.8 % of the world's population, the  
43 Mediterranean region was home to approximately 537 million inhabitants in 2015 with  
44 projections to reach 670 million by 2050; of whom more than 250 million are distributed in  
45 hydrological basins ([World Bank, 2015](#); [FAO 2015](#)). Consequently, food and water demands  
46 have increased in the Mediterranean region, putting higher pressure on water resources  
47 ([Godfray et al., 2010](#); [Lopes, et al., 2020](#)) and soils ([Karamesouti et al., 2015](#)), especially in the  
48 east and southern parts, the most water-scarce areas ([Daccache et al., 2014](#); [Mekonnen and](#)  
49 [Hoekstra 2016](#); [United Nations 2017](#); [Tabari, 2020](#)). Moreover, the Mediterranean basin is  
50 identified as a hotspot of climate change ([Giorgi, 2006](#); [Diffenbaugh and Giorgi, 2012](#)) with a  
51 foreseen increase in temperature, decline in precipitation, and an intensification of the number

52 and intensity of extreme events in terms of floods and droughts, as well as a change in the  
53 seasonal distribution of rainfall (Schilling et al., 2012; EEA, 2012; Trambly et al., 2013).

54 Mountains around the Mediterranean are the water towers for the adjacent lowland basins  
55 (Jarlan et al., 2015, 2016). these mountains supply water for irrigation and other water needs in  
56 piedmonts and downstream plains (Viviroli et al., 2007, 2011; Immerzeel et al., 2010). In a  
57 recent study, Viviroli et al. (2020) showed that almost 1.5 billion people would depend on  
58 runoff contributions from mountain areas by the mid-twenty-first century. However, mountains  
59 are also sensitive systems to climatic variability (Parry et al., 2007; Solomon et al., 2007;  
60 Viviroli et al., 2011; Cuni-Sanchez et al., 2016; Immerzeel et al., 2020). In semiarid basins, the  
61 plains are characterized by low precipitation, high evapotranspiration, and deep unsaturated  
62 zones. However, the piedmont areas at the interface between mountains and plain benefit from  
63 milder climatic conditions and water availability from upstream runoff that have made them  
64 suitable locations for the settlement of rural communities and their farming activities (Van  
65 Steenbergen et al., 2011; Bresciani et al., 2018; Cody, 2018). Water availability in the piedmont  
66 areas is closely related to the rainfall and snowmelt in the surrounding mountains that feed  
67 streamflow and groundwater from winter to early summer. Those conditions have led to the  
68 development of traditional irrigation in these piedmont areas.

69 Piedmont traditional irrigation systems use networks of gravity-fed surface irrigation earth  
70 channels that divert floodwater from the river to supply irrigation from the piedmont to the  
71 plain. The traditional irrigation system is mostly based on redistributing water from streams and  
72 expanding the water flooded areas. In addition to satisfying the agricultural water requirements,  
73 this practice promotes groundwater recharge (Bouimouass et al., 2020). Recent studies have  
74 shown that it has a positive impact on groundwater quality through irrigation returns from high-  
75 quality snowmelt-fed streamflow (Bouimouass et al., 2022, Rotiroti et al., 2019). Conversely,  
76 modern irrigation uses water from dams, and a distribution network of concrete channels and

77 relies more on groundwater abstraction. This system uses also drippers that deliver water  
78 directly to the plant's root zone, losing any additional groundwater recharge supplies, thus  
79 generally inducing negative effects on groundwater quantity and quality (Scanlon et al., 2007;  
80 Bouimouass et al., 2022). The so-called “spate irrigation” is one of the oldest traditional  
81 irrigation systems widely used all over the world. It is found especially in the Middle East,  
82 North Africa, West Asia, East Africa, Europe, and parts of Latin America (Van Steenberg et  
83 al. 2011; Fernald et al., 2015; Leibundgut & Kohn, 2014). However, this irrigation system  
84 underwent a considerable decline in the second half of the 20<sup>th</sup> century (Leibundgut & Kohn,  
85 2014b). This system has been in practical use in very different and contrasted environmental  
86 regions around the globe (Fernald et al., 2015; Leibundgut & Kohn, 2014; Mehari et al., 2007;  
87 Tesfai, & Stroosnijder, 2001). For instance, in the semi-arid upper Rio Grande of the United  
88 States, Fernald et al. (2015) reported that community irrigation systems, known as *Acequia*,  
89 which is derived from the word *segua* in Arabic meaning an irrigation channel, have been  
90 governed by users to divert water from streams to irrigate northern New Mexico's agriculture  
91 for centuries. In the northern side of High Atlas in Morocco, traditional irrigation uses not only  
92 floods (like spate irrigation), but also the baseflow as long as the wadis might flow during  
93 several months, especially thanks to snowmelt (Bouimouass et al., 2020). It is practiced through  
94 a secular network of irrigation channels locally named *seguias*. During the 20<sup>th</sup> century, the  
95 main agricultural plains were converted to modern agriculture (Le Page et al., 2021), irrigated  
96 by dams, concrete canals networks, and wells, thus making the traditional irrigation systems a  
97 typical feature of the High Atlas piedmonts.

98 In a context characterized by droughts, water scarcity, and increasing water demand,  
99 particularly in the semi-arid Haouz-Tensift basin, it is necessary to know how those hydro-agro-  
100 systems are evolving in terms of agricultural activities and hydrological behavior. Towards the  
101 end of the century, average winter temperatures in the Moroccan High-Atlas are expected to

102 increase by 2 to 4°C simultaneously with a 25% to 60% reduction in precipitations (Tuel et al.,  
103 2020b; Hadri et al., 2020; Ayt Ougougdal et al., 2020; Driouech et al., 2020). Therefore, recent  
104 studies based on hydrological models have pointed to a potential decrease in water resources  
105 for the southern Mediterranean region (Prudhomme et al., 2014; Marchane et al., 2016; Tuel et  
106 al., 2020a). Snow constitutes a significant part of the precipitation over the High Atlas  
107 Mountains (Hajhouji et al. 2018; Tuel et al., 2020a). Snowmelt contribute substantially to  
108 streamflow during spring, ranging from 7 to 50% depending on the year (Boudhar et al., 2009),  
109 providing water for irrigation. Temperature rise may result in the degradation of the snowpack  
110 and rapid snowmelt inducing changes in the wadis hydrological regimes (Lopez-Moreno et al.,  
111 2004, 2017; Trambly et al., 2018), threatening irrigation period. Additionally, an overarching  
112 program, the Green Morocco Plan (GMP), was launched by the government to develop the  
113 agricultural sector while preserving water resources by promoting a large expansion of drip  
114 irrigation. However, the promised water savings allowed by this technology have been  
115 challenged by evidence from the field. Indeed, the benefits obtained by increased productivity  
116 and farmers' incomes, and the shift to high-value crops have been accompanied by a greater  
117 pressure on groundwater exacerbating its depletion (Venot et al., 2017). Therefore, assessing  
118 the evolution of water resources and agriculture in a semi-arid context is a prerequisite for a  
119 prospective analysis of their evolution which will help to guide public policies toward  
120 sustainable management of water resources.

121 The present study aims firstly to assess the hydrological variability and water resource trends  
122 in the northern piedmont of the High-Atlas range from 1965 to 2020. Then the evolution of  
123 agricultural land use is analyzed from 1984 to 2020, with a focus on changes affecting the  
124 expansion of trees. The challenges that traditional irrigation systems in the piedmont face, as  
125 well as their sustainability issues are then discussed. Also, the study takes into account the  
126 spatial heterogeneity of the central High-Atlas piedmont, which is divided into three subareas

127 with distinct characteristics (Fig. 1): the Central Haouz, which has high surface water  
128 availability as traversed by the basin's main wadis, the Mejjate, where groundwater is almost  
129 the only available water resource, and the Chichaoua valley, which is irrigated by the region's  
130 largest spring.

## 131 **2 Study area**

### 132 **2.1 Water resources**

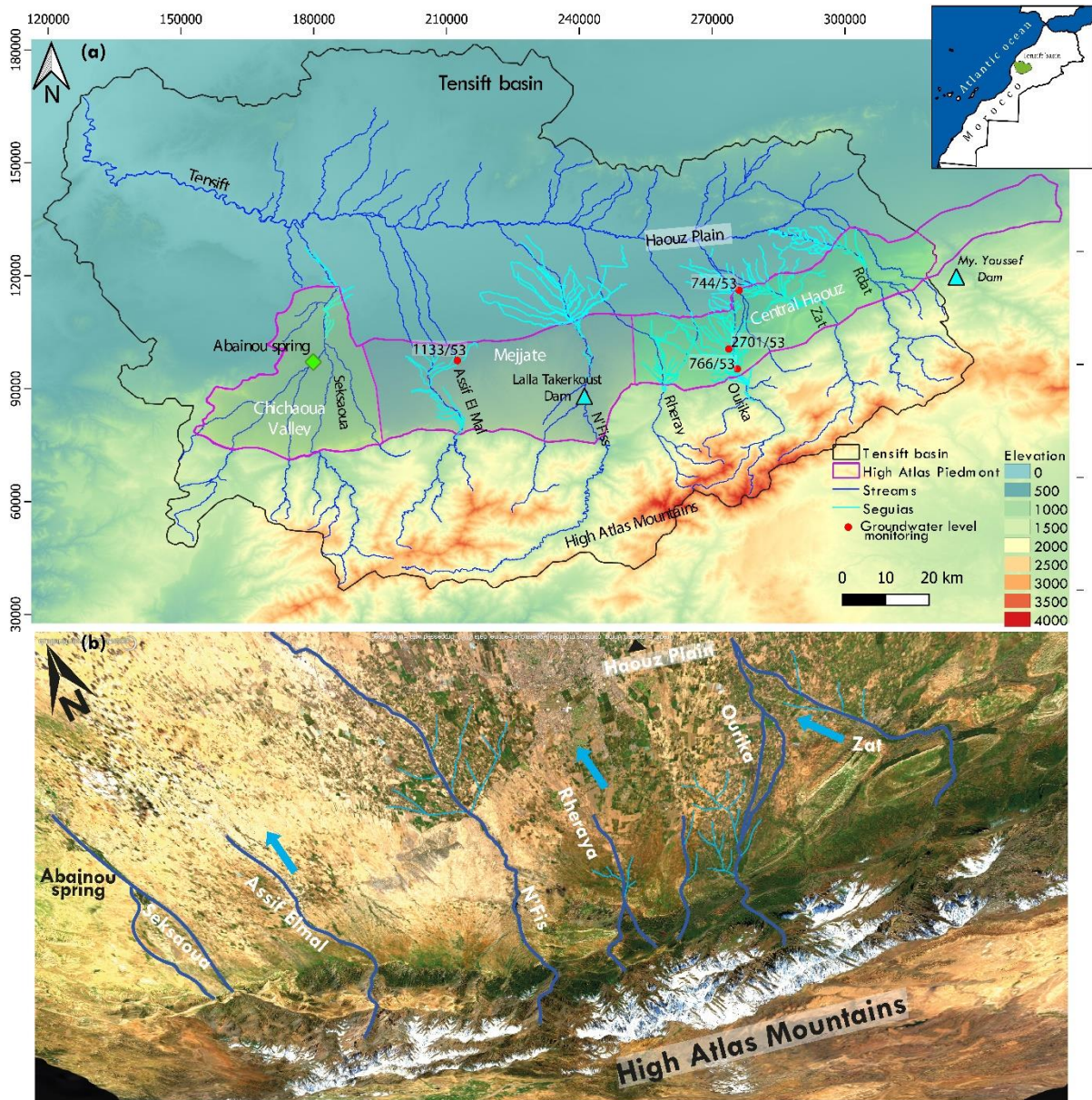
133 The northern piedmont of the High Atlas, covering approximately 4400 km<sup>2</sup>, is located in the  
134 Tensift watershed, in central Morocco. It is a transitional area between the High-Atlas  
135 Mountains (culminating at 4167 m.a.s.l.) and the Haouz plain ranging between 300 and 600  
136 m.a.s.l. (Fig. 1). This piedmont is fed by intermittent and ephemeral wadis issued from the  
137 mountains, but it is also crossed by larger wadis with mainly permanent streamflow, except  
138 during some drought summers. From East to West these wadis are the Rdat, Zat, Ourika,  
139 Rhiraya, N'Fis, Assif El Mal, and Seksaoua. During exceptional rainfall events, these wadis  
140 may flow until the Tensift wadi at the north of the Haouz plain. The streams of the Eastern  
141 piedmont have higher mean streamflow rates: Ourika 4.62 m<sup>3</sup>s<sup>-1</sup>, Zat 3.33 m<sup>3</sup>s<sup>-1</sup>, Rheraya 1.60  
142 m<sup>3</sup>s<sup>-1</sup>, and Rdat 2.34 m<sup>3</sup>s<sup>-1</sup>. The peaking point of runoff occurs during the springtime, around  
143 April, as a result of snowmelt (Boudhar et al., 2009; Marchane et al., 2017; Hajhouji et al.,  
144 2018). The average contribution of snowmelt to annual runoff represents around 19%, 36%,  
145 41%, 22%, and 7% for N'Fis, Rheraya, Ourika, Zat, and Rdat basins respectively (Boudhar et  
146 al., 2009). The wadis in the western piedmont have a pluvial runoff regime and lower average  
147 flow: Seksaoua 0.65 m<sup>3</sup>s<sup>-1</sup>. Groundwater is contained in a large Plio-Quaternary alluvial aquifer,  
148 which extends continuously over the piedmont and the Haouz plain. Groundwater flows from  
149 the piedmont to the plain. It is withdrawn by wells and boreholes for drinking water of rural  
150 population and irrigation in dry seasons. Spring discharge is uncommon in the area, and only a

151 few springs have measurable flow rates. The largest one is Abainou which irrigates the  
152 Chichaoua valley.

## 153 **2.2 Agriculture and Irrigation**

154 Traditional family agriculture is still the main activity in the piedmont area, consisting mainly  
155 of olive trees and winter cereals (wheat and barley). Most of the olive orchards are associated  
156 with an understory of annual crops, mainly cereals or forage, in order to optimize water use.  
157 Local farmers use an extensive network of seguias, to divert water from the streams (Fig.2).  
158 Each irrigation system is managed by local Water Users Associations (WUAs) jointly with the  
159 Office Regional de Mise en Valeur Agricole du Haouz (ORMVAH) which ensures the  
160 distribution of streamflow between seguias with respect of the water rights where the principle  
161 of upstream priority of water use is generally adopted ([Kharrou et al., 2021](#)). The same system  
162 is applied to Abainou spring, located in the valley of Chichaoua (Fig. 1).





163

164 *Figure 1: (a) The High Atlas piedmont (purple line) is located within the Tensift basin (black line) and is divided into three sub-*  
 165 *areas: the central Haouz which is the most important traditional surface water-based irrigation area, the Mejjat area relying*  
 166 *mainly on groundwater for irrigation and the Chichaoua Valley with irrigation based on the Abainou spring; (b) represents a*  
 167 *sentinel-2 scene displaying the main features of the High Atlas piedmont.*

168 This ancestral community-based irrigation system was built to share the water of snowmelt-  
 169 fed streams coming from the High-Atlas between farmers to support their local livelihoods.  
 170 Each major segouia ramifies into several secondary segouias, which in turn ramifies into tertiary  
 171 segouias (Fig. 2). The major segouia is governed by a WUA and each secondary segouia has a

172 delegate chosen in agreement by all the seguia members who are responsible for the water  
173 distribution between beneficiaries according to the historical and recognized water rights. A  
174 major seguia irrigates lands up to thousands of hectares and hundreds of users.



175  
176 *Figure 2: Photos of seguias from the study area, representing Seguias network in the piedmont; A: tertiary seguia irrigating*  
177 *fields, B: secondary seguia uptake, and C: the major Seguia diverting water directly from the Ourika stream.*

### 178 **3 Material and methods**

#### 179 **3.1 Hydro-meteorological data and analysis**

180 For this study, we used several hydro-meteorological datasets concerning rainfall,  
181 streamflow, irrigation water, groundwater level, and spring discharge (Fig. 1 S). Rainfall is  
182 measured by ORMVAH and the basin agency (ABHT, Agence du Bassin Hydraulique du  
183 Tensift), with records available since 1969. A large network of rain gauges was used to  
184 elaborate a spatiotemporal distribution map of the entire Tensift basin. Five gauges were  
185 selected within the piedmont area (Table 1, Fig. 1 S) to analyze rainfall trends and evaluate  
186 droughts.

187 *Table 1: The piedmont rainfall stations network used in the study.*

| Stations   | Lambert coordinates |        | Elevation (m) | Recording periods |
|------------|---------------------|--------|---------------|-------------------|
|            | X (Km)              | Y (Km) |               |                   |
| Sidi Rahal | 303.1               | 117.8  | 690           | 1967-2018         |
| Ait Ourir  | 291.25              | 107.5  | 760           | 1969-2018         |
| Ourika     | 276.15              | 83.05  | 1070          | 1969-2018         |
| Tahannaout | 255.9               | 80.4   | 925           | 1969-2018         |
| Chichaoua  | 181.53              | 111.2  | 340           | 1965-2018         |

188

189 The daily streamflow dataset at the gauging stations of the main wadis from the High Atlas  
190 from 1965 to 2018 were provided by the ABHT. The diversion of streamflow for irrigation was  
191 monitored at the upstream uptake of the seguias jointly by the WUAs and ORMVAH and the  
192 distribution of water among seguias is made according to the recognized water rights. We also  
193 calculated the seguias diversion ratio using water diversion records from 2000 to 2020 provided  
194 by ORMVAH.

195 The variation of the groundwater level over the Tensift basin is monitored by the ABHT. In  
196 this study, four piezometers named 766/53, 2701/53, 1133/53, and 744/53 (Fig. 1, and 1 S) were  
197 selected to show the groundwater variation from 1984 to 2021 upstream and downstream of the  
198 piedmont area. Finally, the Abainou spring discharge was measured by the ABHT at a monthly  
199 timestep from 1973 to 2020.

### 200 **3.2 Landsat imagery**

201 To characterize the agricultural land use evolution, a time series of classifications based on  
202 multispectral Landsat imagery was achieved. Crop classification was performed using a  
203 decision tree (DT) approach based on expert rules. DT can be trained rapidly and executed  
204 quickly (Gahegan & West, 1998). It performs well for land use mapping (Yang et al., 2003;  
205 Waheed et al., 2006; Otukey, & Blaschke, 2010; Jiang et al., 2011; Sharma et al., 2013),

206 especially when phenological data or vegetation index threshold values are incorporated  
207 (Wardlow et al., 2007; Simonneaux et al., 2008b; Masialeti et al., 2010; Ozdogan, 2010). To  
208 that end, all available cloud-free Landsat images corrected in surface reflectance from 1984 to  
209 2020 were downloaded from the USGS (the United States Geological Survey) website,  
210 including Landsat 5 (TM), Landsat 7 (ETM+), and Landsat 8 (OLI).

### 211 **3.3 Methods**

#### 212 *3.3.1 Statistical analysis of hydro-meteorological time series*

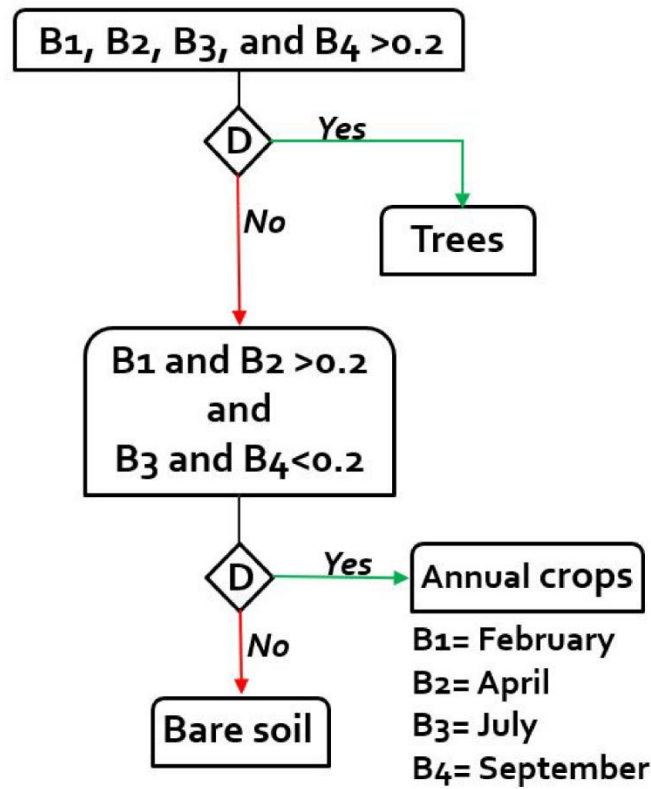
213 The non-parametric statistical test of Mann-Kendall (MK) (Mann 1945, Kendall 1975) and  
214 Sen's slope estimator (Sen, 1968) was performed on precipitation and streamflow time series  
215 to assess the presence or absence of a clear trend in the long-term evolution of water resources  
216 within the High Atlas piedmont. In addition, the Pettitt (1979) test was used to determine the  
217 trend change points and check the homogeneity of the data. Also, the meteorological droughts  
218 over the piedmont were assessed by the Standardized Precipitation Index (SPI). SPI was  
219 developed by McKee et al. (1993) and Edwards and McKee (1997) and recommended by the  
220 World Meteorological Organization (Hayes et al., 2011; WMO, 2012).

#### 221 *3.3.2 Mapping agricultural land use*

222 In traditional systems such as the High-Atlas piedmont, the use of Landsat imagery for  
223 monitoring agricultural activities is quite challenging because of the predominance of small  
224 agricultural fields of less than one hectare, as compared with the 30-meter resolution of Landsat.  
225 However, the simplicity of the land cover, consisting of three classes, and the fact that they are  
226 often aggregated in homogeneous patches, limits the problem of confusion. Another problem  
227 is that historical Landsat data was not always acquired every 16 days and the occurrence of  
228 cloud cover, especially during the crop development phases of winter crops, reduces the

229 availability of usable images. An additional key limitation was the lack of ground data to be  
230 able to train the classifier for past years. Thus, in order to be able to build a land cover time  
231 series for the period 1984-2020, we built a simple decision tree algorithm based on the temporal  
232 signature of the crops using a limited number of key periods for which the land cover classes  
233 have contrasted behaviors. Indeed, there are usually not enough clear Landsat images to be able  
234 to build a temporal profile of vegetation development that would be required to apply a decision  
235 tree approach as proposed by (Simonneaux and Francois, 2003; Simonneaux et al., 2008b).  
236 Instead, for most of the years, we were able to find images distributed over the agricultural  
237 season (February, April, June, and August).

238 The olive tree is an evergreen species and exhibits vegetation all along the year, which means  
239 an NDVI value (Normalize Difference Vegetation Index) is always higher than the ones of bare  
240 soils. Cereal crops are characterized by the first period of bare soil around December/ early  
241 January, then a peak of vegetation around March, and another phase of bare soil after harvest.  
242 Based on these simple rules, a decision tree classifier has been built based on images selected  
243 at four periods (B1= February, B2 = April, B3 = July, and B4 = September) (Fig. 3).



244

245

Figure 3: The decision tree classification based on NDVI over four key periods.

246

In order to validate the classification results, ground truth data were collected during a field

247

mission conducted on December 4, 2020. A total of 76 parcels were observed, 26 plots of olive

248

trees, 28 plots where cereals were grown in winter 2020, and 22 of fallow bare soil showing

249

that no crop was present for at least one year. In addition to the field trip, trees and bare soil

250

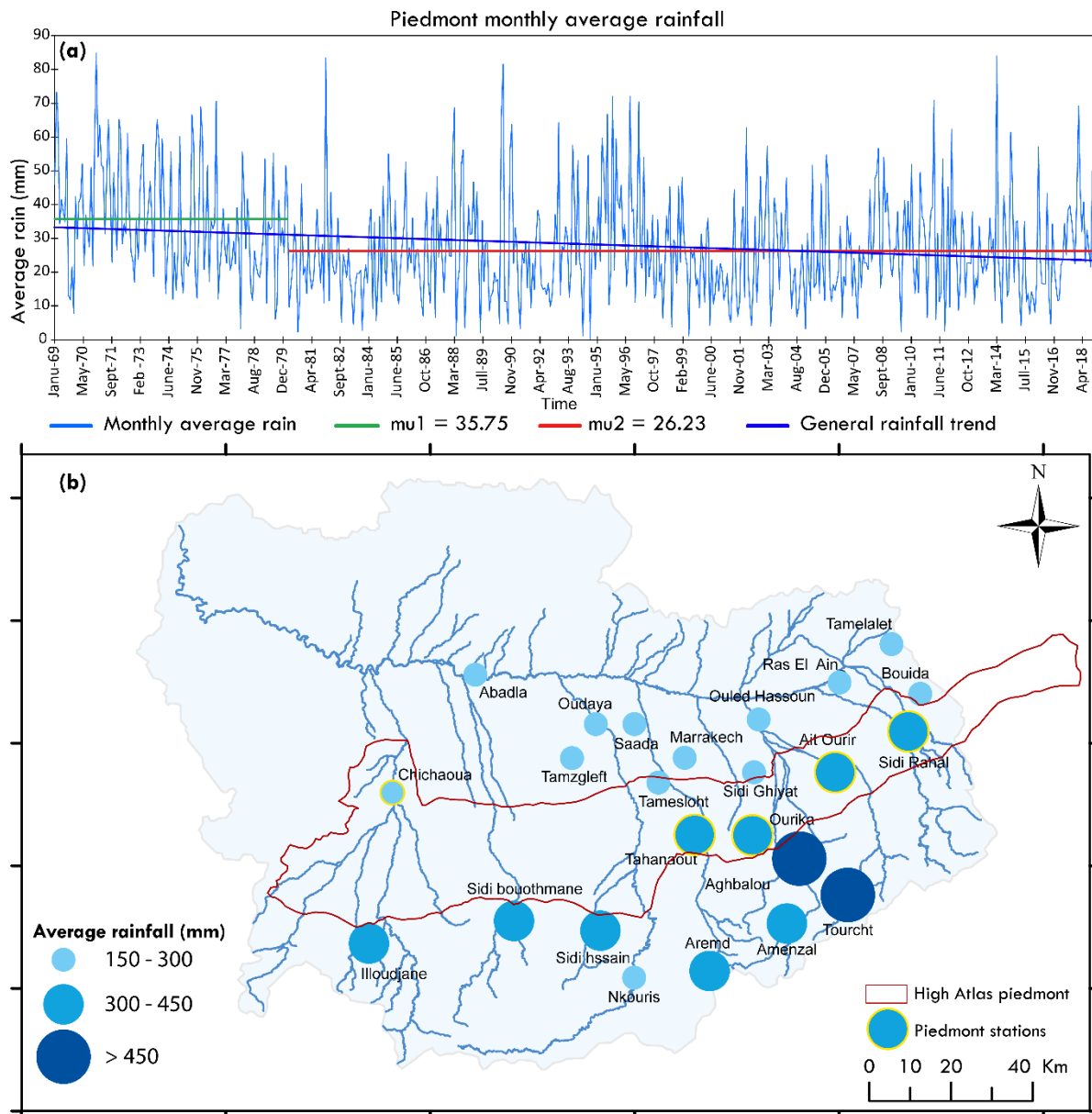
plots (parcels) were selected on Google Earth for the years 2005, 2010, and 2015 to check the

251

presence or absence of trees.

252 **4 Results**

253 **4.1 Rainfall trends and meteorological droughts**



254  
 255 *Figure 4: (a) Monthly average rainfall evolution over the High-Atlas piedmont from 1969 to 2018, where  $\mu_1$  is the mean*  
 256 *annual rainfall (mm) before the change point and  $\mu_2$  as the mean annual rainfall (mm) after the change point. (b) The Tensift*  
 257 *basin with precipitation stations showing the spatio-temporal distribution of average annual precipitation (1969 to 2018).*

258 In figure (4, b), there are three altitude bands, the lowland to the north with altitudes between  
 259 300-600m where the rainfall varies between 150-300mm/year, the piedmont area with altitudes

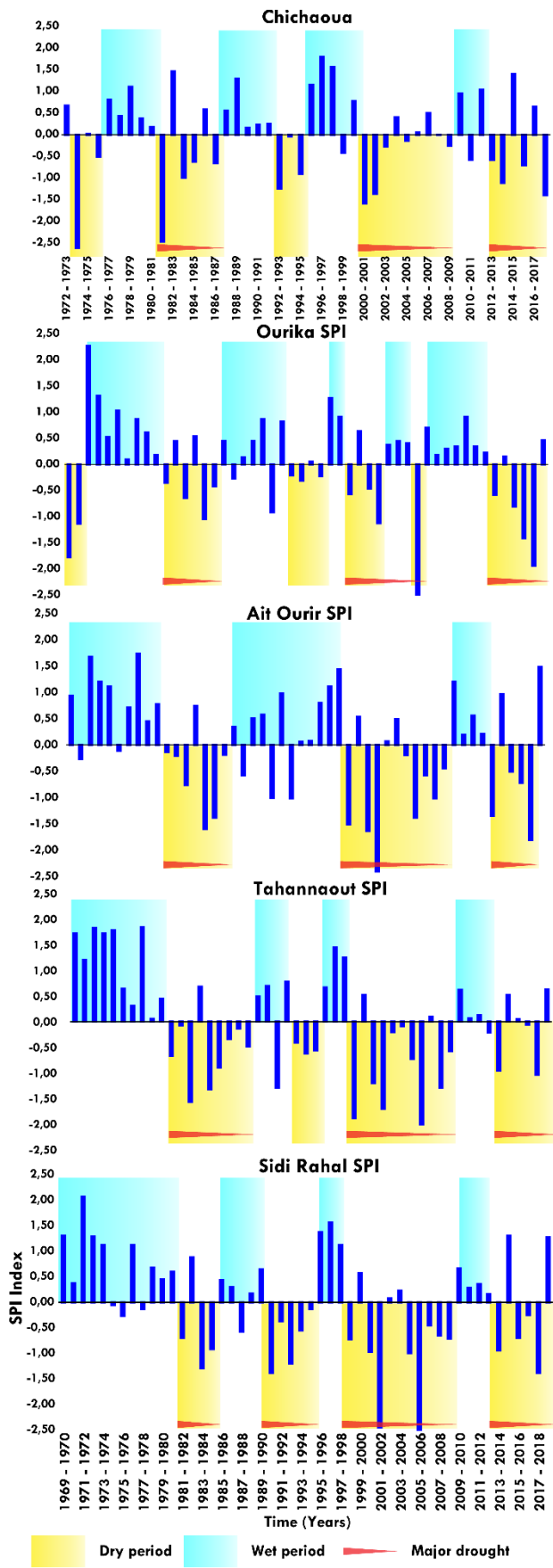
260 from 700 to 1100m where rainfall varies between 300-450mm/year, and finally the mountains  
261 with altitudes above 1500m and rainfall above 500mm/year. Also, the eastern stations receive  
262 more precipitation than the western ones, which can be explained by the higher altitudes in the  
263 eastern part of the Tensift (higher than 4000m) which allows it to benefit from additional  
264 precipitation in the form of snowfall. For a global view of the piedmont area, we computed the  
265 average rainfall series of the five stations. According to Pettitt's test, the rainfall time series  
266 presented a clear change point and the rainfall patterns could be divided into two periods: 1969-  
267 1979 with an average rainfall of 430 mm/yr, and 1980-2018 with an average rainfall of 310  
268 mm/yr (Fig.4, a). This breakpoint in rainfall series has already been observed in other sites in  
269 Morocco, occurring at various dates depending on the location, usually between 1970 and 1980  
270 ([Driouech, 2006](#); [Agoumi et Debbarh 2006](#); [Benassi, 2008](#); [Singla et al.,2010](#)).

271 Looking at each station individually, Tahannaout, Ait Ourir, and Sidi Rahal revealed a  
272 negative trend, but this trend is much weaker for Chichaoua, and Ourika (Fig.5, b). In order to  
273 evaluate if this change was the result of a steady decrease or the result of a break, Pettitt's test  
274 was used on the rainfall data (Tab.2). Among these rainfall stations, only Tahannaout showed  
275 a significant change point in 1977 (Fig.5, b).

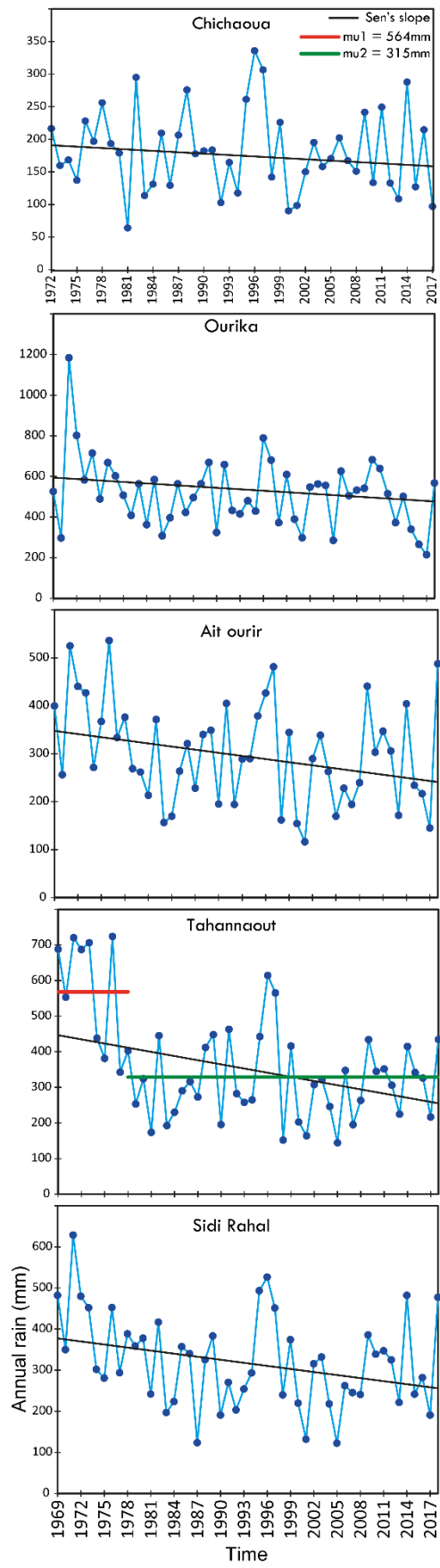
276 The SPI analysis revealed that the High-Atlas piedmont witnessed several droughts over the  
277 period 1969-2018 (Fig. 5, a). Despite some differences, the four stations showed generally a  
278 similar behavior, with three main droughts periods identified in 1981-1988, 1999-2008, and  
279 2013-2018. The second drought, 1999-2008, was particularly severe with an SPI index above -  
280 2.5.

281





(a)



(b)

283 Figure 4: (a) SPI 12-month calculated based on rainfall monthly data. Droughts periods are highlighted in yellow, and wet  
 284 periods in blue. Red arrows highlight major droughts. (b) The linear trend of annual average rainfall at the studied stations.

## 285 4.2 Streamflow trends and variability

286 The analysis of streamflow time series over 1965-2018 showed a general declining trend for all  
 287 the wadis. The MK trend test revealed a decreasing trend for all streamflow stations over the  
 288 period 1963 to 2018, with p-values less than 0.05 (Tab. 2). It is also worth pointing out that the  
 289 streamflow showed a clear sensitivity to the three drought periods with alternations between  
 290 low and high streamflow during dry and wet periods respectively. Pettitt's test results for  
 291 streamflow at the Zat and Rheraya, Rdat, Ourika, and Chichaoua stations revealed transition  
 292 points in 1973, 1980, 1997, and 1998 respectively (Fig. 6).

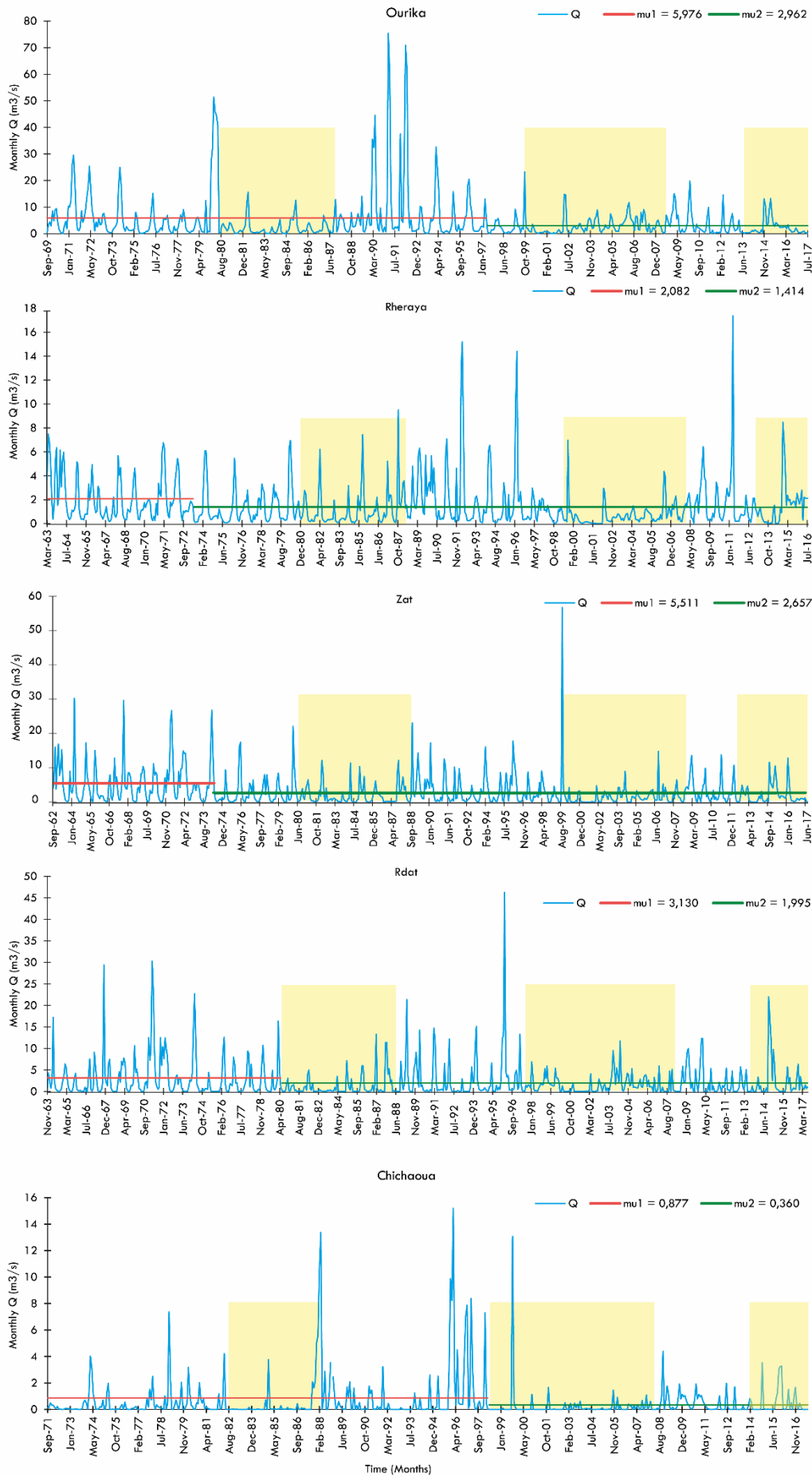
293 Table 2: Monotonic trend (MK) test and significant change (Pettitt's homogeneity) test for the streamflow and rainfall  
 294 stations in the High-Atlas piedmont for the period 1969–2018. MK: Mann-Kendall.

| Streamflow |               |        |         |       |                |         |             |
|------------|---------------|--------|---------|-------|----------------|---------|-------------|
| Station    | MK test       |        |         |       | Pettitt's test |         |             |
|            | Kendall's tau | S      | p value | Trend | K              | p value | Homogeneity |
| Ourika     | -0.076        | -12586 | 0.0064  | Y     | 12943          | 0.019   | P           |
| Rheraya    | -0.101        | -20773 | 0.0001  | Y     | 21378          | 0.0002  | P           |
| Zat        | -0.129        | -27513 | <0.0001 | Y     | 17737          | 0.004   | P           |
| Rdat       | -0.058        | -12094 | 0.0273  | Y     | 25664          | <0.0001 | P           |
| Chichaoua  | -0.058        | -8437  | 0.0472  | Y     | 12443          | 0.0156  | P           |
| Rainfall   |               |        |         |       |                |         |             |
| Station    | MK test       |        |         |       | Pettitt's test |         |             |
|            | Kendall's tau | S      | p value | Trend | K              | p value | Homogeneity |
| Ourika     | -0.161        | -197   | 0.101   | N     | 167            | 0.8358  | R           |
| Tahannaout | -0.229        | -281   | 0.019   | Y     | 312            | 0.0208  | P           |
| Ait ourir  | -0.174        | -214   | 0.074   | N     | 236            | 0.1962  | R           |
| Sidi rahal | -0.209        | -257   | 0.032   | Y     | 266            | 0.0826  | R           |
| Chichaoua  | -0.088        | -91    | 0.396   | N     | 130            | 0.8628  | R           |

Legend = Y: Significant trend; N: No trend; P: Data are not homogeneous; R: Data are homogeneous.

295

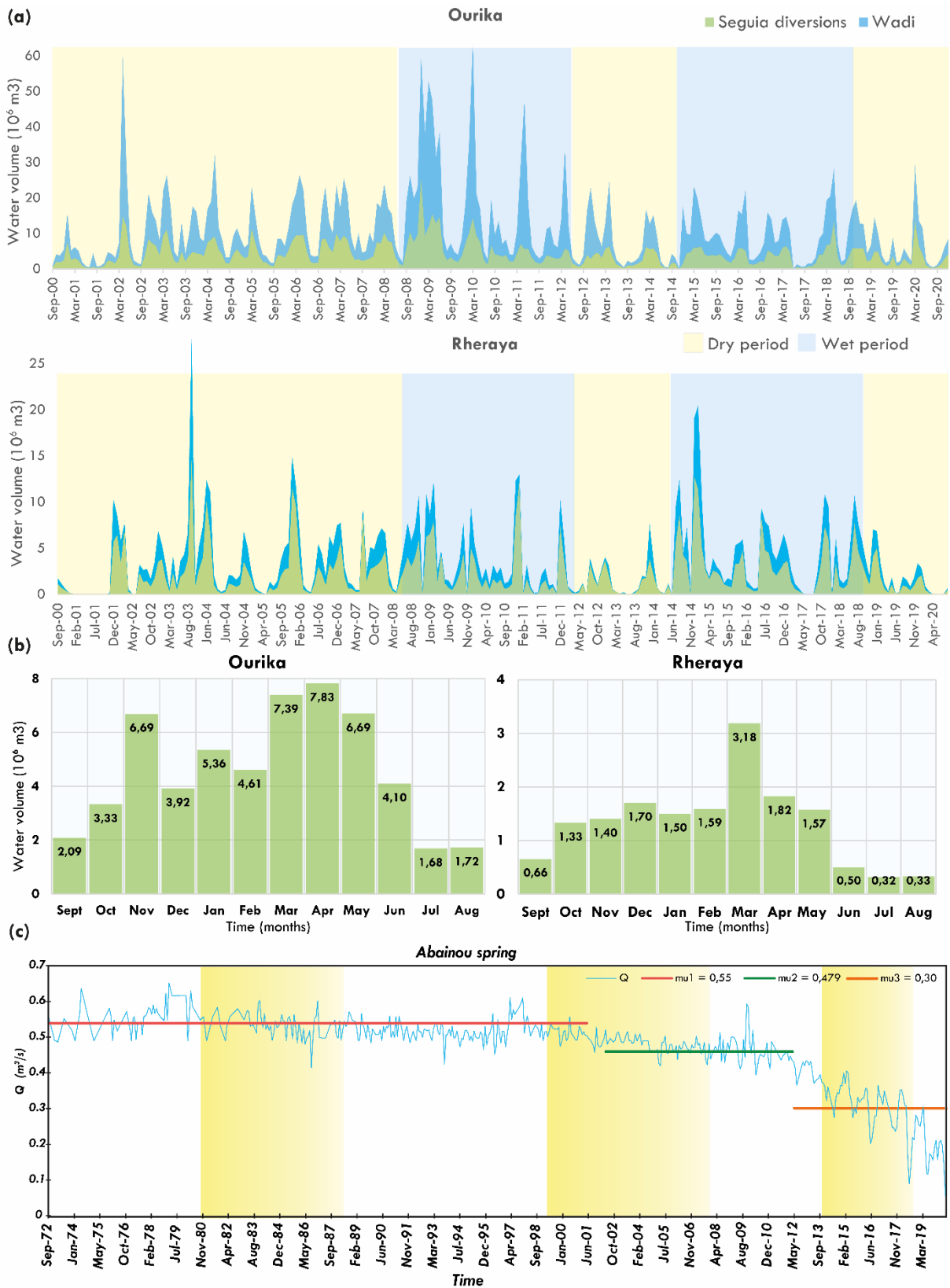
296



298 *Figure 6: Homogeneity test of the monthly streamflow for Ourika, Zat, Rheraya, Rdat, and Chichaoua streams from 1965 to*  
299 *2018, where  $\mu_1$  and  $\mu_2$  are the monthly mean streamflow (m<sup>3</sup>/s) before and after the change point respectively. The y*  
300 *ellow shades indicate the three main drought periods observed in the region.*

### 301 **4.3 Irrigation diversion**

302 Agricultural activities based on irrigation water diverted from streamflow are a defining feature  
303 of the High Atlas piedmont. The highest diverted volume are linked to the wadis with high  
304 discharge, Ourika, and Rheraya. The diversion ratios were always maintained high, up to 80 %  
305 during both wet and dry periods, showing the very high exploitation of these natural resources  
306 by the population in this area. Given that irrigation diversions depend on streamflow rates which  
307 declined by nearly 40% during droughts, it follows that the volume diverted have also decreased  
308 substantially (Fig.7, a).



309

310 Figure 7: (a) Seguias monthly time-series diversions recorded by the ORMVAH over the period of 2000 to 2020 in Ourika and

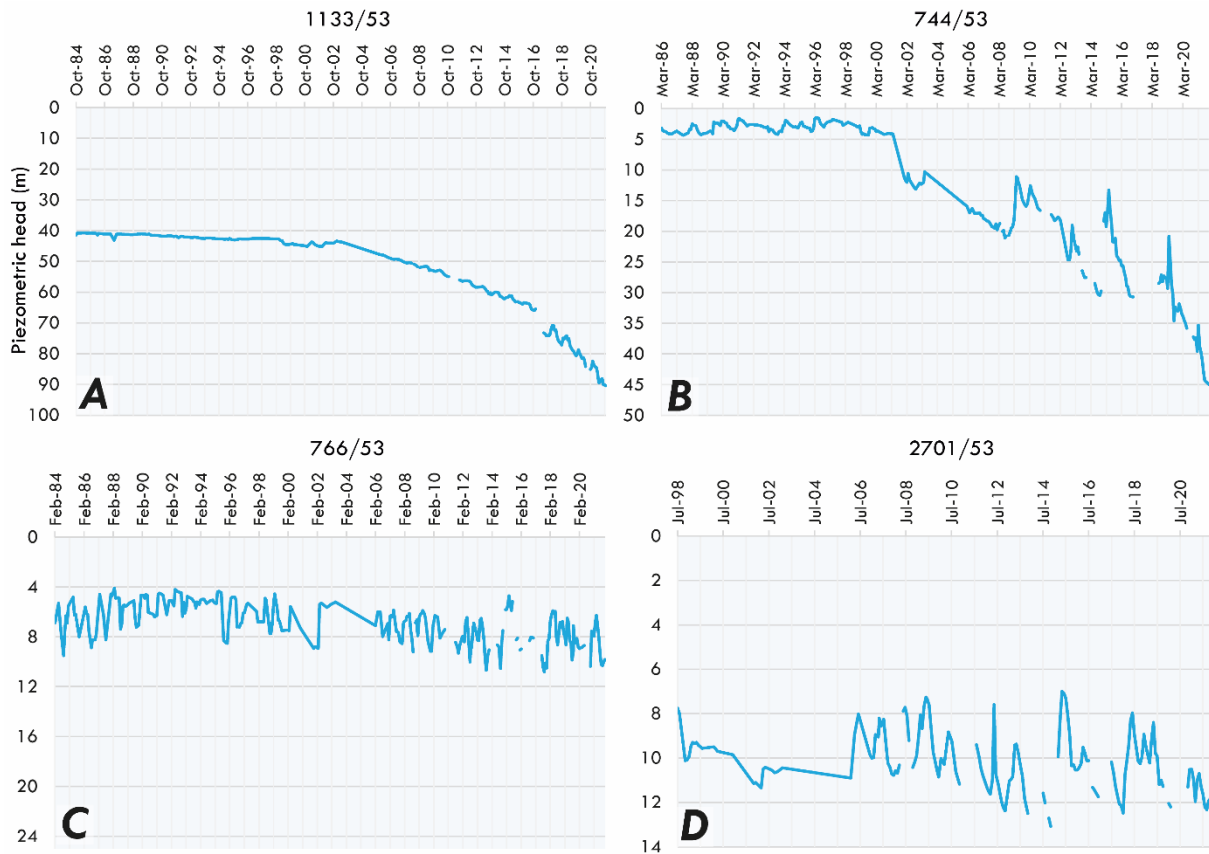
311 Rheraya streams. (b) Monthly water volumes diverted by seguias in Ourika and Rheraya between 2000 and 2020. (c) Abainou

312 *spring discharge evolution from 1972 to 2020, with change point marked in yellow (May 2001). where  $\mu_1$  and  $\mu_2$  are the*  
313 *monthly mean spring discharge ( $m^3/s$ ) before and after the change point respectively.*

314 The streamflow is diverted all along the year by seguias. Two periods of high-water volume  
315 diversion have been identified in Ourika. A first peak is observed in November corresponding  
316 to rainfall, followed by a decrease due to the occurrence of snow. Then a second peak is  
317 observed between March and May, which corresponds to the snowmelt period (Hajhouji et al.,  
318 2018). For Rheraya, the autumn peak is not visible and the snowmelt peak only last in March,  
319 this may be due to the fact that more water uptake is conducted upstream. These variations  
320 reflect the pluvio-nival behavior of these basins (Fig.7, b).

#### 321 **4.4 Groundwater level variation**

322 Changes in groundwater level were analyzed using historical datasets of four piezometers (see  
323 location in Figure 1, a) since 1984. In the upstream part of the Central Haouz, the long-term  
324 variation of groundwater level is low in the piezometers Ourika (766/53), Ghmat (2701/53)  
325 (Fig. 8, graphs C and D); in this area, the groundwater is well recharged seasonally by  
326 streamflow and surface water irrigation returns, due to the proximity of the mountain and the  
327 rivers, over winter and spring. However, downstream of the piedmont of the Central Haouz in  
328 Chouiter (744/53) and in Mejjate (1133/53) where agricultural activities are based mainly on  
329 groundwater, the groundwater level showed a rapid decrease since the 2000s (Fig.8, graphs A  
330 and B), which can be explained by droughts, high withdrawals, and lower recharge due to the  
331 geographical location away from the wadis, which constitute the source of water (Fig. 1, and 1  
332 S). In Chouiter (744/53, B), the decrease rate is around  $2m.y^{-1}$  since 2000, while in Mejjate  
333 (1133/53, A) the pace was around  $1.5 m.y^{-1}$  between 2002 and 2016 and is close to  $5m.y^{-1}$   
334 since 2016.



335

336

Figure8: Groundwater level variation from 1984 to 2021 in the upstream Ourika (766/53) and Ghmat (2701/53 C, D) and

337

downstream piedmont Mejjat(1133/53) and Chouiter (744/53 A, B).

#### 338 4.5 The Abainou spring

339 The spring of Abainou supplies irrigation in the valley of Chichaoua (Fig.7, c) that  
 340 encompasses one of the oldest traditional irrigation systems in the basin. In the 1970s, the spring  
 341 discharge was about  $0.55 \text{ m}^3 \text{ s}^{-1}$ . A severe decline has been seen since 2000, however, the latest  
 342 starting in 2013 is more drastic. The average spring outflow has been reduced by over 70%,  
 343 from  $0.55 \text{ m}^3 \text{ s}^{-1}$  in 1972 down to less than  $0.2 \text{ m}^3 \text{ s}^{-1}$  in 2020. These spring discharge  
 344 breakpoints are correlated with the major droughts identified in the region between 1999-2008,  
 345 and 2013-2017.

346 **4.6 Land-use mapping and change analysis**

347 The piedmont of the High Atlas is generally known for subsistence agriculture (family  
348 farming), with cereals and olive trees as the main crops. Therefore, three landcover classes were  
349 targeted: annual crops, trees, and bare soil. The decision tree classification, based on NDVI  
350 thresholding, was applied to map those classes from 1984 to 2020. The limitations of the  
351 decision tree approach in our case were extremely wet years when weeds grow throughout the  
352 year leading to a possible land use overestimation, especially trees. To help the algorithm  
353 eliminate overestimation errors due to weeds, we tried to introduce more summer images in wet  
354 years (1989, 1996, 1997, 2009). Thus, introducing additional summer images, when the weed  
355 cannot be irrigated and begins to disappear, increases the probability to detect bare soil and  
356 identify the right class. In addition, some other years (i.e., 1987, 1991, 1995, 2008, 2011, 2012)  
357 were not considered in the historical analysis due to the non-availability of Landsat images or  
358 the images presented a significant cloud cover.

359 *Table 3: The confusion matrix.*

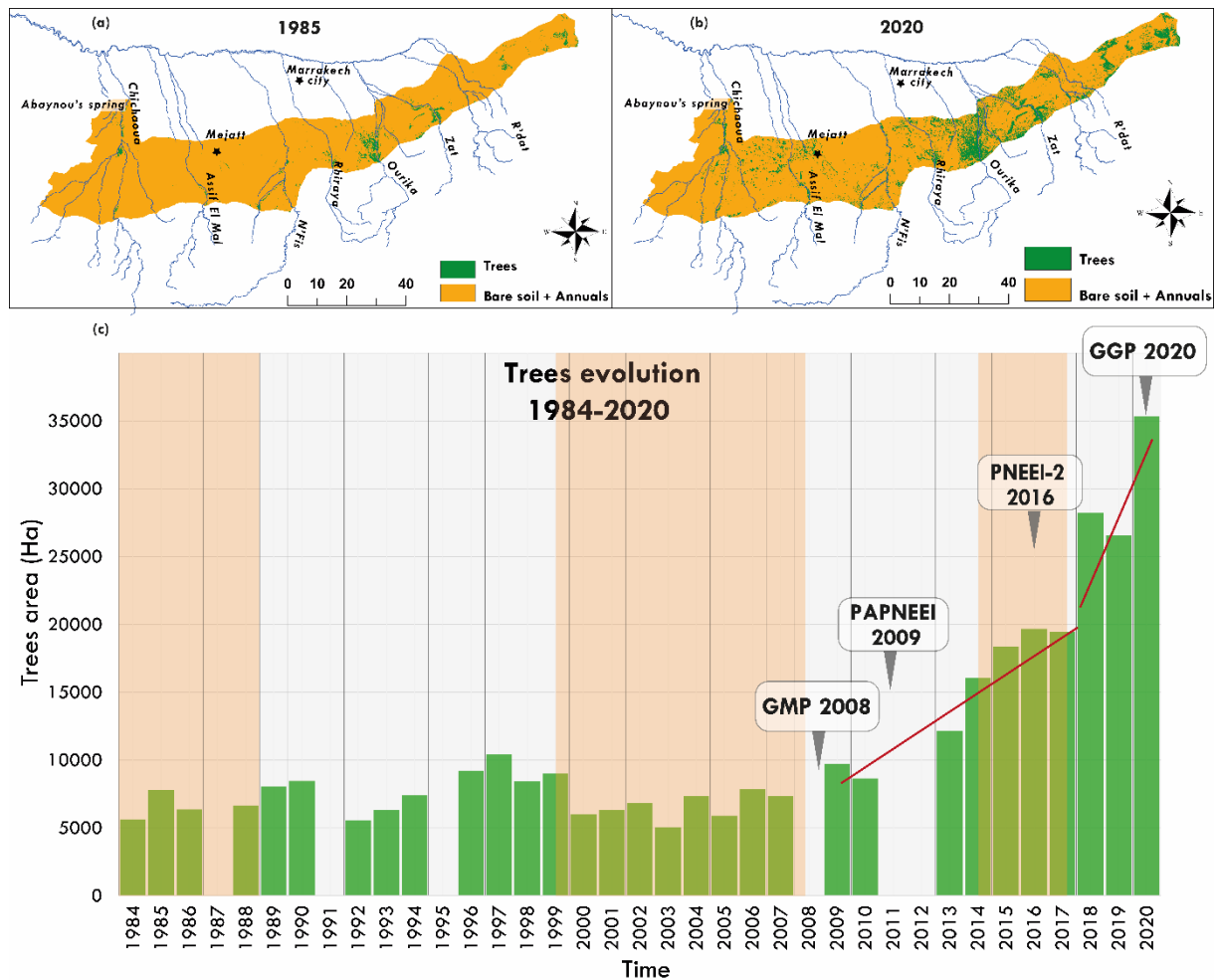
|                |           | Ground truth data |         |           |
|----------------|-----------|-------------------|---------|-----------|
|                |           | Trees             | Annuals | Bare Soil |
| Classification | Trees     | 26                | 0       | 0         |
|                | Annuals   | 0                 | 23      | 5         |
|                | Bare Soil | 0                 | 3       | 19        |

360  
361 To assess the effectiveness of the applied algorithm, the overall accuracy (OA) method was  
362 used. This involves calculating the number of classified sites and then dividing by the number  
363 of reference sites. Using this method, an overall accuracy of 89.4% is obtained for the High  
364 Atlas piedmont land use map based on the field samples for validation (Table 3). Regarding  
365 Google Earth plots for the years 2005, 2010, and 2015, the algorithm was able to identify these  
366 classes with 100% accuracy, since tree and bare soil profiles cannot be confused.



367 The seasonal crops consist mainly of cereal crops, which constitute the most important  
368 nutritional crops for piedmont families. The inter-annual variability of areas cultivated with  
369 cereals is strongly correlated with the annual precipitation patterns. This confirms that these  
370 crops are mainly based on rainfall for irrigation. In wet years, when surface water is available  
371 and rainfall events are well distributed, cereals water needs are well satisfied thus enabling high  
372 production. In dry years, the cereal crops are either not or poorly cultivated as a result of water  
373 shortage (Fig. 2 S); local farmers in the country traditionally wait for the first rain event in late  
374 September or early October before sowing.

375 The trees, dominated by olive orchards, occupied 5604 Ha in 1985 which represents barely  
376 1.3 % of the piedmont area (Fig.9, and 2S). The main tree areas were located in the Eastern part  
377 of the piedmont (Central Haouz) where the trees were planted near the main streams Ourika,  
378 Zat, and Rheraya. They benefit from the most extensive traditional irrigation channel network  
379 of the High Atlas piedmont, and perennial irrigation from sustained snowmelt runoff.  
380 Paradoxically, along the largest stream of the area the Nfis wadi, the trees have not been  
381 developed as much. This could be explained by the presence of the Lalla Takerkoust dam which  
382 supplies water for irrigation since 1935 to N'Fis sectors downstream in the Haouz plain. Due  
383 to limited surface water, there were hardly any arboricultural farms in the western part of the  
384 piedmont, Mejjat, but rather a large area devoted to seasonal rain-fed crops. The Chichaoua  
385 valley was an exception since trees farming was developed essentially due to perennial  
386 irrigation by the Abainou spring.



387

388 *Figure9: (a) Trees cover for the period from 1985 to 2020 (b) within the High Atlas piedmont, and (c) trees evolution from 1984*  
 389 *to 2020, with droughts outlined orange, and the main government programs over the period..*

390 Over the last 36 years, tree crops expansion across the High-Atlas piedmont showed two  
 391 distinct periods: 1984-2010 and 2011-2020. From 1984 to 2010, the expansion of trees over the  
 392 area was generally slow and steady. Then, a rapid expansion occurred reaching its maximum  
 393 pace during 2017-2020 (Fig. 9, c).

394 By 2020 the piedmont tree-covered areas (Fig. 9, b, c) reached 35332 Ha, about 8% of the  
 395 cultivated areas, representing nearly seven times the initial surface (1984). The trees extended  
 396 considerably both over the eastern piedmont irrigated by streamflow and groundwater, and over  
 397 the western piedmont relying mainly on groundwater for irrigation.

## 398 **5 Discussion**

### 399 **5.1 Temporal and spatial changes in water resources**

400 Even though the piedmont areas benefited from water availability favorably than the plain,  
401 all the analyzed hydrological variables have shown a decreasing trend over the past 50 years.  
402 Therefore, the major hydrological changes were revealed since the 1980s. The precipitation has  
403 declined by 28% (Fig.4a, 5b). Recently Ouatiki et al. (2019) pointed out the same general  
404 decreasing tendency in rainfall over a neighboring basin, the Oum Er-Rbia basin. In addition, a  
405 decreasing trend in precipitation for most Mediterranean countries was revealed by Philandras  
406 et al. (2011) through a detailed analysis of data from 40 meteorological stations between 1900  
407 and 2009. Also, three main meteorological droughts were delineated: 1981-1988, 1999-2008,  
408 and 2013-2018 (Fig.5a). The longer and more severe one is between 1999 and 2008, which has  
409 also been reported in various countries of the Mediterranean basin (Cook et al., 2016; Hanel et  
410 al., 2018). Additionally, streamflow has declined by almost 40% (Fig.6). These findings are  
411 consistent with the recent study by Masseroni et al. (2020) who analyzed runoff data between  
412 1965 and 2015 from more than 3,000 stations over the Mediterranean region. They found that  
413 the declining trend of annual streamflow started in 1965, and by 1980 the volumes were  
414 systematically below the average. The overall decrease in runoff resulted in a decrease in  
415 diverted volume of streamflow to irrigation. Despite that, the diversion ratios are high in both  
416 dry and wet periods, ranging from 70 % up to 80 %. They highlighted the great importance of  
417 streamflow-based irrigation to local farmers in a semi-arid context and their strong adaptation  
418 capacity to natural variations, as the area covered by cereals is strongly related to rainfall and  
419 runoff.

420 Concerning the groundwater, except for the upstream areas benefiting from consistent  
421 recharge by irrigation returns (Bouimouass et al., 2020), a severe decrease is observed in

422 piezometric levels elsewhere since the early 2000s. The observed depletion of the piezometric  
423 level occurs over the downstream area at a rate of 2m.y<sup>-1</sup> in Chouiter, while in Mejjate it was  
424 around 1.5 m.y<sup>-1</sup> between 2002 and 2016 and is close to 5m.y<sup>-1</sup> since 2016. These are in line  
425 with other studies highlighted rates, around 1-3 m/year on average (Fakir et al., 2015). The  
426 decline of groundwater level is attributed to recurrent drought periods and intensive  
427 groundwater pumping (Boukhari et al. 2015). Pump wells were introduced in the last century  
428 firstly in the Haouz plain by the French colonization. Those wells have spread in the area and  
429 currently, almost every farm has at least one well dedicated to irrigation during the dry season  
430 and in some cases used for drinking and domestic needs. Unfortunately, there are no records of  
431 the volumes being pumped or accurate statistics on the number of boreholes since most are dug  
432 illegally in the region. Additionally, the Abainou spring, which provides water to irrigate  
433 agriculture in Chichaoua valley, has also been declining since the 1980s, jeopardizing its socio-  
434 economic importance and increasing the risks of its drying up (Fig. 7, c).

## 435 **5.2 Agricultural land use dynamic**

436 The evolution of annual crops (mainly cereals) extent was highly correlated to rainfall. The  
437 decreasing trend in rainfall and droughts resulted in a lower extent and production of rainfed  
438 cereals, which is considered critical for food security in Morocco (Schilling et al., 2012, Karrou  
439 et al., 2012) and rural population incomes. This is a common issue in the semi-arid regions of  
440 the southern Mediterranean, where about 80% of agricultural land is rainfed, therefore highly  
441 vulnerable to droughts (Schilling et al., 2020).

442 The past distribution of trees in the studied High Atlas piedmont showed a clear spatial  
443 variation. In the eastern piedmont of Central Haouz, the olive trees extended mainly along the  
444 main wadis; the water availability has encouraged the settlement of rural communities that  
445 logically led to the development of irrigated agriculture (Awulachew et al., 2007). The western

446 piedmont of Mejjate was known for rainfed seasonal agriculture. Over the last 36 years, the  
447 interannual evolution of tree crops across the High-Atlas piedmont showed two highly disparate  
448 trends. During a long period 1984-2013 (29 years), the expansion of trees remained near stable  
449 over the area, with 2 slight variations: an increase in 1995-1999 and a slight decrease in 2000-  
450 2007, which coincided respectively with a wet period and a dry period. Therefore, the  
451 development of trees during this long period seems to be controlled by climatic drivers.  
452 However, during the last 7 years, 2013-2020, the expansion of trees was spectacular (Fig.9).  
453 Paradoxically, this rapid expansion is occurring in the context of severe droughts and could not  
454 be explained by climate variability. In fact, in recent years several governmental support  
455 programs were launched aiming at the development and modernization of the agricultural sector  
456 (Faysse, 2015; Agricultural Development Agency. 2012, 2014). Particularly, the Green  
457 Morocco Plan (GMP) launched in 2008 aimed to make agriculture a pillar of the socio-  
458 economic development in Morocco through the development of modern agriculture with high  
459 added value both in the irrigated and favorable rainfed areas; and the enhancement of  
460 agricultural income in the most vulnerable areas (ADA, 2018). The GMP helped increase the  
461 production of high-value perennial crops, such as citrus and olive trees, mostly by expanding  
462 cultivated areas thanks to the subsidies awarded (Akesbi, 2013). In addition, the National  
463 Irrigation Water-Saving Program (PNEEI), which is a major component of the GMP, was  
464 implemented to ensure the rational and efficient use of irrigation water resources by promoting  
465 the development of drip irrigation technology (Faysse, 2015; Faysse, and Simon, 2014 Akesbi,  
466 2013). However, these measures have conversely favored the expansion of irrigated agriculture  
467 to traditionally rainfed or uncropped areas (Jaramillo et al., 2020; Molle, 2017), relying on  
468 groundwater withdrawals, which has subsequently led to increased water demand and  
469 groundwater overexploitation (Fig. 3 S).

### 470 **5.3 Sustainability of piedmonts' traditional hydro-agro-systems**

471 The piedmont of the High-Atlas Mountains has been sheltered for centuries and still adopt  
472 over a large area a traditional irrigation system. The latter use large networks of gravity-fed  
473 surface irrigation channels that divert the streamflow (baseflow and floods) at the outlet of the  
474 Mountain ranges (Bouimouass et al., 2020). A key factor of survival for such an ancestral  
475 system is the sense of mutualism between the seguias users, which is defined by Gunda et al  
476 (2018) as the feeling of collective well-being including social identity, pride of place, and  
477 maintenance of historical traditions. This mutualism has not excluded conflicts that have been  
478 raised during periods of severe droughts. These hydro-agro-systems are also characterized by  
479 great flexibility to water resources fluctuations.

480 During the last years, the planting of trees has been performed at a rapid pace, mainly driven  
481 by socio-economic incentives under conditions of droughts and water scarcity. The trees  
482 expansion is creating an increasing and rigid water demand that should be satisfied whatever  
483 the conditions of climate and water resources. Thus, the observed decrease in precipitation and  
484 streamflow would change the traditional irrigation in the piedmont from a surface water-based  
485 irrigation to a groundwater-based one. This is already the case in the Mejjate area (western  
486 piedmont) where the observed expansion of trees is associated with a decrease in groundwater  
487 level. The same situation is spotted in the downstream limit of the central Haouz piedmont  
488 receiving less irrigation water, only during flood events. Also, the irrigation in the Chichaoua  
489 valley by the Abainou spring, whose discharge has been continuously reducing, is undergoing  
490 the same evolution. The consequences of the shifting from surface water-driven irrigation to  
491 groundwater-based irrigation are a severe depletion of groundwater, especially in the  
492 downstream areas. Beyond the question of the durability of this type of agriculture, it raises the  
493 question of the impact on the aquifer recharge downstream. In fact, in the Haouz plain, a  
494 dramatic groundwater depletion of 1 to 3 m year<sup>-1</sup> in average is observed since the 1990s

495 ([Boukhari et al., 2015](#); [Fakir et al., 2015](#)). Although the depletion of the piezometric level  
496 observed in these areas is due to extensive pumping by the plain agriculture itself, it may be  
497 exacerbated by the less recharge from the piedmont that is subject to increasing groundwater  
498 abstraction.

499 Indeed, this agricultural intensification is not only occurring in Morocco but also on a broader  
500 scale. Worldwide, the equipped areas for irrigated agriculture increased from 289 to 342 million  
501 hectares between 2000 and 2020, with nearly 38% being supplied by groundwater-based  
502 irrigation ([Crumpler et al., 2021](#); [Siebert et al., 2010](#)). Furthermore, by employing the PCR-  
503 GLOBWB hydrological model for gross crop requirements for irrigation and the available water  
504 to meet that demand, Wada et al. ([2012](#)) revealed that the use of non-renewable groundwater  
505 withdrawals for irrigation is highest in India, followed by Pakistan, the United States, Iran,  
506 China, Mexico, and Saudi Arabia. Their findings also suggested that globally this contribution  
507 has been tripled over the period 1960-2000. Now, there is no doubt that India, a country with a  
508 similar context as Morocco, has the largest extent of irrigated areas. Despite a low increase of  
509 irrigated area from 58.8 % to 60.4 % between 1961 to 2016 ([World Bank, 2017](#); [Siebert et al.,](#)  
510 [2010](#)), an intensification occurred, triggered by government irrigation facilities, cheap  
511 electricity for pumping, and a diversified crop basket since the 1970s ([Dangar et al., 2021](#); [Paria](#)  
512 [et al., 2021](#)). The cropping intensity was also driven by the use of chemical fertilizers, and a  
513 rapid rise in the number of electric and diesel pumps to reach higher yields ([Paria et al., 2021](#);  
514 [Mishra et al., 2018](#); [Shah, 2010](#)). In such a context, the direct reliance on groundwater  
515 abstraction to meet the growing irrigation water demand exacerbates groundwater resource  
516 depletion, even in areas with abundant rainfall ([Dangar et al., 2021](#); [Zaveri et al., 2016](#); [Rodell](#)  
517 [et al., 2009](#); [Gandhi and Namboodiri, 2009](#)).

518 This issue has also been highlighted in the northern side of the Mediterranean basin ([FAO](#)  
519 [2016](#)). In Spain, for instance, agricultural policies have supported irrigated farming to increase

520 food production and save water. Over the last three decades, the promotion of drip irrigation  
521 over surface irrigation had several consequences. Wells construction has intensified,  
522 redistributing access to groundwater and causing a significant lowering of the water table. In  
523 addition, the expansion of irrigation in the piedmont and Mountain areas, previously rain-fed,  
524 resulted in an increase in water consumption from 4% to 45% per hectare. There was also a  
525 shift to higher-value fruit crops with higher water requirements ([González-Cebollada, 2015](#)),  
526 and finally, the removal of traditional surface irrigation infrastructure dating back to the Middle  
527 Ages ([Sese-Minguez et al., 2017](#)).

528 The socioeconomic and the hydrological functions of the traditional irrigation piedmont as a  
529 secular hydro-agro-system that was sustained for tens of centuries through a sound connection  
530 between natural and human elements to ensure food security, water balance, groundwater  
531 recharge, and droughts survival, are being altered. Their sustainability is currently of great  
532 concern and their degradation would be accelerated by climate change, particularly through  
533 decreased precipitation ([Polade et al., 2017](#); [Barcikowska et al., 2018](#)), increased  
534 evapotranspiration ([Le Page et al., 2021](#)), and reduced groundwater recharge ([Crosbie et al.,](#)  
535 [2013](#); [Wu et al., 2020](#)). Given that the traditional irrigation in the piedmont of the High-Atlas  
536 Mountains in Haouz region has been identified as the main source of groundwater recharge  
537 ([Bouimouass et al., 2020](#)), the preservation of this vulnerable hydro-agro-system should be  
538 considered in the agricultural and socio-economic development policies. Particularly by  
539 limiting the expansion of the irrigated agriculture over the Haouz plain which threatens the  
540 groundwater resources sustainability. Additionally, the government agricultural support should  
541 be revised in a such vulnerable hydro-agro-systems to mitigate the current changes and the  
542 future climate change impacts.



## 543 **6 Conclusion**

544 The traditional irrigation system in the High-Atlas piedmont is similar to several other  
545 systems around the world. They have played through centuries vital roles in socio-economic  
546 development while maintaining a balance between water resources and water needs. The  
547 present study of the High-Atlas piedmont has shown that the overall state of water resources is  
548 declining and deeply affected by droughts during the last 5 decades. Average precipitation has  
549 decreased by almost 28 % and the streamflow has decreased by more than 40% directly  
550 influencing the amount of water diverted by seguias for irrigation. The groundwater is depleting  
551 as attested by water table decline and by the Abainou spring's dramatic drying. Conversely, in  
552 recent years, there has been a spectacular expansion of tree crops despite water scarcity. Also,  
553 it was shown that the agricultural land use is changing from seasonal crops (cereals) to perennial  
554 crops (trees), which creates an increasing and rigid water demand to satisfy, whatever the  
555 conditions of climate and water resources.

556 This challenge is also found in the northern parts of the Mediterranean basin as well as in  
557 northwestern India. Government subsidies intended to support irrigated agriculture in order to  
558 increase food production have led to a direct dependence on groundwater abstraction to meet  
559 the growing demand for irrigation water, thereby exacerbating groundwater resource depletion.

560 The uncontrolled expansion of trees, or generally irrigated areas, which is mainly driven by  
561 strict socioeconomic incentives induced by several governmental agricultural supporting  
562 programs, the multiplication of pumping, and the climate variability, threaten seriously the  
563 sustainability of such ancestral traditional hydro-agro-systems. The climate variability observed  
564 over the last 50 years has already had major impacts on water resources in the Mediterranean  
565 region, particularly in snow-related basins. The land-use changes are evolving in a direction  
566 that is incompatible with balanced hydro-agro-systems. Therefore, interdisciplinary research

567 and management strategies are needed to assess the occurring changes and to provide adaptation  
568 and mitigation measures to preserve their long-term sustainability.

569

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576 CHange: Assessment and Adaptation to Mediterranean region water Scarcity", PRIMA-  
577 ALTOS "Managing water resources within Mediterranean agrosystems by Accounting for  
578 spatiaL sTructures and cOnnectivitiES", PRIMA-IDEWA "Irrigation and Drainage monitoring  
579 by remote sensing for Ecosystems and Water resources management".

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