Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268 (Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 21 | No. 2 | pp. 837-850 | 2022
Original Research Paper
https://doi.org/10.46488/NEPT.2022.v21i02.048
Open Access Journal

Environmental Changes in a Mediterranean River (Upper Sebou, Morocco) Between 1981 and 2017

Mariam Zerrouk*†, Mohamed Dakki*, Mohammed Aziz El Agbani* and Oumnia Himmi*
*Department of Zoology, Laboratory of Geo-Biodiversity and Natural Patrimony, Scientific Institute, Mohammed V University in Rabat, Morocco
†Corresponding author: Mariam Zerrouk; mariam.meknes@gmail.com

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 09-07-2021
Revised: 28-08-2021
Accepted: 22-09-2021

Key Words:
Upper Sebou river
Thermal and hydrological regimes
Abiotic variables
Recurrent droughts
Anthropization

ABSTRACT

The functioning and sustainability of lotic ecosystems depend to a large extent on their thermal and hydrological regimes. In the Mediterranean region, these factors are very sensitive to climate and anthropization which have undergone deep changes over the last four decades. Having noted the drying up of many permanent streams in Morocco, we conducted in 2015-2017 a new study with the aim of analyzing and assessing abiotic changes in the Upper Sebou (Middle Atlas, Morocco). A former study was carried out in 1981-1985. Indeed, over the last four decades, this river has been exposed to multiple disturbances, due to both recurrent droughts and human pressures. To describe and assess these changes, we used 16 abiotic variables that were measured in 11 ecosystems along the central course of the river. The comparison was mainly carried out using the multiple factorial correspondence analysis (MFCA), through a ternary matrix “variables × stations × time”, gathering old and new data in the same mesological structure. The analysis revealed the classical upstream-downstream ordering of the studied ecosystems, where most of the ecosystems recorded a downstream migration from their 1981 position. In this evolutionary perspective, the study involves hydrological and thermal factors, which show mainly a reduction in flow and a slight increase in temperature and water mineralization, both in summer and winter. It is assumed that water withdrawals, especially for irrigation, together with climatic droughts in the region, are responsible for these long-term evolutionary trends.

INTRODUCTION

In the Mediterranean region, the inland aquatic ecosystems are highly vulnerable to climate changes, as their hydrology is intimately linked to climate (Giudicelli et al. 1985), which continues to change globally (Sala et al. 2000, Heino et al. 2009, Whitehead et al .2009). This vulnerability is increased by the natural aridity of the climate and frequent drought crises (Haida et al. 1999, Garouani & Tribak 2006), which directly affect surface waters, mainly their hydrological and thermal regimes, which are fundamental factors for the functioning of these ecosystems (Illies & Botosaneanu 1963, Dakki 1986a, 1987, Doledec & Chessel 1989, El Agbani et al. 1992). Indeed, the climate aridification leads to an increase in water temperature, consequently to a generalized decrease of the flow, or even the drying up of rivers. Several abiotic variables are then simultaneously modified (gas contents, evaporation rate, primary production, etc.). These factors lead to generalized and increasing physiological stress within living populations close to their upper limit of thermo-tolerance (i.e. Botella-Cruz et al. 2016) and can alter both metabolism, growth, and life cycle of the organisms, and the communities organization (Durance & Ormerod 2010, Walther 2010).

These changes are amplified by human activities, in particular by water withdrawals, bearing in mind that the human need for water resources has greatly increased during the last drought crises. Moreover, these same activities continue to generate pollution, which has altered the living communities of most rivers (Webb & Nobilis 2007, Mabrouki et al. 2016, El Foul & El Ghachi 2018).

In Morocco, the rainfall follows a highly irregular pattern both in time and space; which irregularity is also expressed in the river flow, as demonstrated in the Upper Sebou basin for the periods 1957-58 and 2009-10 (Qadem 2015), during which this author revealed similar trends in the annual flow and the rainfall of the wet and dry seasons. In the recent four decades, this trend was clearly negative and marked by frequent drought crises, in rainfall (Tramblay et al. 2012, El Ajhar et al. 2018), hydrological regime of rivers (Haida et al. 1999, Bouaicha & Benabdelfadel 2010) and water reserves (Devos & Nejjari 1998, Devos et al. 2000). Indeed, since the 1980s, these reserves have sharply declined, with even a drying up of several springs and lakes (Dakki & Himmi 2008, El Fellah Idrissi et al. 2017).

The climate change impacts on lotic ecosystems can be revealed using their mesological descriptors (i.e. physico-chemical) or biotic components (i.e. indicators, community richness, and diversity). The present study aims to reveal the direct and indirect effects of climate change on the Southern Mediterranean lotic ecosystems during the last four decades, through a comparison of the mesological state of the Upper Sebou River between two periods (1981-1985 and 2015-2017). During the 35 years separating these two dates, several drought crises happened in the country, concomitantly with the exponential growth of the human pressures on aquatic ecosystems. This study aims also to show how the factorial analysis method can illustrate pattern changes using the mesological components, as it was illustrated by the living components, more especially insect communities (Zerrouk et al. 2021). This last approach revealed a heavy loss of aquatic biodiversity, which can be easily linked to the indirect effects of climate change.

STUDY AREA AND SITES

The Upper Sebou occupies a large catchment area (about 4700 km², with reference to the altitude of 200 m), located in the northern Middle Atlas between latitudes 33°N and 34°N and longitudes 4°W and 5°W (Fig. 1). It overlaps the tabular Middle Atlas, dominated by Jurassic carbonate outcrops (dolomites and limestones), and the folded Middle Atlas, made of long wrinkles separated by large plains (Martin 1981, Fedan 1988).

This hydrographic network is composed of three main branches: Guigou, Mahçar, and Zloul rivers. The first one, 114 km long, corresponds to the central course of the river; its name changes to Mdez at its confluence with Al Mahçar, then to Sebou after its confluence with the Zloul. The dominance of karst in its watershed (Akdim et al. 2011, Abboudi et al. 2014) explains why this river receives, along its course, several major springs (Aghbalou Aberchane, Tit-Zill, Skhounate, Sebou, Timedrine, Ouamender, etc.). These resurgences ensure water sustainability in most of the river's central course, especially during dry periods (Ben Tayeb & Leclerc 1977, Dakki 1986b).

The upper Sebou drains one of the watersheds where the human population records exponential growth, mainly along with the stream courses. This population lived mainly from agricultural and pastoral activities, but during the last four decades, it has developed into villages and even towns. This means a strong increase in human demand for water, with the intensification of agriculture and stream pollution at high and medium altitudes (Nejjari 2002, Qadem 2015).

To carry out this comparative study, we selected eleven stream and spring ecosystems (Fig. 1): nine on the Guigou and two on the Sebou. This choice is explained in the meth-

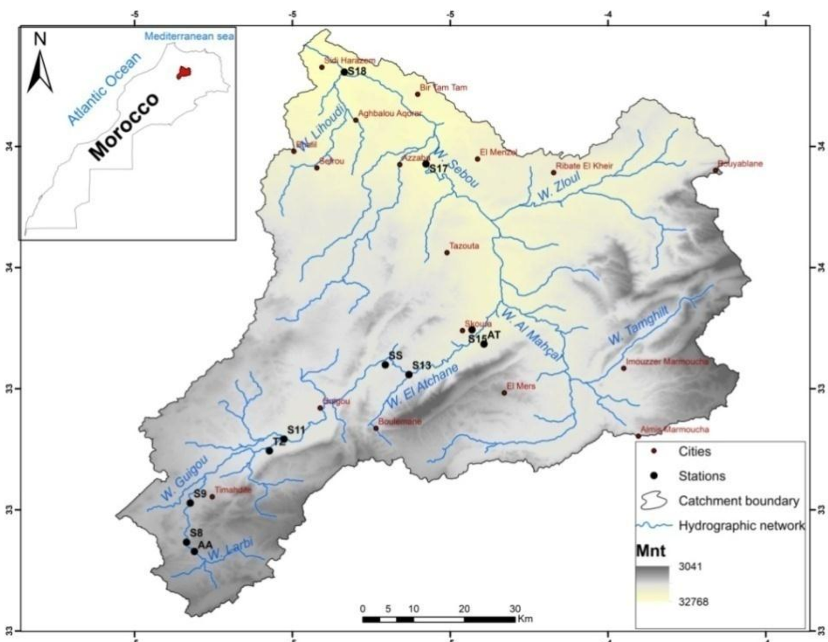

Fig. 1: Location of the prospected stations in the Upper Sebou catchment area.

odology and only their general characteristics are presented here (Table 1) while recalling that they were briefly described by Dakki (1986b, 1987).

MATERIALS AND METHODS

Experimental Design

The principle adopted to characterize the global changes in the Upper Sebou, including the anthropogenic pressures, consists of comparing a set of ecosystems (assimilated here to stations), using abiotic descriptors likely to reveal the climate warming. These stations are not compared separately from each other, but through structures that organize them according to their similarities. In addition, the chosen sample of stations should reflect a wide range of ecological situations in Upper Sebou. This comparative study, therefore, requires the use of the same descriptors and the same methods of sampling and data processing as used by Dakki (1986b, 1987); this minimizes the impact of non-ecological factors in determining the observed differences between stations. Nevertheless, some stations sampled in 1981-85 were not fully accessible (S9, TZ) or deeply modified (AT and TZ sources) in 2015; therefore, the measurement points were slightly displaced from their 1981-locations, knowing that this change can lead to slight variations in station width and depth.

Study Ecosystems (Stations)

Eleven water points were selected for this comparison among the 37 stations studied in 1981-1985 (Table 1); selection was operated in a way to take into consideration a high variation in abiotic variables and habitats (mineral substrate, vegetation, current speed...). Indeed, these stations represent the major types of lotic ecosystems highlighted in Upper Sebou (Dakki 1987); eight of them are located along the central course of the Sebou, between the altitudes of 216 m and 1910 m, including a spring (SS station) that emerges in the river bed. The other three stations are springs with various temperatures (9.7°C to 18.5°C). Until 1985, these ecosystems were relatively close to their natural state, but by 2015, they had undergone more or less deep changes, like the rest of the Upper Sebou (Dakki & Himmi 2008).

Analysis of the Physico-Chemical Parameters of the Water (Comparative Variables)

To assess the mesological changes and characterize water quality in the Upper Sebou ecosystems between the two study periods, we referred to the variables described in the first period (1981-85) by Dakki (1987), among which we selected sixteen variables known to have effects on the benthic fauna and which have a key ecological role.

During each field season, the variables (temperature, dissolved oxygen, and electrical conductivity at 20°C) were measured in-situ using a field multi-parameter (HANNA Instruments, model HI9298). The current speed is taken at 5 cm from the bottom, far from the edges of the stream, using a current meter (Global Water FP111), while the average depth and width of the bed are measured using respectively a ruler and a graduated tape. The mineral substrate is characterized by its dominant components, reduced into two types: coarse materials (pebbles and boulders) and fine/loose materials (gravel, silt, sand). The vegetal substrate was also reduced to two categories (phanerogams and bryophytes), which have been expressed by their coverage of the area in water, while the periphyton (*sensu* perilithon), three states are considered: (1) ‘absent or imperceptible’, (2) ‘scarce’ and (3) ‘abundant’ (covers more than 80% of the sediment surface).

Table 1: Study stations in Upper Sebou: names, geographical coordinates, and habitat types.

Stations	Code	Latitude (N)	Longitude (W)	Altitude (m)	Habitat types
Aghbalou Aberchane	AA	33°08’43”	5°03’19”	1915	Cold spring
O. Guigou at Foum Khnag	S8	33°09’41”	5°04’09”	1910	higher course
O. Guigou at Timahdite	S9	33°19’24”	5°03’44”	1820	higher course
Ain Tit Zill	TZ	33°19’24”	4°55’20”	1550	Temperate spring
O. Guigou at Ait Hamza bridge	S11	33°20’38”	4°53’47”	1520	average course
Source Skhounate	SS	33°28’33”	4°43’01”	1425	average course
O. Guigou upstream of O. El Atchane	S13	33°27’30”	4°40’31”	1300	lower course
Ain Tadoute	AT	33°30’45”	4°32’32”	1340	warm spring
O. Guigou at Skoura	S15	33°32’17”	4°33’49”	880	lower course
Sebou at Azzaba	S17	33°49’54”	4°38’42”	470	lower course
Sebou at Masdoura	S18	33°59’39”	4°47’22”	216	lower course

It should be specified that for both study periods, only one measurement campaign was retained, namely from 3 to 9 June 1985 and from 4 to 19 July 2016. These dates correspond to relatively stable hydrology, in the sense that no floods and drying up of stations happen, and the fauna diversity is close to its optimum (El Alami & Dakki 1998). We are aware that this 'snapshot' approach (according to Huttunen et al. 2018) may have some inaccuracies, but these are overshadowed by the wide range of changes in all factors.

Data Analyses

To describe and assess the changes in the studied ecosystems between the two study periods, we first compared the means of the measured variables between these two periods using a non-parametric Wilcoxon test for two matched samples. The treatment was implemented under the free version of Studio-R software; a difference was considered significant for a p-value < 0.05. Subsequently, we compared the "mesological typologies" established for the ecosystems selected for the two studies. Both typologies were based on the same variables (Table 2), which were reduced to fourteen, as we removed two variables (wet cross-section and geometric mean of thermal maxima), to avoid high data redundancy between variables in the analysis.

The typologies were established using Multiple Correspondence Factor Analysis (MFCA), a method that allows combining both quantitative and qualitative variables in the same analysis (Pialot et al. 1984, Fenehans & Young 1985) and is frequently used to classify Moroccan wetlands (El Alami 2002, El Hamoumi et al. 2007). These treatments were carried out through the software Statistica, which concerned three matrices 'stations × variables', where the values of the variables are transformed into classes (modalities), defined by grouping similar or very close values, but sometimes arbitrarily delimited (Table 3).

Initially, we established an independent typology for each period, via a matrix of '11 stations × 14 variables', which were compared through a visual description of the distribution of stations in the factorial plans provided by the MFCA. In a second step, the data from both periods are merged into a ternary matrix of '11 stations × 2 periods × 12 variables', which was reduced to a binary matrix of '12 variables × 22 stations-periods', where each variable has two values, as proposed by Dakki (1986a) and Doledec & Chessel (1989). In this 'combined typology', the time-invariant parameters (altitude and slope) have not been considered in this matrix and do not directly participate in the structuring of the station network. In both approaches, the results are illustrated on the F1-F2 plan of the MFCA and the significance of both axes is investigated by projecting the mesological variables (as modalities) onto the obtained structures (Table 3).

RESULTS

Long-Term Trends in the Environmental Context

The Wilcoxon test (non-parametric test) applied to the environmental variables in different surveyed stations shows a significant difference in the hydrological factors (average width, wet section, and flow) between the two study periods. An estimated 30% reduction in flow at all stations (p-value <0.05) (Table 4). On the other hand, an increase in flow was recorded at station S8, on the Guigou, downstream from the large AA spring (Table 2); but since the flow of this latter has decreased, this variation can only be explained by the improvement of the Guigou stream inflow upstream to this spring.

The values of mineralization (electrical conductivity) show a significant difference between the two study periods (Table 4). An increase in these values was recorded in almost all stations (Table 2) with an average of 23%. The most notable changes are recorded in the two springs AT and TZ, which are increasingly subject to polluting activities, and in S18 downstream of Oued Lihoudi, which carries the discharges of the city of Sefrou.

The comparison of the thermal component shows a significant difference in winter temperature, summer temperature, and the geometric mean of thermal maxima between the two study periods (Table 4). The increase in water temperature in both winter (21.7%) and summer (12%) is a normal consequence of the decrease in flow and depth. This temperature rise attracts our attention, particularly at the headwaters. Indeed, in the fresh springs (AA and TZ), the temperature would have undergone a winter increase of about 1°C, whereas this increase was greater in summer (2.4°C at AA and 3.9°C at TZ), indicating that a relatively large thermal amplitude of mountainous aquifers. In the SS spring, which is warmer than the two previous ones (20.7°C to 22.8°C), the temperature rise is smaller (1.8°C in summer), but relatively high in winter (6.7°C). To understand this difference, we remind that the SS spring emerges in the Guigou riverbed, and in the past, this stream occasionally drains into winter cooler waters that lower the SS water temperature. However, during the 2015-2017 campaigns, this stream was never flowing upstream of the spring. In the AT spring, the water shows a slight drop in temperature (1.0°C), which remains inexplicable.

The rise in spring's water temperature leads us to assume warming of the superficial water tables, a phenomenon that can be linked to snow decrease (both in terms of

Table 2: Mesological data used for the time comparison of the lotic ecosystems of the Upper Sebou.

1981-1985 data																
Stations	Alt	S	W	WS	F	AS	WT	ST	GM	TA	EC	DO	CS	Bry	Pha	Per
AA	1915	30.0	8.0	60	432	72	9.0	10.4	9.7	1.4	360	6.8	90	60	5	1
S8	1910	2.4	8.0	120	192	16	6.9	19.0	11.5	12.1	236	7.6	60	0	20	1
S9	1820	6.7	7.0	95	560	59	8.6	23.0	14.1	14.4	365	8.3	70	0	20	2
TZ	1550	20.0	6.0	110	836	76	12.8	14.6	13.7	1.8	600	7.9	70	20	50	1
S11	1520	7.6	8.0	140	952	68	8.8	22.8	14.2	14.0	660	7.4	70	0	30	2
SS	1425	33.0	7.0	71	285	35	14.0	21.0	17.5	7.0	900	6.4	60	10	20	3
S13	1300	16.9	7.0	62	409	66	12.6	22.6	16.9	10.0	835	6.9	60	3	10	2
AT	1340	125.0	3.5	3.6	31	86	18.4	18.7	18.5	0.3	560	6.2	80	30	50	1
S15	880	12.2	12.0	58	365	63	12.4	25.6	17.5	13.2	996	5.8	70	0	5	3
S17	470	5.7	20.0	1100	8250	75	13.0	22.3	17.0	9.3	528	6.1	70	0	1	2
S18	216	5.2	25.0	1600	6720	42	14.5	28.0	20.0	13.5	565	5.6	70	0	1	1
2015-2017 data																
Stations	Alt	S	W	WS	F	AS	WT	ST	GM	TA	EC	DO	CS	Bry	Pha	Per
AA	1915	30.0	5.5	51.0	270	53	10.0	12.8	11.3	2.8	375	4.9	70	70	1	1
S8	1910	2.4	7.0	94.5	246	26	10.3	19.5	14.2	9.2	312.5	6.5	70	10	20	2
S9	1820	6.7	5.5	63.3	317	50	7.5	21.3	12.7	14.2	407	5.9	75	20	30	2
TZ	1550	20.0	5.0	88.5	584.1	66	13.6	18.5	15.9	4.9	762	6.6	80	30	60	1
S11	1520	7.6	6.5	100.8	575	57	11.2	21.8	15.6	10.6	771	4.7	75	5	50	3
SS	1425	33.0	5.5	66.0	264	40	20.7	22.8	21.7	2.1	894	4	50	20	20	3
S13	1300	16.9	6.0	45.0	261	58	14.0	25.8	19.0	11.8	896	4.4	80	0	20	1
AT	1340	125.0	1.5	2.5	19	74	17.4	18.6	18.0	1.2	783	5.4	60	40	50	1
S15	880	12.2	8.0	50.0	270	54	15.8	26.3	20.4	10.5	1035	5.9	70	0	10	2
S17	470	5.7	15.0	840.0	5880	70	13.7	23.8	18.1	10.1	623	5.9	70	0	1	1
S18	216	5.2	20.0	1160.0	5220	45	15.9	26.3	20.4	10.4	990	5.4	80	3	10	2

Alt: Altitude, S: Slope, W: Average width, WS: Wet Section, F: Flow, AS: Average speed, WT: Winter Temperature, ST: Summer Temperature, TA: Thermal Amplitude, GM: Geometric mean of extreme thermal maxima, EC: Electrical Conductivity at 20°C, DO: Dissolved oxygen, CS: Coarse Substrate, Bry: Bryophytes, Pha: Phanerogams, Per: Periphyton

Table 3: Mesological data transformation to classes for the factorial correspondence analysis.

Periods >>	1981-1985				2015-2017			Combined			
Parameters	Codes	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 4
Altitude (m)	Alt	Alt<1000	1000≤Alt<1600	Alt≥1600	Alt<900	900≤Alt<1800	Alt≥1800	-	-	-	-
Slope (‰)	S	S<16	16≤S<40	S≥40	S<16	16≤S<40	S≥40	-	-	-	-
Average width (m)	W	w<5	5≤w<12	w≥12	w<5	5≤w<15	w≥15	w<5	5≤w<8	8≤w≤15	w>15
Flow($L.s^{-1}$)	F	F<50	50≤F<1000	F≥1000	F<240	240≤F<1000	F≥1000	F<100	100≤F<500	500≤F<1000	F≥1000
Average speed ($cm.s^{-1}$)	AS	AS<50	50≤AS≤70	AS>70	AS<40	40≤AS≤60	AS>60	AS<30	30≤AS<50	50≤AS< 70	AS≥70
Winter temperature (°)	WT	WT<10	10≤WT<14	WT≥14	WT<11.5	11.5≤WT<17.5	WT≥17.5	WT< 10	10≤WT<15	WT≥15	-
Summer temperature (°)	ST	ST<15	15≤ST<25	ST≥25	ST<15	15≤ST<25	ST≥25	ST<15	15≤ST<25	ST≥ 25	
Thermal amplitude	TA	TA<5	5≤TA<12	TA≥12	TA<5	5≤TA<11	TA≥11	TA<4	4≤TA<10	TA≥10	-
Electrical conductivity (µs.cm^{-1})	EC	EC<500	500≤ EC<800	EC≥800	EC<450	450≤EC<800	EC≥800	EC<450	450≤EC<800	EC≥800	-
Dissolved oxygen ($mg.L^{-1}$)	DO	DO<6	6≤DO<7	DO≥7	DO<5	DO≥5	-	DO<5	5≤DO<7	DO≥7	-
Coarse substrate(%)	CS	CS<60	60≤CS<80	CS≥80	CS<60	60≤CS<80	CS≥80	CS<60	60≤CS<80	CS≥80	-
Bryophytes (%)	Bry	Bry<3	3≤Bry<20	Bry ≥20	Bry<20	20≤Bry<70	Bry ≥70	Bry<10	10≤Bry<50	Bry ≥50	-
Phanerogams (%)	Pha	Pha<20	20≤Pha<50	Pha≥50	Pha<20	20≤Pha<50	Pha≥50	Pha<10	10≤Pha<30	Pha≥30	-
Periphyton	Per	1	2	3	1	2	3	1	2	3	-

duration and quantity) in the high parts of the catchment area.

Dissolved oxygen concentration decreased significantly over the three decades, with an average reduction of 21.8%. This is a logical consequence of decreased flow velocities and warming of the water. However, a comparison of values for mean velocity, the proportion of coarse substrate, and plant cover (phanerogams and periphyton) showed no significant difference between the two study periods (Table 4). While bryophytes characterizing springs appeared at some stations in the central Guigou river from 2015 to 2017.

Changes in the Mesological Structures

Comparison of the mesological structures separately established for the two periods: In this first step, the comparison is focused on the mesological structures of the central course separately established for the two periods (Table 2), using the MFCA (Figs. 2A and 2B). The transformation of variable values into modalities is carried out using a scale specific to each dataset (Table 3). For the two periods, the F1-F2 factorial plan of the MFCA accumulates a relatively high rate of the total inertia of the analysis (60.3% for the first period and 56.6% for the second). As the third axis does not bring any further significant information in the two cases, we limited the analysis of the typological structure to the first F1-F2 plan.

In the two analyses (Figs. 3 and 4), the projection of the variables on the F1-F2 plan reveals a limited number of parameters explaining these structures.

In the 1981-1985 typology structure (Fig. 2A), the F1 axis (37.44%) separates the (AA, TZ, and AT) springs from the river, because of their specificities (low summer temperatures, very low annual thermal amplitudes, and richness of the substrate in bryophytes). The F2 axis (22.87%) reveals the ‘upstream-downstream’ gradient, well explained by the altitude and the flow, in parallel with the average width, electrical conductivity, and winter temperature (Fig. 3). This altitudinal gradient is marked by inversions, the most pronounced of which concerns stations S15 and S17. These inversions are related to the thermal characteristics, mainly the amplitude and the summer temperature, which are lower in S17 (due to its position downstream of great springs) than in S15, whereas the latter is at a higher altitude than S17 (Table 2).

The 2015-2017 typological scheme (Fig. 2B) reveals once again the spring specificities and the ‘upstream-downstream’ gradient, the latter being expressed this time along the first axis (37.21%). Indeed, this axis is mainly explained by altitude, stream size (average width and flow), slope, thermal characteristics (amplitude and summer temperature), and bryophytes. The F2 axis (19.41%), which distinguishes the low-mineralized stations from the others, is explained by electrical conductivity and winter temperature (Fig. 4).

The inversions recorded with the 1981-1985 data are still present in 2015-2017: into the mesological structure, both S13 and SS stations take place upstream of S11 (Fig. 2B), which is naturally at a higher altitude. This inversion is explained by the flow, which is much lower at SS (264 $L.s^{-1}$) and S13 (261 $L.s^{-1}$) than at S11 (575 $L.s^{-1}$). The relative

Table 4: Results of non-parametric Wilcoxon test applied to environmental variables measured in 1981-85 and 2015-17 (*** p-value<0.05; * p-value>0.05).

Variables	p-value	Signif.
Average width	0.003702	***
Wet section	0.0009766	***
Flow	0.004883	***
Average speed	0.05557	*
Winter temperature	0.0326	***
Summer temperature	0.01971	***
Geometric mean of thermal maxima	0.02073	***
Thermal amplitude	0.4131	*
Electrical conductivity	0.001953	***
Dissolved oxygen	0.005056	***
Coarse substrate	0.8571	*
Bryophytes	0.03494	***
Phanerogams	0.05624	*
Periphyton	1	*

similarity between SS, AT, and TZ springs, due to their low thermal amplitude (2.1°C), seems to amplify this inversion.

Analysis of the mesological structure combining the two periods' data: The MFCA processing of ternary matrix '11 stations × 12 variables × 2 periods' gathering old and recent data (excluding altitude and slope, as time-invariant factors), provides for each station two positions in the F1-F2 plan. The moving pattern of each station between both periods was interpreted as temporal changes in its mesological state.

The first two axes express again 56% of the total information on the structure (Fig. 2C) and the projection of the mesological variables on the F1-F2 plan (Fig. 5) shows a great similarity to the pattern obtained using the 1981-1985 data (Fig. 2A). Indeed, the F1 axis (35.34%) separates the three springs (AA, TZ, and AT) from the riverine ecosystems, through thermal amplitude, phanerogams, and dissolved oxygen, while it participates in the upstream-downstream gradient thanks to hydrological parameters (average width and flow). However, this gradient is better expressed by the F2 axis (20.68%), which is correlated with thermal variables (winter and summer temperatures), conductivity, and periphyton.

The most important result revealed by this analysis is that each station (Fig. 2C) operates more or less amplified

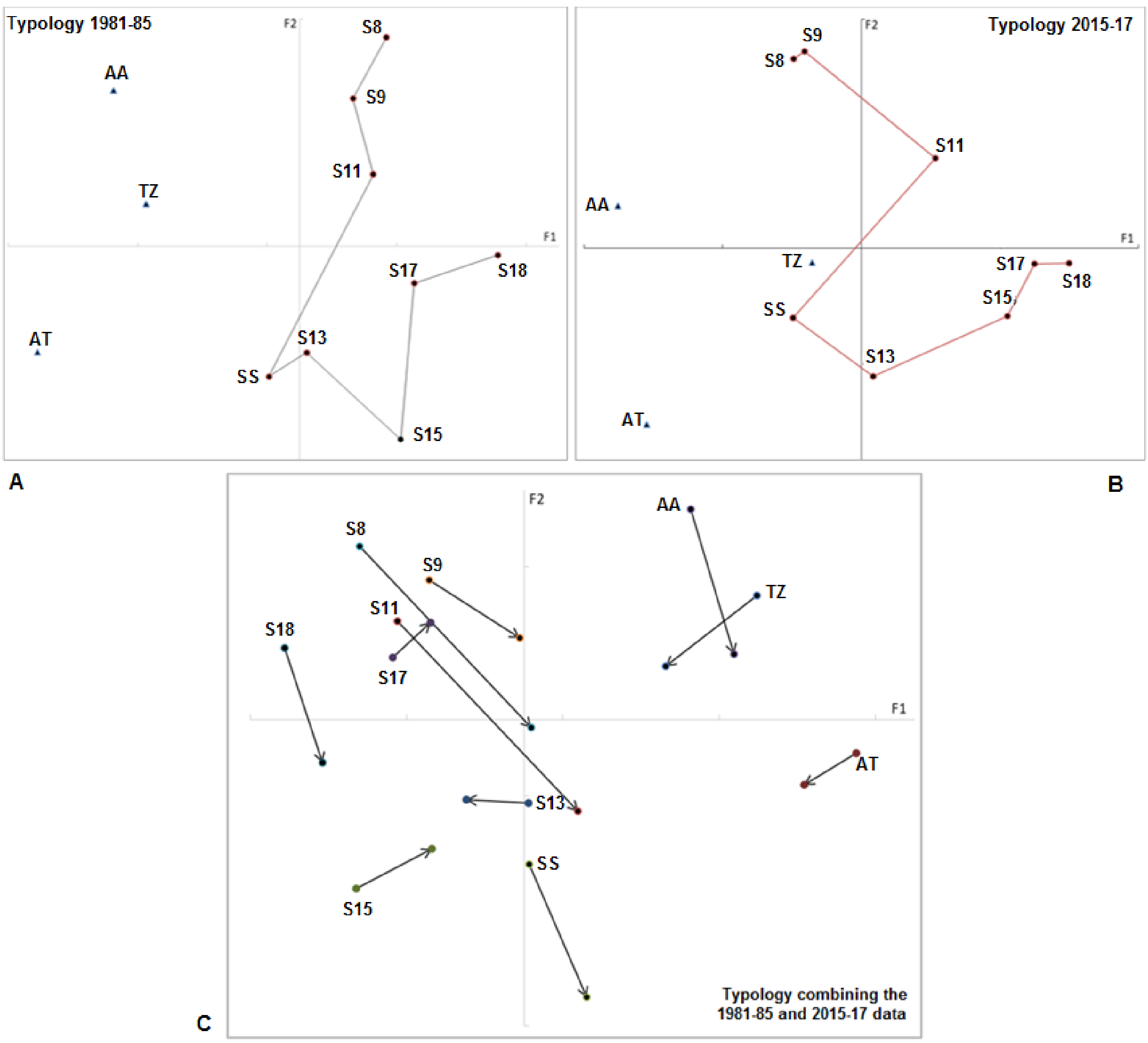

Fig. 2: Mesological structure of the central course of the Upper Sebou on the F1-F2 plan of an MFCA. A) data of the period 1981-1985. B) data for the period 2015-2017. C) combining data from the two periods 1981-1985 and 2015-2017.

changes between the two study periods, as indicated by the arrows. Most of these changes consist of a migration of the stations in the direction of the 'upstream-downstream' gradient, simultaneously expressed by both first axes, knowing that F1 and F2 express the hydrology and the temperature respectively. For two stations (SS spring and S13 stream), this migration is sub-parallel to F2 (thermal change) for the first and to F1 (hydrological change) for the second.

To assess the changes in amplitude in each station over the 35 years, we used the distance between its two points on the F1-F2 plan, which varies from one water body to the other. Two high altitude streams (S8 and S11) operate a large displacement; clearly correlated with the F2 axis, attesting that their waters have undergone a warming and mineralization increase. Moreover, these stations, located downstream of major springs, would have experienced a slight increase in their flow and a decrease in their thermal amplitude, as indicated by the slight development of their bryophytes' cover. The S9 station, located between the two former water points, shows a low downstream migration, in concordance with the loss of its flow.

S13 Station, located downstream of the SS source, underwent a downstream shift, corroborating a decrease in its flow and a slight increase in its thermal amplitude. All the further downstream habitats (S15, S17, and S18) have migrated in the direction of a flow loss (F1) and recent warming (F2); however, S17 is still fed by large springs located upstream, which makes its displacement amplitude low.

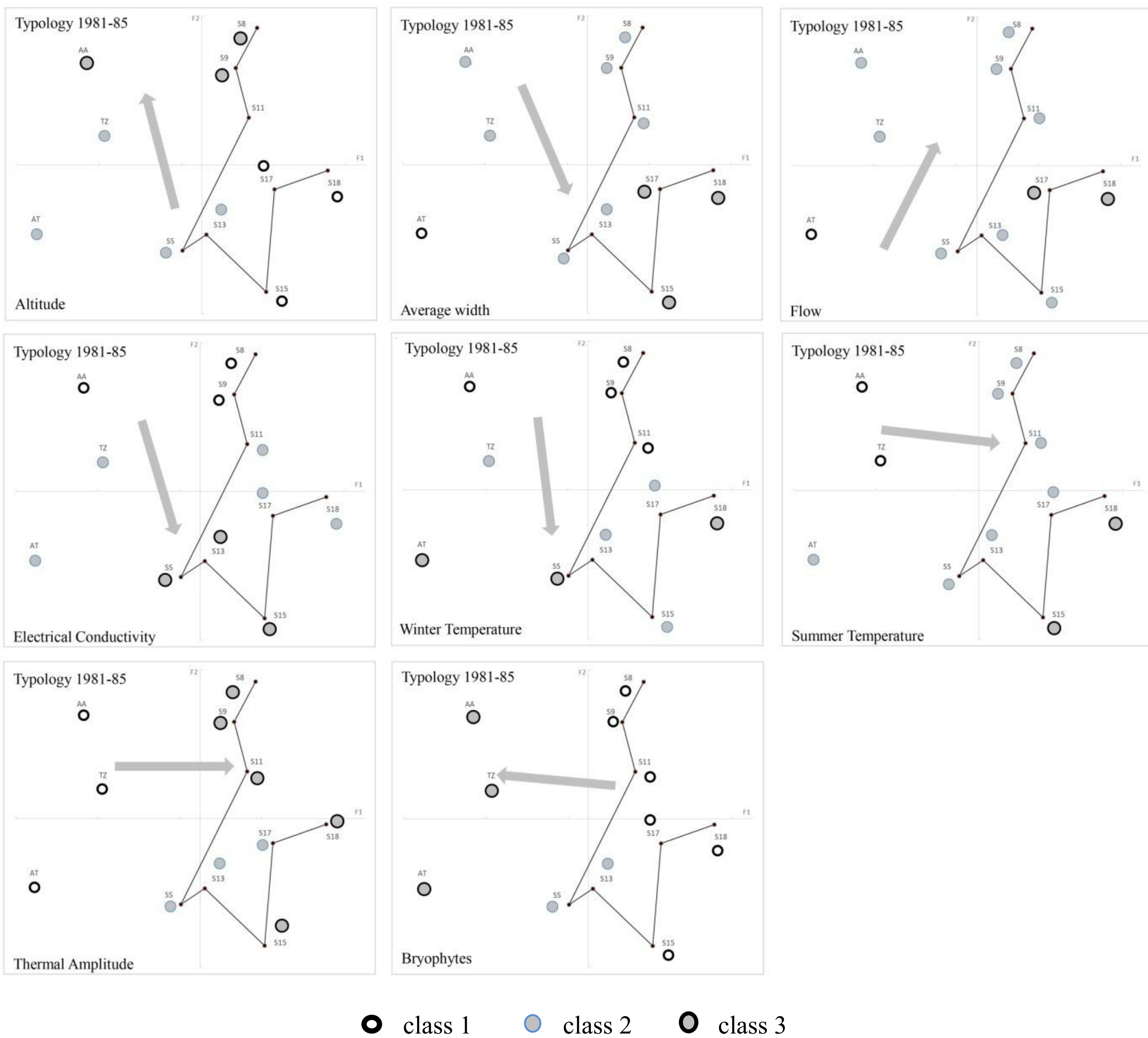

Fig. 3: Interpretation of the 1981-1985 mesological structure of the upper Sebou: Projection of the mesological variables on the F1-F2 plan.

This general typology scheme shows for both periods a very pronounced inversion along the gradient F2, since S15 went downstream even of S18 station, indicating the thermal nature of this inversion, mainly linked to the excessive lowering of the flow.

All the springs show a significant change in their abiotic characteristics between both study periods, which evolution is visibly linked to both thermal factors (water warming) and hydrological factors (flow reduction). These changes appear on the F2 axis and, to a lesser degree, on the F1 axis, with a contribution to the mineralization of the TZ and AT sources. In the absence of groundwater temperature monitoring, we assume that the surface aquifers that give rise to these springs are operating as light warming.

DISCUSSION

In 2015-2017, the general mesological ordination of the Upper Sebou ecosystems (Fig. 2B) is still slightly similar to the pattern established three decades earlier (Fig. 2A), which is dominated by the upstream-downstream gradient, simultaneously determined by hydrological and thermal factors, with some thermal inversions. However, some significant differences have been highlighted between the two classifications and linked to changes in these same factors. It's not surprising

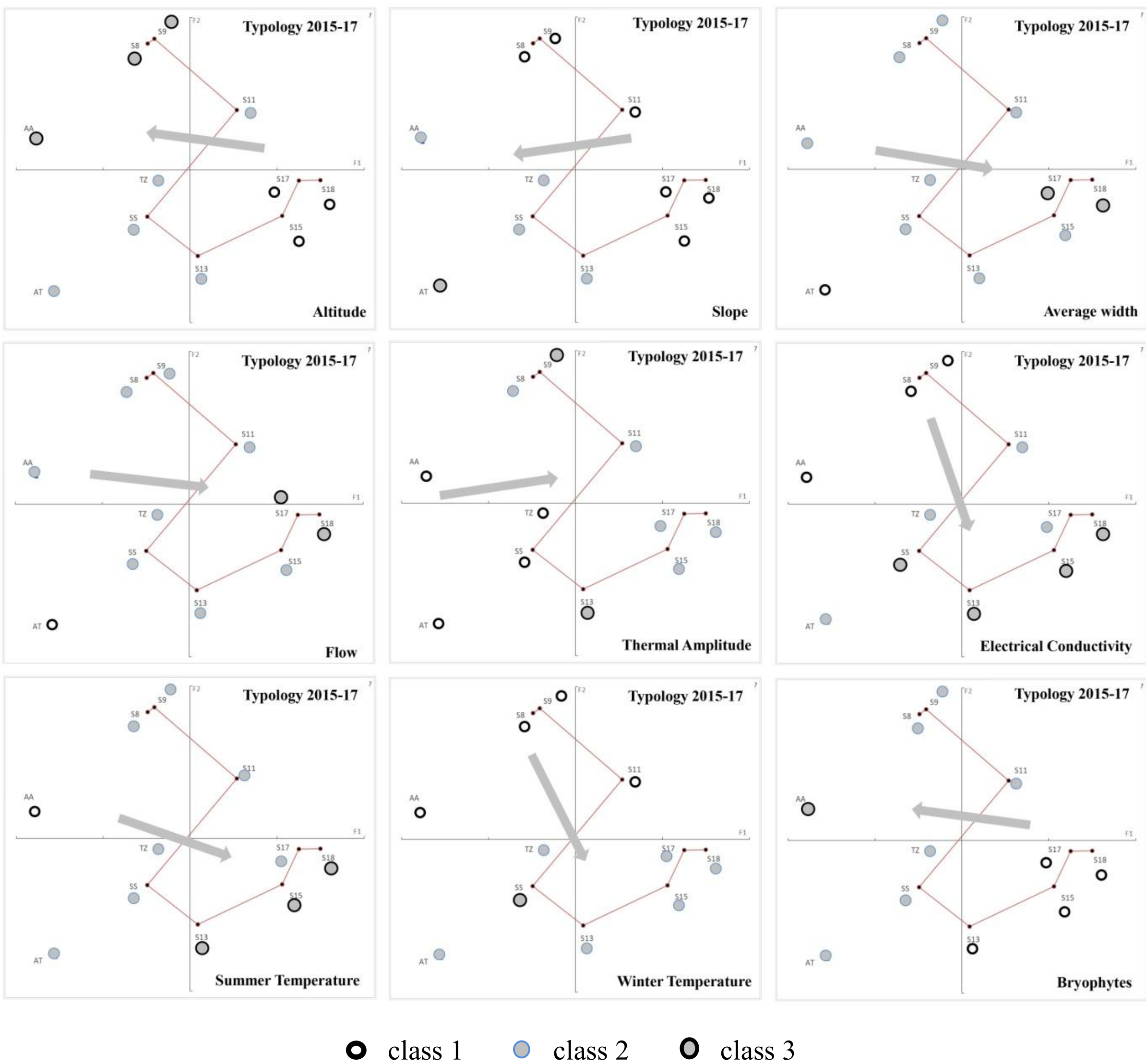

Fig. 4: Interpretation of the 2015-2017 mesological structure of the upper Sebou: Projection of the mesological variables on the F1-F2 plan.

that this pattern is also obtained by merging the data from these two periods (Fig. 2C); however, this approach has the advantage to attribute two positions to each ecosystem, defining a migration pattern that can be characterized by its amplitude and direction in the ordination scheme. In general, this migration reveals an increase in water temperature (both in winter and summer) and mineralization, in parallel with a flow decrease; the few exceptions to this pattern were related to particular situations that were easily explained.

These mesological modifications were largely linked to climate change, reflected in the Mediterranean region by recurrent drought crises, some of which lasted more than three successive winters, particularly during the 1980s and 1990s (Chaouche et al. 2010, Hallouz et al. 2013, Khomsi et al. 2016, Ouhamdouch et al. 2018). These droughts lead to a general flow decrease, which was recorded in various Mediterranean rivers other than the Sebou: the Moulouya in Morocco (Driouech et al. 2010), the Chéllif in Algeria (Meddi

Fig. 5: Interpretation of the Mesological structure of the central course of the Upper Sebou in the F1-F2 plan of an MFCA combining data of the two periods 1981-1985 and 2015-2017: Projection of the mesological variables on the F1-F2 plan.

et al. 2010), the Loire in France (Floury 2012, Floury et al. 2013), etc. The latter study evaluated at 1.2°C the warming of the waters of the Loire between 1977 and 2008, corresponding to a reduction of -25% of its flow. Our results join those of Devos et al. (2000), which show in the Upper Sebou catchment area a spatial disparity in the water resources.

In the Upper Sebou, as in most southern Mediterranean rivers, the flow lowering is not only a direct consequence of droughts but is amplified by water withdrawals, which have even dried up several stretches of the central watercourse of the Sebou (Devos et al. 2000, Dakki & Himmi 2008). Several sectors of the river (i.e. S13 and S15) and even some springs underwent a drying up lasting several weeks; all other areas also experienced severe flow declines, mainly over the 1980s and 1990s (El Ajhar et al. 2018). Thus, the irrigation activity, performed via a large number of seguias and pumping points, occurs mainly in summer and even in spring, when the flow is naturally low. The 'perennial' SS spring, which arises from a relatively deep water table (given its temperature of around 20°C), had stopped flowing downstream towards the S13 station and almost dried up in 2008.

The water mineralization, measured in the summer, increased in almost all the study points, favored by the drop inflow and the summer warming of the water. However, in several stations, particularly the TZ and AT springs, the Guigou stream (S8 and S11), and the Sebou river (S18), high algae abundance (eutrophication) is observed and linked to domestic and agricultural discharges, cattle droppings, etc., bearing in mind that most domestic waters are not treated.

CONCLUSION

The flow drop and the water warming, as the main changes that happened in Moroccan river ecosystems during the last four decades are often directly linked to massive water withdrawals, being themselves considered as consequences of the development of urban and agricultural activities. This latter has indeed gained large areas in the Upper Sebou watershed and withdrawals were already intensive during our 1981-1985 study, but few river sketches showed at that time a summer drying-up, while during more recent droughts this phenomenon affected a large number of streams and even springs of this watershed. Indeed, during a summer visit to the Guigou river, carried out in 2008 (Dakki & Himmi 2008), a catastrophic hydrological crisis has been highlighted, leading with no doubt to link the drying-up directly to the droughts, with an evident amplification by withdrawals. Nevertheless, flow drops were revealed also in some high altitude springs and small streams, indicating deficiencies in water tables that are not pumped; this confirms again the direct link between flow drops and droughts. On another hand, the water warming in river ecosystems, closely linked to insolation, is a direct consequence of the decrease of the water flow; but its evidence in some springs lets us conclude with an effect of droughts on water table temperature.

It is important to note that, in parallel with the present mesological study, we carried out a study of the benthic fauna (Zerrouk et al. 2021) that revealed a catastrophic loss of biodiversity that was explained by the mesological changes described above, but which crucially needs conservation solutions. For such purpose, this paper provides baseline ideas of the impact mechanisms of the droughts, which could constitute guidance for conceiving the said solutions.

In terms of methodology, both mesological and fauna studies demonstrate that among a large panel of possible methods to highlight the changes in running waters, the classification, and ordination techniques have shown their relevance, as they made it possible to reveal trends patterns in the ecosystem changes. We should admit that regular monitoring of these changes could certainly better detail these trends (Huttunen et al. 2018, Cañedo-Argüelles et al. 2020), but in lack of such costly monitoring, the changes revealed by our study provided significant conclusions that can be used as an alert for the urgent need of conservation of the Southern Mediterranean running waters.

ACKNOWLEDGEMENT

We would like to thank the reviewers for their time investment in reviewing this work with high attention. We express also our thanks and gratitude to Prof. Lahcen Chillasse for having granted us some field equipment, to Mr. Hassan Hassani, who improved the English writing of the paper, and to Mr. B. Badaoui and Mrs. A. Alaoui for their contribution to the statistical analyses.

REFERENCES

Abboudi, A., Tabyaoui, H., El Hamichi, F., Benaabidate, L. and Lahrach, A. 2014. Study of the physico-chemical quality and metal contamination of surface water in the Guigou watershed, Morocco. Europ. Sci. J., 10(23): 1857-7881.

Akdim, B., Sabaoui, A., Amyay, M., Louane, M., Emmanuel, G. and Obda, K. 2011. Hydro-karstic influence of the Aïn Sebou-Timedrine-Ou Amender water source system on the hydrology of the Sebou wadi (Middle Atlas, Morocco). J. Geomorphol., 56(2): 165-181.

Ben Tayeb, A. and Leclerc, L. 1977. Water Resources of Morocco: Atlas and South Atlas domains. Volume III. Notes and Memoirs of the Geological Service of Morocco, Rabat, Morocco, pp. 37-66.

Botella-Cruz, M., Carbonell, J.A., Pallarés, S., Millán, A. and Velasco, J. 2016. Plasticity of thermal limits in the aquatic saline beetle *Enochrus politus* (Küster 1849) (Coleoptera: Hydrophilidae) under changing environmental conditions. Limnetica, 35(1): 131-142.

Bouaicha, R. and Benabdelfadel, A. 2010. Variability and management of surface water in Morocco. Sécheresse, 21(1): 1-5.

Cañedo-Argüelles, M., Gutiérrez- Cánovas, C., Acosta, R., Castro-López, D., Cid, N., Fortuño, P., Munné, A., Múrria, C., Pimentao, A.R., Sarremejane, R., Soria, M., Tarrats, P., Verkaik, I., Prat, N. and Bonada, N. 2020. As time goes by: 20 years of changes in the aquatic macu roinvertebrate meta community of Mediterranean river networks. J. Biogeogr., 47:1861-1874.

Chaouche, K., Neppel, L., Dieulin, C., Pujol, N., Ladouche, B., Martin, E., Salas, D. and Caballero, Y. 2010. Analyses of precipitation, temperature, and evapotranspiration in a French Mediterranean region in the context of climate change. Geoscience, 342: 234-243.

Dakki, M. 1985. On the choice of data in the biotypology of running waters by factorial analysis of correspondences. Ecol. Bull., 16(4): 285-296.

Dakki, M. 1986a. Biotypology and spatio-temporal thermal gradient, study on a stream in the Middle Atlas (Morocco). Ecol. Bull., 17(2): 79-85.

Dakki, M. 1986b. Hydrobiological research on the Haut Sebou (Middle Atlas); A Contribution to the Faunistic, Ecological and Historical Knowledge of South-Mediterranean Running Waters. Thesis in Science, Mohammed V University, Morocco.

Dakki, M. 1987. High Sebou Running Water Ecosystem (Middle Atlas): Typological Studies and Ecological Analyzes and Biogeography of the Main Entomological Populations. Works of the Scientific Institute Zoology Series. Institut scientifique, Rabat, pp. 42-99.

Dakki, M. and Himmi, O. 2008. Strategic Bases for the Conservation of Freshwater Biodiversity in the Sebou Basin (Morocco): Inventory of Biodiversity and Ecological Conservation Targets. WWF/GREPOM Report, Morocco, pp. 26+58.

Devos, A. and Nejjari, A. 1998. The Recent Hydrological Drought in the Upper Sebou Basin (Middle Atlas). AUPELF- Mosella Report, UREF, Metz University and Sidi Mohamed Ben Abdellah University, pp. 3-4.

Devos, A., Benjlloul, B. and Nejjari, A. 2000. Water resources and their uses in the plain of Guigou (Middle Atlas, Morocco). Mosella, 3(4): 327-339.

Doledec, S. and Chessel, D. 1989. Seasonal rhythms and stationary components in the aquatic environment. II. Consideration and elimination of effects in a faunal table. Acta Oecol. General., 10(3): 207-232.

Driouech, F., Mahé, G., Déqué, M., Dieulin, C., Heirech, T., Milano, M., Benabdelfadel, A. and Rouche, N. 2010. Evaluation of Potential Impacts of Climate Change on the Hydrology of the Moulouya Watershed in Morocco. Global Change: Facing Risks and Threats to Water Resources. In: Proceedings of the Sixth World Friend Conference, Fez, Morocco, October 2010, IAHS Publ., Wallingford, Oxfordshire, UK, pp. 340.

Durance, I. and Ormerod, S.J. 2010. Evidence for the role of climate in the local extinction of a cool-water triclad. J. North Am. Benthol. Soc., 29(4):1367-1378.

El Agbani, M.A., Dakki, M. and Bournaud, M. 1992. Typological study of Bou Regreg (Morocco): Aquatic environments and their populations of macroinvertebrates. Ecol. Bull., 23 (1-2): 103-113.

El Ajhar, L., El Khachine, D., El Bakouri, A., El Kharrim, K. and Belghiti, D. 2018. Evolution of rainfall from 1960 to 2015 in Morocco. Int. J. Res. Sci. Manag., 61: 2349-2497.

El Alami, M. 2002. Taxonomy, Ecology, and Biogeography of Ephemo eroptera from the Rif (Northern Morocco). State Doctorate Thesis, Abdelmalek Essaâdi University, Morocco.

El Alami, M. and Dakki, M. 1998. Ephemeroptera and Trichoptera populations of Oued Laou (Western Rif, Morocco): Longitudinal distribution and biotypology. Sci. Inst. Bull., 21: 51-70.

El Fellah Idrissi, B., Cherai, B., Hinaje, S. and Mehdi, K. 2017. Climate variability and its influence on water resources in the northern part of the Moroccan Middle Atlas: The case of the causes of Sefrou and Anoceur. Larhyss J., 32: 155-179.

El Foul, M. and El Ghachi, M., 2018. Impact of anthropogenic actions on the hydrological balance in the Tassaout watershed (Upstream of the Moulay Youssef dam): ORCHY II hydrological model (1986-2010) Morroco. J. Water Environ. Sci., 2: 305-318.

El Hamoumi, R., Dakki, M. and Thevenot, M. 2007. An ecological study of anuran larvae in Morocco. Bull. Sci. Instit., 29: 27-34.

Fedan, B. 1988. Geodynamic evolution of an intraplate basin on strike-slip: The Middle Atlas (Morocco) during the Meso-Cenozoic. Doctoral thesis Mohammed V University, Morocco.

Fenehans, M. and Young F.W. 1985. Analysis and synthesis of multiple correspondence analysis optimal scaling, dual scaling, homogeneity analysis, and other methods for quantifying categorical multivariate data. Psychometrika, 50(1): 91-119.

Floury, M. 2013. Analysis of Evolution Trends of Benthic Macroinvertebrate Populations in a Context of Water Warming. Doctoral thesis, Blaise Pascal University, France.

Floury, M., Delattre, C., Ormerod S.J. and Souchon, Y. 2012. Global versus local change effects on a large European river. Sci. Total Environ., 441: 220-229.

Garouani, A. and Tribak, A. 2006. Relationship between Hydrology and Climate in the Oued Inaouene Watershed (Moroccan Pre-Rif): Climate Variability and Change Hydrological Impacts. In Proceedings of the Fifth FRIEND World Conference 447 held at Havana, Cuba, November 2006, IAHS Publ., Wallingford, Oxfordshire, UK, pp.308.

Giudicelli, J., Dakki, M. and Dia, A. 1985. Abiotic and hydrobiological characteristics of Mediterranean running waters. Int. Assoc. Theoretical Appl. Limnol. Negot., 22(4): 2094-2101.

Haida, S., Ait Fora, A., Probst, J.L. and Snoussi, M. 1999. Hydrology and hydroclimatic fluctuations in the Sebou watershed between 1940 and 1994. Sècheresse, 10(3): 221-6.

Hallouz, F., Meddi, M. and Mahé, G. 2013. Modification of the hydroclimatic regime in the Oued Mina Basin (North-West of Algeria). J. Water Sci., 26(1): 33-38.

Heino, J., Virkkala, R. and Toivonen, H. 2009. Climate change and freshwater biodiversity: detected patterns, future trends, and adaptations in northern regions. Biol. Rev., 84: 39-54.

Huttunen, K.L., Mykrä, H., Paavola, R. and Muotka, T. 2018. Estimates of benthic invertebrate community variability and its environmental determinants differ between snapshot and trajectory designs. Freshwater Sci., 37(4): 769-779.

Illies, J. and Botosaneanu, L. 1963. Problems and methods of the classification and ecological zoning of running waters, considered especially from the faunistic point of view. Int. Assoc. Theoret. Appl. Limnol., 12(1): 1-57.

Khomsi, K., Mahé, G., Tramblay, Y., Sinan, M. and Snoussi, M. 2016. Regional impacts of global change: seasonal trends in extreme rainfall, run-off, and temperature in two contrasting regions of Morocco. Nat. Hazards Earth Sys. Sci., 16: 1079-1090.

Mabrouki, Y., Taybi, A.F. and Berrahou, A. 2016. Spatio-temporal evolution of the quality of running water in the Melloulou wadi (Morocco). J. Water Sci., 30(3): 213-225.

Martin, J. 1981. The Central Middle Atlas: Geomorphological Study. Notes and Memoirs of the Geological Survey, No. 258, Rabat.

Meddi, M., Boucefiane, A. and Sadeuk Belabbes, A. 2010. Impact of climate change on flows in the Chellif basin (Algeria). Global Change: Facing Risks and Threats to Water Resources. In: Proceeding of the Sixth World Friend Conference, Fez, Morocco, October 2010. IAHS, Wallingford, Oxfordshire, UK, pp. 340.

Nejjari, A. 2002. Drought, Water, and Man in the Haut Sebou Basin (Northern Middle Atlas-Morocco). Doctoral thesis from the University of Metz.

Ouhamdouch, S., Bahir, M. and Carreira, P.M. 2018. Impact of climate change on water resources in a semi-arid environment: Example of the Essaouira basin (Morocco). J. Water Sci., 31: 13-27.

Pialot, D., Chessel, D. and Auda, Y. 1984. Description of the environment and multiple correspondence factor analysis. Acad. Sci., 298 (11): 309-314.

Qadem, A. 2015. Quantification and Management of Water Resources in the Upper Sebou Watershed. Doctoral Thesis, Sidi Mohammed Ben Abdallah University and the University of Lorraine.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E. and Huenneke, L.F. 2000. Biodiversity-global biodiversity scenarios for the year 2100. Science, 287: 1770-1774.

Tramblay, Y., Badi, W., Driouech, F., El Adlouni, S., Neppel, L. and Servat, E. 2012. Climate change impacts extreme precipitation in Morocco. Glob. Planet. Change, 82(83): 104-114.

Walther, G.R. 2010. Community and ecosystem responses to recent climate change. Philos. Trans. R. Soc. B: Biol. Sci., 365: 2019-2024.

Webb, B.W. and Nobilis, F. 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. Hydrol. Sci. J., 52(1): 74-85.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M. and Wade, A.J. 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J., 54(1): 101-123.

Zerrouk, M., Dakki, M., El Agbani, M.A., El Alami, M., Bennas, N., Qninba, A. and Himmi, O. 2021. Evolution of the benthic communities in a North-African river, the Upper Sebou (middle atlas-Morocco) between 1981 and 2017: Effects of global changes. Biologia, (2021).