Mechanisms driving streamflow alterations in Algerian catchments along a hydroclimatic gradient

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ABSTRACT

WATER security is a major issue in semi-arid and arid regions in which the hydrological cycle is adversely impacted by extensive anthropogenic and climatic changes. Consequently, understanding the mechanisms that underline the hydrologic alteration of rivers in these regions is a key to sustainable water resources management. Algeria is a country in these regions that can be considered a hot spot for climate change. Due to its particular position in North Africa, its climate differs significantly from east to west. Also, other geographical properties such as topography and land use differ along the climatic gradient. As a result, the streamflow regime of Algerian rivers is characterized by high spatial and temporal variability and subjected to long-term alterations. Yet the contribution of the different climatic and geographic variables to these alterations still needs to be quantified. The major aim of this thesis is to investigate the long-term changes of hydroclimatic variables in three catchments in Northern Algeria (the Medjerda, the Isser, and the Macta catchment) and to explore the potential driving factors of streamflow alteration in these catchments. This investigation is expected to identify to what extent the hydrological changes in the Algerian basins are driven by climate or human activities. In the first part, we analysed the temporal trends of the different hydrometeorological variables using non-parametric Mann-Kendall and Sen's slope estimator tests respectively. In the second part, we used an empirical method, Convergent Cross mapping (CCM), to identify causal drivers of streamflow change in hydrological systems. This latter method is based on nonlinear state space reconstruction and has been considered

recently as being a powerful method for causality analysis in complex dynamic systems. The trend analysis showed that the streamflow of the Medjerda and Macta basins have predominantly decreasing trends, while the trend is increasing for the Isser catchment. The observed trends of streamflow are not necessarily coherent with the trends of climate and crop vigor factors, such as temperature, evapotranspiration, and NDVI, which all are increasing within the 3 basins. This incoherency between trends of streamflow and possible driving factors justifies that more advanced causal analysis methods are used to unravel the determining factors of streamflow alteration. The results of such advanced analysis using CCM analysis indicate that climate-related factors, particularly precipitation variability, temperature, and evapotranspiration, are the main drivers of streamflow changes in the selected basins. In a second order, human activities, such as changes in land use, increased agriculture area, water withdrawal for irrigation, and excessive groundwater extraction, have also played a role in altering streamflow. Yet, the alteration in streamflow is largely attributed to the interaction between climate change and anthropogenic activities. The specific mechanisms by which human activities alter streamflow and the extent to which they contribute to these changes on top of climate change require further analysis. In summary, this part of the research shows that the CCM method can provide valuable causal links from common hydroclimatic and environmental time series, which is crucial to a wide range of applications, but it should be used and interpreted with caution.

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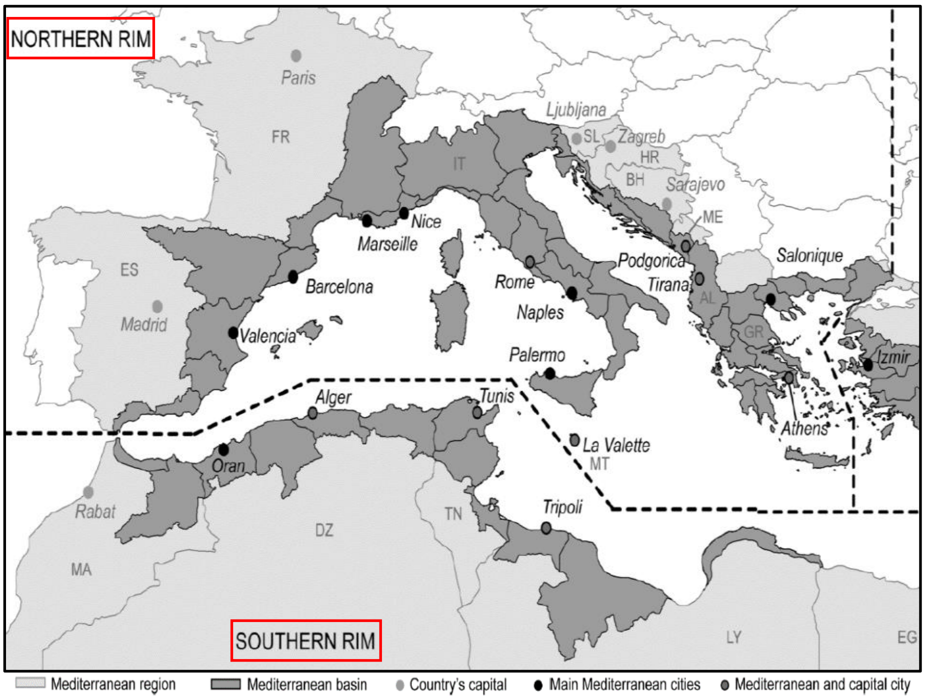
Introduction and Objectives

1.1 Introduction

1.1.1 Mediterranean water systems under pressure

THE Mediterranean area is being strongly impacted by climate change. The region is therefore considered a hotspot of climate change where, without mitigation, temperatures are likely to increase sharply. The increased temperatures are observed in summer seasons, with more frequent and intense heatwaves. In terms of precipitation regime, the area is already characterized by a high degree of spatial and temporal variability (Oueslati and Bellon, 2015) and all climate scenarios highlight a decrease in precipitation with a consequent increase in the frequency and duration of drought events (Djebbar et al., 2020). The combination of an increase in evapotranspiration related to an increase in temperature and a decrease in precipitation sets the conditions for climate drying and warming in the region. Additionally, climate change has enforced changes in the hydrological cycle resulting in a strong decrease in streamflow for many basins in the Mediterranean that will increase the pressure on already water-scarce river basins (De Girolamo et al., 2022). Conversely, heavy precipitation events are projected to increase in several Mediterranean countries due to climate change, possibly leading to more severe floods, particularly in urban areas. Alongside these climatic drivers, the region has seen an increase in water demand by various sectors (agriculture, industry, and services) due to high population growth, particularly in southern countries where supply is already limited. Irrigation requirements are expected to increase by the end of the twenty-first century due to population growth and rising demand. In addition, intensive groundwater extraction has caused groundwater levels to drop in many catchments, and groundwater quality is deteriorating as a result of over-exploitation, pollution, urbanization, tourism development, and seawater intrusion due to rising water levels and aquifer drawdowns. As a consequence, the Mediterranean is expected to experience significantly decreased freshwater availability, and meeting the growing demand for drinking water and irrigation and industrial use will become increasingly problematic.

The southern Mediterranean (Morocco, Libya, Tunisia, Algeria, and Egypt) (Fig.1.1) already has, less than 1000 m^3/per capita/year water availability. With the projected increase in the Mediterranean population, which is expected to reach 550 million by 2025, southern countries are likely to experience a further decrease in per capita available water (Scoullos et al., 2002). In the southern Mediterranean and according to the hydrological water stress index (HWSI), Algeria and Tunisia are faced with the highest level of water scarcity (31% and 23% respectively), while in Egypt and Morocco, water is less scarce. Since economic activities are closely dependent on water availability, water stress threatens human livelihoods and the socio-economic stability in this part of the Mediterranean region predominantly. For instance, Algeria experienced in the recent 30 years significant cropland extension as well as a high level of intensification. Agricultural activities are in all Mediterranean countries already by far the largest consumer of water, mostly reaching values above 80% of total water consumption (FAO, 2018). Under the current conditions, the overexploitation of water resources is already observed in most Mediterranean regions. Water demand is projected to increase as a direct result of socioeconomic activities. For example, the global water demand for domestic, industrial, and agricultural uses, at present about 4600 km^3 yr^{-1}, is predicted to increase by 20-30% by 2050 (Huang et al., 2019). However, human activities are projected to be the main driver of future water scarcity at regional scales (Huang et al., 2021). For instance, in 2000 the percentage of water withdrawals extracted for agricultural purposes is about 65 % for Algeria and 82% for Tunisia. This expansion and intensification of agricultural activities will further increase the total water demand.



Source: (Milano et al., 2013)

Figure 1.1: The Mediterranean basin. ES: Spain, FR: France, IT: Italy, SL: Slovenia, HR: Croatia, BH: Bosnia and Herzegovina, ME: Montenegro, AL: Albania, GR: Greece, TR: Turkey, MT: Malta, CY: Cyprus, SY: Syria, LB: Lebanon, EG: Egypt, LY: Libya, TN: Tunisia, DZ, DZ: Algeria, MA: Morocco.

In some Mediterranean countries, a non-negligible amount of available water resources situates in transboundary rivers and/or aquifers. This is the case for the Northern Sahara Aquifer System (SASS), shared by 3 countries, namely Algeria, Tunisia, and Libya. The SASS includes considerable water resources that cannot be exploited in their totality and which are renewed in very small proportions. The SASS extends over 10^6 km^2. It includes the two big water bodies of the Infill Continental Terminal Complex. For the last thirty years, the exploitation of this water body through drilling went from 0.6 up to 2.5 billion m^3/year. The water resources are used in the agricultural field, for the irrigation of oases, and the supply to cities and industries, notably in the sector of oil and tourism. Another example is the Medjerda river. The Medjerda River Basin (MRB) is a transboundary watershed in North-East Africa shared by Algeria and Tunisia. The water resources of the MRB play an important role in the economic development of the two countries and their water and food security. The majority of the agricultural activities (70 %) are rainfed, and thus, their production is highly affected by the spatiotemporal variability of precipitation in the area. Within these transboundary water systems, multilateral water cooperation, transboundary water resources, and ecosystem management are highly considered and needed to underpin the current large-scale development plans.

1.1.2 Hydrological implications of climate change and human activities

Generally, hydrological processes vary geographically at the catchment scale and are mainly dependent on climatic and physiographic factors such as rainfall, temperature, evapotranspiration, soil characteristics, topography, geology, and on land-use changes (Fortesa et al., 2021). The Mediterranean basin has been considered one of the sensitive areas for climate change with an expected significant decrease of precipitation and a prominent increase in temperature. These expected climatic conditions are likely to increase summer drought events and floods, increase soil evaporation and vegetation transpiration (Foley et al., 2005), decrease soil moisture, and reduce river discharge (García-Ruiz et al., 2011). As a result, climate change will induce hydrologic alteration, which will affect negatively the water resources availability (Yang et al., 2017). Sellami et al. (2016) have explored the potential effects of climatic change on the streamflow alteration of the Thau and the Chiba catchments in the Mediterranean basin, which are located in Southern France and North-eastern Tunisia, respectively, between a baseline (1971-2000) and projected (2041-2071) periods. Their results indicate that both catchments are likely to experience a decrease in precipitation and an increase in temperature in the future. Consequently, streamflow and soil water content are projected to decrease whereas potential evapotranspiration is likely to increase in both catchments. Climate change can indeed significantly alter the timing, quantity, and distribution of streamflow at the basin scale (Mesfin et al., 2021). Climate change, as reflected in precipitation behaviors, directly influences the streamflow alteration in a basin (Acuña-Alonso et al., 2021). The hydrological alteration is also associated with other factors such as changes in evapotranspiration, irrigation water demand, and biomass production (Gutiérrez-Jurado et al., 2019). Both land use and climate change are considered to be the most causal factors that influence the alteration of streamflow (Rogers et al., 2020). The interconnection between climate and human influences considerably modifies the availability of water resources in a basin (IPCC, 2022). However, in the literature review, there is no clear comprehension of which causal factors are dominant for the alteration of streamflow in a given catchment. For instance, it has been reported in the scientific literature that the alteration of hydrological flows in the Blue Nile river is due to climate change by the variability of rainfall over the basin (Kim et al., 2008). In contrast, other studies by Tekleab et al. (2013) and Gebremicael et al. (2019), have found that human activities related to land use have altered the streamflow regimes more significantly than climate change in Ethiopia. Indeed, the impact of direct human actions on water resources is often reported as an important factor to be considered in to study of the variability of streamflow in hydrological basins (Gebreyohannes et al., 2013). In the Mediterranean basin, the magnitude, as well as spatial and temporal heterogeneity of hydrological alteration in terms of all these processes are often poorly understood (Piqué et al., 2016). Therefore, there is a need to understand the mechanisms of the hydrological alteration process and the main factors controlling its response.

1.1.3 Exploring causal factors of hydrological alteration

Understanding the underlying processes and causal factors of hydrological alteration is crucial to conceptualize a realistic modeling approach for simulating the hydrology of catchments. Hydrological alterations have already been documented in many studies (e.g., De Girolamo et al., 2022b; Aboelnga et al. 2020, Pilgrim et al., 1988), but it remains difficult to disentangle exactly the dominating factor of the alteration. In semi-arid areas, for instance, evapotranspiration, which controls also streamflow, is conditioned by the availability of water content whereas the available energy is the main factor controlling evapotranspiration in humid areas. In other studies, the researchers indicated that streamflow in semi-arid areas is primarily controlled by surface properties rather than by the amount and intensity of rainfall (Yair and Kossovsky, 2002). The interaction between vegetation, topography, and the hydrological response in catchments is expected to be more significant in semi-arid than in humid areas (Pilgrim et al., 1988). Land cover and land use change may increase the infiltration capacity of soils and reduce streamflow generation (Yair and Kossovsky, 2002). Also, Pilgrim et al. (1988) reported that less vegetation cover in semi-arid areas may conduct to lower organic matter in the soil which can have significant effects on interception, infiltration, evapotranspiration process, and streamflow response. Another causal factor that exerts a significant influence on the hydrological processes of a catchment is the fluctuation of precipitation in space and time. Precipitation regime in semi-arid areas tends to be more variable and complex than in humid areas (Camacho Suarez et al., 2015). Hence, high-energy rainfall events generate almost all streamflow (Love et al., 2010), and can consequently cause soil erosion, reducing the infiltration capacity and thus increasing surface runoff production in a catchment. Tramblay et al. (2019) further consider that antecedent soil moisture content is rooted as one of the many streamflow governing factors in semi-arid areas within Mediterranean basins. However, the contribution of initial moisture in the soil to the streamflow process is secondary as compared to surface properties and rainfall regimes in the semi-arid basins. In a literature review, the main potential drivers of streamflow alterations were structured as follows (Merz et al., 2012):

- climatic changes: changes in precipitation (P), atmospheric circulation (NAO, ENSO, PDO), temperature (T), and evapotranspiration (ET);

- land-use changes: irrigation infrastructure development, urbanization, changes of the Normalized Difference Vegetation Index (NDVI), deforestation, changes in types of crops or agricultural management practices, drainage of wetlands and agricultural areas, construction of flood storage areas, etc; and river modifications: straightening, narrowing, deepening (by dredging for example), construction of dams or changes in their operation.

Some of these drivers were selected and analyzed more closely in this study.

1.1.4 Problem statement, challenges, and motivations

Algeria is characterized by large temporal variability of rainfall and streamflow both at intra-annual and inter-annual scales as well as spatial variability (west to east) in soil, geology, vegetation cover, and topographic properties within catchments. Human activities also vary strongly in space. As a result, the hydrological processes are highly variable and complex in space and time. The dynamic interactions and associated mechanisms between the hydrological process, climatic factors, and human activities remain unexplored and poorly understood (Di Baldassarre et al., 2013). It is more difficult to identify and quantify the impact of land-use change for large basins where the interactions between land use, climatic factors, and the underlying hydrological processes are often more complex and need more data. Hence, the local scale is to be considered an important unit when assessing the impact of land-use changes on streamflow (Sellami et al., 2016).

The identification of the causal variables contributing to hydrological alteration remains challenging since natural systems are often non-linear, making them difficult to understand using linear statistical methods. Recently, nonlinear methods that recognize state dependence concepts have been developed and incorporated into time series analysis. State dependency means that the interrelationships among interacting variables vary with different states of the system and is another feature of non-linearity (Ye et al., 2015). These nonlinear statistical approaches are implemented in state-space reconstruction (SSR) methods, i.e. methods that consider lagged coordinate embedding of time series data (Sugihara et al. 2012). Nonlinearity is also known to affect the correct identification of causal drivers, a key prerequisite for understanding and predicting system patterns. In nonlinear systems, because interacting variables can exhibit transient (mirage) correlations that change in magnitude or sign (Deyle et al. 2013, Sugihara et al., 2012), the use of correlation criterion to explore causal environmental variables can be misleading, inducing both false positives (i.e., correlation does not imply causation) and false negatives (i.e., lack of correlation does not imply a lack of causation) (Sugihara et al., 2012). The concept "correlation does not imply causation" means that just because two variables are related (i.e., they correlate), it does not automatically mean that one causes the other. For example, consider the relationship between ice cream sales and crime rates. In the summer, both ice cream sales and crime rates tend to go up. However, it would be incorrect to say that ice cream causes crime or vice versa. Rather, there is likely a third, unrelated factor (such as warm weather) that is driving both ice cream sales and crime rates. On the other hand, "lack of correlation does not imply lack of causation" means that just because two variables are not related (i.e., there is no correlation), it does not necessarily mean that one does not cause the other. For example, consider the relationship between daily Vitamin C intake and the frequency of colds. While it is true that people who take Vitamin C are no less likely to get colds than those who do not, it does not mean that Vitamin C does not help in preventing colds. The reason for the lack of correlation might be that many other factors, such as genetics and lifestyle, also play a role in determining whether or not someone gets a cold. Given the prevalence of nonlinear interactions in hydrology and climate, mirage correlations can be misleading as well as the limits of linear approaches. We therefore explore in this thesis a non-linear method for assessing the causality of streamflow alteration in the Algerian catchments. As a consequence, Convergent Cross Mapping (CCM), a non-linear causal inference method is interesting for analyzing time series data with underlying nonlinear dynamics.

1.2 Objectives of thesis

The main objective of this Ph.D. thesis is to assess the hydrological alteration and to explore the mechanisms responsible for streamflow variability at the local catchment scale along a hydroclimatic gradient in Algeria. Hence, we aim at disentangling the causality network between climate variables, vegetation cover, and streamflow under the semi-arid climate conditions in Algeria. The study is conducted on three selected catchments in Algeria which are quite diverse in hydroclimatic features, i.e. the Medjerda catchment (north east), the Isser catchment (north central), and the Macta catchment (north west) (Figure.1.1)

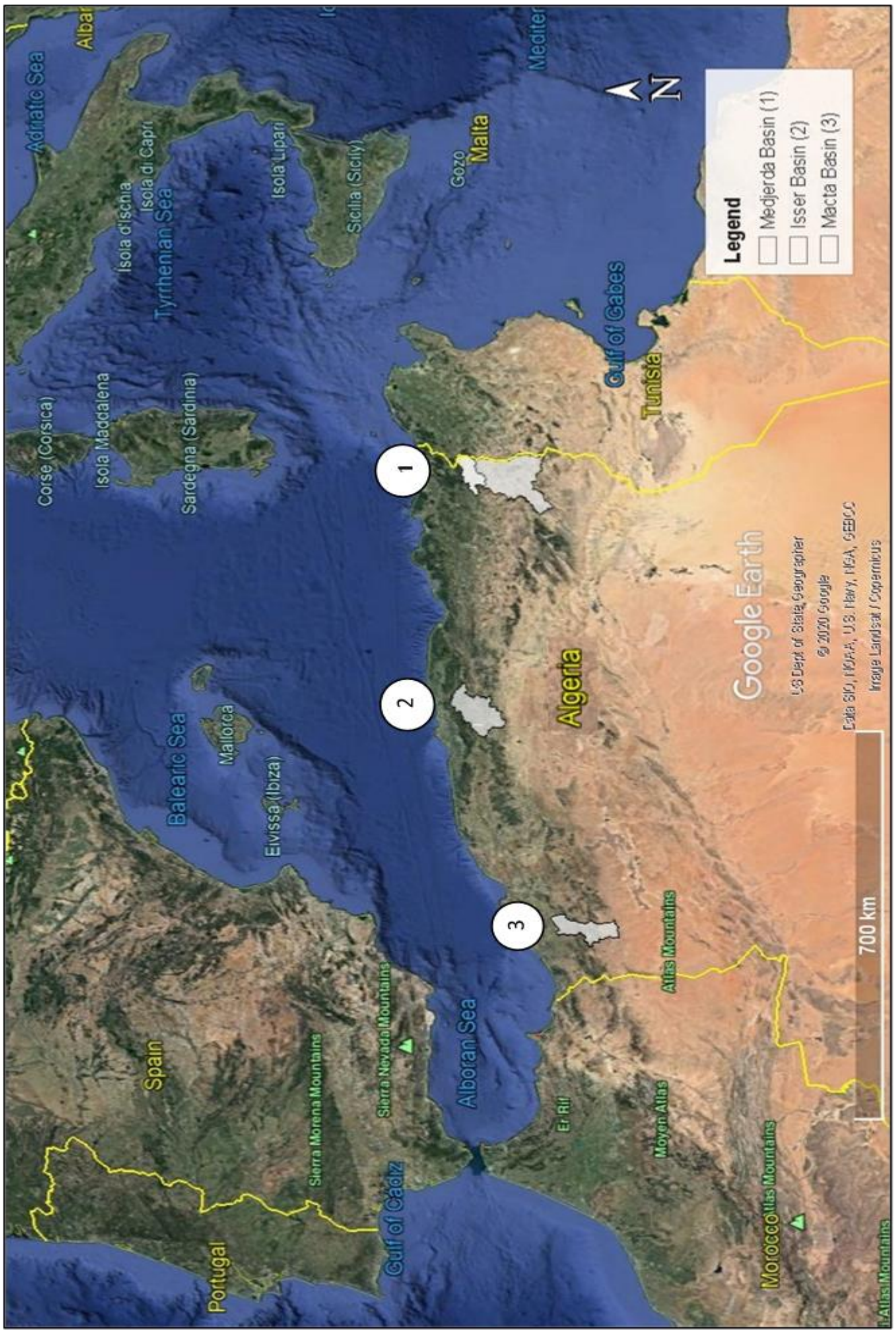


Figure 1.2: Location of the selected three river basins: Medjerda (1), Isser (2), and Macta (3).

To address this main goal, the following specific objectives (SO) are considered.

SO.1: First, to characterize the hydro-climatic trends in the selected catchments. A comprehensive analysis of trends of different variables (precipitation, temperature, evapotranspiration, NDVI) and their implications for the alteration of streamflow is made.

SO.2: Second, to investigate a new causal inference method based on the theory of nonlinear dynamical system. In this study, Cross Convergent Mapping (CCM) is explored to identify the causal factors of streamflow alteration.

SO.3: Lastly, to provide inter-catchment comparisons that identify the influences of the main driver's river flow regime changes along the hydroclimatic gradient in Algeria.

1.3 Outline of the thesis

The thesis is structured into six specific chapters.

In **chapter 2** a general review of the literature is presented regarding hydrological alteration (definitions, process, potential factors and its impact on streamflow components, human influences, and climate change).

In **chapter 3**, the study sites (Medjerda, Isser, and Macta), materials, and available data are presented and described.

Chapter 4 to 6 describes the potential drivers of the variability of streamflow in the Medjerda (**chapter 4**), Isser (**chapter 5**), and Macta (**chapter 6**) catchment. Statistical analysis of trends in streamflow, hydroclimatic, and other causal variables was conducted using the non-parametric test. Causal drivers for such trend analysis were identified at the basin scale using the CCM. Implications of the identified trends for the streamflow regime and the causal relationships are also discussed.

In Chapter **7** all relevant findings from the preceding chapters are compiled to provide inter-catchment comparisons that explore the influences of the main driver's river flow regime changes under the impacts of climate variability. The factors that control the differences in streamflow responses between three catchments (Medjerda, Isser, and Macta) have been investigated, and their different hydrological alterations to climate change have been compared.

Finally, conclusions and perspectives are developed in the last part of the document.

2

Impact of climate change and human activities on streamflow alteration in the Mediterranean region

2.1 Introduction

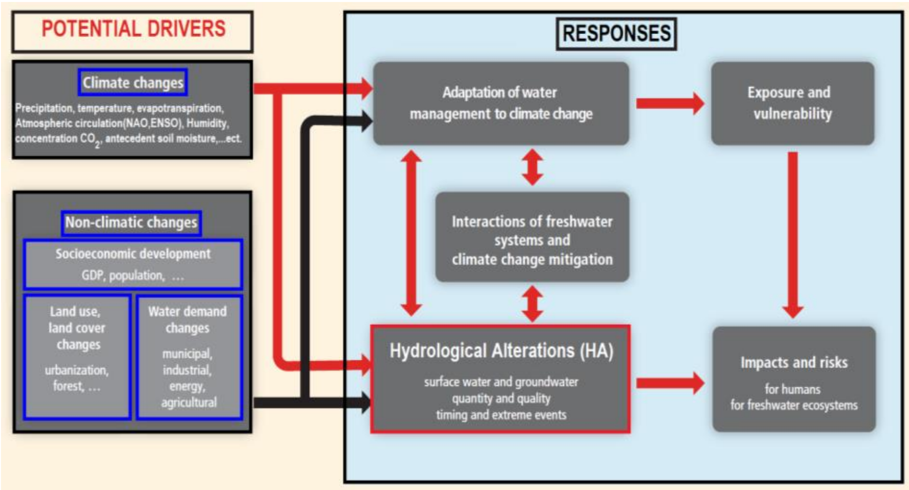
Hydrological alteration challenges the sustainability of water resources management by changing the water supply in the context of changing water demand. Alterations in the hydrological cycle can lead to diverse impacts and risks, and they are conditioned by both climatic and non-climatic drivers of change (see Figure 2.1). Hydrological alteration is a broad concept and it is often difficult to disentangle the effects of hydrological alterations from other environmental perturbations, particularly in heavily developed catchments (Rosenberg et al., 1997). The effects of hydrologic alteration on water systems functions may be multiple. Alteration of the natural flow regime is considered to have impacts on river ecosystem functions (Peñas and Barquín, 2019). The alteration of the flow regime alone or in combination with other anthropogenic stressors (Dudgeon et al., 2006; Malmqvist and Rundle, 2002) results in damage to river biodiversity (Vitousek et al., 1997). Hydrological regimes are hence linked to habitats and biotic communities. Yet, the impacts do not only affect ecological functions. A vast body of literature has elucidated the impact of hydrological alteration on other water resources management functions in the watershed (Tian et al., 2019; Poff et al., 1997), including water supply and allocation, agricultural development, flood disaster, droughts, ecological restoration.

The relevant influence of climate change on the hydrological alterations of the water cycle in Mediterranean regions is widely recognized, particularly in the south of Mediterranean catchments such as Algeria, Tunisia, Spain, and Southern France (Sellami et al., 2016; Gampe et al., 2016). Several studies suggest indeed that recent variations in precipitation patterns and the rise of temperature with the consequent intensification of evapotranspiration induce alteration of the hydrological regime in these regions (see e.g., Longobardi et al., 2016; Sellami et al., 2016). Additionally, anthropogenic factors related to land-use changes, irrigation and agricultural development, and population growth have been shown to contribute also to hydrologic alterations (Chiogna et al., 2016). The influence of these anthropogenic factors should be quantified with caution and separated from the climatic drivers of hydrologic alteration.

The role of climate on hydrological alteration was echoed in the key messages from the Working Group II Fourth Assessment Report (AR4; IPCC, 2013) with respect to freshwater resources, saying that:

- the observed and projected impacts of climate change on freshwater systems and their management are due mainly to increases in temperature and sea level, local changes in precipitation, and changes in the variability of those quantities;
- the semi-arid and arid areas are particularly exposed;
- more intense precipitation and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services;
- climate change affects water management infrastructure and practice.

Yet, disentangling climatic from other anthropogenic drivers is challenging since all driving factors propagate through the hydrological system in a complex nonlinear manner. Some of the available studies explored trends in streamflow (see e.g., Khedimallah et al., 2020; Burn and Elnur, 2002; Bard et al., 2015), precipitation (see e.g., Taibi et al.,2017), evapotranspiration and temperature (see e.g., Trambaly et al., 2019 ; Chaouche et al., 2010) separately, without assessing their interaction and the consequences on overall hydrological dynamics. There is however a need for exploring the multiple and concurring variables of hydrological alteration moving from the identification of alteration in streamflow and climatic variables to a deep understanding, detection, and attribution of the processes driving the observed alterations of the hydrological cycle. Large uncertainties still govern hydrological processes, while time series of observed hydrological variables are often incomplete and affected by measurement errors jeopardizing the inference of causal factors of hydrological alterations (Serinaldi et al., 2018). In this chapter, the issue of hydrological alterations with their causing factors will be further reviewed.



(Source: Jiang and Mwakalila, 2018)

Figure 2.1: Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic and non-climatic drivers have changed natural freshwater systems and are expected to continue to do so. They also stimulate adaptive measures. Hydrological and water management changes interact with each other. Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks.

2.2 Detected and attributed hydrological alteration

Hydrological processes are highly variable in time and space due to the great variability of the rainfall regime, and the complexity of the land-use characteristics such as the topography, the geology, and the soil. In particular, the hydrological change reflects fluctuation of the precipitation and the evapotranspiration associated with climate, vegetation, and other hydrological controls on the water balance at the land surface (Stewardson et al., 2017).

The detection-attribution research of direct (i.e., land use and water management) and indirect (i.e., climate-related) effects of human activities on streamflow remains however challenging (Dai, 2016; Alkama et al., 2011). Understanding the natural and anthropogenic contributions to the evolution of hydrological alteration is considered a key issue for improving the response to the global water crisis.

The concept of detection-attribution of alteration used here follows the terminology in the IPCC guidance paper (Cramer et al., 2014). Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense. An identified change is detected in observations if its likelihood of occurrence by chance alone is determined to be small (Cramer et al., 2014). Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence. However, attribution is more complicated than detection; combining statistical analysis with physical comprehension is equally essential (Hegerl and Zwiers, 2011).

The detection and attribution of hydrological alteration of streamflow are complex, and this is due to many reasons:

First, assessing alteration is already not evident. For instance, according to Alkama et al. (2011), the observed global trend of streamflow remains unclear and uncertain, given the scarcity and heterogeneity of river discharge measurements. Moreover, the length and reliability of the available time series vary greatly from one river basin to another, and gaps are usually found.

Second, the attribution supposes that it can be shown, usually, statistically, that part of the detected change is not due to the natural variability of the water cycle. For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions (Hegerl and Zwiers, 2011).

2.3 Streamflow alteration

Streamflow signal has been complexly altered by climate change and human activities in major rivers worldwide. Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature. In Europe, streamflow (1962-2004) decreased in the south and east and generally increased elsewhere (Stahl et al., 2010), particularly in northern latitudes (Wilson et al., 2010). In Wallonia (Belgium) some regional patterns of streamflow alteration have also been observed throughout 1967-2017: the positive trends are mainly located in the Scheldt and Lesse catchments, while trends in the east and south of the region are mostly negative (Grandry et al., 2020). In North America (1951-2002), increases were observed in the Mississippi basin and a decrease in the U.S. Pacific Northwest and southern Atlantic-Gulf regions (Kalra et al., 2008). In China, a decrease in streamflow in the Yellow river during (1960-2000) is consistent with a reduction of 12 % in summer and autumn precipitation, whereas the Yangtze river shows a small increase in annual streamflow driven by an increase in monsoon (Piao et al., 2010).

Yet, these and other streamflow trends and the causal relationships must be interpreted with caution because of other factors such as land-use changes (Zhang and Schilling, 2006), excessive agricultural irrigation, and urbanization (Kustu et al., 2010).

2.4 Controlling factors

Climate change is considered to be one of the major drivers behind the alteration of the hydrological cycle associated with human influences. As reported in various studies, global warming, acting as a catalyst in the process of climate variability, accelerates the variability of different atmospheric factors (Arnell, 1999). Apart from climatic action, human influences such as modification of land use/land cover (LULC), industrialization, and urbanization also alter hydrological processes and exert a negative impact on the environment with significant implications on water resources in the Mediterranean area. Among different components of the hydrological cycle in a catchment, streamflow affects the water use pattern significantly in different sectors like irrigation, domestic, and industry. In the following sections, the most potential drivers controlling the alteration of streamflow are discussed.

2.4.1 Climatic and human factors

2.4.1.1 Precipitation

According to regional observations, most droughts and extreme rainfall events have been the worst since the 1950s (Hänsel et al., 2022), and certain trends in total and extreme precipitation amounts are observed. Most regional alterations in precipitation are attributed either to the internal variability of atmospheric circulation or global warming (Allan et al., 2020). Zittis et al. (2022) estimated that the 20th-century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation regimes. However, the variability of precipitation characteristics may also be influenced by the biophysical features in the semi-arid catchments (Djebou et al., 2014; Oguntunde et al., 2014). Also, an acceleration in precipitation and evaporation processes does not always mean an increase in streamflow or a significant trend (McGregor, 2017). In natural environments, changes in precipitation patterns are expected to reflect on streamflow; but in reality, the extent of the impact is more complex (Camarasa-Belmonte and Soriano, 2014). Changes in precipitation in terms of intensity, duration, and distribution may induce great variability in streamflow, such as floods of longer duration and droughts.

2.4.1.2 Evapotranspiration and temperature

Evapotranspiration (ET) is another fundamental component of the hydrological process and a route for energy transfer between the earth's surface and the atmosphere, especially in arid and semiarid regions, where water is often a limiting factor. Assessing evapotranspiration is important for evaluating water resources (Xu, 2000), drought forecasting (Tsakiris and Vangelis, 2005), and managing irrigation (Miao et al., 2016). Climate change can influence the water balance via increased temperatures, which conduct to increased evapotranspiration, as well as the melting of the glaciers and changes in the timing and amount of snowfall and snowmelt. The first main driver of evapotranspiration is the incoming solar radiation. Further, evapotranspiration is also driven by vegetation development and available water in the top soil, and it depends also on water availability through rain and irrigation amounts, frequency, and intensity (Boulet et al., 2020). In the Mediterranean area, evapotranspiration is often limited by the availability of water, considering that more than 80% of annual precipitation is consumed by evapotranspiration in semi-arid regions (IPCC, 2022).

2.4.1.3 Land use

Land-use change is an important factor that changes the river discharge, and humans play a dominant role in recent rapid land-use change evolutions (Liu and Tian, 2010). One of the major environmental effects of land-use changes worldwide is the hydrological alteration, which directly affects the quantity and quality of water resources (Foley et al., 2005; Szewrański et al., 2018). There are different types of land-use changes like urbanization, deforestation, and reforestation. They affect the flow in different ways and their impact on discharge varies in regions, in space, and in time (Liu and Tian, 2010; Liu et al., 2003). Land-use changes can cause changes in baseflow, and annual mean discharge (Li et al., 2009). The changes in the land use would enforce the changes in the return of moisture to the atmosphere through evapotranspiration, which would consequently affect the rainfall and runoff characteristics over the catchment (Moraes et al., 1998), which could alter the streamflow regime (Buendia et al., 2016). Also, vegetation may increase the infiltration capacity of soils and reduce overland flows (Yair and Kossovsky, 2002).

2.4.1.4 Irrigation agriculture

The water needs of humans and natural ecosystems are generally considered as competing with each other. The over-usage of water could lead to severe alteration to the hydrological regime of a river basin (Poff and Zimmerman 2010, Lytle and Poff 2004;). The effect of water consumption on the river change is direct as water is withdrawn from water bodies (e.g. rivers, reservoirs, lakes, groundwater) and transferred to different sectors (e.g. farms, factories, residences) over space. The irrigation water demand varies by month according to the crop growth period. Water extraction is related to the available water at the local scale.

According to "Bleu pour la Méditerranée (2005)" and FAO (2018), irrigation is the most water-demanding sector in the Mediterranean region, accounting for 65% of the total water extraction, with a clear contrast between the northern (48%) and the southern and eastern rims (82%) of the Mediterranean basin. The impact of irrigation remains a key issue in the development of sustainable basin management strategies. But irrigation affects also land use and, therefore, causes indirectly hydrological changes in the basin, and water supply in irrigated lands may increase crop transpiration and subsequent water consumption (Molle and Tanouti, 2017).

3

Material and methods

3.1 Introduction

In the context of climate and environmental change, this research project aims to study the mechanisms driving streamflow in Algeria catchments along a climate and environmental gradient. The hydroclimatic gradient in Algeria refers to the variation in water availability and climate conditions across the country. Due to its geographical location and topography, Algeria experiences different types of climate patterns, from arid to semi-arid to Mediterranean, resulting in varying levels of precipitation. This variation creates a hydroclimatic north-south gradient, with the coastal catchments receiving higher amounts of rainfall and having more humid conditions compared to the drier interior regions and a west-east gradient, with the western part, much more subjected to Atlantic depressions and hence less rainfall. These gradients affect the distribution of water resources and agriculture production in Algeria. Over the past five decades, climate and land use change have caused significant changes in the long-term hydrological time series in catchments all over the world (Chen et al., 2016). It is hypothesised that such changes will also affect the hydrological regime of Algerian catchments.

To study hydrological alteration and identify the associated causal factors in Algeria, three river basins were selected along the west-east hydroclimatic gradient. The catchments are already affected by water scarcity or high spatiotemporal variability in rainfall and multiple conflicting water uses (irrigation, industrial, and urban). The selected river basins are the Medjerda basin in the north-eastern part of Algeria, the Isser basin in the north-center part, and the Macta basin in the north-western part (Fig.1). In this chapter, the general features of the selected study sites and the available data are described. The catchments are selected based on the complex topography (moving from west to east), human activities (expansion of irrigated lands), the availability of the data set, and because precipitation variability patterns vary across the study area and differ from region to region.

3.2 Data sets & methods

3.2.1 Selected river basins

1) Medjerda catchment

The Medjerda basin (Fig 3.1) is located northeast of Algeria and northwest of Tunisia. The Medjerda river is the longest river of the Tunisian-Algerian transboundary basin, with a total length of 485 km among which 135 km are situated in Algeria. The basin is characterized by rugged topography consisting of mountains, highlands, and terrains of weak slopes. This may indicate that topography may be a key driver in influencing microclimates in the basin. The upstream part of the river basin is situated in the mountains of eastern Algeria and includes Ras Alia mountain with a height of 1317 m. The river subsequently flows into the northern part of Tunisia and discharges in the Mediterranean Sea. The Medjerda basin has a total surface of 23 700 km^2 among which 7 870 km^2 are located in Algeria (Fig 3.1).

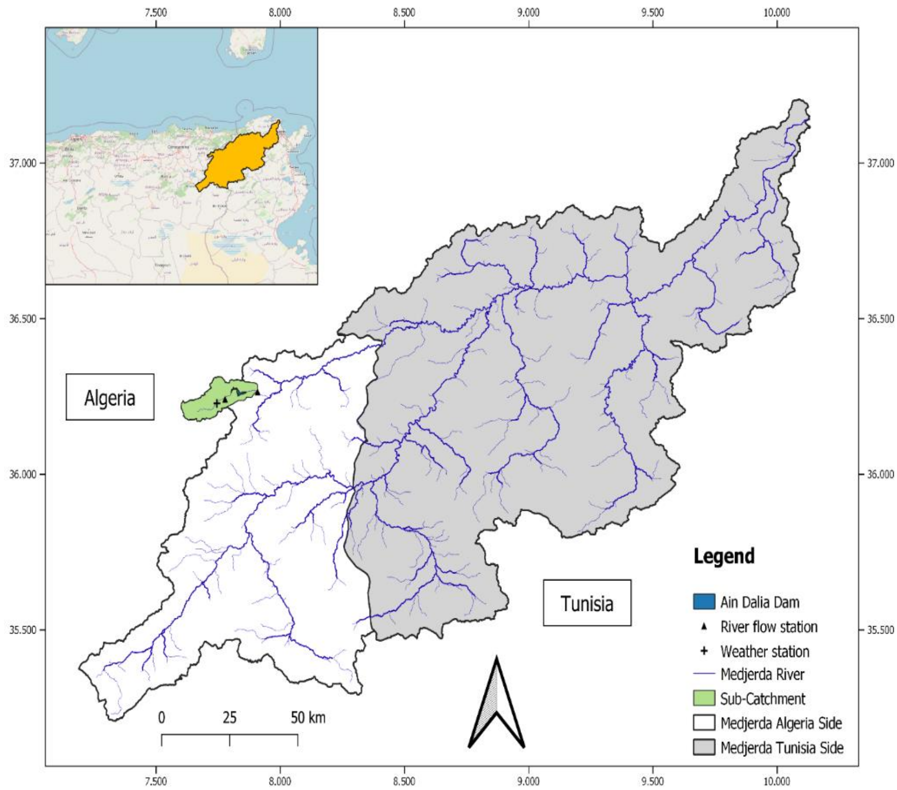


Figure 3.1: Location of the Medejerda catchment.

The basin is characterized by a semi-arid climate with Mediterranean influence and warm summers and cold winters. More than 60 % of the total annual rainfall falls in the winter season (December-January-February) which varies from 500 mm/year in the east to less than 300 mm/year in the south and is affected by limited water supplies. The climate of the basin is dominantly semi-arid, with distinctive dry and wet seasons with high spatial variability of rainfall in time and space. The dry period over the region extends up to 5 months, and the rainy season extends from 30 to 90 days with intense precipitation in autumn. The hottest months are July and August when the maximum temperature can exceed 38°C. The general pattern of rainfall over the basin is controlled by the complex topography which implies that the movement of air moisture can be substantially impacted to create contrasting rainfall regimes in the region. The elevation changes can obstruct the air mass movement to create a microclimate or cause an updraft over the mountains to create orographic rainfall. In the north-eastern parts of the Medjerda basin rainfall increases with elevation due to the orographic effects.

Agriculture represents the basin's major economic activity. Most of the water resources are used for agricultural purposes (70%) and only about 30% is used for services and industries (Bouraoui et al., 2005). The dominant land use in the basin includes cultivable land (>70 %), very high forest coverage, bushes, and shrubs. Land use in most of the basin is dominated by irrigated agriculture, main crops include vegetables, fodder culture, arboriculture, wheat, barley, maize, sorghum, and pulses, followed by shrubs. According to the Ministry of Agriculture (2012), irrigated agriculture has also increased significantly in terms of areas over the years in Medjerda. However, the project launched by the Ministry of Agriculture of Algeria has resulted in the modernization of farms, the development of steppe areas, and the implementation of local rural development projects for irrigation. Following this program, the irrigated areas have increased from 10,000 ha in 1985 to 40,000 ha in 2000, and from 40000 ha to 60000 ha in 2012. This increase in irrigated lands is estimated to exert considerable pressure on the available water resource very often leading to water scarcity.

Upstream, on the Algerian side of the basin, the Ain Dalia dam was built in 1987 along the mainstream and controls an area of about 193 km^2. The dam has a total capacity of 82 million m^3 and is principally used for drinking and irrigation water supply to the different regions within the basin: Souk-Ahras, M'Daourouch, Mechroha, Tébessa, and Oum El Bouaghi. The Medjerda catchment is a typical case where groundwater depletion occurs under a semi-arid climate due to the large quantities of water withdrawn mainly for irrigation purposes. The population within the Medjerda river basin was estimated to be 600,627 habs in 2012 (ONS, 2015)

2) Isser catchment

The Isser river basin (Fig 3.2), located in the central northern part of Algeria, covers a total area of 4154 km^2. The elevation of the basin varies from sea level to 1810 m.a.s.l. The Isser river is the principal stream within the basin with a total length of 98.2 Km. The geographical environment in which the catchment evolves is constituted by the Tellien Algerian atlas in the north, which culminates at 1130 m in the Tamesguida mountains, and the Bibans chain in the south at an elevation of 1810 m in the Dira mountains. These two chains are separated by the plain of Aribs at 550 m of altitude. The geomorphological characteristics of the Isser basin have led to the formation of a dense hydrographic network whose outlet is the Mediterranean Sea. It drains the contributions of 5 sub-basins. The Isser basin has a major economic importance, it encompasses four Wilayas: M'sila, Tizi Ouzou, Bouira, and Boumerdes, and are considered the most economically sensitive regions in the basin.

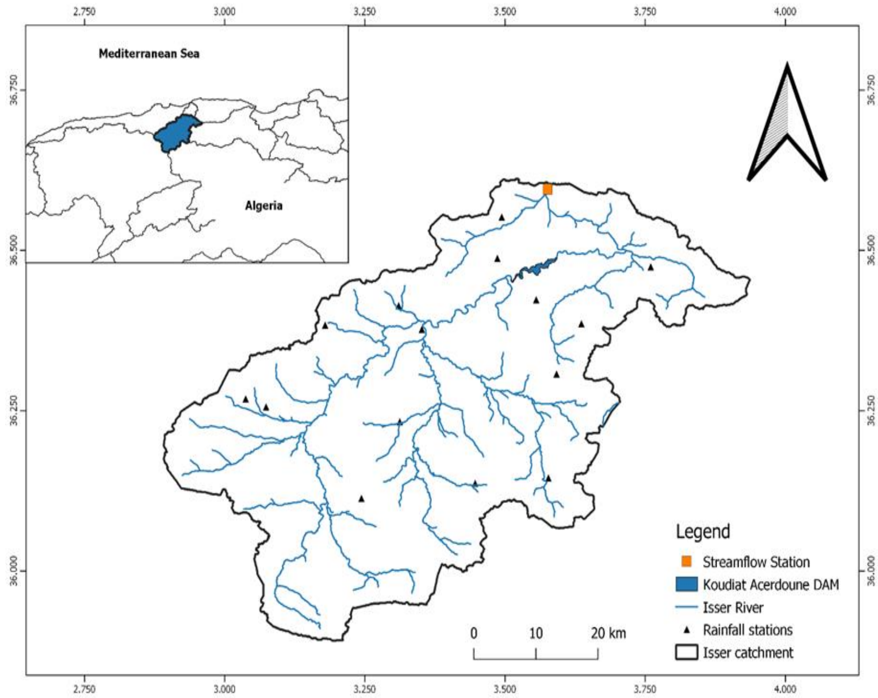


Figure 3. 2: Location of the Isser catchment.

The climate of the Isser basin is Mediterranean and subtropical characterized by rainfall that occurs mostly in summer or at the end of spring. The study area receives an average annual rainfall of 300 to 600 mm (ANRH, 2013) and is characterized by an average annual temperature of 22 °C. The temperature can exceed 40 °C during the summer season. The rainfall is seasonal with high temporal and spatial variability. The wettest months are December and January, while the driest months are July and August. The cyclonic rainfall represents about 60% of the annual total of which a significant part comes from stormy rains (due to the proximity of the sea) or from the orographic effect forced by the mountain barrier.

Agriculture is considered a major economic activity within the basin. Most of the water resource allocation is used for agriculture, municipal water supply, and industry (MADR, 2018; MRE, 2017). The main economic activities within the catchment are related to agriculture where most of the cultivated plots are intended for growing cereals, vegetables, arboriculture, and olive groves. Irrigated lands have also increased rapidly over the years in the Isser Basin. The irrigated areas have increased from 10,000 ha in 1985 to 95,000 ha in 2012 (MADR, 2018).

Water resources in the basin have been significantly developed and supply water for agricultural activities, urban and industrial activities, and ecosystems. A dam with a total capacity of 640 million m^3 was constructed in the downstream part of the Isser catchment along the mainstream in 2010 (ANBT). It is principally used for drinking and irrigation water supply and industry (MRE, 2017). It supplies drinking water to urban and rural agglomerations located on the Koudiat Acerdoune-Ain El Hadjel axis in the highlands in the south of Algiers, as well to the governorates of Tizi Ouzou, Bouira, Boumerdes, Médéa, and M'sila. The dam also allows irrigation of more than 60 000 hectares in the Mitidja plain, the Oued Isser valley, and the Bouira plain (MADR, 2018). The domestic, industrial, and agricultural sectors exert huge pressure on the water resources of the catchment which is a result of the increase in population growth in the area. The population within the Isser basin has been growing significantly over the last two decades, from 1 million in 2008 to 2 million in 2015 (ONS, 2015).

3) Macta Catchment

The Macta catchment (Fig 3.3) is located in a semi-arid climate in the North-Western part of Algeria and drains an area of 3 600 km². It is a relatively flat catchment in its central and northern parts with an average slope of 3%. Approximately, 11% of the entire basin has elevations less than 200 m, 7.6% between 201 and 400 m, 41.8% between 401 and 800 m, 34.5% between 801 and 1200 m, and 5.4% higher than 1201 m, whereas almost 90.0% of the basin has slope angle less than 10°. The Mekerra river is the principal stream within the basin with a total length of 120 km.

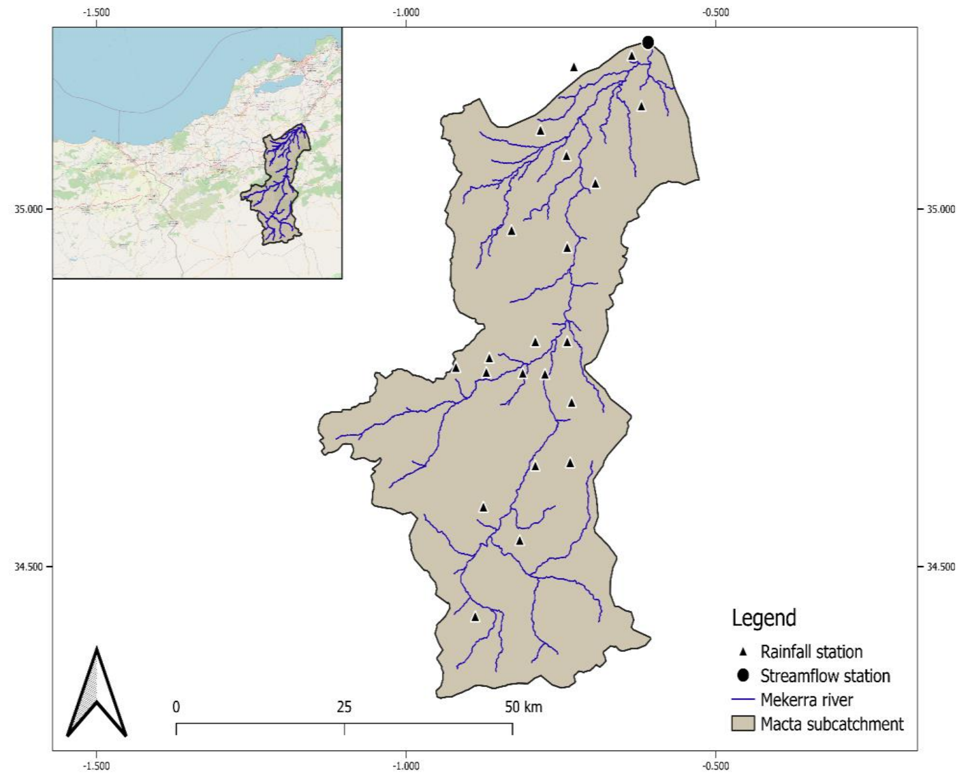


Figure 3.3: Location of the Macta catchment.

The basin is characterized by varied climates, the north having a Mediterranean influence, while the southern part is dominated by a semi-arid climate, with cold and humid winters and dry and hot summers. The precipitation regime is seasonal with high spatiotemporal variability and mean annual precipitation of 234 mm.year^{-1}.

The landscape is covered by desert to the shrub in the south part, and a dense forest area in the middle side, whereas agriculture, represents the main economic activity where irrigated lands dominate in its downstream side (the Ghriss and Sidi Bel Abbes plains)(El Mahi et al., 2012). Most of the cultivated plots are managed for growing cereals, and vegetables. The main economic activities within the catchment are related to agriculture activity located in the plain of Sidi-Belabes. Irrigated lands represent about 60% of the total basin, and are rapidly increasing over the years, which have increased from 11,000 ha in 1985 to 14,000 ha in 2000, and from 20,000 ha to 50,000 ha in 2012 (MADR, 2018), and similarly water pumping activities dramatically increased in the region, which exerts pressure on the available water resources (Baahmed et al., 2015). The population within the Macta catchment has been growing significantly from 671,410 in 2008 to 763,482 in 2015 (ONS, 2015).

The hydrology of the basin is complex and characterized by a seasonal hydrological regime with long low flow periods in summer causing severe water scarcity with severe periods of drought and dominated by short intense precipitation. The catchment is mainly drained by the Mekerra stream and numerous little streams. The most important alluvial aquifers are constituted by large plains of collapse, filled by an alluvial deposit. They are relatively well supplied by rainfall and by the wadis that cross them. These aquifers are generally characterized by good permeability and average depths (100 to 300 m). This is the case of the aquifers of Sidi Bel Abbes and Mascara. The number of hydrogeological units in the Macta region is 16 units, whose groundwater potential is estimated at 140 Hm^3 (ANRH, 2013).

3.2.2 Data Sources

Hydroclimatic conditions in the study sites are assessed in terms of the main climate variables precipitation (P), streamflow (Q), evapotranspiration (ET), and temperature (T), which generally have significant implications for the hydrologic cycle and vegetation dynamics. The brief description of field data collected from the relevant agencies for the analysis reported in the present research is described in the following paragraphs.

1) Rainfall data

Monthly rainfall data for the period from 1981 to 2012, were collected for each basin from the Algerian National Agency of Hydraulic Resources (ANRH) and the National Meteorological Office (NMO) of Algeria (Tableau 3.1). The annual rainfall (P) data were aggregated from the monthly data. The average rainfall values corresponding to each basin were estimated using the Thiessen polygon method by the spatial analyst tool of ArcGIS® 10.4. Rainfall stations were selected for the trend analysis based on the following criteria:

- A length of serial data equals or exceeds thirty years;
- Times series of the same period;

2) Streamflow

Streamflow data from all gauging stations for the 1981-2012 period over the selected basins were obtained from the National Agency of Hydraulic Resources (ANRH) (Table 3.1) (Fig.3.1). Although the recording of flow data over the basins started in the late 1960s, it was discontinued and damaged for most of the gauging stations during the civil war in the 1990s. To this effect, only three stations have been selected to be representative, and have an extended period of more than 30 years of data within the basins, and these were used in the analyses. The location and general information of all flow stations of the basin are summarized in Figure 4.1 and Table 3.1. The annual hydrological flow data were aggregated from the monthly data. To be coherent with the units of precipitation and evapotranspiration, streamflow measurements have been expressed in terms of runoff in mm (i.e. we have considered the catchment area to transform $m^3 . s^{-1}$ to $mm.yr^{-1}$).

3) Evapotranspiration and Temperature

The information about the monthly actual evapotranspiration and temperature is not consistent and limited in time and space as it doesn't cover all the selected catchments. To overcome this limitation, we used the TerraClimate product, hosted by the University of Idaho's Northwest Knowledge Network for monthly scale, which is validated using observed station-based data obtained from the Global Historical Climatology Network database (GHCN). Actual evapotranspiration as well as air temperature variables used in this study are characterized by a spatial resolution of 4 km and monthly temporal resolution (Table 3.1). The data were downloaded from the TerraClimate, accessing through their website: (https://app.climateengine.com/climateEngine#climateEngineHome). This database comprises monthly climate data and climatic water balance data for global terrestrial surfaces. It uses climatically aided interpolation, combining high-spatial-resolution climatological normal data from the WorldClim dataset and the Japanese 55-year reanalysis (JRA55) dataset (Abatzoglou et al., 2018). Air temperature and evapotranspiration data were extracted for each basin by selecting pixels falling within the catchment boundaries and then averaged to provide basin-averaged monthly air temperature and evapotranspiration time series from 1981 to 2012.

4) NDVI

In the past 30 years, remote sensing (RS) has provided a wide range of tools for monitoring the health and condition of vegetation cover, especially for large-scale studies. Several indices have been defined based on remotely sensed reflectance data for the study of Earth surface characteristics, among which the normalized difference vegetation index (NDVI) is a useful and well-studied index for vegetation study (Schultz et al., 2016). The Normalized Difference Vegetation Index (NDVI) can be used as an indicator for irrigated lands (Ambika et al., 2016) as it represents the amount of green biomass with index values varying in response to changes in vegetation conditions. The NDVI was first used by Rouse et al. (1974) and is calculated based on the response of vegetation to electromagnetic waves in red (RED) and Near-Infrared (NIR) bands: (i.e. NDVI = (NIR - Red) / (NIR + Red)) and ranges from -1.0 to 1.0. NDVI is a dimensionless parameter and its value ranges between -1 and 1. Generally, values greater than 0.4 represent temperate and tropical rainforests, while NDVI values between 0.2 and 0.3 indicate irrigated lands and agricultural areas. Negative low values near -1 normally refer to water, and small values close to zero (between -0.1 and 0.1) represent urban areas or areas covered by rock, soil, etc... (Weier and Herring, 2000). As suggested by many studies (e.g., Delbart et al., 2005; Khazaei et al., 2019b), an NDVI value of 0.35 can be used as a threshold for distinguishing vegetation from other types of land cover. This can be used to classify land into vegetated and non-vegetated land cover types. In this study, NDVI data are obtained from NOAA Climate Data Record (CDR) AVHRR NDVI. The NOAA CDR contains gridded monthly NDVI derived from the NOAA AVHRR Surface Reflectance product (Franch et al., 2017). The NDVI-CDR summarizes the temporal changes of surface vegetation coverage activity, gridded at 0.05° spatial resolution and computed globally over land surfaces. The data were downloaded from the website:

(https://app.climateengine.com/climateEngine#climateEngineHome). NDVI time series were extracted for each basin at a monthly scale by selecting pixels falling within the catchment boundaries and then averaged to provide basin-averaged annual NDVI time series for the 1981-2012 period (Table 3.1).

Table 3.1: Informations on hydroclimatic time series in the selected basins.

Characteristics	**Medjerda**	**Isser**	**Macta**
Drainage area (km^2)	7870	4154	3600
Average annual precipitation (mm)	341	441	234
Average annual streamflow (mm)	214	56	7
Average annual temperature (°C)	16	17	19
Average annual evapotranspiration (mm)	550	534	562
Average annual NDVI (-)	0.32	0.30	0.25
Number of river gauges	1	1	1
Number of rainfall stations	1	14	21
Time period	1981-2012	1981-2012	1981-2012
Temporal resolution	Monthly	Monthly	Monthly

3.2.3 Trend Analysis: The Mann-Kendall (MK) Test

When human activity and climate change on the hydrological system are intensive, these variables could present varying degrees of alterations, and the forms of these changes mainly include abrupt change (sudden change) and gradual change (trend) (Ahmed et al., 2022). The focus of this study is on the gradual change of hydrological time series. The nonparametric MK (Mann, 1945; Kendall,1962) test is applied for the detection of monotonic increasing or decreasing trends in the time series of hydroclimatic variables and possible explaining factors (Su et al., 2018a; Khazaei et al., 2019). The MK test has been widely used for trend analysis of hydrological time series Yue et al., 2002). The slope of the trend is estimated in the time series using the non-parametric method Theil–Sen estimator developed by Sen (1968) and Theil (1992). The MK-test was selected because of its robustness with respect to non-normality.

The MK statistic *S* is defined as the total sgn of the whole time series which is measured as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) ; \qquad (3.1)$$

where:

$$sgn(x_j - x_i) = \begin{cases} 1 \text{ if } (x_j - x_i) > 0 \\ 0 \text{ if } (x_j - x_i) = 0 \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \qquad (3.2)$$

In the MK test, sgn is used to count the difference between two values (x_i and x_j) where x_i and x_j are the data value at times i and j, n is the length of the data set. Under the null hypothesis that x_i are independent and randomly ordered. For n greater than 8, the statistic *S* is approximately normally distributed with zero mean, E(S), and variance, Var(S), defined as follows:

$$E(S) = 0,$$

$$Var(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^{p} t_i(ti-1)(2ti+5)\right]/18 \quad (3.3)$$

In Eq. (4.4), t_i is the number of data values in a tied group, and p is the number of tied groups. A tied group is a set of sample data that have the same value (there is a tie when xj= xi). The standardized test statistics Z follows a standard normal distribution and is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \quad (3.4)$$

In this study, the significance level alpha= 0.05 was used. At the 5 % significance level, the null hypothesis (H0) of no trend is rejected if the p-value< 0.05, and retains the alternative hypothesis (Ha), indicating that a significant trend exists in the time series. All analyses for trend detection were performed using the "trend" package version: 1.1.4, published on 2020-09-17 in RStudio, Build 382 (RStudio, 2009-2022). The “trend” package includes several Non-Parametric Trend tests and Change-Point Detection (CPD).

3.2.4 Convergent Cross mapping (CCM) method

Convergent Cross Mapping (CCM) is a bivariate causal inference approach proposed by Sugihara et al. (2012) based on nonlinear dynamical systems theory. CCM tests for causal links between two-time series. Hence, CCM measures the extent to which the historical record of the affected variable Y can correctly forecast the state of the causal variable

X. This occurs only if X has a causal influence on Y. In other words, CCM looks for the signature of the variable X in the response variable Y by examining if there is a correspondence between phases spaces reconstructed from time series of points in the shadow manifold built from Y, M_Y, and points in the X shadow manifold, M_X, where these two manifolds are built from lagged coordinates of the time-series variables Y and X, respectively following Takens' embedding theorem (Takens, 1981). As a result, we can infer that information about X is recorded in Y. Then, it becomes possible to make predictions about the values of X, the causal variable, based on the values of Y, the affected variable (Sugihara et al., 2012). The following animation summarizes the essential ideas: tinyurl.com/EDM-intro. Takens' theorem, states that in a multi-dimensional dynamical system, the essential information can be memorized in the time series of any single variable of the system (Sugihara et al., 2012). To identify if X causally influences Y, Sugihara et al. (2012) rely on the predictive skill, which can be estimated with Pearson's correlation coefficient. Therefore, a plot of Pearson's correlation coefficient against the increasing time-series length (L) should increase to a plateau value, which is defined as convergence, indicating a strong causal link.

In our study, exploring the causal relationships of the couple: P-Q, T-Q, ET-Q, and NDVI-Q, respectively, was done using the "rEDM" package in RStudio version 1.13.0 published on 2021-06-22 Build 382 (RStudio, 2009-2022). The package has been developed by Sugihara et al. (2012) and is available at https://github.com/SugiharaLab/rEDM. The rEDM package collects several Empirical Dynamic Modeling (EDM) methods, including the simplex projection (Sugihara and May, 1990), the S-map (Sugihara, 1994), the multivariate embeddings (Dixon et al., 1999), and the

Convergent Cross Mapping (CCM) (Sugihara et al. 2012). The CCM method has been applied to monthly time series. The power of influences exerted from one variable on another variable is evaluated by the value of Cross Map skill (ϱ value) between estimated and observed values. This skill ranges from 0 to 1. The causality is consequently revealed if the forecast skill (ϱ value) converges with the length of the time series (L). Conversely, no causation is detected between the two variables when no convergence appears with increasing the length of the time series (L).

The CCM algorithm involves the following steps:

Step 1: Identify embedding dimension (E)

The embedding dimension (E) represents the number of dimensions for which the reconstructed attractor is best unfolded, producing the highest forecast skill. In other words, it denotes how many time lags one counts back in time to the Euclidean space used to build the shadow manifold. In the case of a state space reconstruction, the embedding dimension is the dimension of this space, that is, the number of axes of the lagged variables plot. The best embedding dimension of the attractor is determined by evaluating the attractor's prediction skill for different embedding dimensions. The prediction is done by using simplex projection using a nonlinear forecasting algorithm developed by Sugihara and May (1990). The identification of the optimal embedding dimension (*E*) is computed using the simplex projection technique from the rEDM package (Sugihara and May 1990) to individual time series. In this method, the ability of one variable to predict its dynamics is estimated using different embedding dimension values of E, ranging from 1 to 10. The correlation coefficient ϱ between predictions and observations represents the forecast skill, and the optimal embedding dimension E corresponds to the highest forecast skill selected by plotting predictability with respect to the embedding dimension.

Step 2: Constructing the shadow manifolds M_x, M_y.

The theory of nonlinear dynamical systems applied to univariate time series analysis (Kantz, 2019) based on Takens's (1981) embedding theorem suggests that the dynamic of a system can be represented by its state space so-called attractor manifold (**M**)(Van Nes et al., 2015). The manifold of the Lorentz attractor consists of three variables, represented by the time series $x_{(t)}$, $y_{(t)}$, and $z_{(t)}$. Interestingly, the dynamics of a system can also be reconstructed into a pseudo-state space M_x and M_y respectively (also called the shadow manifolds) using only one of the time series, which reproduces the two-lobed butterfly of attractor manifold (**M**), i.e. M_y and M_x represent the dynamics of **M**. Similarly, shadow manifolds M_z can be created using z(t). For example, M(x) or M(y) are created using the embedding dimension *E* and its lagged coordinates as follows:

$$M_x(\tau, E_x) = \{x_{(t)}, x_{(t-\tau)}, \ldots, x_{(t-(E_x-1)\tau)}\} \tag{3.5}$$

$$M_y(\tau, E_y) = \{y_{(t)}, y_{(t-\tau)}, \ldots, y_{(t-(E_y-1)\tau)}\} \tag{3.6}$$

where $\mathbf{E_x}$, $\mathbf{E_y}$ are the embedding dimension, and $\boldsymbol{\tau}$ is the lag of time delay embedding assumed to be 1 (it depends on the time scale of time series (day, month, year), **M** is the dimensional space reporting the states of a system with respect to variables called attractor **M**. $\mathbf{M_x}$ and $\mathbf{M_y}$ respectively called the shadow manifolds)

Step 3: Cross-mapping from M_X to M_Y (*X*_xmap_*Y*) or from M_Y to M_X (*Y*_xmap_*X*)

Let's consider two-time series $X = x_t$ and $Y = y_t$ of length L. To establish a cross-mapping from X to Y, first, we reconstruct the shadow manifolds M_Y and M_X for each variable based on the delay coordinate embedding (Taken, 1981) (step 1). The CCM algorithm measures how well the local neighborhoods in M_x correspond to those in M_y. The cross-mapping estimate of a given $y_{(t)}$, denoted $\hat{y}_t|\mathbf{M}_x$, is based on a simplex projection method (Sugihara, 1990; Sugihara, 1994), which is a nearest-neighbor method involving E+1 nearest neighbors points of x_t in M_x. Sugihara, et al. (2012) noted that E+1 is the minimum number of points needed for an embedding with E dimensions. The time indices of E+1 nearest neighbors are denoted as by t_1, t_2,…, t_{E+1} in the order of distances to $x_{(t)}$ from the nearest to farthest, for instance, point $x_{(t1)}$ is the nearest neighboring point of $x_{(t)}$ in M_x. These time indices are used to identify the points in M_Y, namely, to find the points at the corresponding instants: $y_{(t1)}$, $y_{(t2)}$, …, and $y_{(tE+1)}$, which are used to estimate the predicted value $\hat{y}_t$ through the weighted average by:

$$\hat{y}_t|\mathbf{M}_x = \sum_{i=1}^{E+1} w_i \; y_{t_i} \tag{3.7}$$

where:

$i = 1 \ldots (E+1)$ and w_i is the weight that we multiply by the corresponding y_{t_i}.

$$w_i \;=\; u_i \;/\sum_{j=1}^{E+1} u_j \quad where\, j = 1 \ldots (E+1) \tag{3.8}$$

$u_i = \exp[-d\left(x_t, x_{t_i}\right)/d(x_t, x_{t_1})]$ where $d(x_t, x_{t_i})$ is the Euclidean distance between the two vectors x_t, x_{t_i} in M_x. Note that we divide each weight by the sum of all weights. The cross-mapping from Y to X is defined analogously to infer the causative influence of x(t) on y(t). The skill of cross-map estimates is estimated by Pearson's correlation coefficient (ρ) between the observed values of y_t and the predicted values of $\widehat{y_t}|\mathbf{M}_x$. If the correlation coefficient is significant, this means we have enough information from Y that is stored in X. We can thus use X to predict Y. Same goes for X influencing Y. All analyses rely on embedding dimension (E) of 2, a delay $\boldsymbol{\tau}$ was considered constant and equal to 1 month depending on the time step of time series. The nearest neighbor is the simplex k= E+1. To determine the significance of the correlation coefficient (at the 5 % level, alpha = 0.05) in cross-mapping of the causal factors affecting the streamflow alteration in the selected catchments, three statistical tests were applied namely, Pearson's correlation test, Kendall's τ test, and Spearman's rho test. The results are considered significant if the p-value < 0.05.

4

Exploring Causes of Streamflow Alteration in the Medjerda river, Algeria

This chapter is a modified version of a published manuscript in Journal of Hydrology: Regional Studies.

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Abstract

THE Medjerda is a transboundary catchment located in North-Eastern Algeria and shared with Tunisia. In this study, we explore the causes of the hydrological alteration of streamflow in a sub-catchment of the Medjerda in Algeria. The hydrological alteration was explored through the application of the Mann-Kendall test based on possible explanatory factors, namely, precipitation, evapotranspiration, temperature, irrigation, and Normalized Difference of Vegetation Index (NDVI). Furthermore, the causal factors of streamflow variation were addressed using Convergent Cross Mapping (CCM) method. Results of the trend analysis yield that the streamflow is altered during the period 1981-2012. This is consistent with the trends of the possible explanatory factors of this alteration. The Convergent Cross Mapping (CCM) method showed that streamflow alteration is unidirectionally caused by changes in patterns of precipitation, temperature, evapotranspiration, irrigation, and NDVI and that there is little feedback from streamflow alteration to these causing factors. Overall, our assessment showed that the method used to identify the causal relationships in dynamical systems based on the CCM algorithm is suitable for exploring the drivers of the hydrologic alteration in multivariate time series, in particular when nonlinear dynamics determine the system

4.1 Introduction

The hydrological regime of a river strongly controls its different functions and ecosystem services. Land cover and climate change may significantly alter the hydrological regime (Milly et al. 2005; Barnett et al., 2005; Liechti et al., 2014), particularly in areas characterized by arid and semi-arid climates such as the Mediterranean region (Schilling et al., 2012). In this region, rainfall regimes have been altered by climatic and/or physiographic characteristics, strongly affecting the streamflow regime (Zamoum and Souag-Gamane, 2019). Within the Mediterranean region, Algeria and Tunisia are considered as highly water-stressed countries, suffering from extreme water scarcity in recent decades (FAO, 2018; Schilling et al., 2012). Indeed, Algeria is facing low precipitation affected by high spatial and temporal variability, low runoff, high evapotranspiration, and increased drought severity, which will significantly reduce the streamflow of rivers. The potential effects of climate change are expected to increase current pressures on water resources (Sellami et al., 2016). As a result, surface water and groundwater will be reduced with a direct effect on the allocation of water among sectors (irrigation, water supply, and industry) (FAO, 2018). However, climate change includes also alterations in temperature, evapotranspiration, vapor pressure, and wind speed regimes that could conduct to structural changes of streamflow indirectly. In addition, other factors like land cover change, dam construction, and irrigation development, also contribute to the hydrological alteration. Understanding the role of each possible causal factor on the hydrological alteration is pivotal and plays an important role in the agricultural development of the whole region. The identification of the causal factors and their specific contribution to the hydrological alteration remains a challenging task.

Several studies used correlation tests in multivariate time series to study causality including hydro-climatic variables like temperature (T), precipitation (P), wind speed (WS), evapotranspiration (ET), relative humidity (H), soil moisture (SM), Normalized Difference of Vegetation Index (NDVI), and streamflow (Q) (Meng et al.,2014; Khazaei et al., 2019; Miao et al., 2011). However, the correlation criterion does not necessarily imply causation and vice versa. It is neither necessary nor powerful for establishing a causal map of factors in multivariate time series contributing to the hydrologic alteration, in particular when nonlinear dynamics determine the system (Van Nes et al., 2015, Duan et al., 2018). An alternative approach to identifying causal relationships in dynamical systems is based on the Convergent Cross Mapping (CCM) algorithm. This approach is based on the theory of nonlinear dynamical systems developed by Takens (1981). The CCM has recently been introduced in hydroclimatology to detect the causal effects of soil moisture on precipitation (Wang et al., 2018), to quantify causal feedback in climate change (Van Nes et al., 2015), and to detect the causality of individual meteorological factors on local atmospheric pollution in China (Gao et al. 2017). The CCM algorithm is particularly suitable to extract causality links from mirage correlation (Sugihara et al., 2012). The CCM method has also the ability to detect time-delayed causality and to distinguish causality in both directions from the phenomenon of synchrony influenced by strong unidirectional causation (Ye et al., 2015). Yet, the efficiency and robustness of the CCM algorithm compared to other causality detection methods need to be further explored.

The current study includes comprehensive research on the detection of causal factors and their role on streamflow variation for an Algerian sub-catchment of the Medjerda catchment. The Medjerda basin is a Tunisian-Algerian transboundary basin subjected to hydrological alteration and water stress (Fehri et al., 2019). The economy of the Medjerda catchment depends largely on irrigated agriculture (Bouraoui et al., 2005). The assessment of the hydrological alteration, in addition to the identification of the causal factors using the CCM algorithm, would be most valuable for long-term water resources planning and management within the region. The main objectives of this study are: (1) to investigate the hydrological alteration of the Medjerda river by assessing long-term time series of possible explanatory factors using the Mann-Kendall trend test, and (2) to identify and explain the causal relationships between possible explanatory factors and river flow using the CCM algorithm.

4.2 Material and methods

4.2.1 Study area

A detailed description of the study site is in chapter 3, section 3.2.1

4.2.2 Data sources

A detailed description of the data collection is in chapter 3, section 3.2.2

4.2.3 Trend Analysis: The Mann-Kendall (MK) Test

A detailed description of the Mann-Kendall (MK) test in chapter 3, section 3.2.3

4.2.4 Convergent Cross Mapping (CCM)

A detailed description of the Convergent Cross Mapping (CCM) method is in chapter 3, section 3.2.4

4.3 Results and discussion

4.3.1 Trend detection analysis

Results of the Mann-Kendall trend analysis of streamflow (Q), precipitation (P), temperature (T), evapotranspiration (ET), and Normalized Difference of Vegetation Index (NDVI) are shown in Figure 4.1. As illustrated in Figure 4.1a, the application of the Mann-Kendall trend test over the period from 1981 to 2012 has shown a statistically significant downward trend in annual rainfall (p-value < 0.05). The trend magnitude yields -11.5 mm/year across the study area and, therefore, a significant reduction of P has been identified. It reveals that the rainfall pattern is altered over time. In the previous research carried out on the eastern region of Algeria, Khedimallah et al. (2020) found similar patterns of annual and seasonal rainfall in the Algerian side of the Medjerda watershed over the period 1968-2013 using the same test (Mann-Kendall). They found a decreasing trend in the upstream of the Medjerda sub-catchment and an upward trend in other locations of the basin at an annual scale. However, as shown in another study conducted by Taibi et al. (2017), no significant trend was found for annual rainfall in the Medjerda catchment over the period 1936-2008. While in other previous research conducted by Mrad et al. (2018) in the Medjerda catchment from 1969 to 2015, significant increasing trends were observed in several stations. This fact may be explained by different length record periods used for the trend analysis and depending on the position of these. These different record lengths of data may have introduced some discrepancies in the trend analyses. In a recent study conducted by Boulmaiz et al. (2022) on the spatiotemporal variability of precipitation over the Medjerda transboundary basin during 1970-2007 to identify the possible links at different time scales for all stations separately between the climate indices (the North Atlantic Oscillation (NAO), the Mediterranean Oscillation (MO), and Southern Oscillation (SO)) and rainfall time series confirmed that trend rainfall is not affected by the climatic teleconnection index (NAO, SO, or MO) and are not statistically significant. This finding may explain some local variability patterns related to the detected trend. However, they argued that these alteration of rainfall trends in each sub-catchment suggest the existence of several microclimates in the basin or different local influencing factors such as topography. Figure 4.1b shows a negative trend with a significant decrease trend also observed for the annual Q for the period 1981-2012 in the hydrological station. The trend magnitude assessed by means of the Sen's slope yields -6.77 mm/year. We can therefore confirm that the hydrologic regime of the Medjerda river has been significantly affected during the study period by climate variability. The consistency between the negative trends of P and Q suggests further that the change in P contributes to the river flow downward in the upstream region of the Medjerda catchment. The rainfall time series exhibit a similar dynamic pattern as the streamflow pattern. The alteration of streamflow is indeed generally dominated by precipitation variability (Alkama et al., 2011). This change observed in streamflow is in agreement with the findings of Khedimallah et al. (2020). They also revealed significant decreases in annual streamflow (p-value<0.05) over time for their studied Madjerda catchment using Mann-Kendall in the period 1968-2013.

Figure 4.1c shows a statistically significant upward trend for mean annual temperature from 1981 to 2012. The trend magnitude reaches 0.047 °C/year. The result showed that the climate of the Medjerda catchment had become warmer during the last 30 years. The same results were reported by Zeroual et al. (2017) about the significant rinsing of air mean temperature over Algeria from west to East. They revealed that the long-term trend of the temporal variability of temperature is characterized by a significant increase during the study period from 1972 to 2013 both at the annual and seasonal (winter and summer) scales using the Mann-Kendall test. According to the fourth IPCC report (Solomon et al. 2007), a warming trend of 0.2-0.4 °C per year in Northern Africa for different regions has also been observed from 1975 to 2004. Similar results were also detected in the Mediterranean region by Sellami et al. (2016), and Trambaly et al. (2019), for various periods during the 20th century. Under climate projections, they suggest that the air temperature is likely to increase in the future over Mediterranean basins. The same trends were observed in several regions of the Mediterranean basin, for instance in the Eastern Mediterranean (Philandras et al., 2015) and in Morocco (Driouech et al., 2010). Further, the annual ET trend reported in Figure 4.1d also shows a statistically significant upward trend. The Sens's slope confirms that the ET has increased by about 3.770 mm/year. In coherence with the positive trends of T, ET is also following an increasing trend during the period 1981-2012 (Fig 4.1d). The projected global temperature rise is expected to lead to a significant increase in severe drought and frequency and intensity in the Mediterranean regions. These changes are consistent with the results from Trambaly et al. (2019), who found distinct progressive increases in evapotranspiration and the temperature in the Mediterranean basins.

As shown in Figure 4.1e, the mean annual NDVI in the upstream sub-catchment indicates a significant upward trend from 1981 to 2012. The trend magnitude reaches 0.002/year. The increase of the NDVI in the region is mainly attributed to the expansion of irrigation schemes as well as the significant increase in agricultural activities and the increase in evapotranspiration from increased vegetation cover. This negatively impacts the availability of water resources in the region. However, considering the sub-catchment as a small part of the Medjerda catchment, and their land use changes, the significant increase in agricultural activities and intensive use of water may be the possible reason for the decrease in streamflow and an increase of NDVI. This increase in the vegetation cover is a result of the high demand for irrigation and the increase of irrigated areas (from 10,000 ha in 1985 to 40,000 ha in 2000, and from 40,000 ha to 60,000 ha in 2012) (MADR, 2018), and the increasing population in the Medjerda during this period (around 600,627 habs in 2012 (ONS, 2015), which implies higher water demand for drinking water provision.

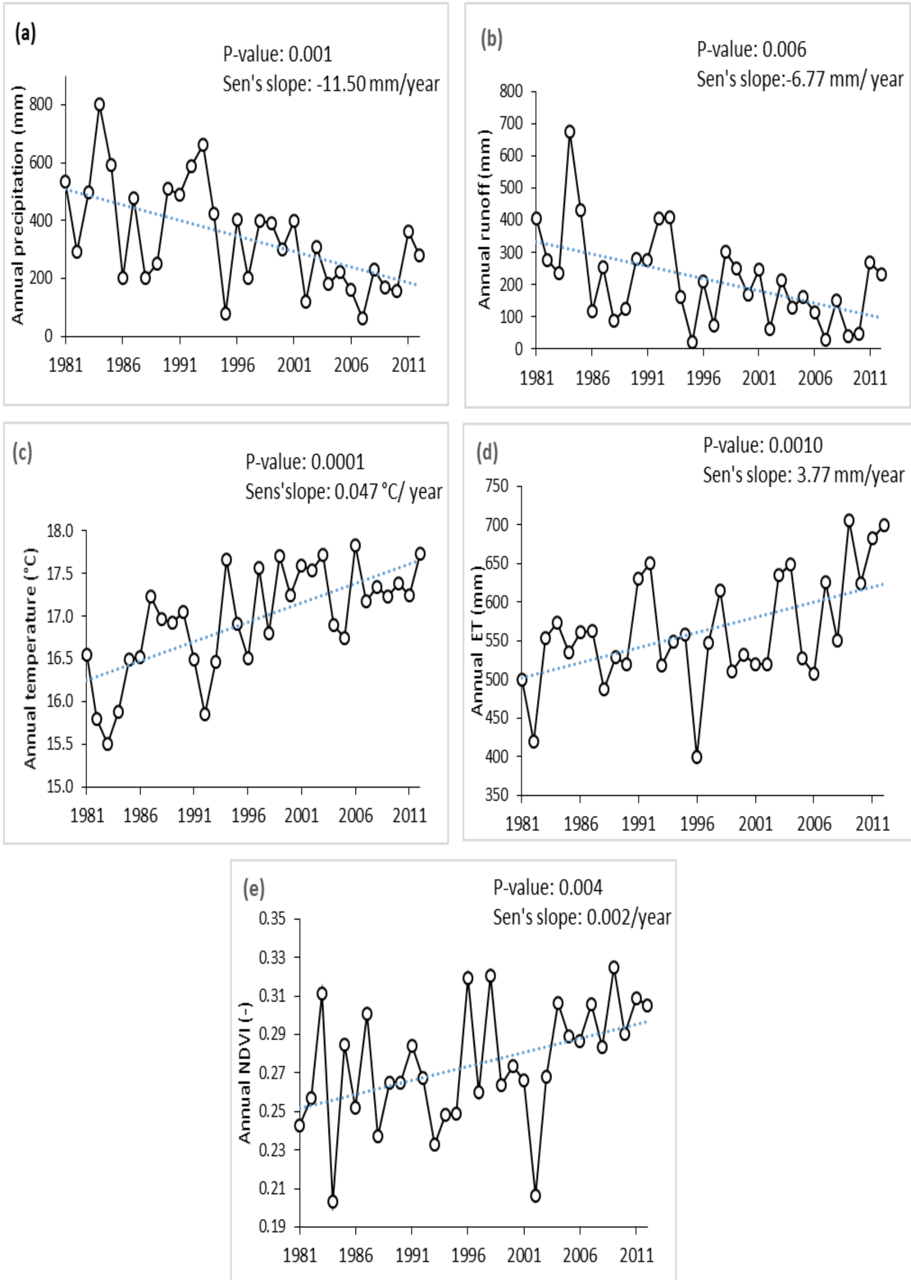

Figure 4.1: Results of the MK trend analysis (SL= 0.05) applied to the annual precipitation (a), streamflow (b), annual temperature (c), mean annual evapotranspiration (d), and NDVI (e).

4.3.2 CCM analysis

Here, the CCM approach was applied to identify the causal relationships of P-Q, NDVI-Q, ET-Q, and T-Q, respectively. When applying the CCM method, the cross-map skill or forecast skill denoted by ϱ value is defined by calculating the Pearson's correlation coefficient between predictions and observations values, and the length of the library (L) refers to the number of observations of the time series. The causality is confirmed when ϱ substantially increases with the increasing L. As shown in Fig. 4 (a-d), for these four relationships, the correlation coefficient (ϱ) increased with the length of the library (L) and converged, suggesting significant causal effects of P on Q, NDVI on Q, ET on Q, and T on Q, respectively. In the hydrological processes, the causation of P on Q is well known. Figure 4.2a confirms cross-mapping P from Q. CCM method detects correctly that P drives Q. The results of the CCM method exhibit convergence with increasing the length of the time series, demonstrating causation between the P and Q ($\varrho = 0.79$). Hence, high P is likely to cause high Q and vice versa.

From the discussion in the preceding section, it is reported that the annual streamflow in the Medjerda sub-catchment has been found to decrease at the station. Also, the rainfall exhibits a similar pattern with streamflow, wherein decrease in the annual streamflow. CCM method detected there is a significant causal relationship between the annual streamflow in the Medjerda mainstream and the annual precipitation ($p < 0.05$) (Fig 4.2a). The causal link indicates that the precipitation influences the streamflow directly, which is a completely climatic factor, as would be expected.

We additionally found that NDVI is a forcing variable of Q, which means that NDVI exerts an influence on Q, revealing the causal relationship between the NDVI and Q (ϱ = 0.20) (Fig 4.2b).
Surprisingly, we found that the NDVI, an environmental factor that was rarely discussed in the literature, is the influential environmental variable in affecting streamflow change. The decrease in annual streamflow could be due to a significant increase in the vegetation cover in the Medjerda sub-catchment, wherein, the irrigated areas have been found to increase (from 10,000 ha in 1985 to 40,000 ha in 2000, and from 40,000 ha to 60,000 ha in 2012) (MADR, 2018) during the period 1985-2012 (see section 3.6). This drastic expansion in the agricultural areas is one of the major factors affecting the streamflow due to excessive exploitation of the available water resources for irrigation. Hence, anthropogenic activities in form of land use changes and irrigation are partially the drivers of streamflow changes in the Medjerda sub-catchment. It is revealed also that the air temperature and evapotranspiration are forcing variables of Q in the Medjerda sub-catchment (Fig 4.2c). The CCM method shows further convergence with increasing the length of the time series between T-Q and ET-Q, respectively. Indeed, the correlation coefficient for the cross-map of T from Q and ET from Q reaches a value of rho (ϱ =0.79) and (ϱ =0.60) (Fig 4.2(c-d)), respectively. Convergence suggests therefore that Q is causally forced by T and ET. A possible explanation is the rapid expansion of irrigated lands ((from 10,000 ha in 1985 to 40,000 ha in 2000, and from 40,000 ha to 60,000 ha in 2012) (MADR, 2018), which induces the increase in demand for irrigation from the river in the Medjerda sub-catchment. In addition, the evapotranspiration rate has also increased, as a consequence of the increasing air temperature. Thus, resulting in increased water loss by evapotranspiration, thereby, a decrease of

streamflow. The Medjerda sub-catchment exhibits a semi-arid type climate, hence, there would be considerable loss of water through evapotranspiration (ET) as a result of temperature rise, which would increase the crop water requirements. Thereby, more water would be withdrawn for irrigation. Furthermore, the observed decreasing trends in rainfall as well as streamflow could likely escalate the risk of meteorological, hydrological, and agricultural droughts in the region in the future.

We applied statistical tests to estimate the correlation coefficient of the causal links as well as the significance namely, Pearson's correlation test, Kendall's τ test, and Spearman's rho test (Table 4.1).

Table 4.1: Results of the statistical tests to test the significance of the correlation coefficient (ϱ) of the causal factors

Catchment	CCM test		Correlation tests					
	Causal links	Rho value(ρ)	Pearson's correlation test		Kendall's τ test		Spearman's rho test	
			Correlation	p-value	Correlation	p-value	Correlation	p-value
Medjerda	P-Q	0.790	0.795	2.20E-15	0.643	2.20E-15	0.789	2.20E-15
	ET-Q	0.600	0.606	2.20E-16	0.434	2.20E-16	0.603	2.20E-16
	T-Q	0.790	0.801	2.20E-16	0.661	2.20E-16	0.791	2.20E-16
	NDVI-Q	0.201	0.203	1.09E-05	0.131	1.40E-03	0.192	1.53E-04

Results show that the correlation coefficient was statistically significant, with p-values lower than 0.05 for precipitation, evapotranspiration, and temperature respectively (Table 4.1). However, for NDVI the result is not clear although the correlation value is lower but statistically significant. In addition, the correlation coefficient estimated by Pearson's correlation test and Spearman's rho test is almost similar. Thus, we can conclude that linearity between observed and predicted values of the outcome exists.

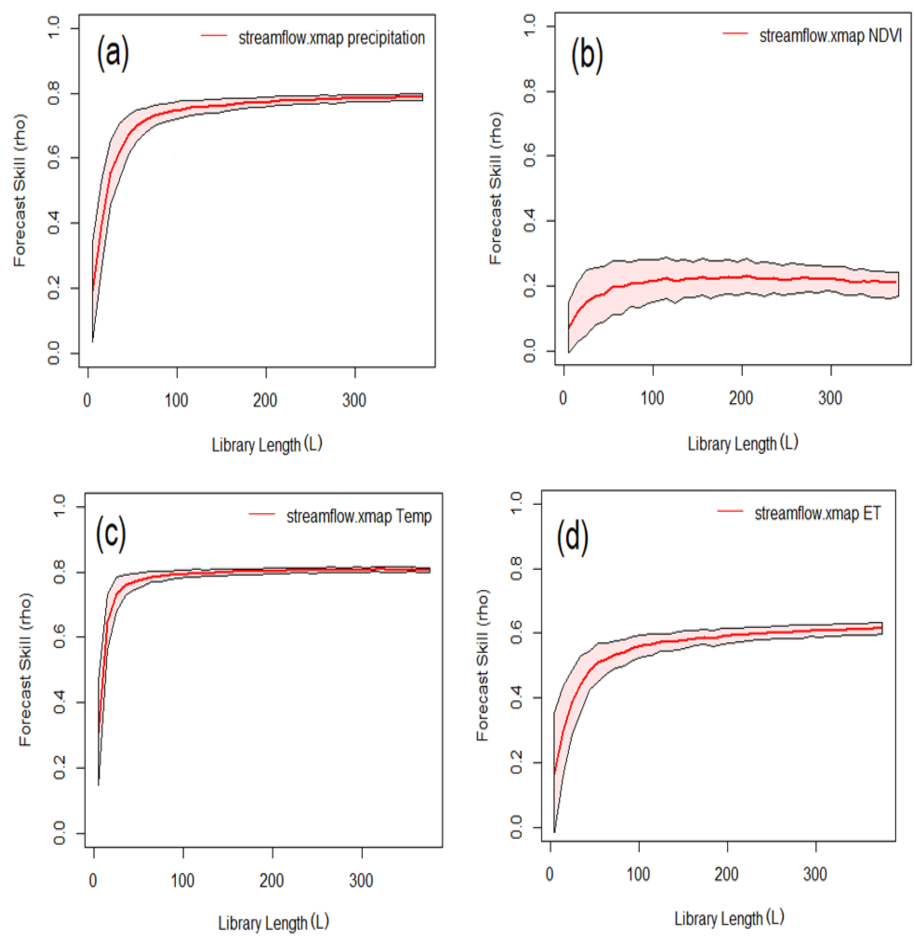

Figure 4.2: CCM results to demonstrate the causality of meteorological factors and NDVI on streamflow. L: the length of the time series. X xmap Y stands for convergent cross-mapping Y from X, in other words, the causality influence of variable Y on X. For instance, streamflow xmap precipitation stands for the causality influence of precipitation on streamflow. Shaded areas indicate 95% confidence interval.

4.4 Conclusion

In this study, the hydrological alteration of streamflow and its causes was explored for the Medjerda upstream sub-catchment (North-East of Algeria) using Mann-Kendall (MK) trend analysis, and nonlinear time series analysis tool, Convergent Cross Mapping (CCM). The major conclusions are as follows:

(1) The streamflow (Q) in the study area showed a significant decreasing trend during the period 1981-2012 with a magnitude of -6.77 mm/year. Thus, a significant hydrological alteration of the upstream part of the Medjerda river was observed. The trends of possible explanatory factors were also assessed. Similar and different trend behaviors to Q were found, i.e. a decrease of P (-11.500 mm/year), and an increase of T, ET, and NDVI with magnitudes of 0.047 °C/year, 3.77 mm/year, and 0.002/year, respectively.

(2) The causality analysis using the CCM method revealed causal links between Q and P, T, ET, and NDVI.

(3) It is concluded that both climate change and human activities, mainly agricultural development, and irrigation, are the dominant causal factors that altered the hydrological regime in the Medjerda river. This suggests the implementation of better operational integrated water resources plans in the region to reduce the pressure exerted on the Medjerda river as an important water resource in the North-East Algerian region.

5

Using convergent cross mapping to explore causes of streamflow alteration: A case study of Isser catchment, Algeria

Abstract

The water resources of Mediterranean countries are strongly affected by climate change and anthropogenic activities, which exert considerable pressure on overall water security. Understanding the relative contributions of each of the possible causal factors to the hydrological alteration is pivotal to designing sustainable water resources management strategies. In this study, the streamflow alteration of the Isser catchment in Algeria is assessed and explained in terms of possible explanatory factors. A long-term hydrometeorological dataset was reconstructed and the nonparametric Mann-Kendall test was used to detect the alteration of streamflow and the possible causal factors. To identify the role of causal factors in hydrologic alteration, Convergent Cross Mapping (CCM) was used, which is an advanced nonlinear time-series analysis tool. The results of the trend analysis show a significant upward trend for streamflow for the period 1981-2012. The CCM method shows that the streamflow alteration is caused by changes in precipitation, temperature, evapotranspiration, and NDVI pattern. Statistical tests were applied to estimate the correlation coefficient as well as the significance namely, Pearson's correlation test, Kendall's τ test, and Spearman's rho test. Results show that the correlation coefficient was statistically significant, with p-values lower than 0.05.

5.1 Introduction

The alteration of streamflow regimes of Mediterranean catchments exerts significant pressure on water resource availability and services. The alterations are likely to affect the water quantity and quality, increasing the risks of floods and droughts. The understanding of the hydrological alteration of rivers as well as its driving forces is therefore crucial for designing climate-resilient water resources management and engineering strategies.

The detection and attribution of streamflow alterations is still a matter of scientific debate (IPCC, 2022). Indeed, drivers of streamflow alteration differ from river to river and vary from one region to another. Also, as we move from the local to regional scale, the heterogeneity and variability in both climatic and hydrological process control change, which makes the assessment of hydrological alteration more complex. Some drivers may have controversial impacts on streamflow alteration. For example, precipitation increase is often acknowledged as being a driver for streamflow increase. Many studies showed that the potential driving factors of streamflow (Q) within a watershed can be attributed to climate, including hydro-climatic factors like temperature (T), precipitation (P), wind speed (WS), evapotranspiration (ET), relative humidity (H), soil moisture (SM). On the other hand, other important factors altering streamflow regimes are related to human activities such as water resources development projects and land use land cover changes (Ahn and Merwade, 2014; Kundzewicz and Robson, 2004).

Different techniques exist to evaluate the causality of streamflow alteration. The assessment of the causal relationships and the quantification of the contribution of the different factors to the streamflow alteration can be made using linear statistical approaches. Yet inferring causality by means of linear statistical approaches remains difficult due to their complex interaction. Statistical approaches rooted in correlation suffer also from the fact that correlation can occur without causation, and causation could also occur in the absence of correlation. Thus, correlation-based models are probably less appropriate when data show complex nonlinear dynamics as within water systems. Here, we aim at disentangling the causality network between climate variables, vegetation cover, and streamflow and explore how environmental factors may alter the streamflow. To overcome the limitation of linear methods, we use the empirical dynamical modelling (EDM) framework, which is specifically dedicated for analysing time series data with underlying nonlinear dynamics (Grziwotz et al., 2018). New approaches such as causal inference methods have been established and used to map causal relationships from nonlinear dynamic time series analysis. These techniques include the PCMCI method (Runge et al., 2019), Granger causality (Granger, 1980), Transfer Entropy (Schreiber, 2000), and the Cross Convergence Method (CCM) (Sugihara et al. 2012). The latter method has found applications in a wide range of domains, which have recently been introduced in hydroclimatology to detect the causal effects of soil moisture on precipitation (Wang et al., 2018); to quantify causal feedback in climate change (Van Nes et al., 2015), and to detect the causality of individual meteorological factors on local atmospheric pollution in China (Chen et al., 2017). Algeria is considered one of the most semi-arid countries in the Mediterranean region, suffering from extreme water scarcity (FAO, 2018), constraining agricultural production, and food security. Most climatic change impacts research in Algeria investigated trends of annual streamflow and precipitation while the possible underlying factors and their relative contribution have not yet been fully explored. In this regard, the current study focuses on the detection and attribution of streamflow alteration in the Isser basin, which represents one of the most important river basin. The main objectives of the study are: (1) to identify the trends of streamflow (Q) across the Isser basin and the possible causal factors (P, T, ET, NDVI) using the Mann-Kendall test; (2) to identify the critical environmental variables that causally affect the streamflow alteration using convergent cross mapping (CCM).

5.2 Material and methods

5.2.1 Study area

A detailed description of the study site is in chapter 3, section 3.2.1

5.2.2 Data sources

A detailed description of the data collection is in chapter 3, section 3.2.2

5.2.3 Trend Analysis: The Mann-Kendall (MK) Test

A detailed description of the Mann-Kendall (MK) test in chapter 3, section 3.2.3

5.2.4 Convergent Cross Mapping (CCM)

A detailed description of the Convergent Cross Mapping (CCM) method is in chapter 3, section 3.2.4

5.3 Results and discussion

5.3.1 Trend detection analysis

Figure 5.1 shows long-term variations in annual precipitation (P), temperature (T), evapotranspiration (ET), Normalized Difference of Vegetation Index (NDVI), and streamflow (Q) of the Isser basin from 1981 to 2012 using the Mann-Kendall test. The annual rainfall at Isser stations for the period 1981-2012 exhibits a significant increasing trend at 5% significance level (Fig .5.1a). The trend magnitude yields 5.878 mm/year. Further, the streamflow analyses of the Isser catchment revealed a significant increase in annual streamflow at the stream gauging station (p-value < 0.05), see Fig. 5.1b. The magnitude of such an increasing trend, represented as Sen's slope value, was 1.154 mm/year across the study area. Further, a similar pattern between rainfall and streamflow behavior is observed in Fig 5 (a,b), i.e., increase in annual rainfall is associated with an increase in annual streamflow. Therefore, the climatic variability is suggested to drive the streamflow change at the Isser catchment. Furthermore, the observed increasing trends in rainfall as well as streamflow could be an indicator of more flow and humid conditions in the basin. Several studies based on long-term precipitation databases in Algeria have indicated an increase in rainfall over the last 30 years. Analysis of the rainfall data using the Mann-Kendall test revealed positive trends at the catchment level, such as in the basins of Isser and Soumam in Northern Algeria (Nouaceur and Murărescu 2016, Taibi and Souag 2012) Upward trends in precipitation observed in this catchment may also be explained by an atmospheric pattern such as the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO). The NAO and MO indices show significant correlations with annual rainfall for the center north regions of Algeria which is a transition zone between the western and the eastern side of Algeria (Djebbar et al., 2020). At the seasonal scale, significant correlations are observed between winter rainfall and the NAO and MO circulation indices (Taibi et al., 2017a). The observed correlations are positive, likely because NAO and MO are in a strongly negative phase that results in an increase in precipitation over the basin (Djebbar et al., 2020). Also, Taibi and Souag (2012) have studied the rainfall regime in northern Algeria and show that proximity to the sea leads to higher rainfall like in the coastal catchments. Also, recent research conducted by Benali et al. (2022) argued that the increase in precipitation regime in the Isser catchment can be explained by the influence of the orography and the proximity to the sea.

Figure 5.1b shows a positive trend with a significant increase at the scale of the Isser catchment is also observed for the annual Q over the period 1981-2012 in the hydrological station. The trend magnitude assessed by means of the Sen's slope yields 1.154 mm/year. We can therefore suggest that the hydrologic regime of the Isser river has been significantly affected by the rainfall regime directly.

Figure 5.1c shows a statistically significant upward trend for mean annual temperature from 1981 to 2012. The trend magnitude reaches 0.03 °C/year during the last 30 years. The same results were reported by Zeroual et al. (2017) for northern Algeria both at the annual and seasonal scales.

Similar to air temperature, the annual ET trend is illustrated in Figure 5.1d. The figure shows a statistically significant upward trend for ET. The Sens's slope confirms that the ET has increased by about 3.630 mm/year. These trends are in agreement with the results from Trambaly et al. (2019)

conducted on the Mediterranean basins (Algeria and Tunisia), who found an increase in evapotranspiration and temperature. The NDVI time series were used to illustrate vegetation change in the region. As shown in figure 5.1e, the mean annual NDVI in the Isser catchment indicates a significant upward trend from 1981 to 2012. The trend magnitude reaches 0.004/year. The increasing trend of the NDVI in the Isser catchment is primarily due to the rapid expansion of irrigated lands (from 10,000 ha in 1985 to 95,000 ha in 2012 (MADR, 2018)) and irrigation practices. Irrigated agriculture is indeed the largest economic activity in the region. The NDVI trend may also be due to an increase in rainfall regime that influences positively the growth of vegetation cover. We conclude that the alteration of streamflow is concurrent with an increasing trend in P, T, ET, and NDVI over time in the study area. However, the relationship may induce complex dynamics. For instance, increasing transpiration and evaporation may also increase local P as T and P both interact in the atmosphere system (Gampe et al., 2016). These interactions are therefore further investigated with the CCM method to identify the causal relationships between Q on the one hand, and P, T, ET, and NDVI on the other hand.

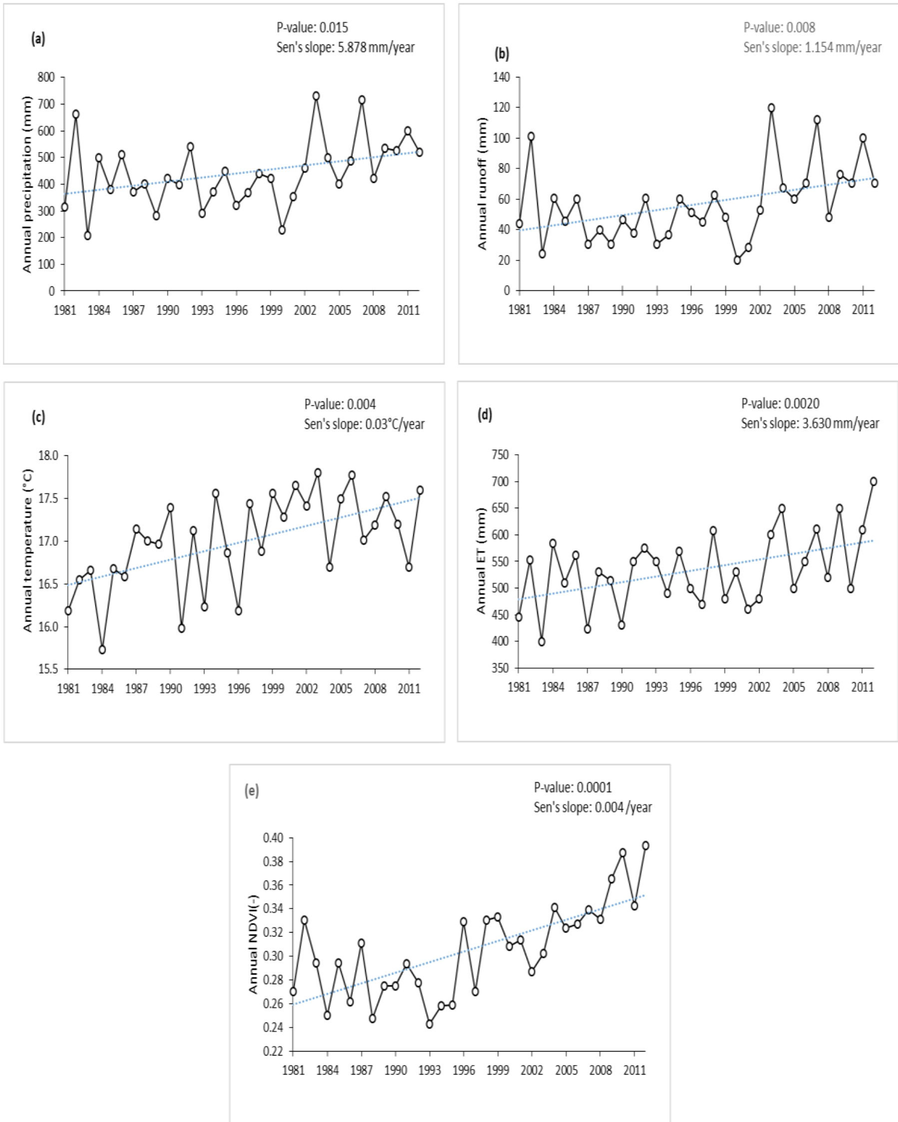

Figure 5.1: Results of the MK trend analysis (SL=0.05) applied to the annual precipitation (a), streamflow (b), annual temperature (c), mean annual evapotranspiration (d), and NDVI (e)

5.4 CCM Analysis

The assessment of the causal factors of streamflow based on Convergent Cross Mapping is shown in Figure 5.5. In the CCM method, the cross-map skill or forecast skill denoted by ϱ value is defined by calculating Pearson's correlation coefficient between predictions and observations values, and the length of the library (L) refers to the number of observations of the time series. The causality is thus detected when ϱ substantially increases with the increasing L. As shown in Fig. 5(a-d), for these four relationships, the correlation coefficient (ϱ) increased with the length of the library (L) to a plateau value and converged around L 100, confirming significant causal effects of P on Q, NDVI on Q, ET on Q, and T on Q, respectively.

In Figure 5.3a, the application of the CCM method between P and Q shows convergence with increasing library length (L), suggesting a causality link from P to Q (ϱ = 0.70), which confirms that cross-mapping of P from Q detects that P generates Q. Taking the trend analysis into account, it is confirmed that precipitation has a positive influence on streamflow. Also, the precipitation shows similar behavior with streamflow, wherein increase in annual streamflow. In this case, increasing precipitation in the basin is more likely to cause high streamflow, which results in even more water resources.

Furthermore, the result shows clear evidence of convergence for NDVI cross-mapping the streamflow (Q), with ϱ = 0.20 (Fig 5.2b). Thus, the CCM method detected that Q is causally driven by NDVI, which means that vegetation cover influences the streamflow change. The increase in annual NDVI was also detected by the trend analysis (see section 5.3.1). Yet the cross-correlation is weaker as compared to the cross-correlation of the precipitation. The causal link between NDVI and Q could be due to a confounding effect between the increase of precipitation and NDVI, as well as to the expansion of the irrigated area (from 10,000 ha in 1985 to 95,000 ha in 2012 (MADR, 2018)) during the period 1985-2012. The increasing precipitation influences positively streamflow generation, resulting in excessive available water for irrigation in the basin.

Our results suggest that temperature (T) and evapotranspiration (ET) are also causal drivers of streamflow (Q). We can see that forecast skill (ϱ value) substantially improves as library length increases (L). The correlation coefficient (ϱ value) reaches 0.71 for ET and 0.76 for T, with a clear convergence of the curve, indicating the presence of a significant causal effect of temperature (T) and evapotranspiration (ET) on streamflow (Fig 5.2c, Fig 5.2d).

Over the whole period (1981-2012) of the trend analysis, the streamflow has increased whereas evapotranspiration (ET) and temperature over the catchment have also increased. This is due to the increase in natural vegetation cover and the increase in agricultural land, expressed by NDVI. The results of the CCM indicate that the increase in streamflow during 1981-2012 is attributed to the increase in rainfall regime, T, ET, and NDVI. We further tested whether the correlation in the CCM method was consistent. The correlation coefficients between predicted and observed causal factors in the unfolded manifold were estimated by using a combination of statistical tests, namely Pearson's correlation, Kendall’s test, and Spearman's rho (Table 5.1)

Table 5.1: Results of the statistical tests for the significance of the correlation coefficient (ϱ) of the causal factors affecting the streamflow in the Isser catchment.

Catchment	CCM test		Correlation tests					
	Causal links	Rho value(ρ)	Pearson's correlation test		Kendall's τ test		Spearman's rho test	
			Correlation	p-value	Correlation	p-value	Correlation	p-value
Isser	P-Q	0.701	0.702	2.20E-15	0.562	2.20E-15	0.689	2.20E-15
	ET-Q	0.710	0.762	2.10E-15	0.579	2.10E-15	0.751	2.10E-15
	T-Q	0.760	0.715	2.20E-16	0.589	2.10E-15	0.702	2.10E-15
	NDVI-Q	0.200	0.209	1.09E-06	0.135	1.40E-03	0.191	1.56E-04

Results show that all correlation coefficients for precipitation, evapotranspiration, and temperature were statistically significant with p-values lower than 0.05 (Table 5.1). For NDVI, the result is not clear, despite a lower correlation value that is statistically significant. Additionally, the correlation coefficients estimated by Pearson's correlation test and Spearman's rho, are relatively similar. Based on these findings, we can conclude that the estimated correlation between observed and predicted values of the causal factors in the reconstructed shadow manifold are statistically significant and linearly related.

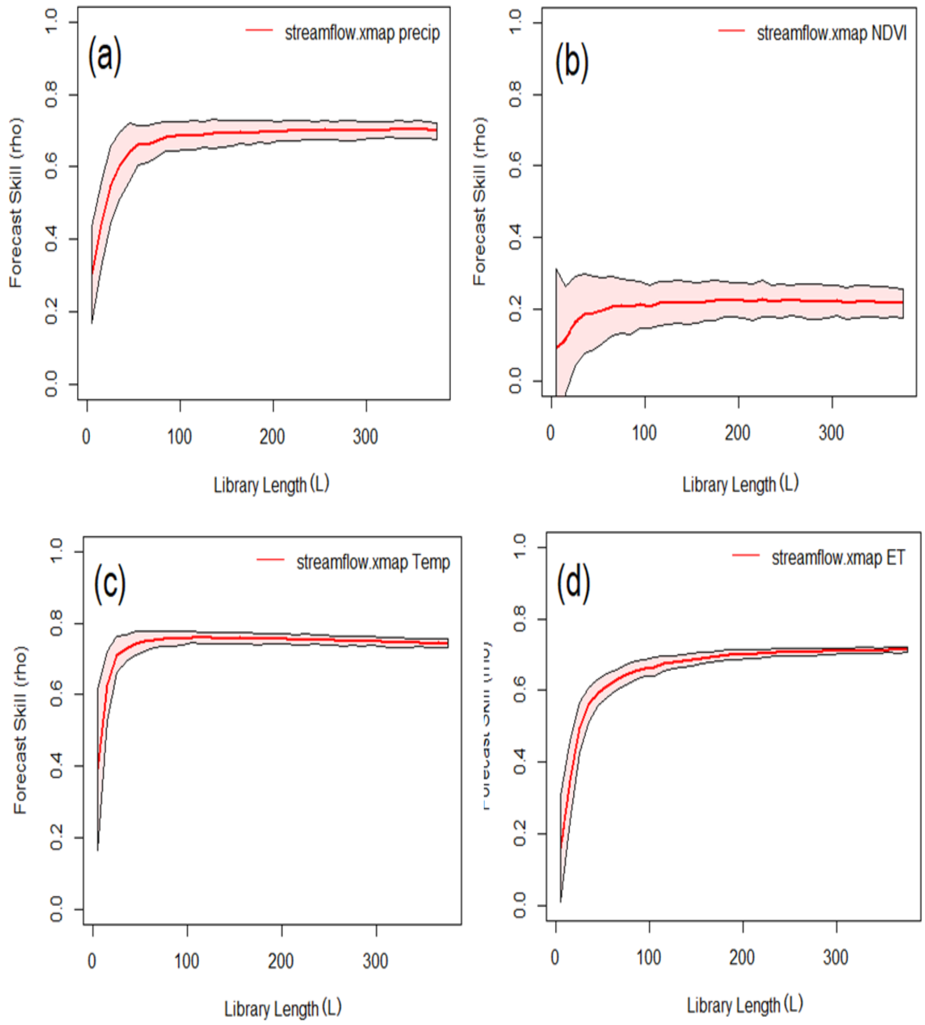

Figure 5.2: CCM results to demonstrate the causality between meteorological factors, NDVI, and streamflow. L: the length of the time series. X xmap Y stands for convergent cross mapping Y from X, in other words, the causality influence of variable Y on X. For instance, streamflow xmap precipitation stands for the causality influence of precipitation on streamflow. Shaded areas indicate 95% confidence interval.

5.5 Conclusion

In this study, we applied Mann-Kendall (MK) test to analyse the temporal variation and to assess the hydrological alteration of streamflow and its possible underlying causes for the Isser catchment in Algeria. The nonlinear time-series Convergent Cross Mapping analysis tool (CCM) was used to assess causal relationships and the contribution of different factors on the streamflow alteration, which generally have significant impacts on the hydrologic process and vegetation dynamics. The main conclusions of this study are summarized below:

The trends in annual streamflow (Q) were found to increase significantly over the Isser basin during 1981-2012 with a magnitude of 1.154 mm/ year. The precipitation revealed also a significant increasing trend with a magnitude of 5.878 mm/year. The trends of possible explanatory factors were also assessed. The trends in T, ET, and NDVI, were respectively 0.030 °C/year, 3.630mm/year, and 0.004/year, respectively.

The causality analysis using the CCM method revealed significant causal relationships between P-Q, NDVI-Q, T-Q, and ET-Q with the cross-map skill of 0.70, 0.20, 0.76, and 0.71, respectively. The causal link between P, T, ET, and NDVI on Q was confirmed. For the Isser catchment, climatic factors, especially precipitation, are the main factors that influence streamflow. However, it was also revealed that NDVI affects streamflow through evapotranspiration and temperature. It was further shown that the results of the linear correlation analysis between predicted and observed causal factors in the unfolded shadow manifold are statistically significant.

6

Hydrologic alteration and analysis of the causal relationships in the Macta basin, Algeria

Abstract

EXPLORING the intensity and potential causal factors of streamflow alteration is an important hydrologic challenge. A better understanding of these causal factors may improve the conceptual models that underpin sustainable water management. In this research, we implemented a Mann-Kendall trend analysis for exploring streamflow alteration and trends in possible causal factors (precipitation, evapotranspiration, temperature, and Normalized Difference of Vegetation Index (NDVI)) for the sub-catchment of Macta, north western Algeria for the period from 1981 to 2012. In addition, the Convergent Cross Mapping method was used to identify and quantify the causal relationships of the different drivers on the alteration of streamflow. The results of the trend analysis indicated that streamflow exhibits a downward trend as well as precipitation. The analysis of potential drivers using the CCM method detects that the streamflow is causally influenced by climate and human variables. It reveals that alteration in precipitation is a causal factor of the change in streamflow, while anthropogenic influences accounting for irrigation, water abstraction, and extension of agriculture areas play a significant role in streamflow variation. The increase in vegetation cover and higher evapotranspiration rate, caused by the increase in air temperature, could have contributed to the decrease in streamflow.

6.1 Introduction

THE relevant role of climate change and human activities on streamflow alteration is widely recognized, particularly in the Mediterranean areas. Several studies suggest that recent alterations in precipitation patterns and the contemporaneous increase of temperature have led to a high intensification of evapotranspiration with a consequent alteration of streamflow, causing significant pressures on water resources. In addition, anthropogenic pressure drivers such as land use, agricultural developments, and increasing population have been identified to drive important streamflow alteration. The concurrent increase in water extractions for various needs (irrigation, population, industry) would decrease water availability and access, which could induce water scarcity. Their influence should be carefully explored and separated from the climatic one. However, disentangling climatic and anthropogenic factors on hydrological fluxes is a challenging task since they combine in a complex nonlinear manner (Sharma et al. 2019; Yan et al., 2018; Yang et al., 2018).

Most of the available research has explored trends in many catchments in streamflow, precipitation, evapotranspiration, and temperature separately without inferring causal relationships between hydrological components and human activities. Therefore, exploring streamflow changes at the catchment scale in the Mediterranean area as well as their driving factors remains important to understand the mechanisms of generation of streamflow and to assess their multiple and concurring causes of human activity and climate variability (Zhang et al., 2021).

The assessment of the causal relationships and the contribution of different factors on streamflow alteration using linear statistical approaches in time series remains unclear due to their complex interaction and nonlinear pattern. Linear statistical approaches, such as correlation analysis, can effectively translate the time series association between input factors but the correlation is inadequate for inferring the causal relationships as well as incapable to capture nonlinear features hidden between them (Nauta et al., 2019). Although the correlation is symmetrical, it can occur without causation, and causation could also occur in the absence of correlation. By contrast, causation is particularly asymmetrical and consequently gives the directionality of a relation between them (Nauta et al., 2019). Here, we apply the Convergent Cross Mapping, a bivariate method of the Empirical Dynamic Modelling (EDM) framework, which is specifically designed for analyzing causal links between two-time series data with underlying nonlinear dynamics (Sugihara et al., 2012).

In this context, we aim in this research to assess the causal factors of streamflow alteration at the scale of the Macta sub-catchment using the CCM approach. The Macta river basin is an important catchment in water-limited regions of western North Algeria. The Macta sub-catchment has experienced several droughts and is highly impacted by water scarcity due to pressures and high spatiotemporal variability in rainfall and multiple conflicting water uses on its water resources.

To reach this aim, we first conducted statistical trend analysis (see e.g., Mann, 1945, Kendall, 1975) on the hydro-meteorological variables aggregated at the catchment scale. The comparison among observed trends allowed the detection patterns of alterations and the identification of the possible associated drivers' effects on the streamflow component. Subsequently, CCM causality analysis was applied to identify the attributed causal relationships between alterations in streamflow and possible concurrent underlying drivers (P, T, ET, and NDVI).

6.2 Material and methods

6.2.1 Study area

A detailed description of the study site is in chapter 3, section 3.2.1

6.2.2 Data sources

A detailed description of the data collection is in chapter 3, section 3.2.2

6.2.3 Trend Analysis: The Mann-Kendall (MK) Test

A detailed description of the Mann-Kendall (MK) test in chapter 3, section 3.2.3

6.2.4 Convergent Cross Mapping (CCM)

A detailed description of the Convergent Cross Mapping (CCM) method is in chapter 3, section 3.2.4

6.3 Results and discussion

6.3.1 Trend detection analysis

The trend analysis was performed on the meteorological and hydrological variables time series, precipitation (P), streamflow (Q), temperature (T), evapotranspiration (ET), and NDVI using time series of mean annual data. The Mann-Kendall test results of the Macta sub-catchment are presented in Figure 6.1. The result in Figure 6.1a shows that the annual rainfall decreased significantly ($P<0.05$) from 1981 to 2012. The trend magnitude through Sen's slope estimator yields -2.112 mm/year across the whole basin. These results are in agreement with Elouissi et al. (2016) who detected similar decreasing trends of precipitation in the northern part of the Macta basin (Algeria) using the innovative trend analysis (ITA) method over the period 1970-2011 with 25 rain gauges. The same decreasing trend had also been detected by Hamlaoui-Moulai et al. (2013) in most of the investigated rainfall stations for the period 1914 to 2004 by using the Mann-Kendall test. However, Baahmed et al. (2015) detected no significant trends in annual rainfall in the 1975-2005 period with 15 rain gauges in the same basin using Mann-Kendall. More Recently, Berhail et al. (2021) found the same results in the Macta basin using time series of rainfall data for 42 years (1970-2011) from 40 rainfall stations using Mann-Kendall (MK) test and the Innovative Trend Analysis (ITA) method. They detected decreasing trends in the northern part of the Macta basin which is in proximity to the Mediterranean coastal area. Also, Meddi et al. (2010) detected a decrease of at least 20% in total annual rainfall in five stations in the Macta basin from 1950 to 2004. Overall, most studies indicate a substantial decrease in rainfall regime despite the different lengths of time series. According to the authors, the decreasing trends of the precipitation regime in the western part of Algeria are due to the influence of the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO). The NAO and MO show a significant correlation with the precipitation in winter. The correlations are negative, likely because NAO and MO were in a strongly positive phase since 1979, which resulted in a decrease in the precipitation regime and severe droughts that impacted negatively the hydrologic regime (Djebbar et al., 2020; Taibi et al., 2017a). In addition to the atmospheric circulation pattern, the contrasting topography could be another factor explaining the observed decrease.

Figure 6.1b shows a negative trend with a significant decrease for the annual Q over the period 1981-2012 at the scale of the Macta catchment. The trend magnitude assessed using the Sen's slope yields -0.107 mm/year, suggesting the dependence of streamflow on the rainfall regime. We observe that the hydrologic regime variability of the Macta river is consistent with the climate variability of the region. Therefore, the similar pattern between the negative trends of P and Q suggests that the change in P contributes to the decrease of the river flow. Previous studies over the same catchment detected a similar trend. Baahmed et al., (2015) found a downward trend in annual streamflow from 1975 to 2005. According to Achite et al. (2017), the decreasing streamflow in rivers crossing the study area during recent decades is related to drought events that have affected northwestern Algeria since the mid-1970s, which is closely related to the teleconnection indices. As shown in Figure 6.1c, a significant positive trend is observed for the temperature during the period 1981-2012 in the study area, with a magnitude of about 0.046 °C/year. Our results are in agreement with other studies over the same basin and neighboring catchments in the north-western part of Algeria (see e.g. Baahmed et al., 2015, Hadour et al., 2020). Additionally, the evapotranspiration (ET) analysis reveals a significant rising trend at the annual scale. The Sens's slope confirms that the ET has increased by about 6.501 mm/year (Fig 6.1d). The increasing trend of yearly evapotranspiration (ET) is mainly due to the increase of temperature in north western Algeria.

Figure 6.1e shows the yearly NDVI at the scale of the Macta catchment for the period 1981-2012. It follows a significant increasing trend. The trend magnitude reaches 0.005/ year (Fig 6.1e). As stated by Baahmed et al. (2015), the positive NDVI trend is mainly attributed to human activities such as the extension of farmlands and water withdrawal for irrigation.

The irrigation sector in the western region of Algeria is a major consumptive water user accounting for more than 50% of the total water consumption in the region (MADR, 2018). The irrigation water is abstracted from the river as well as groundwater resources. However, groundwater pumping activities have also increased significantly due to demographic growth as well as the increase of demand for irrigation. Irrigation methods in the area are still majorly based on traditional irrigation, which includes flood irrigation and furrow. Water-saving irrigation schemes such as sprinkler and mulched drip irrigation are less used (MADR, 2018).

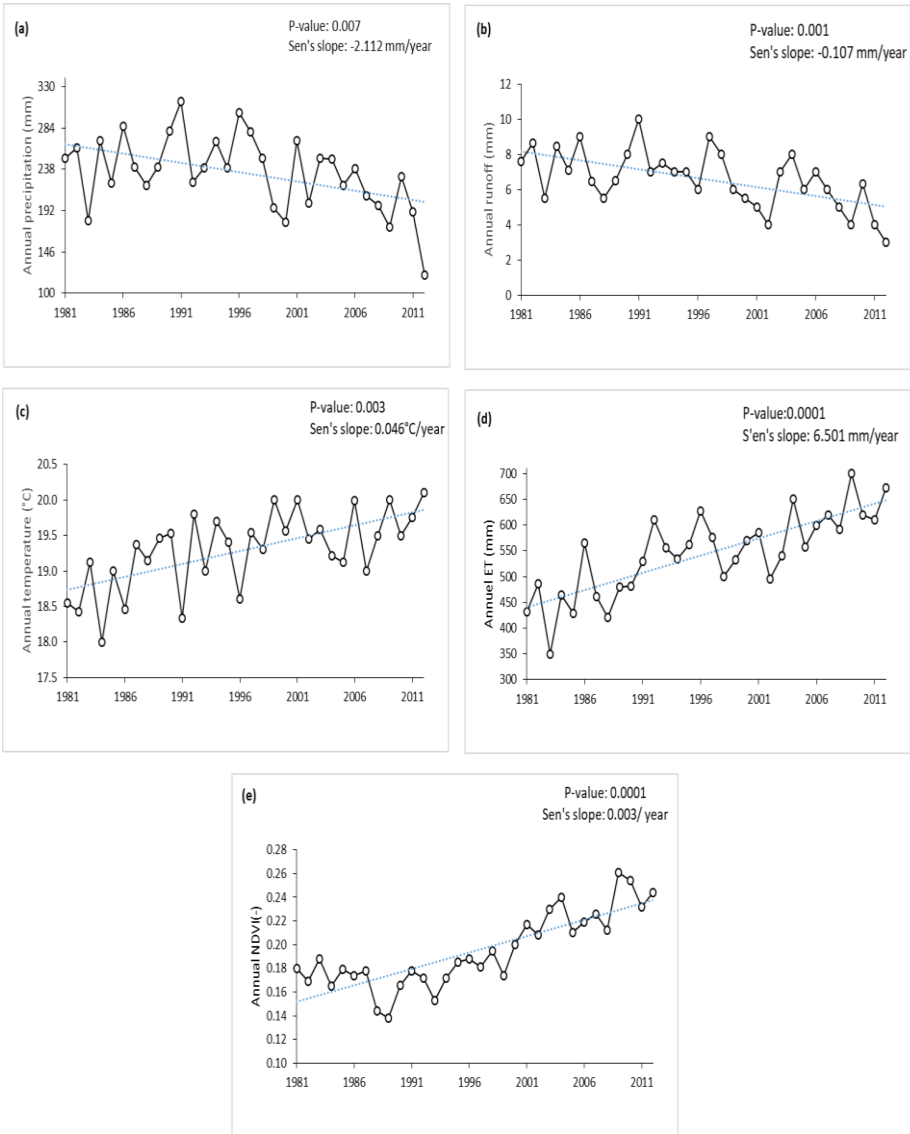

Figure 6.1: Results of the MK trend analysis (SL = 0.05) applied to the annual precipitation (a), streamflow (b), annual temperature (c), mean annual evapotranspiration (d), and NDVI (e).

6.3.2 CCM analysis

The CCM method was used to explore the causal relationships of P-Q, NDVI-Q, ET-Q, and T-Q, respectively. The cross-map skill or forecast skill denoted by ϱ value is defined by calculating Pearson's correlation coefficient between predictions and observed values on the reconstructed manifolds, and the length of the library (L) refers to the number of observations of the time series. Causality by the CCM method is detected if ϱ substantially increases with the increasing length library (L). As illustrated in Fig. 6(a-d), for these four relationships, the correlation coefficient (ϱ) increased with the length of the library (L) and converged around L 100, suggesting significant causal effects of P on Q, NDVI on Q, ET on Q, and T on Q, respectively.

The forecast skill converges to ϱ= 0.76, from P to Q (Fig. 6.2a) This supports the trend analysis showing that the precipitation trend is consistent with the streamflow trend. In this case, decreasing precipitation in the basin is very likely to cause low streamflow, which results in low water resource availability.

Furthermore, the result shows a convergence of the cross-mapping between NDVI and streamflow (Q) with the forecast skill ϱ = 0.35 (Fig 6.2b). Thus, the CCM method detected that Q is causally driven by NDVI, which means that vegetation cover influences the streamflow change.

The increase in annual NDVI detected in the studied area by the trend analysis could be a due to significant increase in irrigated lands. Since the year 1985, the agriculture areas have increased from 10,000 ha to reach 50,000 ha in 2012 (MADR, 2018). This fast increase is a result of a high irrigation demand, which contributes to the overexploitation of the available water resources. About 70% of the groundwater of the Macta aquifers was overexploited as well as the surface waters (MRE,2013). This critical situation negatively impacts the availability of water resources and indicates the dependence of irrigation on the hydrological regime of the Macta river.

The results also suggest that temperature (T) and evapotranspiration (ET) contribute as causal drivers to streamflow (Q). We can see that forecast skill (ϱ value) substantially improves as library length increases (L). The correlation coefficient (ϱ value) reaches 0.60 for T and 0.68 for ET, with a clear convergence of the curve, indicating the presence of a significant causal effect of temperature (T) and evapotranspiration (ET) on streamflow (Fig 6.2c, Fig 6.2d). Vegetation cover growth seems to be more dependent on P, T, and ET. One possible explanation for the causal links of T and ET on streamflow reduction is that the expansion of irrigated lands in the catchment correlates well with the high demand for irrigation, indicating that human activities are the most important drivers affecting the streamflow decrease. For the period from 1981 to 2012, evapotranspiration increased. This increase is consistent with the increase of irrigated lands as well as the increase of irrigation demand which implies an increase in the excessive withdrawal of groundwater resources and surface waters under the rising of the air temperature. As a result, the streamflow decreased. Furthermore, statistical tests were used to examine whether the cross-map skill ϱ for the causal links is significant, including Pearson's correlation test, Kendall's test, and Spearman's rho test. Statistical significance was observed for the correlation coefficients, with p-values below 0.05 for precipitation, evapotranspiration, and temperature (Table 6.1).

Table 6.1: Correlation tests to examine the significance of the causal relationships

Catchment	CCM test		Correlation tests					
	Causal links	Rho value(ρ)	Pearson's correlation test		Kendall's τ test		Spearman's rho test	
			Correlation	p-value	Correlation	p-value	Correlation	p-value
Macta	P-Q	0.760	0.761	2.20E-15	0.595	2.20E-15	0.755	2.20E-15
	ET-Q	0.680	0.681	2.20E-15	0.433	2.20E-15	0.678	2.20E-15
	T-Q	0.601	0.603	2.20E-16	0.493	2.20E-15	0.591	2.20E-15
	NDVI-Q	0.340	0.351	1.09E-06	0.269	1.31E-03	0.332	1.53E-04

In the meantime, the results for NDVI are not clear, although the correlation value is lower but statistically significant. Accordingly, we can infer that there is linearity between observed and predicted values of the causal factors on the unfolded manifold.

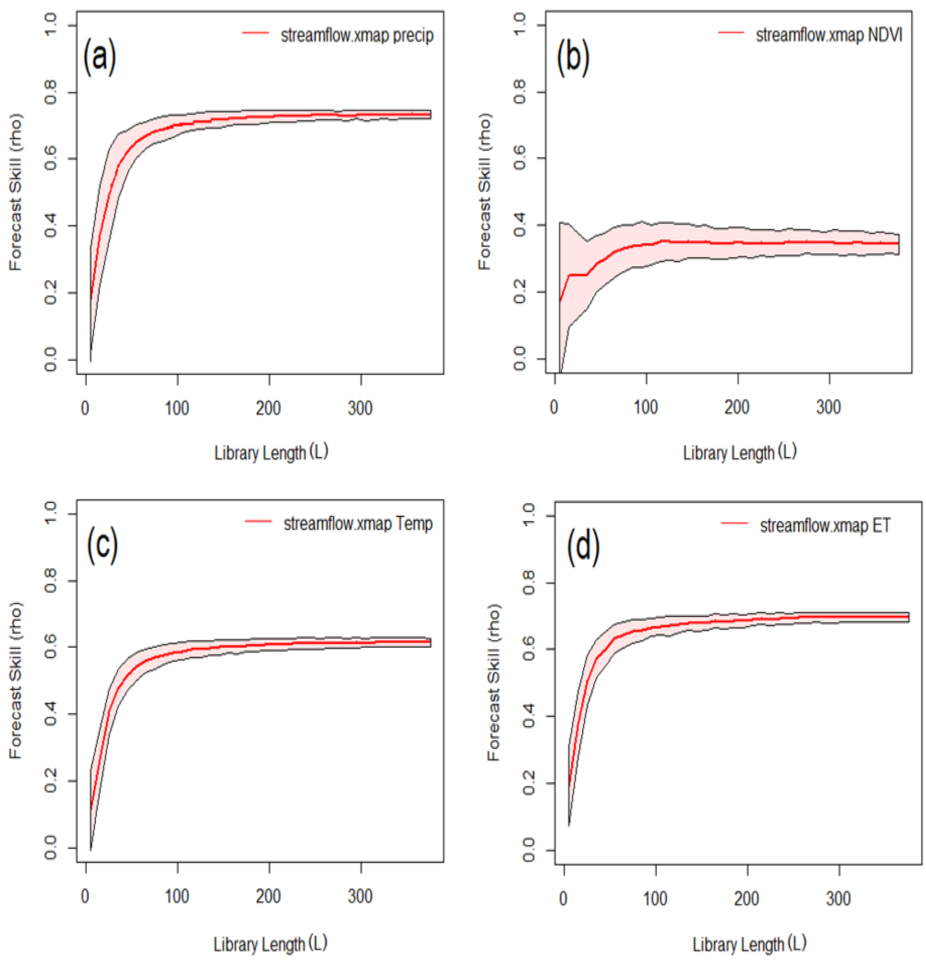

Figure 6. 2: CCM results to demonstrate the causality of meteorological factors and NDVI on streamflow). L: the length of time series. X xmap Y stands for convergent cross-mapping Y from X, in other words, the causality influence of variable Y on X. For instance, streamflow xmap

precipitation stands for the causality influence of precipitation on streamflow. Shaded areas indicate 95% confidence interval.

6.4 Conclusion

In this research, we implemented a Mann-Kendall trend analysis for exploring stream flow alterations and trends in possible causal factors for the Macta catchment in north western Algeria for the period from 1981 to 2012 and we used the Convergent Cross Mapping method to identify and quantify the causal relationships of different drivers on the alteration of streamflow. The key findings of the study are summarized below.

First, the mean annual rainfall in the region during the considered period experienced a significant decrease that potentially impacts streamflow. On the other hand, air temperature, as well as evapotranspiration, have increased during the same period, which may also contribute to explain the decrease in streamflow. Climate change is not the only factor affecting streamflow variability, as other human-caused drivers may also play a major role.

In the second part, the CCM causal detection analysis has been used to demonstrate the causal links between streamflow and precipitation, temperature, evapotranspiration, and NDVI. The CCM method revealed complex interaction and causal relationships between the climatic factors and human activities on streamflow decrease. The CCM test demonstrated significant strong causal relationships between the climatic factors and streamflow, as well as the NDVI. It is apparent that the agricultural area in the basin has increased considerably over the period. This increase in agricultural land has led to intensive extraction of water, which might have further played a critical role in intensifying the decline of streamflow.

Increased water pumping in the catchment is also likely to be a contributing factor to the reduced streamflow, but the lack of data on water withdrawal makes this difficult to confirm on a statistical basis. The change in seasonal climate patterns, particularly winter rainfall, may also have influenced the decrease in streamflow.

These findings are helpful to elucidate the complexity involved in streamflow change and will enable the evolution of streamflow to be predicted under changing climate scenarios. Moreover, our research has important implications for planning and operational strategies concerning the sustainable use of available water resources.

7

Inter-comparison of hydroclimatic regimes across Mediterranean catchments

Abstract

WATER security is a major issue in semi-arid and arid regions, which are impacted by important anthropogenic land use changes and climatic changes. The present research explores the long-term changes in streamflow and their associated causal factors for a climatically sensitive region in northern Algeria. The gradual changes in streamflow and the climatic factors have been detected over the period 1981-2012 using Mann- Kendall, and Sen's slope estimator tests respectively. The streamflow and precipitation analyses revealed heterogeneity across the catchments. The streamflow exhibited predominantly decreasing trends in the Medjarda and Macta catchments, except in the Isser basin. The Convergent Cross Mapping method revealed that the decreasing trends in streamflow are largely attributed to climatic factors (precipitation, temperature, evapotranspiration) and anthropogenic activities such as an increase in agricultural areas, excessive groundwater extraction, and streamflow from rivers. The results highlight that the impact of climate change and human activities on the Mediterranean catchments is multifaceted, and interconnected with the negative impacts of changes in water resources.

7.1 Material and methods

7.1.1 Study area

A detailed description of the study site is in chapter 3, section 3.2.1

7.1.2 Data sources

A detailed description of the data collection is in chapter 3, section 3.2.2

7.1.3 Trend Analysis: The Mann-Kendall (MK) Test

A detailed description of the Mann-Kendall (MK) test in chapter 3, section 3.2.3

7.1.4 Convergent Cross Mapping (CCM)

A detailed description of the Convergent Cross Mapping (CCM) method is in chapter 3, section 3.2.4

7.2 Results and discussion

7.2.1 Spatio-temporal characteristics of streamflow and precipitation

Trend analysis was computed at the annual time scale by using the Mann-Kendall test with the significance level set to 0.05 to detect significant changes in time-series records for streamflow and the associated driver variables (precipitation, temperature evapotranspiration, and NDVI). The resulting trends of the selected catchments namely the Medjerda, Isser, and Macta are shown in tables as follows:

Table 7. 1: Characteristics of annual precipitation and streamflow trends.

Factors	Catchments	Average (mm)	Mann-Kendall test	Sens's slope
Precipitation	Medjerda	341	Significant trend	-11.50 mm/year
	Isser	441	Significant trend	5.878 mm/year
	Macta	234	Significant trend	-2.112 mm/year
Streamflow	Medjerda	214	Significant trend	-6.770 mm/year
	Isser	56	Significant trend	1.154 mm/year
	Macta	7	Significant trend	-0.107 mm/year

The annual precipitation from 1981 to 2012 showed large spatial differences with average values of 341 mm in Medjerda, 441 mm in Isser, and 234 mm in Macta. The Mann-Kendall trend test showed that the Isser catchment observed a significant upward trend in precipitation ($p<0.05$) while a downward trend was found to be significant in Medjerda and Macta catchments, respectively. The Sen's slope values were -11.500

mm/year in Medjerda, 5.878 mm/year in Isser, and -2.112 mm /year in Macta.

The precipitation records were characterized by important interannual variability of annual rainfall, which could be explained by atmospheric circulation indices and a topographic gradient going from the west to the east. However, as reported by Djebbar et al. (2020) and Taibi et al. (2017), the absence of a significant correlation between the circulation indices (NAO, MO) and annual rainfall for the eastern part of Northern Algeria (Medjerda catchment) implies that other factors independent of climate affect rainfall variability of this region. The spatial-temporal variability of the rainfall regime is affected by topography, which is higher in the east than in the west. The amount of precipitation in north-eastern Algeria is higher than that in the north-western part of the country, a fact that could be accounted for by the more pronounced topography in the east. Most researchers have shown the importance of the east-to-west spatial variability of rainfall in Northern Algeria (Zerouali et al. 2020; Taibi et al. 2017b; Taibi et al. 2013). Topography plays a crucial role to influence climate variability at the regional to local scale by forcing the temporal and spatial distribution of rainfall. Furthermore, proximity to the sea also leads to higher rainfall like in the coastal areas. In the western part of Algeria, the North Atlantic Oscillation (NAO), and Mediterranean Oscillation (MO) index strongly impact winter precipitation and summer droughts (Djebbar et al., 2020). Some studies have shown that the MO and NAO indices particularly affect the variability of rainfall in the Mediterranean basin in the winter season (Djebbar et al., 2020;). The precipitation of the north-western portion of the Macta catchment may therefore significantly be correlated with the MO and NAO index, especially in the winter season (December-February). The observed correlations are negative because

NAO and MO indices have been in a strongly positive phase since 1980, which has resulted in a decrease in precipitation in the north western part. This can explain, at least in a part, the significant decrease in rainfall over the north western part of Algeria.

Also, the temporal characteristics of the annual average streamflow along the three catchments from 1981 to 2012 showed different variations in space and time with average values of 214 mm in Medjerda, 56 mm in Isser, and 7 mm in Macta (Table 7.1). The Mann-Kendall trend test showed that streamflow in the Isser catchment was observed to have a statistically significant increasing trend ($p<0.05$), while streamflow in Medjerda and Macta was observed to have a significant downward trend ($p<0.05$). The Sen's slopes in all of the areas except Isser catchment (1.154 mm/year) were less than zero, with the top two lowest values in Medjerda (-6.770 mm/year) and Macta (-0.107 mm/year). The detected decreasing and increasing trend for streamflow was in agreement with the conclusions of Khedimallah et al. (2020), Baahmed et al. (2015), and other researchers in the respective catchments (Medjerda, Isser, and Macta) that found a decreasing trend of streamflow with an increase in the frequency of droughts event. Severe droughts have been recorded after 1980 in both basins. In Algeria and Tunisia for instance, the drought of 1999-2002 was the worst since the 15th century due to critical rainfall deficits (Touchan et al., 2008).

Many possible factors may explain this spatio-temporal variability of streamflow in these catchments. First, the streamflow changes between catchments during the reference period (1981-2012) could be due to the dependence of the hydrometric regime on precipitation. The latter is conditioned by a Mediterranean climate variability affected by its high seasonality, with a minimum rainfall recorded in the winter precipitation. Second, the streamflow alteration could be attributed to changes in human activities such as irrigation demand, which varies between the study regions and depends on the climate conditions and increase in agricultural areas. Such factors may increase water abstraction from the river. Third, streamflow alteration could be due to other geographic features such as soil types. As reported by Atallah et al. (2016), the geology of the Macta catchment is characterized by the predominance of humic calcareous soils, which produce high permeability, leading to more infiltration and inducing a reduction in the streamflow.

7.2.2 Spatio-temporal characteristics of temperature and evapotranspiration

The average temperature from 1981 to 2012 showed an increasing spatial trend from east to west, with values of 16 °C in Medjerda, 17 °C in Isser, and 19 °C in Macta (Table 7.2). Temporally, all three areas exhibited upward trends in temperature (Table 7.2). The Mann-Kendall trend test showed that these upward trends were all significant, with p-values lower than 0.05. The value of Sen's slope was the highest in Macta (0.046 °C/year) and the lowest in Medjerda and Isser (0.030 °C/year) (Table 7.2). These findings at the annual scale agree with the conclusions found on temperature by Taïbi et al. (2022) in northern Algeria. They argued that this warming is mainly caused by an increase in the seasonal summer temperature. This warming has contributed to a long period of drought characterized by a significant decrease in precipitation and more evapotranspiration, negatively affecting the availability of water resources for drinking water supply and agriculture in Algeria (Taibi et al., 2022).

The annual average evapotranspiration (ET) showed spatial differences with average values of 562 mm in Macta, 534 mm in Isser, and 550 mm in Medjerda. (Table 7.2). The Sen's slopes in all of the areas were greater than zero, with the top two highest values recorded in Macta (6.300 mm/year) and Medjerda (3.770 mm/year). The Mann-Kendall trend test indicated also that annual evapotranspiration has a statistically significant increasing trend (p <0.05) in the selected areas (Medjerda, Iseer, and Macta). The evapotranspiration trend generally follows the air temperature trend. Moreover, it should be noted that the possible increases in evapotranspiration (ET) could be related to the development of irrigated lands and the expansion of agricultural areas in the last decades in the selected study sites.

Table 7.2: Characteristics of temperature and evapotranspiration trends.

Factors	Catchments	Average	Mann-Kendall test	Sens's slope
Temperature	Medjerda	16 °C	Significant trend	0.03 °C/year
	Isser	17 °C	Significant trend	0.03 °C/year
	Macta	19 °C	Significant trend	0.046 °C/year
ET	Medjerda	550 mm	Significant trend	3.770 mm/year
	Isser	534 mm	Significant trend	3.630 mm/year
	Macta	562 mm	Significant trend	6.30 mm/year

Several authors have explored the evolution of air temperature/evapotranspiration in the Mediterranean area (Algeria Tunisia, and Morocco). Tramblay et al. (2019) and Taibi et al. (2022) found that the temperature increased faster in the Mediterranean basins in north-west Algeria. These warming conditions are associated with an increase in the summer temperature. Similar results have been also detected by

Berhail et al. (2021), who identified that the Macta catchment is under an increase in temperature and evapotranspiration at annual scale. The same results have been detected in the western region of the Mediterranean (Morocco) under global warming, with significant increases in the summer season and spring (Sebbar et al., 2012; Ouhamdouch et al., 2019b).

7.2.3 Spatio-temporal characteristics of NDVI

At the annual scale, the average NDVI from 1981 to 2012 exhibited an increasing spatial trend from west to east, with values of 0.25 in Macta, 0.30 in Isser, and 0.32 in Medjerda (Table 7.3). The Mann-Kendall trend test showed also positive temporal trends of annual averaged NDVI that all were significant with p-values lower than 0.05. For NDVI, the value of Sen's slope was the highest in Isser (0.004/year) and the lowest in Medjerda (0.002/year).

Table 7.3: Characteristics of NDVI trends

Factors	Catchments	Average	Mann-Kendall test	Sens's slope
NDVI	Medjerda	0.32	Significant trend	0.002 /year
	Isser	0.30	Significant trend	0.004 /year
	Macta	0.25	Significant trend	0.003/year

The results obtained using Mann Kendall and Sen's slope indicate a significant increase in vegetation cover (NDVI) which reflects plant productivity and forest with a distinct environmental gradient from east to west. The significant increasing trends of NDVI reported, in particular in the western catchment, are mainly attributed to anthropogenic activities. This is due to an increase in irrigation water and the rapid extension of irrigated lands. Agriculture is the main economic activity influencing the hydrological process. The water is abstracted from the rivers as the groundwater resources in the region, which are overexploited and therefore remain insufficient to support the local agricultural activities. The irrigation sector is a principal water consumer accounting for more than 50% of the total water consumption in Algeria. In the 3 considered catchments, irrigation methods are based on traditional irrigation, which includes flood irrigation and furrow. Water-saving irrigation schemes such as sprinkler and mulched drip irrigation are less used (MADR, 2018). The positive trend in the vegetation cover expressed by NDVI implies increased evapotranspiration (ET) (as a result of intensive or inefficient irrigation) in this period, over which the overall temperature trends remain increasing in the selected catchments.

7.2.4 The causal links

The causal links between streamflow (Q) and precipitation (P), evapotranspiration (ET), temperature (T), and NDVI for each catchment were explored by means of CCM.

Moreover, the results of the significance of correlation coefficients in this study ($p < 0.05$) were tested by using a combination of statistical tests, namely Pearson's correlation, Kendall's test, and Spearman's rho (Table 7.4). In the CCM method, the cross-map skill or forecast skill denoted by ϱ value is defined by calculating Pearson's correlation coefficient between predictions and observed values of causal factors on the unfolded shadow manifolds. It measures the strength of the causal link.

In the studied catchments (Medjerda, Isser, and Macta), climate variables predominantly drive streamflow as confirmed for instance by the causality link from P to Q. Over the past decades, the precipitation has decreased in the Medjerda and Macta catchment and increased in the Isser which directly is translated in streamflow alteration. For the causal link of precipitation-streamflow, the range of correlation coefficients varies from 0,79 in the Medjerda, 0,70 in the Isser catchment, and 0.76 in Macta (Table 7.4). Results show that all correlation coefficients supporting the precipitation-streamflow causal link were statistically significant with p-values lower than 0.05 (Table 7.4) and that these causal links were somewhat more important in the drying catchments.

Our results reveal that temperature (T) and evapotranspiration (ET) are also causal drivers of streamflow (Q) in the considered catchments, but their impact is slightly lower as compared to P. The forecast skill (ϱ value) is significant for ET with high positive values, which range from 0,60 in the eastern part (Medjerda), 0.71 in the Isser catchment, and 0.68 in the western part (Macta) (Table 7.4). Generally, the ET increases due to the increase of irrigated surface area. This is associated with an increase in the consumptive use of water (related to the irrigation and water diversion and storage developments in the watershed). This contributes to explain the decrease of streamflow from the Medjerda and Macta catchment. Similarly, there is a statistically significant causal link between temperature to streamflow, which is highly positive. The correlation varies from 0.79 in the Medjerda catchment, 0.76 in the Isser catchment, and 0.60 in the Macta catchment (Table 7.4).

We additionally found that NDVI contributes as a causal variable of Q (Table 7.4). The correlation values of the causal factors affecting the streamflow alteration estimated with Pearson's correlation and Spearman's rho test in three catchments are similar, which suggests that the observed and predicted values are linearly related (Table 7.4).

Table 7.4: Results of the statistical tests per study site to test the significance of the correlation coefficient (ϱ) of the causal factors affecting the streamflow alteration. The results indicate the significance of the cross-map skill ϱ, with p-value with p-values <0.05).

Catchment	CCM test		Correlation tests					
	Causal links	Rho value(ρ)	Pearson's correlation test		Kendall's τ test		Spearman's rho test	
			Correlation	p-value	Correlation	p-value	Correlation	p-value
Medjerda	P-Q	0.790	0.795	2.20E-15	0.643	2.20E-15	0.789	2.20E-15
	ET-Q	0.600	0.606	2.20E-16	0.434	2.20E-16	0.603	2.20E-16
	T-Q	0.790	0.801	2.20E-16	0.661	2.20E-16	0.791	2.20E-16
	NDVI-Q	0.201	0.203	1.09E-05	0.131	1.40E-03	0.192	1.53E-04
Isser	P-Q	0.701	0.702	2.20E-15	0.562	2.20E-15	0.689	2.20E-15
	ET-Q	0.710	0.762	2.10E-15	0.579	2.10E-15	0.751	2.10E-15
	T-Q	0.760	0.715	2.20E-16	0.589	2.10E-15	0.702	2.10E-15
	NDVI-Q	0.200	0.209	1.09E-06	0.135	1.40E-03	0.191	1.56E-04
Macta	P-Q	0.760	0.761	2.20E-15	0.595	2.20E-15	0.755	2.20E-15
	ET-Q	0.680	0.681	2.20E-15	0.433	2.20E-15	0.678	2.20E-15
	T-Q	0.601	0.603	2.20E-16	0.493	2.20E-15	0.591	2.20E-15
	NDVI-Q	0.340	0.351	1.09E-06	0.269	1.31E-03	0.332	1.53E-04

The forecast skill (ϱ value) of the causal link NDVI-Q is similar in the Medjerda and Isser catchments with a value of 0.20, and 0.34 for the Macta catchment which is much lower than the correlation strength for P, ET, and T. Yet, the lower correlation remains statistically significant (*p-value* < 0.05). NDVI is thus a driving factor explaining streamflow alteration but its strength is much lower as compared to P, T, and ET. NDVI is an environmental factor that rarely is reported in the literature as being a driver for streamflow alteration. In the Medjerda and Macta catchments, NDVI changes can be explained by an increase in vegetation cover. Irrigated areas have been found to increase (from 10,000 ha in 1985 to 40,000 ha in 2000, and from 40,000 ha to 60,000 ha in 2012) in the Medjerda, and from 10,000 ha to reach 50,000 ha in 2012 in the Macta catchment (MADR, 2018) during the period 1985-2012. Most of the cultivated plots are managed for growing cereals, fruit trees, vegetables, and olive groves. This drastic expansion in the agricultural area affects the streamflow directly due to excessive exploitation of the available water resources for irrigation. Hence, anthropogenic activities in form of land use changes and irrigation are contributing as drivers of streamflow changes. Similar results were also reported by Baahmed et al. (2015) while exploring the effects of climate change and human activities on the streamflow of the Macta basin in western Algeria. The authors argued that increased water pumping from aquifers influences the decrease of streamflow, the water use has increased considerably over the three past decades and the alteration in winter precipitation also has affected the decrease in streamflow. Also, evapotranspiration in irrigated crops can be 3 times higher than in rainfed crops (Salmoral et al., 2015). Therefore, the growth of irrigated land associated with the increase in temperature in the basin is very likely to contribute to changes in streamflow. Vicente-Serrano et al. (2019) highlighted that the expansion of irrigation agriculture in the Mediterranean basin since the 1960s and the increase in evaporative demand are the main causal factors explaining the reduction in streamflow.

The Isser catchment was also affected by the changes in land use (rapid expansion of irrigated lands (from 10,000 ha in 1985 to 95,000 ha in 2012 (MADR, 2018)), but this did not contribute to a reduction of streamflow. On the contrary, streamflow increased and the NDVI correlation with Q suggests that NDVI drives streamflow increase. This could be explained for instance by the fact that water withdrawals to meet irrigation requirements and domestic demands could be from groundwater origin rather than from surface water origin. Hence for a better understanding of the interaction of potential drivers of streamflow alteration, additional information on groundwater use would be needed. Unfortunately, these data were not available for the 3 studied catchments in Algeria.

7.3 Conclusion

i. In this research, the alteration of streamflow and its causal relationships were explored in a typical Mediterranean region for the following three basins: (i) the Medjerda upstream sub-catchment (north-east of Algeria), (ii) the Isser catchment (north-central of Algeria), and (iii) the Macta catchment (north-west of Algeria), respectively. The Mann-Kendall (MK) trend analysis and Sen's slope test were used to identify the temporal trends. The causal detection analysis was made using the nonlinear time series analysis tool, Convergent Cross Mapping (CCM). The changes in streamflow have been linked to possible climatic factors and/or anthropogenic activities at the catchment scale. The following conclusions can be made.
ii. The temporal trends in annual streamflow are found to decrease predominantly over the Medjerda and Macta catchments and to increase in the Isser catchment.
iii. The temporal trends in the annual precipitation varies also in space: precipitation trends in the north eastern part of the Medjerda catchment and the north western part of the Macta catchment are predominantly decreasing, while the central Isser catchment displayed an increasing trend.
iv. The decreasing trends in streamflow for the Macta and Medjerda catchment were largely attributed to climatic factors (precipitation, temperature, and evapotranspiration) and human activities such as

an increase in agriculture areas expressed by trends in NDVI. The impact of NDVI on streamflow alteration suggests to be much lower than the impact of climatic variability on streamflow alteration.

v. The increasing trends for the Isser catchment were also largely attributed to climatic factors, and, surprisingly, also to NDVI. The role of NDVI in streamflow alteration, in this case, is likely due to the fact that groundwater resources are used to support irrigation.

vi. Algeria is characterized by a semi-arid climate. The decreasing trends in rainfall, as well as streamflow as elucidated in the Medjerda and Macta catchment, could exacerbate the impact of droughts in the future. According to Djebbar et al. (2020), the frequency of meteorological and agricultural droughts in semi-arid countries like Algeria will rise considerably by 2050 and would account for 78% of increased water scarcity. Yet, the case of the Isser catchment shows that these types of conclusions cannot be generalized over the whole territory and that the impact of climate and land use change on hydrological fluxes needs to be studied at the smaller regional or local scale. This latter case shows also that the unraveling of causal factors of hydrological alteration is a complex problem, and that a detailed assessment of the groundwater dynamics should be integrated in future analysis of causality of streamflow alteration.

8

Conclusion and outlooks

8.1 Main achievements

To date, streamflow trends and their causal links with climate and human activities are not well understood in Algeria. Filling this gap is important because of many reasons:

First Algeria is a primarily semi-arid country with high climatic variability. Due to the particular position of Algeria in North Africa, its precipitation regime is characterized by high spatiotemporal variability from west to east. Conversely, the temperature variability is more uniform than the precipitation. It is over the winter seasons that both precipitation and temperature vary the most. Most of the climatic studies in Algeria have focused on studying precipitation variability and classifying the country into different climatic regions, trend detection in the observed climatic data, and studying the large-scale atmospheric circulations and their linkages with the local climate.

Second, most of the Algerian major rivers are vulnerable to climate change and human influences with potentially adverse subsequent impacts on agriculture and the environment in the country. Exploring the fundamental questions on the nature and scale of the alterations in hydroclimatic time series and water availability is critical for informed water management and adaptation. Therefore, the major goal of this Ph.D. thesis is to understand the complex hydrological pattern of the drivers of streamflow changes in semi-arid catchments in various space and time dimensions. Previous research has shown that a large part of the spatial and temporal variability of streamflow is closely related to precipitation variability. In addition to this standard factor, particular attention is paid to identifying, assessing, and analyzing long-term trends of other possible drivers of streamflow alteration, in particular those related to land use change. To achieve this goal, the non-parametric Mann-Kendall (MK) and Sen's slope tests were applied to analyze the trends and the magnitude of the time series of streamflow and the selected factors such as rainfall, temperature, evapotranspiration, and NDVI. Trends have been assessed at 5% significance to detect whether the hydroclimatic conditions have changed and hence impacted the hydrology of the selected basins. Subsequently, the study attempted to assess the causal factors of streamflow variation, which were addressed using the Convergent Cross Mapping (CCM) method. The Convergent Cross Mapping method (CCM) is a bivariate method that can particularly map the complex nonlinear relationship between input factors and streamflow in studied catchments. We implemented this methodology systematically for three Algerian catchments from north-east to north-west across a hydroclimatic gradient.

In chapter 4, we investigated available records of hydro-climatic and vegetation variables (P, T, ET, and NDVI) for the north eastern Medjerda catchment during the 1981-2012 period. The results of the trend analysis of rainfall and streamflow detected a significant decreasing trend. The temperature, evapotranspiration, and NDVI also showed statistically significant increasing trends. In addition to trend analysis, we performed a causal analysis of possible explanatory factors on streamflow change using the Convergent Cross Mapping method. Results showed that climatic factors (P, T, ET) and vegetation cover (NDVI) together alter significantly the streamflow regime.

Based on the correlation strength in the CCM analysis, we concluded that direct climatic factors, especially precipitation, are the main factors that influence streamflow alteration. Furthermore, increased agricultural crop transpiration and thus total ET, associated with the human-driven increase in vegetation cover (inherently including irrigation, and expansion of land use), lead also to a decreased streamflow from the watershed. Yet, given the correlation strength in the CCM analysis, it is suggested that this is rather a secondary effect. The impact of vegetation cover expansion on water availability in the watershed may be further investigated based on additional data for changes in the total water balance of the catchment, considering all main water fluxes and storage changes. In this regard, we suggest to analyse more in detail the role of groundwater in this hydrosystem. The study results are consistent with the research of other parts of the world in indicating landscape changes in human land use and water use as main drivers of streamflow alteration (Jaramillo and Destouni 2015; Destouni et al. 2013). Those studies have also shown that, additionally, climatic factors (P, T, and ET) may intensify or dampen water changes, such as decreasing streamflow, relative to those driven by land/water use.

In Chapter 5, a similar analysis is made for the Isser catchment in the north-central part of Algeria. The Isser basin faces a notable increase in the streamflow regime, as well as the precipitation, temperature, evapotranspiration, and NDVI. The results demonstrate that the rainfall and streamflow behave in the same manner suggesting that precipitation is a dominant contributor to streamflow. However, agricultural developments in this area, particularly regarding the increase of water use for irrigation and the rapid expansion of irrigated lands, have not affected the water availability in the catchment in terms of streamflow, which was found to increase during the study period. In addition, a significant causality between T-Q, ET-Q, and NDVI-Q was detected with cross-map skill between 0.30 and 0.79, which supports the assertion that NDVI affects streamflow through evapotranspiration and temperature.

In Chapter 6, the hydrological alteration of streamflow and its causes were explored for the Macta catchment (North-West of Algeria) Results of the Mann-Kendall-based trend analysis have shown that the streamflow, as well as precipitation, was associated with significant downward statistically significant. Conversely, the other variables were associated with significant upward alterations within the basin. The evapotranspiration increased significantly in the basin, as a result of an increase in temperature. This increase could also explain the streamflow reduction. The increase in vegetation cover (NDVI) is related to the expansion of irrigated lands and the volume of water withdrawn. Results of the causality analysis using the CCM method revealed that precipitation, temperature, evapotranspiration, and NDVI have a significant causal effect on streamflow. Despite the important effect played by direct climatic factors on streamflow variability, especially precipitation, temperature, and evapotranspiration, many other human activities, mainly agricultural development, and irrigation may account for a reasonable proportion of decreasing streamflow in the Macta river. Increased water withdrawal by pumping from aquifers may also influence the alteration of streamflow. The water demand mainly from the irrigation and domestic sectors has probably increased considerably over the study period. The change in seasonal climate patterns particularly winter rainfall may also have affected the decrease in streamflow.

In the last chapter of the thesis, the inter-catchment comparison of the flow regime and the potential causal drivers between the Medjerda, Isser, and Macta rivers in the semi-arid area, of Northern Algeria was conducted. The results illustrate distinct temporal and spatial patterns differentiated between the catchments depending on climate variability and human influences. Different alterations are detected in the streamflow time series:

i) a reduction of streamflow for the Medjerda and Macta catchment; and ii) an increase in streamflow for the Isser basin. This goes hand in hand with i) a decrease in rainfall regime observed in the Medjerda and Macta catchment, and ii) a positive precipitation trend for the Isser basin. The trends of the other concurrent explanatory factors at the annual scale are positive but exhibit some regional differentiation. For example, the temperature trend varies from the Medjerda to the Macta catchment.

The causality analysis using the CCM method shows that causal factors of streamflow alteration were similar for the Medjerda, Isser, and Macta catchments. The changes in streamflow have primarily been linked to the variability of precipitation, which seems to be an important climatic factor, and/or anthropogenic activities at the catchment scale, given that basins are impacted by agricultural activities such as the expansion of the agricultural areas. The precipitation during the studied period is conditioned by a Mediterranean climate variability affected by its high seasonality, with a minimum rainfall recorded in the winter season. The spatial distribution of rainfall shows a significant heterogeneity going from west to east. The role of land use change is less obvious. It is evident that agricultural area in the basin has increased considerably over the period in the selected catchments. The increase in the agricultural area has therefore increased irrigation water requirements in the basin, which often reduces surface water availability and therefore streamflow. But, such a significant increase in agricultural land, has also conducted to excessive extraction of groundwater. Groundwater extraction might have reduced the impact of irrigation expansion on the availability of streamflow, but this could not be demonstrated in detail since the information on groundwater extractions was not integrated with the CCM analysis.

The streamflow alterations could also be attributed to the geology of each region. As reported by Attallah et al (2016), the geology of the Macta catchment is characterized by the predominance of humic calcareous soils, which produce high permeability, inducing more infiltration and resulting in a reduction in the streamflow.

We conclude that streamflow alteration remains a complex process and that the attribution of hydrological trends to their causes should be made with caution and need to be supported by compelling evidence. In this work, attempts have been made with the CCM methodology for attributing anthropogenic and climatic factors to streamflow alteration, but the methodology suffers from some weaknesses. First, limited coverage and the density of hydro-climatic data across the basins may have introduced some uncertainties in the results. Second, we assessed the impact of anthropogenic activities on streamflow through the ET and NDVI, which is considered a proxy for irrigation development. Yet ET and NDVI change can also be impacted for instance by changes of crop management strategies. Third, it is suggested that groundwater could play a complementary role to mitigate to water scarcity and reduce the impact of scarcity on streamflow alteration. However, detailed data on groundwater use in the studied catchments was not introduced in the CCM analysis. Fourth, the CCM analysis suffers from some methodological issues. As it is a bivariate method, it is not easy to discriminate the role of different potential causal factors if the correlation strength with increasing library length during the cross-mapping is similar. The findings of this research highlight the fact that the selected catchments (the Medjerda basin in the north-eastern part of Algeria, the Isser basin in the north-center part, and the Macta basin in the north-western part) are impacted differently by climatic factors and human activities, which may affect streamflow alteration in various ways. This response depends on a complex interaction of factors, such as rainfall patterns, temperature, evapotranspiration, land use change, hydrological infrastructure, and other environmental variables (e.g., geology, soil), as well as the catchment characteristics. The impact of these factors on the basins' hydrological regimes has significant implications for water resource management. Therefore, it emphasizes the need for more local and regional-scale studies. If additional data becomes available, it would be valuable to carry out similar studies in other catchments in Algeria. This would allow for a comparison of the results with those obtained in the current research.

8.2 Perspectives

Our research made an attempt to identify and understand the drivers of streamflow alteration in semi-arid catchments in Algeria.

The complexity of mechanisms involved in streamflow changes and associated drivers in Algeria as well as the lack of appropriate information on some other expected drivers such as groundwater use showed that the quantitative identification of the role of different drivers in streamflow alterations remains cumbersome. Nevertheless, several other perspectives remain. In the following, some potential ideas are presented.

The length of the time series has a direct effect on the results of the trend analyses and some of the observed discrepancies in our research could be because of using different periods series compared to other research. This shows that trend analyses are sensitive to the time scale and careful attention should be given during analyses. The limited time scale of the time series represents a constraint towards the exact monitoring of trends.

Therefore, a record length of more than 30 years is crucial and should be considered to confirm the presence or absence of trends.

Many studies (e.g., Li and Sivapalan 2011; Brito-Castillo et al. 2003; Yair and Kossovsky 2002) reported that the spatiotemporal streamflow generation in semi-arid areas is strongly non-uniform as streamflow generation controlling factors are different from that of a humid environment. In this research, we focused mainly on climatic and human factors such as precipitation, temperature, evapotranspiration, and NDVI in the context of streamflow alteration. Although the results of this analysis give some insights into the factors that could potentially be causal for the alteration in streamflow, they did not quantify the relative contribution between the evolution of each factor or their combinations. Data set availability constitutes the main limitation since it is often scarce in time and space and is affected by multiple sources of uncertainty. Other factors could be included in the causality analysis to deliver more reliable and robust results of streamflow changes in a semi-arid climate such as antecedent soil moisture, irrigation, atmospheric circulation (NAO, ENSO, SO), baseflow, and groundwater use. Across the Mediterranean area, the networks for hydro-meteorological measurements are often scattered and poorly adapted to the real-time demand and needs of water-resource managers. Remote Sensing (RS) has shown great potential to complete and support the poorly monitored national database with a high space-time resolution of components of the hydrological cycle. These include precipitation, evapotranspiration, vegetation cover, soil moisture, surface and subsurface water storage. To this must be added the possibility of generating accurate descriptions of land use and mapping the development of vegetation cover and irrigation. Remote sensors contribute substantially to providing essential information for the management of water resources as well as the monitoring of extreme events and their impacts. The wide spatial coverage of these data should allow a better assessment of risk in terms of regional water and food security. Therefore, the use of remote sensing products is highly recommended to overcome these limitations.

In this study, an advanced nonlinear bivariate causal detection methodology was tested. However, other quantitative causal inference methods, such as optimal fingerprints, factorial analysis (FA), or PCMCI methods should also be investigated and are suggested for further work. It would be interesting to compare these algorithms based on their performance for detection and attribution of the causal factor.

In addition, other methods emerged based on fuzzy logic and subjective perception to infer causality. This can for instance be explored using multi-criteria decision-making (MCDM) techniques. With such methods, causal factors explaining streamflow alteration are assessed by expert judgment. Methods include AHP (Analytical Hierarchy Process) modelling, ANP (Analytic Network Process), and FAHP (Fuzzy Analytical Hierarchy Process). These latter methods are considered as more effective methods for the prioritization of factors and criteria into a hierarchical order and for analyzing the data using pairwise comparison matrices with the integration of fuzzy logic techniques (Aher et al., 2014; Kharat et al., 2016).

While the CCM method proved its efficiency in taking into account capturing the complicated nonlinear relationship between input factors and streamflow, it still has a constraint in quantitatively analyzing the contributions of anthropogenic factors and climate change to streamflow change. Causal inference methods present major challenges if the underlying causal model is complex. For instance, bivariate methods, that only reveal causal relationships between two variables, are often unable to distinguish direct from indirect causes. On the other hand, the presence of a confounder variable, a common cause of at least two variables, is a well-known problem for causal discovery approaches. A confounding variable is a third variable that influences the relationship between an independent variable and a dependent variable in such a way that the relationship appears to be different from what it is. Confounding variables can create spurious relationships or hide true relationships in exploring causal relationships. A particular challenge occurs when a confounder is hidden. It is important that a causal discovery method can hypothesize the existence of a hidden confounder. To overcome this limitation, it would be interesting to apply a multivariate method, which takes all variables into account to distinguish between direct and indirect causality. The proposed method of Factorial analysis (FA), viewed as a multivariate inference method, can efficiently identify the main effect of a single factor and different-level interactions of multiple input factors (Zhang et al., 2019). However, future research should explore the sensitivity of the CCM results using a global sensitivity analysis method. Additionally, the study should examine the impact of data autocorrelation, prediction horizon (lagged version of CCM), and embedding delay (tau) as parameters of the CCM test (Bonotto et al., 2022).

Finally, in this study, an empirical approach was followed to unravel causality. Last decades, considerable advances have been made to assess the impacts of climatic and other anthropogenic drivers on streamflow alteration using physically based hydrological models. Notwithstanding that physically based hydrological models are contaminated with other flaws such as limited validity. Future work should consider how physically based hydrological modelling could be used in combination with empirical methods to infer the causality of streamflow alteration.

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