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Variability of surface water resources and extreme flows under climate change conditions in arid and mediterranean area: Case of Tensift watershed, Morocco

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Abstract

Within the context of climate change and increasing demographic pressures, problems of water resources variability have become particularly crucial. The management of arid watersheds, which are highly exposed to droughts and floods, needs to be supported by a thorough understanding of their susceptibility to these hazards. The watershed of Tensift in Morocco includes a high mountainous area and a large alluvial plain. In the mountainous part, the bedrock has a low permeability and steep slopes, while the main valleys are narrow and deep. The important rainfall events, which are usually short but intense, are favoured by high elevation and good exposure to oceanic disturbances. Furthermore, predictions of climate change consequences on several socio-economical fields in Morocco are very alarming. For example, climate trends and future climate projections at Marrakech show a clear trend towards higher temperatures and lower rainfall. Consequently, surface water resources are directly affected and the flows of Tensift river have fallen significantly. For the extreme events, the conjunction of physical and climatological factors in the mountainous basins, is at the origin of violent floods, which are characterized by the highest velocities and peak flows. The frequency analysis of floods shows that these extreme events are repetitive with a variable intensity. The rising time of floods is very short, and human and material damages can often be substantial. plain's floods are slower, but their water volumes are very important and can submerge wide areas around the rivers as the case of the flooding of November 30, 2014.

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Introduction

Freshwater resources are vital to the support of livelihoods and most countries are developing institutional frameworks for the implementation of measures to protect the quantity and quality of water resources. These measures are often based on indices quantifying the variability of these resources. These indices are determined by crossing a lot of information (Lei *et al.* 2007) related to the physical characteristics of the environment (rainfall, temperature, climate moisture, surface flow... etc.). In the countries with arid or semi-arid climate, surface water resources are becoming more limited and more variable. These resources are conditioned by the very irregular precipitations in time and space and the large variability of flood flow.

Extreme flows have always been one of the most important natural hazards with a lot of material damage, as in the case of the famous flood disaster of Oued Ourika on August 17, 1995 (Saidi *et al.*, 2003). Otherwise, the use of water in arid or semi-arid environment depends on the availability of this resource and its regularity. In the absence of this regularity, a good water resources management is needed. Arid and semi arid areas have rightly a reputation for having a variability of these resources, and the Tensift Watershed doesn't make exception to this rule. Its plain is an agricultural area whose activities and demand for water continues to increase.

The study of the variability of water resources and climate and their hydrological consequences are paramount. They will allow to make the right decisions to better manage water scarcity. Some studies have already begun to identify the variability of rainfall and temperatures in the region (Riad *et al.*, 2006; Khomsi *et al.*, 2013; Zamrane *et al.*, 2016). They all reported the obvious climate variability, but the hydrological consequences, especially on extreme flows still need to be investigated. For this purpose, the aim of this study is to understand the variability of the precipitation and temperatures in the Tensift watershed and to determine how their fluctuations are expressed in the river discharges and in the extreme flows.

Keeping above in consideration, this research presents informations on hydroclimatic conditions in an arid watershed with examples of flash floods related to climate change.

Materials and methods

Description of study area

Tensift area lies between latitudes 30°50' and 32°10'N and longitudes 7°25' and 9°25' W (Fig. 1). The catchment occupies an area of 18500 km² with a perimeter of about 574 km. The altitude varies between 53m at Talmest and 4167m at Mount Toubkal (Fig. 2) with an average altitude of 1028 m. The basin is elongated with an important time of water concentration. The climate spatial variability in this area is related to its extension and its relief. The climate is actually semi-arid and influenced by the cold ocean current of the Canaries in the coastal zone, semi-arid and warm in the Jbilet and continental arid in the Haouz. (Fniguire *et al.*, 2014).

The basin comprises two major morphological entities: (i) a very high mountainous set and (ii) a vast alluvial plain. The strong mountain range of the High Atlas of Marrakech is a real water tower and a provider of normal and extreme flows towards the plain of Tensift. This part of the catchment receives the largest amounts of rainfall, thanks to its high altitude and Northwest exposure.

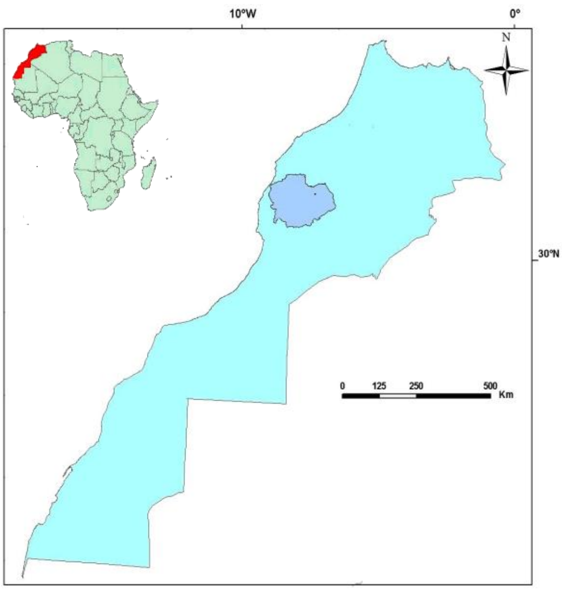

Fig. 1. Geographic position of Tensift catchment.

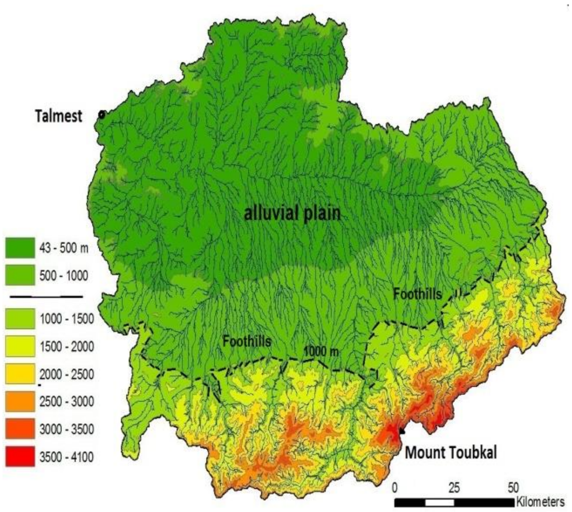

Fig. 2. Hypsometry of the Tensift basin.

Climatic context of Tensift catchment

The climate in the area of Tensift catchment is characterized by a high aridity in the plain zone, for which the intensity is controlled by the low altitude, the subtropical latitude and the continental effect. However, the mountainous areas are characterized by high rainfall amounts, thanks to their high altitudes and their wind exposure, which slightly reduces the aridity degree. The seasonal contrast is very important and most of the rain events occur in the autumn and the winter. These rains are usually irregular and sometimes intense and violent. During the rest of the year, drought occurs mainly in the lowland areas where temperatures and evaporation are elevated. Moreover, the annual thermal amplitudes are quite important: the minimum winter and maximum summer temperatures range between 5 and 45°C respectively.

For the rainfall study in Tensift area, we used rainfall datasets from six stations in the mountains and four stations in lowlands (Fig. 3). The records of the lowland stations in Talmest, Chichaoua, Marrakech and Abadla indicated annual heights between 200 and 250 mm, while the mid-mountain stations recorded more important heights, especially in Aghblaou with 550 mm (Table 1). These rainfall heights are even greater in the upstream part of the catchment, beyond 2000 m of altitude, where the annual average precipitation may exceed 600 mm.

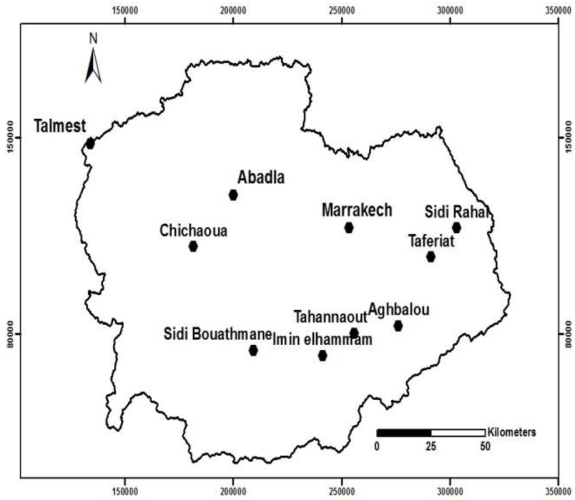

Fig. 3. Location of the main rain gauge stations in Tensift catchment.

Table 1. Annual rainfall amounts from the main stations of Tensift basin.

Station	Elevation (m)	Annual rainfall (mm)
Talmest	53	286
Chichaoua	340	185
Abadla	250	176
Marrakech	460	250
Sidi Bouathmane	820	356
Imin Elhammam	770	375
Tahannaout	925	357
Aghblaou	1070	537
Taferiat	760	352
Sidi Rahal	690	348

The rainfall data analysis has shown great spatial and temporal variability of annual precipitation. This variability is illustrated by the alternation of dry years and wet years (Fig. 4). Spatially, the lowland station of Abadla and the station of Aghbalou (located at 1070 m of altitude) indicate the greatest rainfall gaps.

Temporally, all the stations exhibit quite high annual and monthly variation coefficients. Thus, the variability is significant within annual and seasonal scales. The months of May, June, July and September are generally the less rainy.

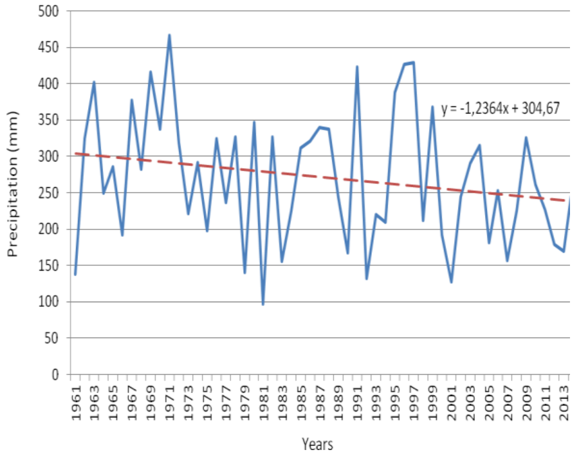

Fig. 4. Annual precipitation trends (mm) in Marrakech from 1961 to 2014.

Observed climate change in Tensift area

Drought has always been present in the history of Morocco, but during the recent decades, it has forcefully become a structural element of the country climate. Morocco is currently experiencing the longest dry period in its modern history, which is characterized by a decrease in precipitation and a clear trend of rising temperatures (Stour and Agoumi 2008). This fact is also confirmed by the fourth report of the Intergovernmental Panel on Climate Change, which also predicts a decrease of up to 20% in rainfall by the end of this century in Morocco. The increase in temperature is expected to reach 2.5°C to 5.5°C under the same scenarios (IPCC, 2007, IPCC, 2013). For this purpose, our study is focused on the observed climate trends and variability at Marrakech station. The aim of this part is to characterize the recent climate change that affected this city since 1961 and the eventual impacts on natural resources through analyses of temperature and rainfall evolutions and calculation of climatic and extreme indices.

Temperature and precipitation

Temperature shows an irregular character in Marrakech with important amplitude between minimum and maximum temperatures (Fig. 5).

It thus confirms the continental character of this city. Moreover, the trend lines indicate increasing temperatures. Average annual temperatures have actually increased by 1,5°C between 1961 and 2014. Also, simulations predict for the city, a temperature increase of about 2.3°C by the year 2050 and about 4.7°C by the year 2099 (Kouraiss and Ait Brahim, 2010).

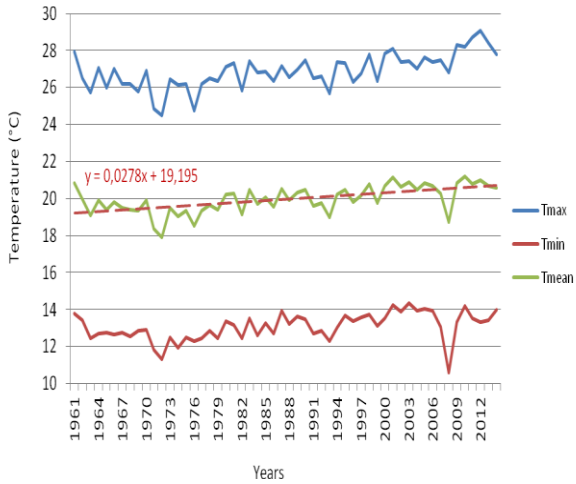

Fig. 5. Annual temperature trends (°C) in Marrakech from 1961 to 2014.

On the other hand, precipitations are even more variable than temperatures. Morocco is highly vulnerable to extreme precipitation events (Tramblay *et al.*, 2012). This irregularity depends on atmospheric circulations, including the movement of the Azores High towards South-West and the installation of depressions on the Moroccan offshore, which would produce interesting rainy disturbances over the country (Jury and Dedebant, 1925).

During the last decades, there is a strong tendency towards a decrease of precipitation totals and wet days together with an increase in the duration of dry (Tramblay *et al.*, 2013). This decrease varies, by region, between 3% and 30% (Sebbar *et al.*, 2011). At Marrakech city, analysis of the annual rainfall data revealed that this climatic parameter is highly variable and irregular from one year to another (Fig. 4). Furthermore, there is an overall trend toward decrease in these annual rainfall heights. According to the trend line, the rainfall decline is about 65 mm over the period 1961-2014.

The Standardized Precipitation Index

The Standardized Precipitation Index (SPI) is a tool, which was developed primarily for defining and monitoring droughts. It allows a characterization of rainfall deficits for a given period for any rainfall station with historic data (Wu *et al.*, 2005; Wu *et al.*, 2007). It can also be used to determine periods of anomalously wet events. In fact, the SPI reflects the impact of drought on water resources availability. It is particularly calculated when the precipitation is not normally distributed (Hayes *et al.*, 1999).

The SPI can be calculated with the formula: SPI = (Pi - Pm)/σ, with: Pi: Precipitation of year i; Pm: Average precipitation of the whole study period; σ: Standard deviation. As shown in table 2, a classification of drought levels can be established thanks to SPI values (Mckee *et al.*, 1993).

Table 2. SPI classification.

SPI ≥ 2	Extreme humidity
1,5 ≤ SPI < 2	High humidity
1 ≤ SPI < 1,5	Moderate humidity
-1 < SPI < 1	Normal
-1,5 < SPI ≤ -1	Moderate drought
-2 < SPI ≤ -1,5	High drought
SPI ≤ -2	Extreme drought

In our case, SPI values are calculated for 44 years and indicate a downward evolution for Marrakech city. The trend line is therefore suggesting an evolutionary trend towards drought (Fig. 6). Although SPI values are highly irregular, it is also clearly noticeable that the occurrence of negative SPI values became increasingly more frequent after the year 1980. This observation demonstrates longer periods of annual drought and an increase of their persistence.

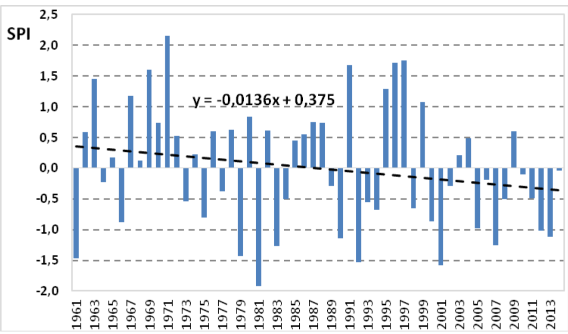

Fig. 6. SPI trends in Marrakech from 1961 to 2014.

Results and discussion

Variability of surface water resources

The types of river discharge on Tensift catchment differ from the mountains to the plains. On mountainous sub-basins, the flow is usually permanent despite its high temporal variability. The annual average can reach 5m³/s as in Ourika, at Aghbalou station, in an area of 503 km², or in N'Fis at Imin El Hammam (1100 km²). In the plain zone, the flow is neither regular nor permanent; it is intermittent and characterized by a high spatiotemporal heterogeneity. This is because of scattered rains in a few weeks, but mainly because of the long plain course that favours infiltration and evaporation. Otherwise, changes in precipitation conditions and evapotranspiration, owing to the climate change, had visible impacts on the river discharge. Much of the inter-annual flow variability is explained by the influence of temperature and especially the precipitation.

The analysis of four decades of annual flows in the Ourika basin at Aghbalou for example (Fig. 7). Shows a clear downward trend and the deficits are important especially from 1992-1993. Before that date, the interannual mean was 6,15 m³/s and dropped to 3,44 m³/s afterwards (a decrease of 44%).

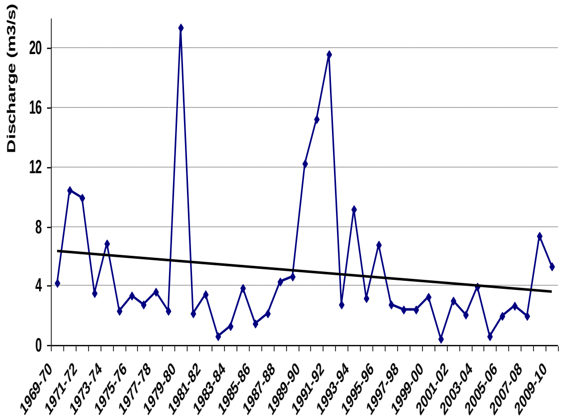

Fig. 7. Trend and variability of annual discharge at Aghbalou station (1070 m).

On monthly and seasonal scales (Fig. 8), the discharges decrease is even clearer. From the hydrologic year 1969/70 to 1991/92, the monthly average flows were relatively important, especially those of spring. But starting from 1992/93, the flows of March, April and May, for example, dropped respectively by 42%, 49% and 59,5%.

All the other months recorded more or less important lessening, except October and August. This summer month recorded increasingly stormy localized phenomena. Those phenomena trigger flash floods, as it was the case in August 1995, August 2006 and August 2010 (El Alaoui El Fels and Saidi, 2014; Saidi *et al.*, 2010).

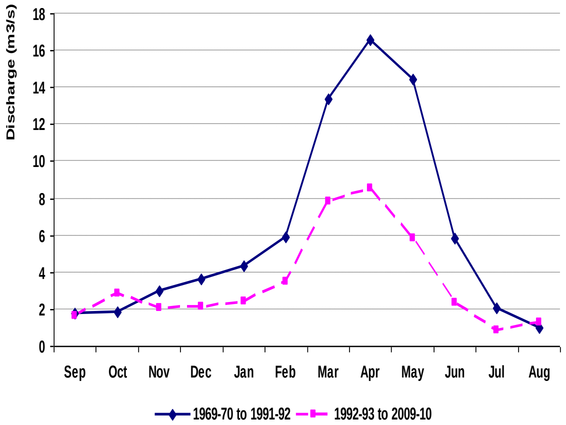

Fig. 8. Variability of monthly discharge at Aghbalou station during the periods 1969/70 to 1991/92 and 1992/93 to 2009/2010.

At the Tensift Plain, there is roughly the same conclusion at Abadla station where the downward trend is even more pronounced at an annual scale (Fig. 9). Here, the interannual average discharge was approximately 5,85 m3/s before 2000 and then declined to an average of 2,92 m3/s after the year 2000 (a decrease of 50%).

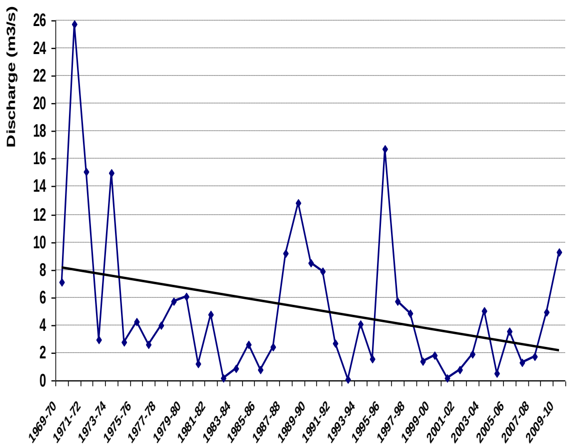

Fig. 9. Trend and variability of annual discharge at Abadla station.

The overall decrease of water resources has rightly been observed by global institutions. For example, the World Resources Institute has combined twelve indicators for calculating the risk of water stress in each country of the world (Gassert *et al.*, 2013). According to his report, most of the Moroccan territory is now on a "high stress" alert. Some regions are even classified as "extremely high stress", like that of Marrakech. Furthermore, the water quality is closely dependent to its quantity. The quantity decrease also induces a quality decrease because of the increasing saline concentration.

The adjustment of new hydro climatic conditions is therefore required in the Tensift catchment. Hydraulic water storage structures must be enhanced as well as a rational use of the available resources.

The extreme flows and the rivers floods in Tensift watershed

The floods of different rivers in Tensift catchment are exclusively from a rain origin. They usually result from heavy rains, which can be localized in space. Actually, the physiography of Tensift watershed offers a conducive environment to the development of strong floods for several reasons: (i) the wind exposure is favorable to precipitation, (ii) the slopes are strong, (iii) the bedrock has a low permeability, (iv) the vegetation cover is weak and discontinuous and (v) the runoff network is hierarchical. This morphological configuration contributes to amplifying the observed peak flows at the catchment outlets (Saidi *et al.*, 2003; Saidi *et al.*, 2012).

The hydrographs related to floods are often individualized with quite short base and rise times. The time of flooding ranges from few hours for the short floods to two days for the long ones (Fig. 10). The hydrographs are usually quite sharp with fairly high peak flows. However, the most dreadful character of flood events in the High Tensift is their suddenness. Several floods had a rise time of 1 to 4 hours, while other events lasted 4 to 10 hours, which is the most common class.

These periods are relatively short and risky for the local residents and tourists who are often surprised by the rapid and sudden rises of water levels and flow rates, due to the difficulty to launch evacuation alerts in time.

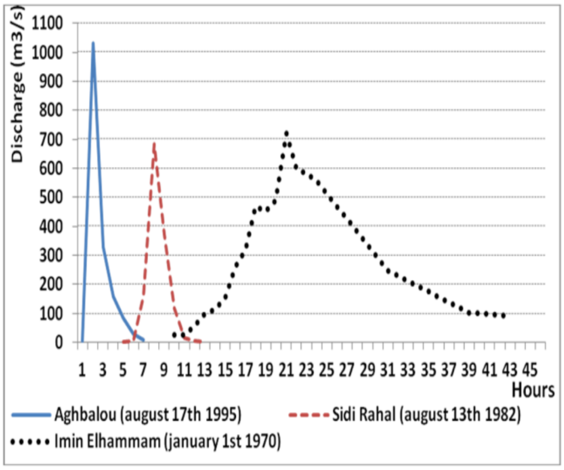

Fig. 10. Example of floods hydrograph of Ourika at Aghbalou, Ghdat at Sidi rahal and N'Fis at Imin elhammam.

The flood of August 17th, 1995 for example is one of the most deadly and devastating floods in the modern history of Morocco. It was the result of violent storms that broke out in a summer afternoon in the upstream part of the catchment in the areas between 2000 and 3000 m of altitude. The flood lasted only 3 hours in Ourika catchment at Aghbalou station and the rise time was particularly short (barely 15 minutes). The peak flow and the mobilized water reached 1030 m^3/s and 3,3million m^3 respectively during the three hours of flooding (Fig 10). Moreover, the flood of October 28, 1999 was similar to that of August 17, 1995 with exceptional peak flows. These flows beat a record in the N'Fis River at Imin Elhammam station where the recorded peak flow is 1575 m^3/s and the rise time is of 9 hours. These violent floods always transport blocks, pebbles, sand, silt and branches on their way. These materials usually form dams, which give way under the pressure of water. The result is a flood of mud, armed with fine and coarse sediment load, sweeping fields and taking trees, roads, bridges and houses (Aresmouk, 2001).

The exceptional hydrological event of november 2014

From November 20 to 30, 2014, the basin of Tensift has experienced an important rainfall sequence (Saidi *et al.*, 2015). The stations recorded precipitation amounts outstanding from usual standards. Two stations in upstream Ourika, for example, have recorded 291 and 519 mm of rainfall during 11 days. After these heavy rains, all the rivers of the basin have responded with strong hydrological swelling and increasingly large flows downstream. The stations in the foothills of Atlas Mountains in Marrakech, like Aghbalou, Taferiat and Sidi Rahal, which control the sub-catchments of Ourika, Zat and Ghdat, recorded respective peak flows of 347, 442 and 340 m^3/s. These are peak flows for which the return period intervals are between 10 and 20 years. However, the most spectacular flows, with a very rare frequency, were recorded in lowland stations, collecting the runoff from mountainous sub-catchments, especially in the stations of Abadla and Talmest. According to observers, the water levels and flood flows of November 2014 have never been seen before. Thus, no less than 1597 m^3/s was recorded in Abadla and even 3500 m^3/s in Talmest station. These new flood peaks have challenged engineers and researchers who built their studies and forecasts from a sample, for which the maximum reaches to 1022 m^3/s in Abadla (recorded on November 3, 1987) and 1275 m^3/s in Talmest (recorded on November 10, 1988). Today, with the new peaks of 1597 and 3500 m^3/s, all the frequency studies of floods in Tensift have to be updated. Using a statistical tool that uses a series of mathematical laws of extreme flows, forecasts and flood occurrence probabilities in Abadla before the floods of November 2014 attributed a return period of 500 years; while with the integration of the same floods of 2014 in the statistical adjustments, the peak flood of November 30, 2014 (1597 m^3/s) would have a return period of only 200 years. For Talmest station, the peak of 3500 m^3/s which had a return period of 900 to 1,000 years would only have a return period of 200 to 250 years.

Updating the hydrological forecasting models by inserting the recent and exceptional flood peaks will prompt to update all the estimates about the return periods of extreme hydrological events. Thus, the estimates of decennial or centennial floods for example will be revised and the hydraulic structures of the future should be established based on the new hydrological thresholds.

The hydrological explanation of the very strong peak flows and water volumes observed in Talmest is based on the exceptional fact that all the sub-catchments of Tensift (Fig. 11). Contributed to swelling the flow in the main stream. The recorded flows, from east to west, in the rivers of Lagh, Ghdat, Zat, Ourika, Issil, Gheraya, N'fis, Assif Elmal, Chichaoua and Mramer were all important. The rain disturbances responsible for these floods had a temporal and most importantly geographical extension.

These floods have caused significant infrastructure damages, the remoteness of many communities and the submersion of agricultural lands, compounded by the intrusion of water from the river beds into public water resources. Several damages were reported at certain hydrometric stations, dams and some groundwater recharge thresholds of Haouz aquifer (Hydraulic Agency of Tensift Basin, 2014).

The updating of knowledge and studies about the floods in the region is, for this purpose, required in a climate change situation and repetition of extreme hydro-rainfall events.

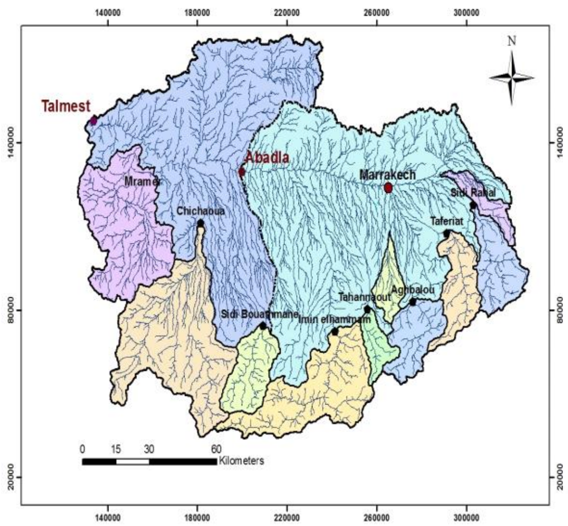

Fig. 11. Sub-catchments of the Tensift basin, contributing to the flow of the main river.

Conclusions

The Tensift river basin is a semi-arid hydro system of Morocco. It consists of two global morphological entities: a very high mountainous system and a large alluvial plain. Rainfall can be heavy on the high mountains of Atlas, but they are weaker on the Tensift Plain. However, annual rainfall tends to decrease in the plain as in the mountains. The trend lines sag slightly indicating a gradual evolution towards more droughts. Furthermore, the temperature trends in Marrakech shows a clear trend towards the increase. Those evolutions indicate warming and drought trends, which negatively impacted the surface water resources in the watershed. In recent years, the rivers runoffs in the mountain and in the plain have declined significantly either at annual, seasonal or monthly scales. Some monthly discharges fell by about 40 to 60% over the past two decades. Climate change has also affected the strength of extreme events. Intense rains and strong floods are now observed at the measuring stations, as was the case in November 2014, when the upstream of Tensift watershed received between 200 and 300 mm in a few days. The peak flows resulting from these downpours were pretty high for some hydrometric stations and even exceptional for others.

Thus, in the mountainous stations, the peak flows observed had a return period of 10 to 20 years. The plain stations, especially Abadla and Talmest, have collected peak flows that were observed for the first time since the beginning of hydrometric measurements more than forty years ago. So, whereas climate changes affect negatively water resources, they tend to accentuate the extreme hydro climatic events. Improving the knowledge of the predictable impacts of climate change on those resources should promote the implementation of appropriate adaptation strategies and actions to the situation of the concerned countries. This knowledge should also initiate and strengthen cooperation between countries to minimize and counteract climate fluctuations effects.

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