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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**

3 Youness Ouassanouan¹, Younes Fakir^{1,2}, Vincent Simonneau³, Mohamed Hakim Kharrou⁴, Houssne
4 Bouimouass⁵, Insaf Najjar⁶, Mounia Benrhanem⁶, Fathallah Sguir⁷, and Abdelghani Chehbouni^{1,3,4}

5 1 Center for Remote Sensing Applications (CRSA), Mohammed VI Polytechnic University (UM6P), Ben Guerir 43150,
6 Morocco (youness.ouassanouan@um6p.ma)

7 2 Department of Geology, Faculty of Sciences–Semlalia, Cadi Ayyad University, Marrakech 40001, Morocco

8 3 Centre d'Etudes Spatiales de la Biosphère (CESBIO), Université de Toulouse, CNES/CNRS/INRAE/IRD/UPS, 31400
9 Toulouse, France

10 4 International Water Research Institute (IWRI), Mohammed VI Polytechnic University (UM6P), 43150 Ben Guerir,
11 Morocco

12 5 Hydrogeology Laboratory, UMR EMMAH, University of Avignon, Avignon 84000, France

13 6 ABHT- Agence du Bassin Hydraulique du Tensift, Marrakech, Morocco

14 7 ORMVAH-Office Régional de Mise en Valeur Agricole du Haouz, Marrakech, Morocco

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 Steenbergen 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 20th 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 20th 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**

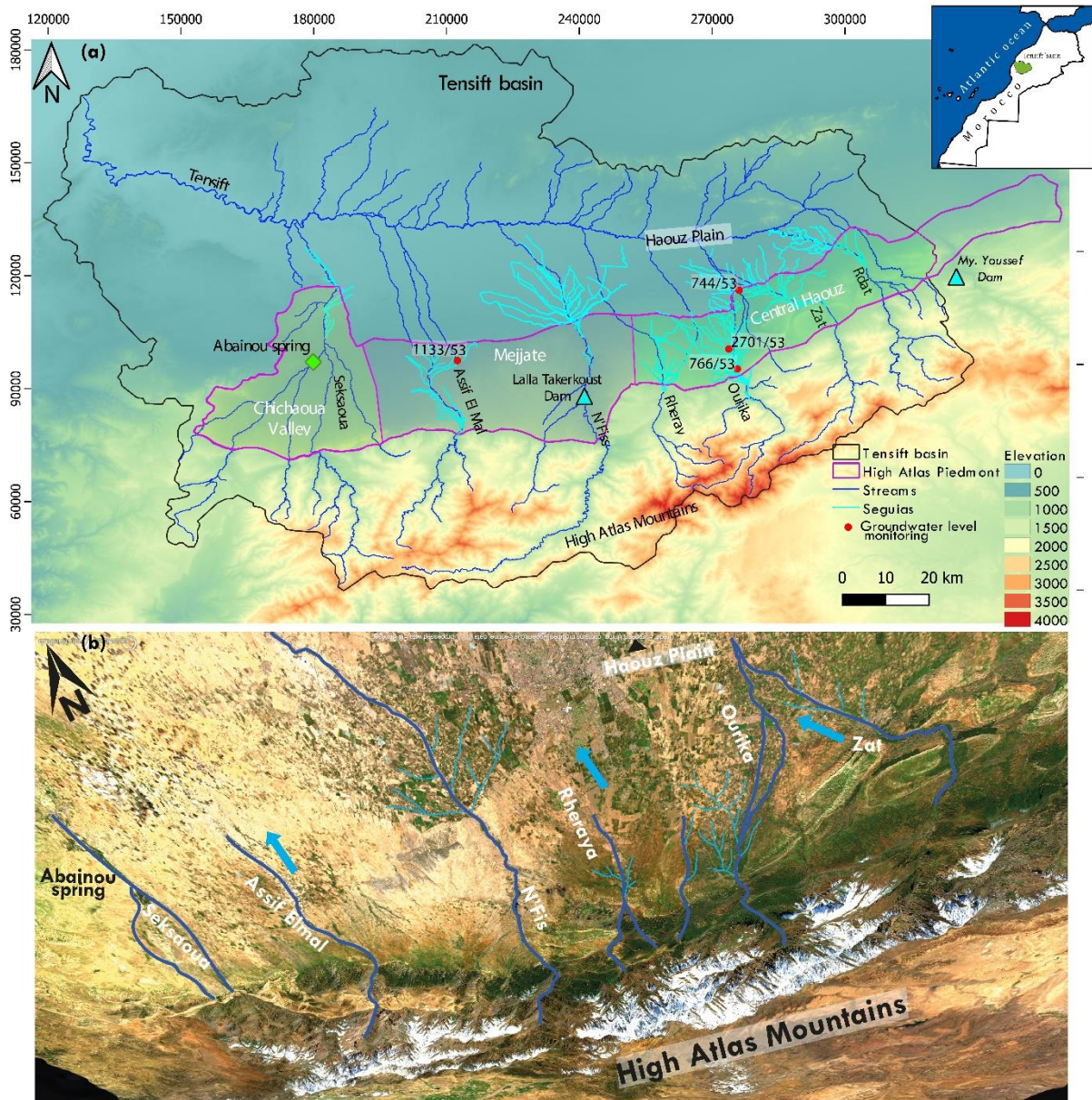
132 **2.1 Water resources**

133 The northern piedmont of the High Atlas, covering approximately 4400 km², 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 m³s⁻¹, Zat 3.33 m³s⁻¹, Rheraya 1.60
142 m³s⁻¹, and Rdat 2.34 m³s⁻¹. 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 m³s⁻¹. 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 seguia ramifies into several secondary seguias, which in turn ramifies into tertiary
 171 seguias (Fig. 2). The major seguia is governed by a WUA and each secondary seguia 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*

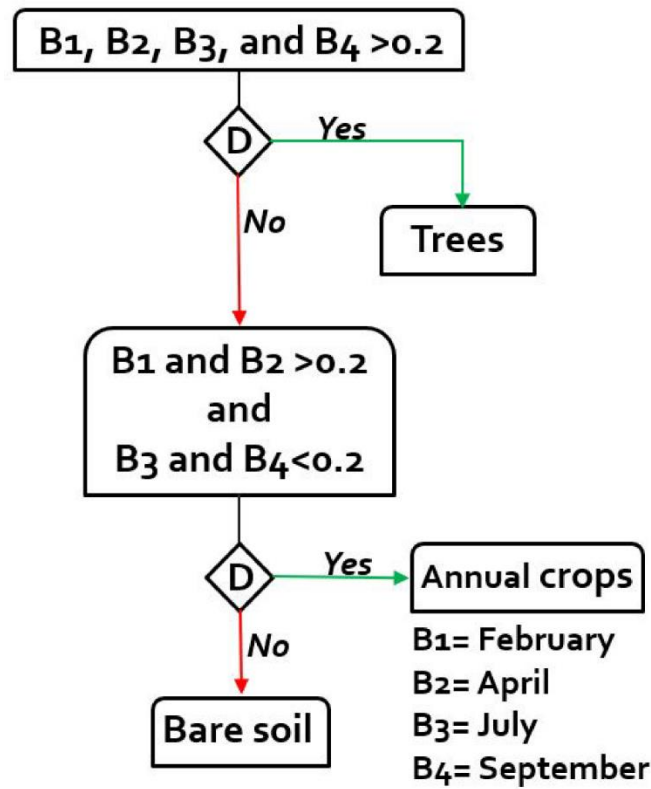
213 The non-parametric statistical test of Mann-Kendall (MK) (Mann 1945, Kendall 1975) and
214 Sen's slope estimator (Sen, 1968) was performed on precipitation and streamflow time series
215 to assess the presence or absence of a clear trend in the long-term evolution of water resources
216 within the 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

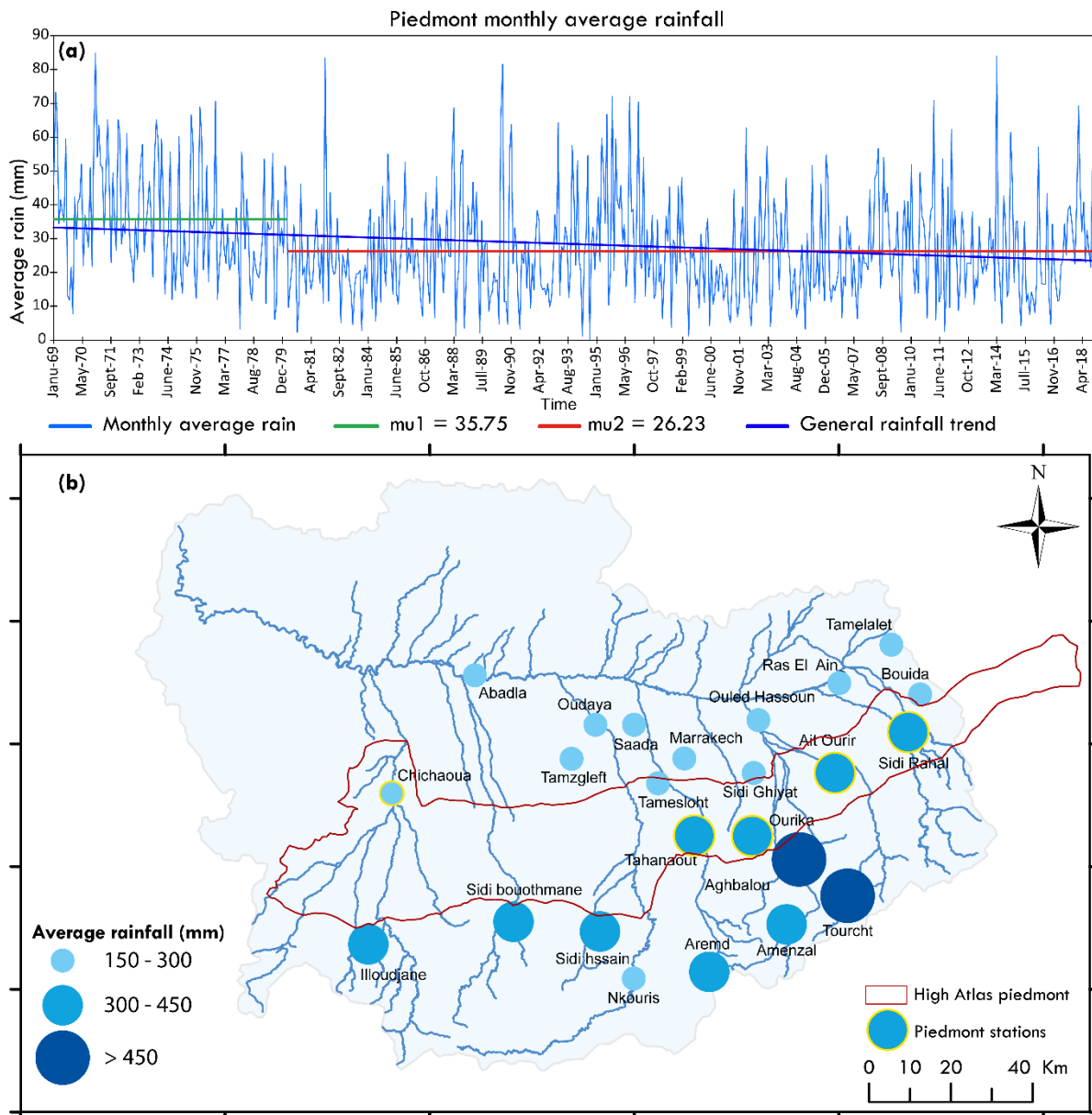
plots (parcels) were selected on Google Earth for the years 2005, 2010, and 2015 to check the

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 μ_1 is the mean*
 256 *annual rainfall (mm) before the change point and μ_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).*

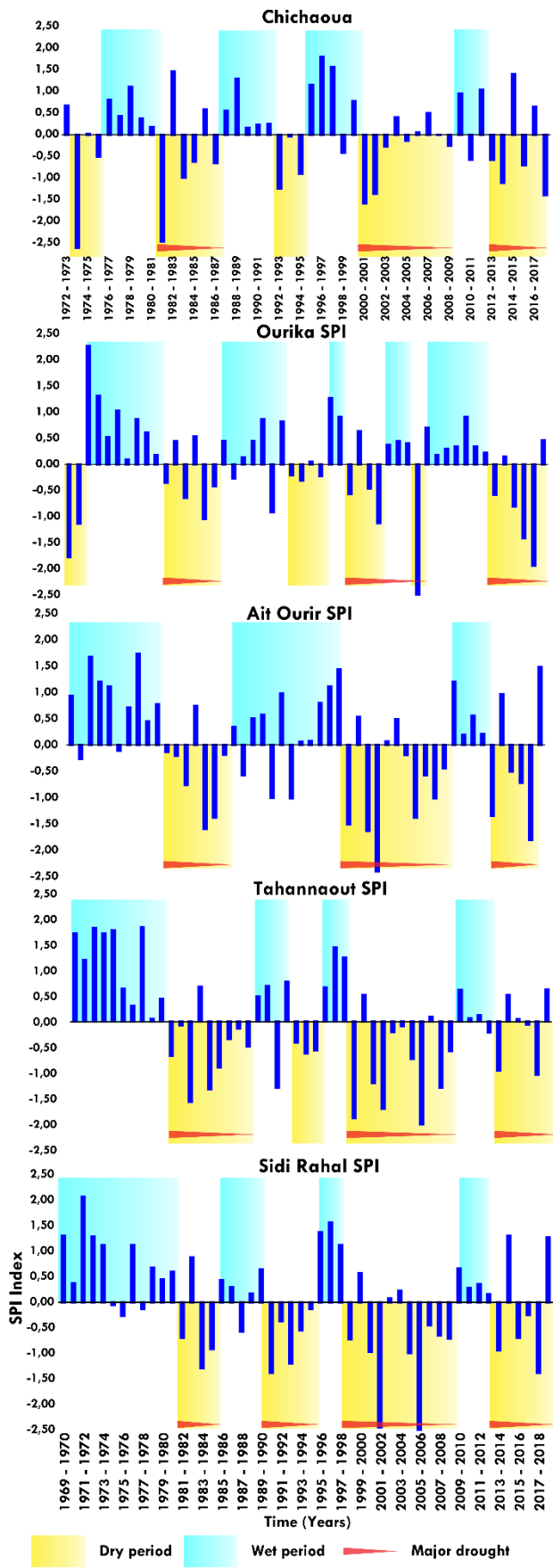
258 In figure (4, b), there are three altitude bands, the lowland to the north with altitudes between
 259 300-600m where the rainfall varies between 150-300mm/year, the piedmont area with altitudes

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](#)).

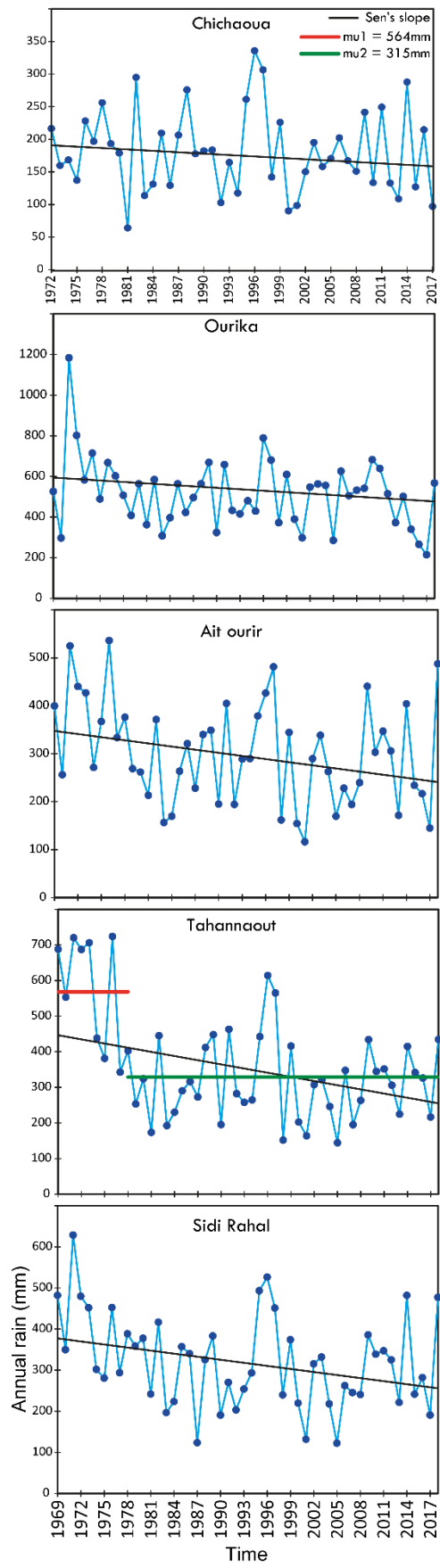
271 Looking at each station individually, Tahannaout, Ait Ourir, and Sidi Rahal revealed a
272 negative trend, but this trend is much weaker for Chichaoua, and Ourika (Fig.5, b). In order to
273 evaluate if this change was the result of a steady decrease or the result of a break, Pettitt's test
274 was 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).

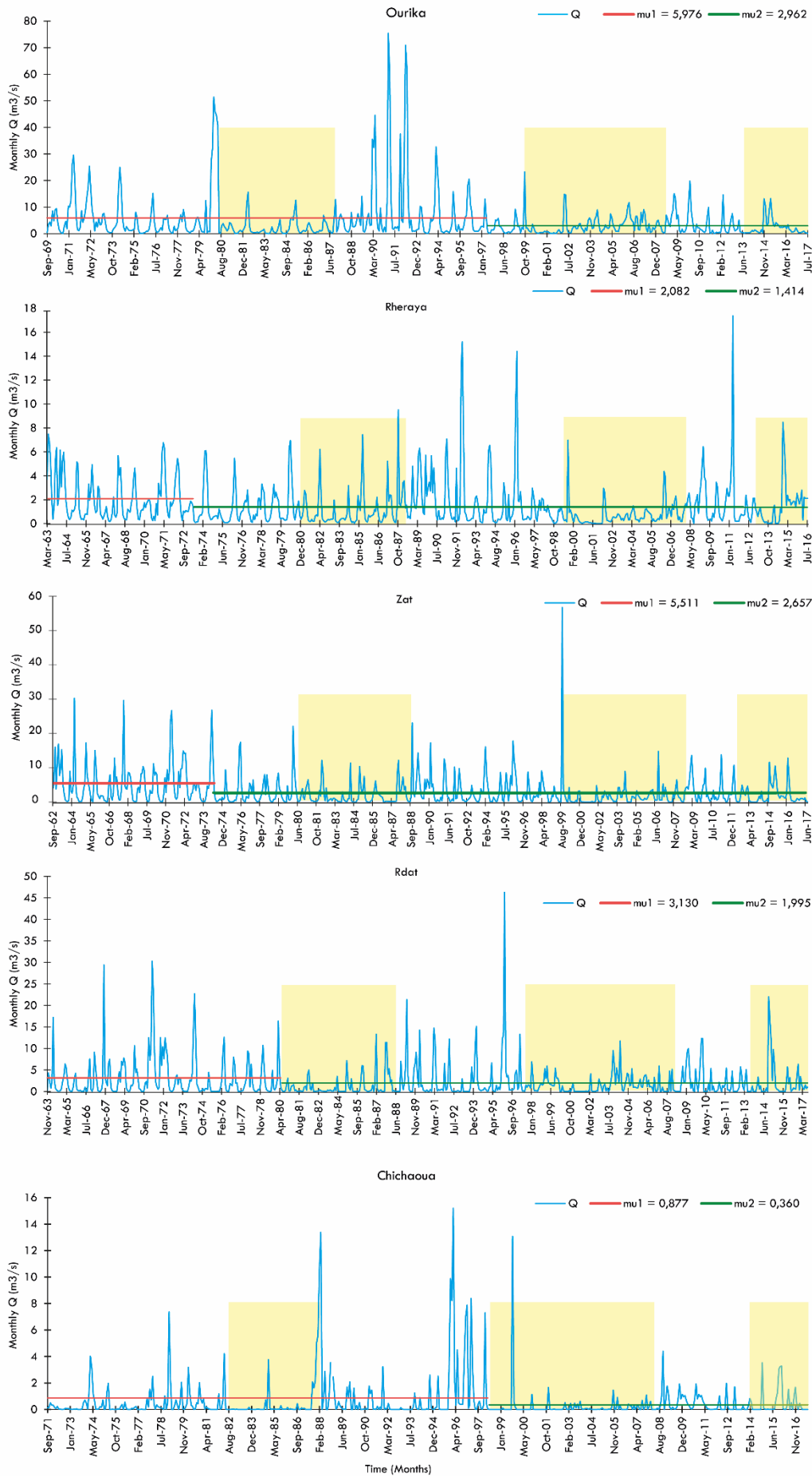
293 Table 2: Monotonic trend (MK) test and significant change (Pettitt's homogeneity) test for the streamflow and rainfall
 294 stations in the High-Atlas piedmont for the period 1969–2018. MK: Mann-Kendall.

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

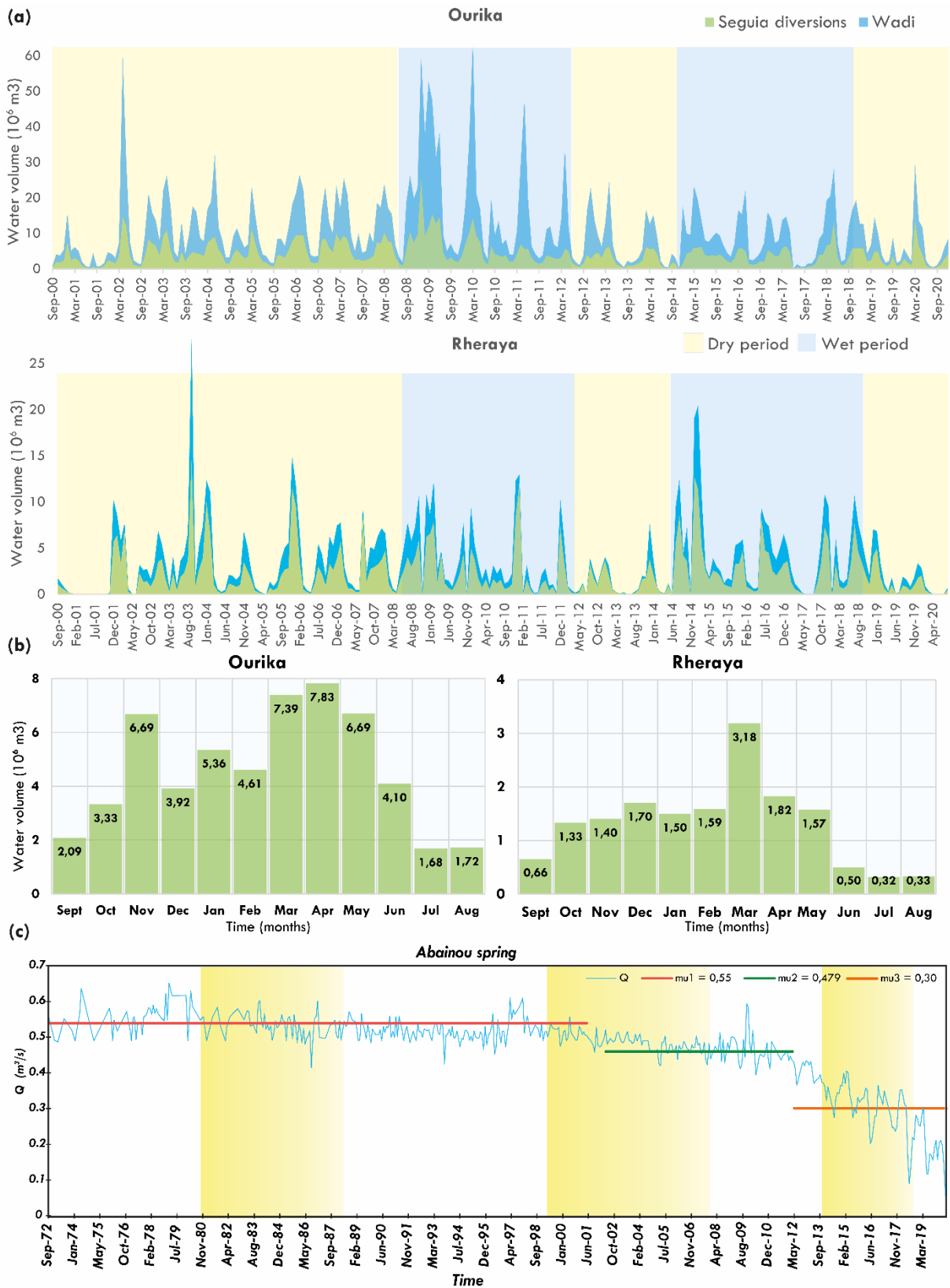
296



298 *Figure 6: Homogeneity test of the monthly streamflow for Ourika, Zat, Rheraya, Rdat, and Chichaoua streams from 1965 to*
299 *2018, where μ_1 and μ_2 are the monthly mean streamflow (m³/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

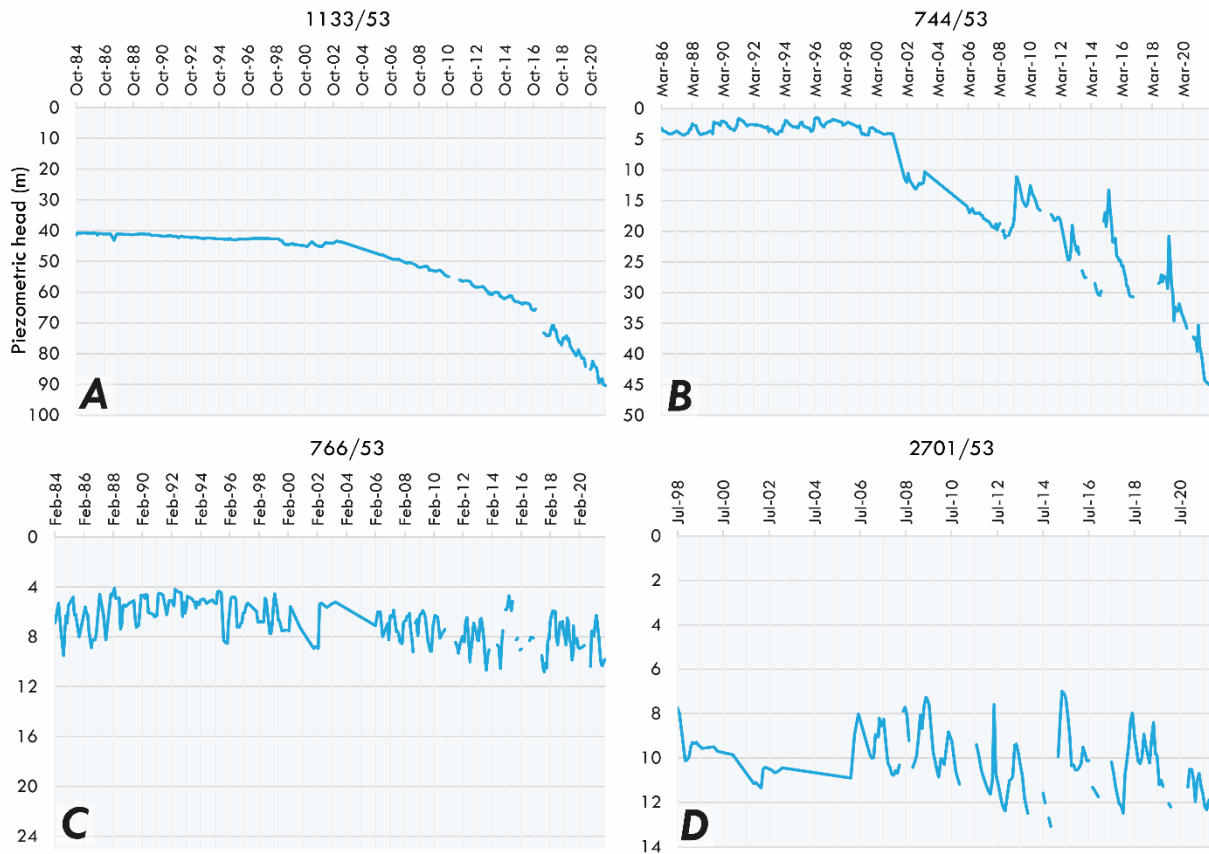
311 Rheraya streams. (b) Monthly water volumes diverted by seguias in Ourika and Rheraya between 2000 and 2020. (c) Abainou

312 *spring discharge evolution from 1972 to 2020, with change point marked in yellow (May 2001). where μ_1 and μ_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.

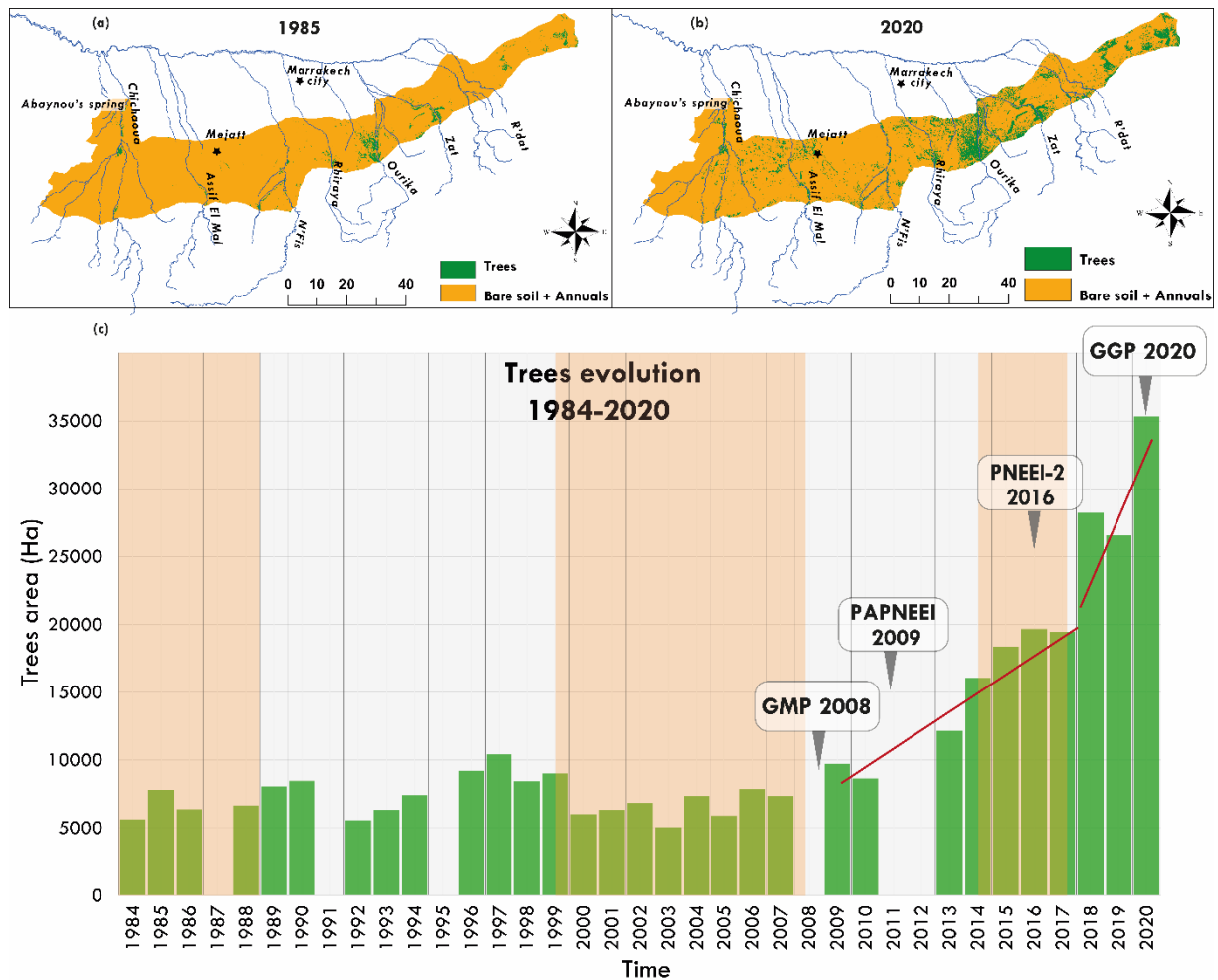
359 *Table 3: The confusion matrix.*

		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-1 in Chouiter, while in Mejjate it was
424 around 1.5 m.y-1 between 2002 and 2016 and is close to 5m.y-1 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⁻¹ 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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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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