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Article

Climate Change Impacts on Water Supply and Demand in Rheraya Watershed (Morocco), with Potential Adaptation Strategies

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Abstract: Rheraya watershed already suffers from the impacts of climate variability and will be further affected by climate change. Severe water shortages and extremely fragile ecological conditions necessitate careful attention to water resources management. The aim of this study is to analyze Rheraya's future water situation under different scenarios of socio-economic development and climate change until 2100. The Water Evaluation and Planning System model (WEAP) has been applied to estimate the current water demands and the increased water demands resulting from climate change. WEAP was calibrated using meteorological and demand observations, then, updated with present-day and future climatic conditions using the Statistical Down-scaling Model with two projections (A2, B2) of the Intergovernmental Panel on Climate Change. Those projections show an increase in temperature of about 2–3 °C and a reduction in precipitation of 40–60% with respect to baseline. The results show that the pressure on Rheraya's water resources will increase, leading to greater competition for surface water, and that domestic, tourist,

livestock and agricultural demands will not be met by the year 2100. The Results also demonstrate that the assessments of adaptation strategies proposed by decision makers are effective but not sustainable for the watershed.

Keywords: climate change; water management; adaptation strategies; Rheraya watershed; WEAP; scenario development

1. Introduction

On a worldwide basis, Mediterranean countries are among the most threatened by water stress, because of extreme natural inter-annual variability, seasonality of water resources, and decreasing streamflows forecast in coming decades [1]. Changes in water resources are particularly relevant in areas where water availability is a limiting factor for economic development. This is the case in the Mediterranean basin, where both developed and developing countries have a common dependence on water availability to meet the needs of increasing populations and living standards, development of irrigated agriculture, and increasing industry and tourism activities [2].

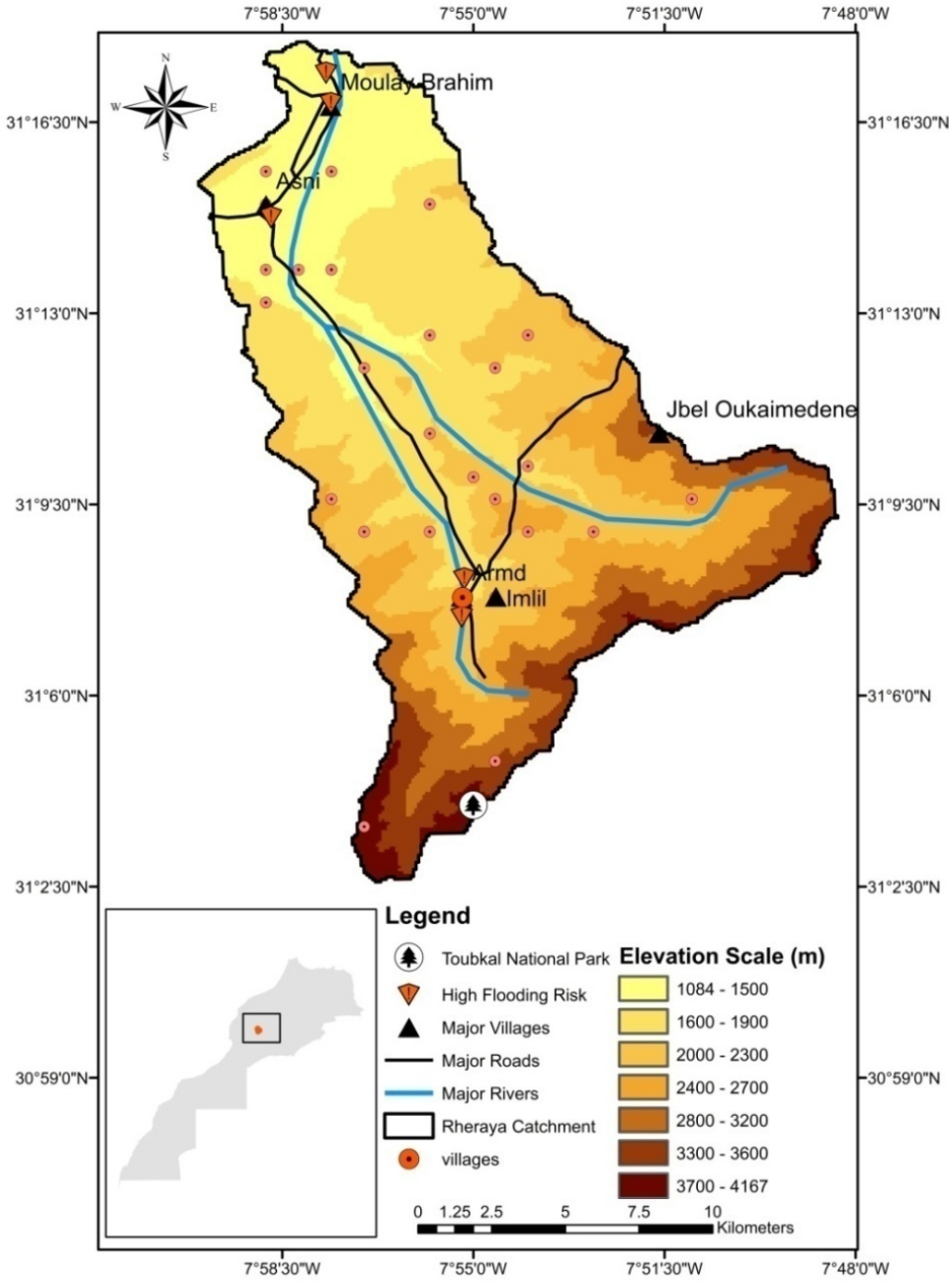
The Mediterranean region lies in a transition zone between the arid climate of North Africa and the temperate and rainy climate of central Europe and it is affected by interactions between mid-latitude and tropical processes. Because of these features, even relatively minor modifications of the general circulation, e.g. shifts in the location of mid-latitude storm tracks or sub-tropical high pressure cells, can lead to substantial changes in the Mediterranean climate. This makes the Mediterranean a potentially vulnerable region to climatic changes as induced, for example, by increasing concentrations of greenhouse gases [3,4]. The Mediterranean region is considered to be a global "hot-spot" in terms of climate variability and change [5].

According to Intergovernmental Panel on Climate Change (IPCC) methodology, the development of climate scenarios for Morocco reveals a trend towards an increase in average annual temperature (between 0.6 °C and 1.1 °C) as well as a decrease in average annual rainfall volume by about 4% in 2020 compared to 2000 levels [6]. Climate projections on Morocco show gradually increasing aridity because of reduced rainfall and higher temperatures [7]. Changes in temperature and precipitation patterns may affect the hydrologic processes and water resources availability for agriculture, population, mining, industry, aquatic life and hydropower. Climate changes will accelerate the global hydrologic cycle with increase in the surface temperature, changes in precipitation patterns and evapotranspiration rates [8]. The change in intensity and frequency of precipitation will affect the streamflows. Consequently, it will increase the intensity of floods and droughts, with substantial impacts on the water resources at local and regional levels [9,10].

In Rheraya catchment (Figure 1), as in most semi-arid regions of the world, water resources are limited and under severe pressure due to the expanding needs of the population, tourism and agriculture. Data analysis between two distinct periods in the temperature series (1990–1997 and 1998–2007) show that the temperature rose by 0.8 °C. The Oukaimeden (Figure 1) recordings show a decrease in the proportion of snow. It was slightly higher than rain until 1997, and became lower from 1998 on. This tendency can be linked to the raise of temperatures from about 1998 [11]. The decrease of the

streamflow at Rheraya catchment appears to be much more rapid than the decrease in precipitations. This suggests that climate change impacts could have further dramatic consequences on runoff.

Figure 1. Rheraya catchment within its regional context.



The planning of water resource systems requires a multi-disciplinary approach that brings together an array of technical tools and expertise along with parties of varied interests and priorities. Often, the water management landscape is shaped and influenced by a set of linked physical, biological, and socioeconomic factors that include climate, topography, land use, surface water hydrology, groundwater hydrology, soils, water quality, ecosystems, demographics, institutional arrangements, and infrastructure [12]. Climate change is important to water planners and managers because it may change underlying water management conditions and increase the need for new water management programs and capital investments [13,14]. Climate change presents new challenges to the way that

water managers plan for the future. Historical data may not be a good predictor of the future, and as a result, water managers will need to develop new tools [15].

Processing hydrological and water-demand data and forecasting the effects of different management strategies under the impacts of climate change are still a challenge. Integrated water resource models try to assist the planner in managing water resources [16].

The development of a Water Management Support System, that integrates all current and future resources as well as all current and future demands into one tool, is crucial to the sustainability of the water resources management in Rheraya watershed.

In this paper, we use results from a climate-forced rainfall-runoff model to explicitly simulate intra-basin hydrologic dynamics and understand localized sensitivity to climate change. Insights presented here are intended to help guide local adaptation strategies by highlighting regional and basin-specific trends in the quantity and timing of water resources under regional climate change, and to illustrate which sectors are the most vulnerable to climate change.

The large numbers of currently available global climate models (GCMs) enable the comparison of climate projections between the models. Most of them have horizontal grid spacing coarser than 200 km [17]. Therefore, they fail to capture the strong spatial variations in precipitation and temperature that characterize Morocco which are the key for representing the hydrological system of small basins. To improve such representation, we have used the outputs from the software Statistical DownScaling Model 4.2 (SDSM4.2). SDSM is a decision support tool for assessing local climate change impacts using a robust statistical downscaling technique [18]. The future simulations consider IPCC A2 and B2 scenarios of greenhouse gasses concentrations [17]. B2 is based on a more "ecological" world and the projections are more conservative than those of A2.

The high resolution SDSM outputs are then used to force the Water Evaluation and Planning (WEAP) model, a climate-driven hydrology and water resources model. WEAP was previously calibrated using historical supply observations in the Rheraya watershed. The impact of future climate change is evaluated by comparing various WEAP outputs between the future scenarios and baseline conditions.

2. Study Area

The High-Atlas is a Moroccan mountain chain of approximately 60 km in width and 800 km in length and is aligned along a NE–SW axis. It culminates at an altitude of 4,167 m at the Jbel Toubkal, the highest summit of North Africa. The vegetation is generally sparse and is growing mainly at the bottom of the valleys.

The High-Atlas Mountains are mainly composed of metamorphic and eruptive formations, which are impervious and generate overland flow. Some pervious zones are still present, due to calcareous and marly sandstone formations or local weathering of the impervious formations. These pervious zones are probably responsible for additional delay in lateral subsurface flow. The relief of the Atlas Mountains is very sharp with steep slopes [19].

The study area is one of the main catchments of the High-Atlas range, the Rheraya (224 km^2) whose altitudes range from 1,084 to 4,167 m (Figure 1). The hillslopes are covered by degraded rangelands with little vegetation and a stone cover usually over 50%, whereas a thin strip of irrigated crops are

found in the valley on either side of the river. Precipitation is very variable in time, with an average of about 350 mm/year at the outlet (Tahanaout) [20].

3. Data Sets

To analyze the water demand and supply at the catchment level, it was necessary to disaggregate the information available on the municipality level, in order to account for different development paths. It was also necessary to aggregate the information at the village level in order to achieve a manageable amount of data. We developed a data and information base supported by ample field work and expert consultations carried out in the area of study in 2008, 2009 and 2010.

In addition, this work is based on an extensive data base of ecological, meteorological, hydrological, hydrogeological, water management, GIS, remote sensing, vegetation, social, cultural and economic information. Historical hydro-meteorological conditions of Rheraya watershed are characterized using data from a network of stations operated by the SudMed project, the Regional water agency (Agence du Bassin Hydraulique de Tensift), and the Regional Office of Agricultural Development of Al Haouz (Office Régional de Mise en Valeur Agricole d'AlHaouz ORMVAH). Tourist water consumption refers to the water consumed by hotels. Tourist demands were added to the closest domestic demand site as the water for tourist activities is supplied by the domestic water supplier.

4. Applied Methodology

4.1. Climatic Model Development

The impact assessment applications often require specific climate projections in order to capture fine-scale climate variations, particularly, in regions with complex topography and in areas of highly heterogeneous land-cover [21]. Therefore, a gap exists between climate models predictions about future climate change and information relevant for environmental studies. SDSM are commonly used to fill this gap. In addition, in this work we have used SDSM, which performs ancillary tasks: of data quality control and transformation, predictor variable pre-screening, automatic model calibration, basic diagnostic testing, statistical analyses and graphing of climate data [22].

Daily mean temperature, maximum temperature, minimum temperature and precipitation data, recorded at three weather stations (Oukaimden, Tahannaout and Marrakech) over the period 1961–2000, were used to simulate A2 and B2 scenarios. A2 and B2 are two IPCC greenhouse gases scenarios [18]. A2 is a pessimistic scenario which describes a world where global populations rapidly increasing, with strong economic growth based on polluting technologies in a world that has become more protectionist with increasing disparities between North and South. There is continued use of fossil fuels and uneven regional economic growth. In contrast, B2 Scenario is an optimistic scenario which describes a world where the focus is on local solutions, from the point of view of economic, social and environmental viability. The world population increases in a continuous way, but at a slower rate than in A2, as shown in Table 1. For the two IPCC scenarios A2 and B2, we worked in four time horizons: each of the time horizons actually stands for a period of about 30 years. They include the "current period" (or "baseline", covering the years 1961–2000, for which crop statistics are available), 2020 (from 2011 to 2040), 2050 (2041–2070) and 2080 (2071–2099).

Table 1. Overview of A2 and B2 scenarios parameters.

Storylines	**A2 scenario**	**B2 scenario**
Regionalization (heterogeneous world)	regionally oriented economic development	local environmental sustainability
Population growth	high	medium
GDP growth	medium	medium
Energy use	high	medium
Land-use changes	medium/high	medium
Resource availability	low	medium
Pace and direction of technological	slow	medium
Change favoring	regional	"dynamics as usual"

4.2. Hydrologic Model Development

WEAP software developed by the Stockholm Environment Institute (SEI) was selected for the purpose of this study. WEAP system is a demand-, priority-, and preference-driven water planning model [23]. It aims at closing the gap between water management and catchment hydrology by addressing both bio-physical factors influencing the river and socio-economic factors affecting the level of domestic, agricultural and industrial demand and management of artificial reservoirs. These factors vary over time, for example due to increased gross domestic product, changes in consumptive attitudes, or climate change, and therefore make it difficult to forecast future demand requirements. With its focus on scenario analysis, WEAP supports the planner in forecasting demand and supply structures under various assumptions and management practices and helps in developing resources management policies to meet future demands and solve allocation problems [24,25]. WEAP also compares future development with a snapshot of actual water demand, resources and supplies for the system which is called current accounts year.

4.3. Future Trends in Water Demands in the Study Area

Several workshops were held in the study area to identify driving forces on water demands as well as their future trends. Stakeholders from different governmental organizations (GO) and non-governmental organizations (NGOs) participated in the workshops. The workshops showed that there will be an increase in domestic water demand over the next twenty years. This is due to continuous population growth and the improvement of the standard of life which will result in an increased per capita use. Agricultural demand was projected to decrease over the next thirty years as a result of better management of irrigation water. It was also concluded that there will be some growth in the water demand for tourism as a result of building new hotels in the region.

4.4. Management Responses to the Climate Change Scenarios

The Rheraya catchment WEAP model allows us to analyze various global change and water management scenarios. Scenarios are self-consistent story-lines of how a future system might evolve over time. These can address a broad range of "what if" questions [26]. This allows us to evaluate the implications of different internal and external drivers of change, and how the resulting changes may be

mitigated by policy and/or technical interventions. For example, WEAP can be used to evaluate the water supply and demand impacts of a range of future changes in demography, land use, and climate [27]. The result of these analyses can be used to guide the development of adaptation portfolios, which are combinations of management and/or infrastructural changes that enhance the water productivity of the system.

WEAP model was used to evaluate the impact of A2 and B2 climate scenarios in the region, and to investigate whether water management adaptation could reduce potential impacts. Each of the two climate sequences was run for four management scenarios. All scenarios were run for a period 2010–2100:

(a) No Adaptation: Applying A2 and B2 data scenarios, without any adaptation strategy in the catchment.
Throughout this study several stakeholder meetings were held (including central and regional government officials, river basin managers, irrigators, Irrigation Communities, environmental NGOs and research institutions); two adaptation strategies that managers plan to implement in the watershed were assessed.

(b) The agricultural technology development (S1): Drip irrigation is progressively implemented to save water. This is included in the analyses by gradually increasing water use efficiency by 25%. The successive implementation follows a linear trend. Thus, drip irrigation is applied to 50% of the cropping area after 35 years.

(c) The public awareness (S2): The instruments through which water issues public awareness can be increased include: marketing and management consultants, media exposure, communication support materials, training institutes, and partnerships at an international level. Following this strategy the managers expect a 20% decrease in water consumption per person by 2020.

(d) The combination of the two adaptation strategies S1 and S2 (S3): takes into account S1 and S2 assumptions.

5. WEAP Calibration and Validation

The watershed model was calibrated with streamflow data from the ORMVAH. Calibration is performed by comparing observed and modeled inflows to Rheraya watershed.

The range of resulting values from the calibration process is shown in Figure 3. In this figure we present results for the calibration period corresponding to the 1993–2003 period. The figure shows good agreement between calculated and measured inflows to Rheraya catchment.

This result is also verified by Figure 4, which shows the absolute value of the calculated error between observed and simulation results. It can be seen from the figure that the error is small, remaining under 8×10^{-2}(pu), per unit (pu) is equivalent to normalizing the quantities used; thus, confirming the pertinence of the Rheraya catchment WEAP model.

Figure 3. Observed and WEAP simulated streamflow time series at Rheraya catchment.

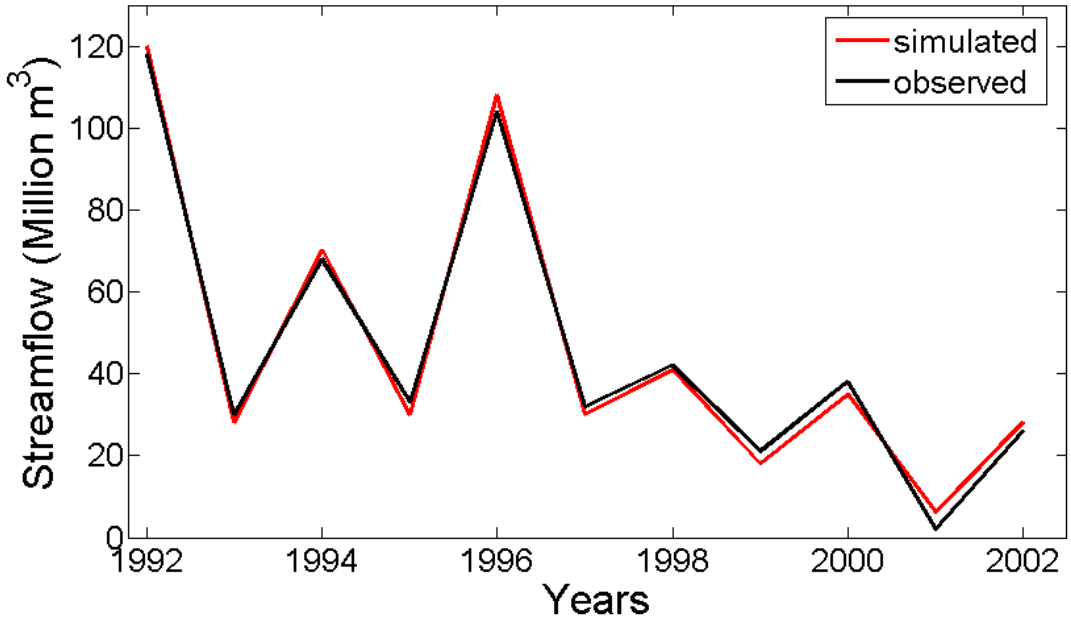


Figure 4. The error absolute value for validation of the proposed model.

6. Results and Discussion

6.1. Climatic Analysis

The high resolution future climate change scenarios obtained in this work are very similar in magnitude to those shown in the fourth report of IPCC. In fact, the calculation of future climate anomalies (2011–2040, 2041–2070 and 2071–2099) relative to the current climate (1961–2000) for the four parameters (mean temperature, maximum temperature, minimum temperature and precipitation) shows increased temperatures and decreased precipitation for the mentioned periods as presented in Figure 5 and Figure 6. Regarding the increase of mean temperature, models predict it may reach in

Rheraya catchment 1 °C, 3 °C and 4 °C during 2011–2040, 2041–2070 and 2071–2099 respectively. The decrease in precipitation is predicted to be, following the technique SDSM, 5 to 10% during 2011–2040, from 10 to 40% during 2041–2070 and 40 to 60% for the end of the century (2071–2099).

Figure 5. Seasonal and annual anomalies (°C) of mean temperature for the three future horizons 2020, 2050 and 2080 and for both A2 and B2 scenarios at Rheraya catchment.

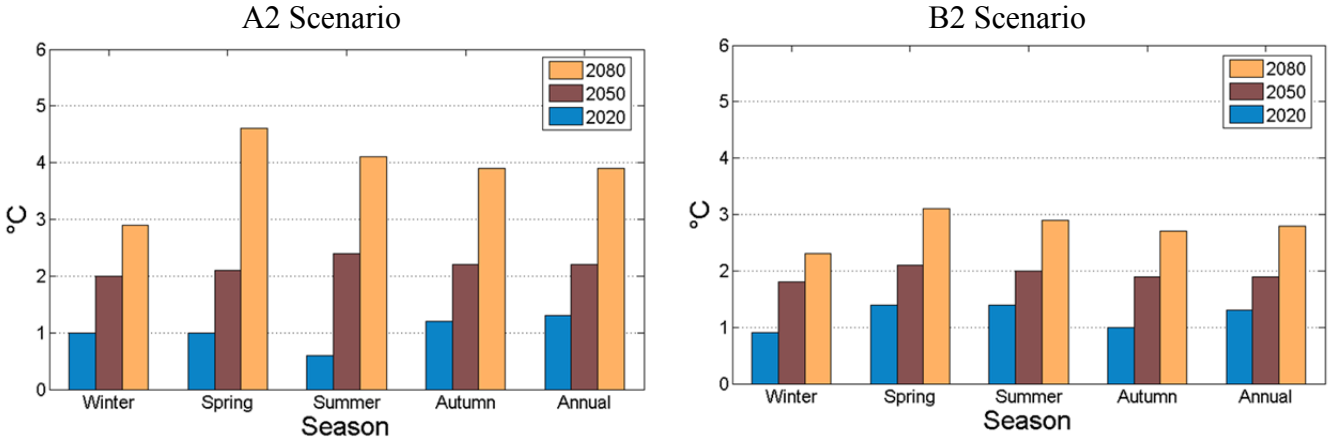
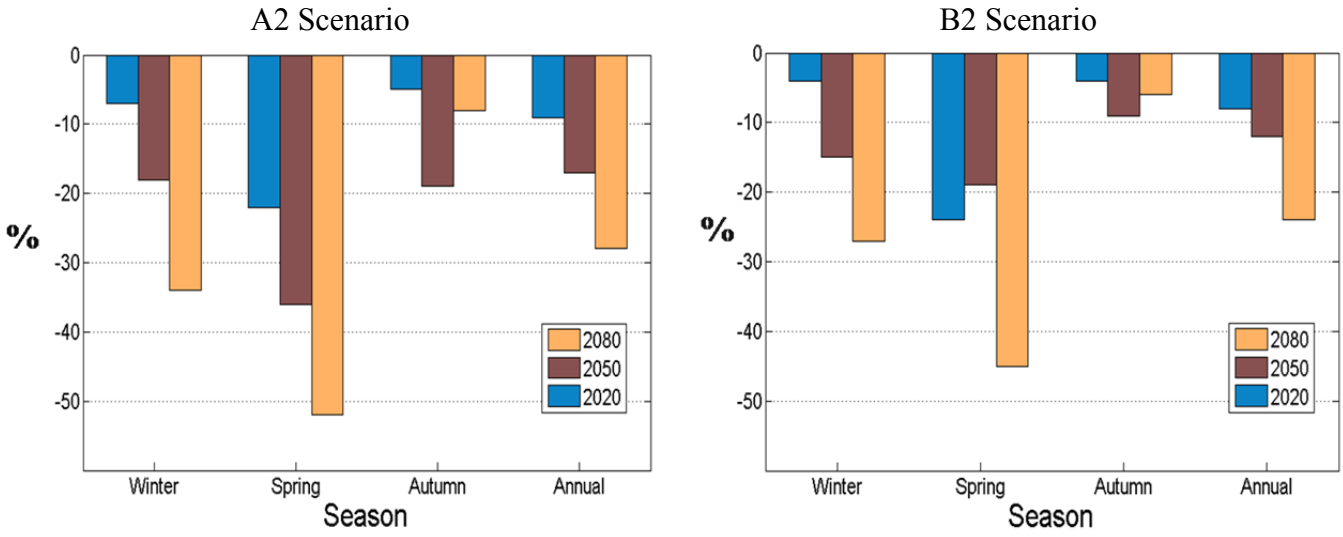


Figure 6. Percentage change in the level of cumulative seasonal (winter, spring and autumn) and annual rainfall for the three future horizons 2020, 2050 and 2080 and for both A2 and B2 scenarios at Rheraya catchment.

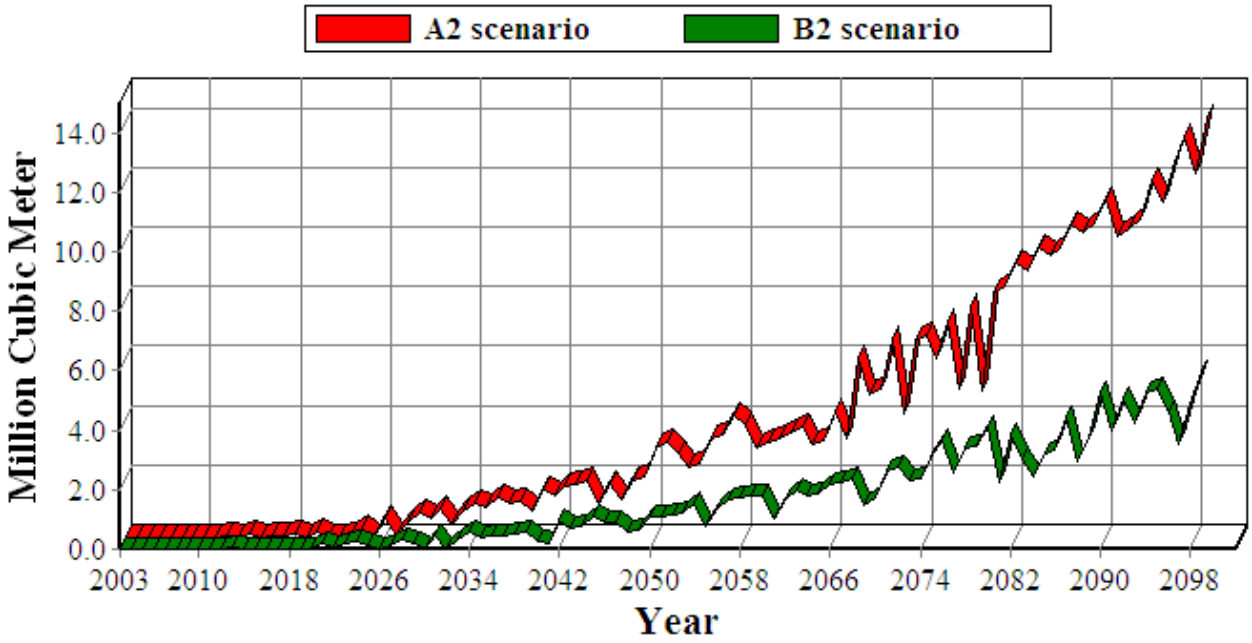


6.2. Hydrologic Analysis

6.2.1. Operations Analysis Without Adaptation Strategies

Both scenarios showed an increasing trend in water demand over time. A2 scenario exhibits a more pronounced increase than B2 scenario. Simulation results shown in Figure 7 demonstrate that the average annual unmet demand (quantity of water that cannot be physically delivered to the demand site) will dramatically increase over 70% and 90% of the total annual demand, respectively for B2 and A2 scenarios.

Figure7. Annual unmet demand for all demand sites.



Decreased precipitation and increased temperatures, which enhance evapotranspiration and reduce soil moisture, are important factors that have contributed to more regions experiencing droughts [28]. Based on the value of the annual precipitation, a water year was classified as very wet, wet, normal, dry, or very dry, using Poissonnet method. Droughts were assumed to occur during years designated as very dry. In A2 scenario, during the studied period, 45% of years were very dry and dry, 35% were normal and 20% were very wet and wet, as shown in Figure 8. While in B2, 40% were very dry and dry, 42% were normal and 18% were very wet and wet, as shown in Figure 9. In general, the A2 scenario predicted more severe droughts than the B2 scenarios, which agrees with the lower precipitation seen with these scenarios.

Figure 8. Sequence of wet and dry years for A2 scenario. Water year type: 1 = Very Dry, 2 = Dry, 3 = Normal, 4 = Wet, 5 = very Wet.

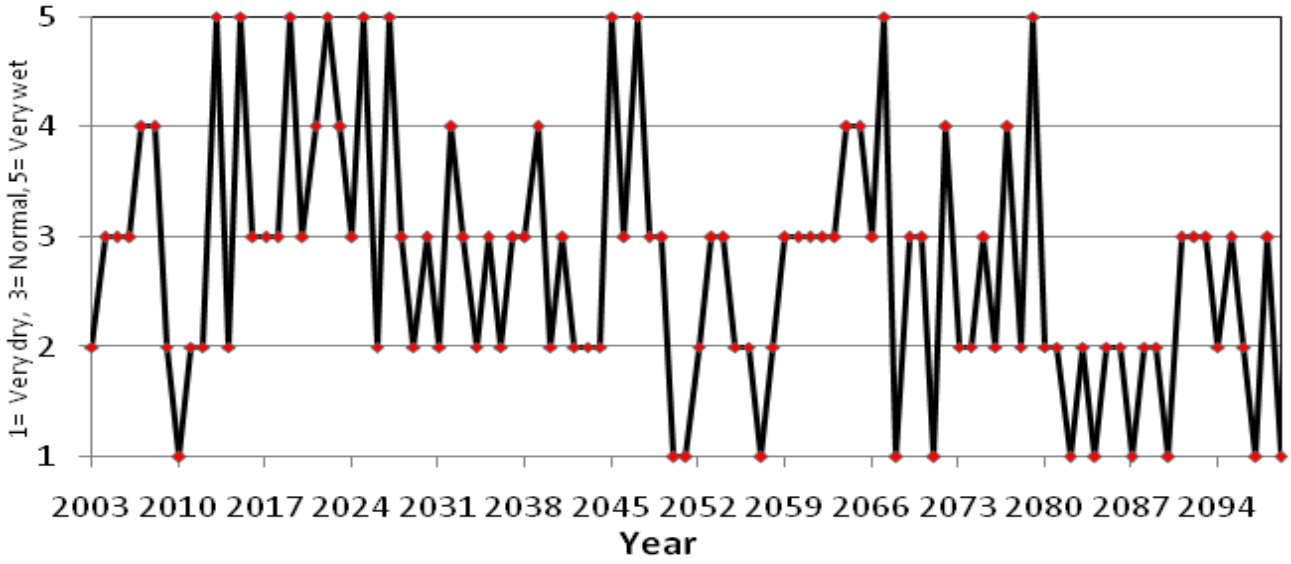
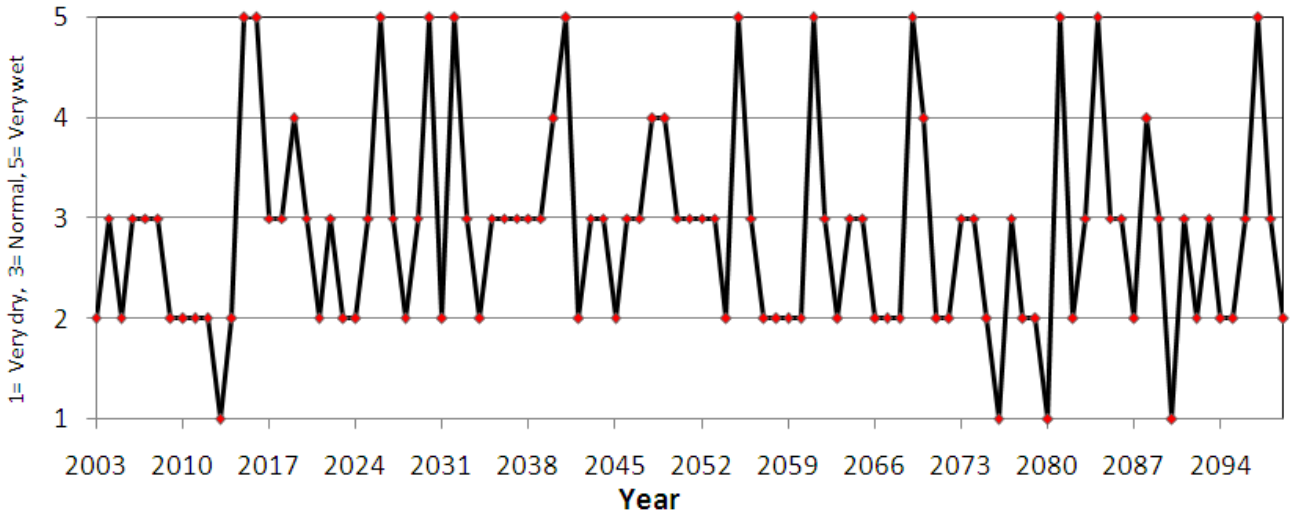


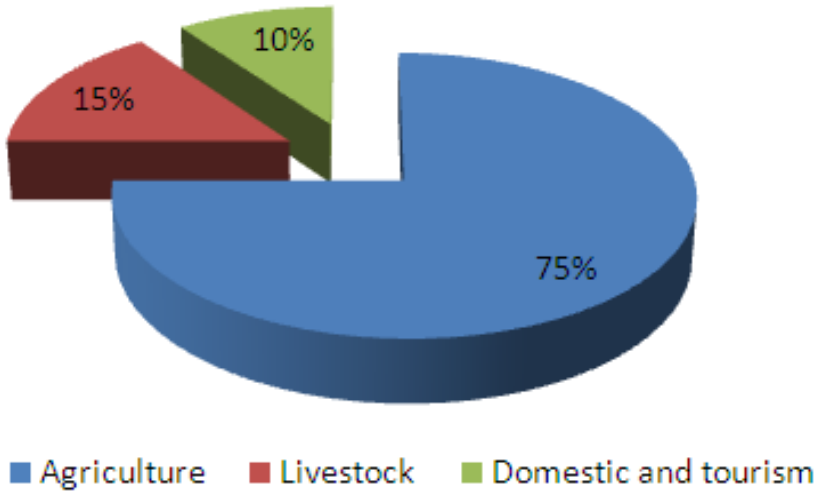
Figure 9. Sequence of wet and dry years for B2 scenario.Water year type: 1 = Very Dry, 2 = Dry, 3 = Normal, 4 = Wet, 5 = very Wet.



The socio-economic impacts of droughts may rise from the interaction between natural conditions and human factors such as changes in land use, land cover and the demand for water. Droughts affect rain-fed agricultural production as well as water supply for domestic and agricultural purposes. The results show that Rheraya watershed will suffer from more intense and more prolonged droughts.

Agriculture is the largest water consumer in Rheraya catchment as seen in Figure 10. The agricultural demand for the year 2003 was about 15 MCM. While the domestic and tourism demand for the current account year in the watershed was about 3.12 MCM and the livestock demand was about 2.2 MCM. Livestock is of a great traditional importance in the Rheraya catchment. It is not only a source of income, but also plays a role with regard to food supply, hedging and prestige. The number of animals is subject to yearly fluctuations due to varying forage availability as a consequence of precipitation availability.

Figure 10. Percentage of the total water consumption by sector in Rheraya catchment.



Tourism is an expanding sector in Rheraya, the influence on the local labor market is rather small. Major beneficiaries are international tourist companies that run hotels and travel agencies in the urban

centers. Moroccan entrepreneurs only benefit in some tourist hot spots. As water is a highly fragile resource, tourism, especially the big luxurious hotels recently constructed in the region, can increase the ecological problems.

6.2.2. Operations Analysis with Adaptation Strategies

We considered the ability of the water resources system to deliver water to satisfy future demands, and evaluated water management strategies to offset anticipated consequences of climate change. We separately considered three "adaptation" strategies: improvements in irrigation efficiency through investments in technology, public awareness strategy and the combination of the two adaptation strategies.

In scenario A2, the water demand for agriculture would continue to increase whereas which the adoption of adaptation strategy (S1) could partly offset (Figure 11). As it can be seen in Figure 12, the offset in water demand was greatest in B2 scenario. The differences in forecasted temperatures and precipitations between the two scenarios explain the greater capacity of improvements in irrigation efficiency to offset water demands in B2 scenario.

Figure 11. Changes in unmet demand in Rheraya watershed associated with agricultural technology development strategy (S1), public awareness (S2), and the combination of the two adaptation strategies (S3) for A2 scenario.

Figure 12. Changes in unmet demand in Rheraya watershed associated with agricultural technology development strategy (S1), public awareness (S2), and the combination of the two adaptation strategies (S3) for B2 scenario.

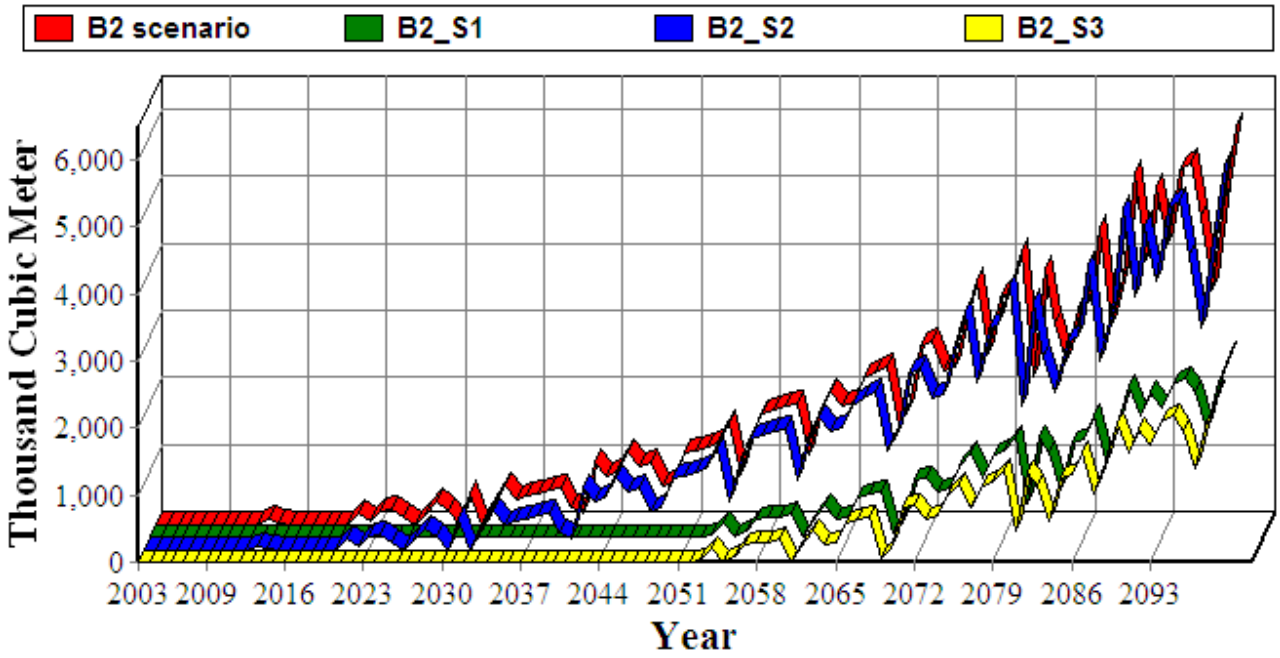


Figure 13. Unmet water demand under the combination of the two proposed adaptation strategies for A2 scenario in a thousand cubic meters.

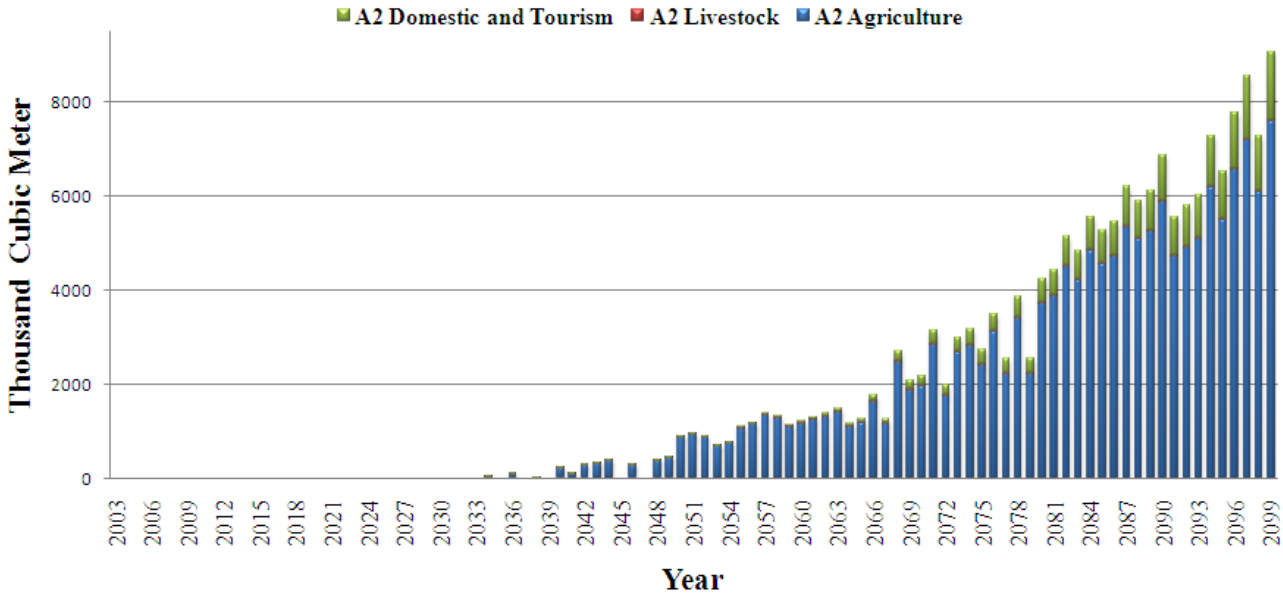
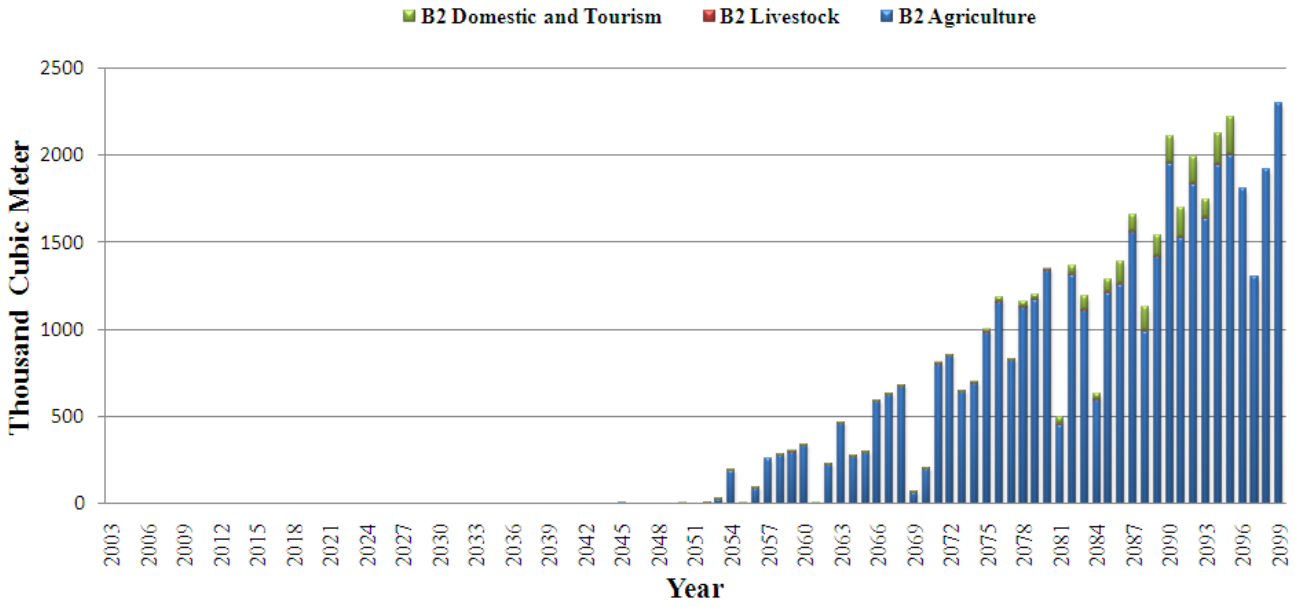


Figure 13 and Figure 14 show that, using the combination of the two proposed adaptation strategies, the water demand for domestic use, tourism and livestock sectors are fully met until2033 for A2 scenario and until2053 for B2 scenario. Supply for agriculture will fall short of demand for A2 and B2 scenarios. There are two reasons for the increase in unmet demand in the last decade of the study period. The first one is the increased demand due to higher per capita use rates and population growth,

while the other reason is the declining inflow to the catchment due to climate change. New investments in irrigation infrastructure and improved water management can minimize the impact of water scarcity.

Figure 14. Unmet water demand under the combination of the two proposed adaptation strategies for B2 scenario in a thousand cubic meters.



Being the largest user of water, irrigation is the first sector to lose out as water scarcity increases. The challenges of water scarcity are heightened by the increasing costs of developing new water sources [29], land degradation in irrigated areas [30], groundwater depletion [31], water pollution [32], and ecosystem degradation [33]. Governments have a fundamental role in promoting resilience in the water sector because individual farmers do not have the resources to collect and analyze the massive volume and complexity of information needed to design and build the most resilient farming systems. The role of governments in the agricultural sector includes: (i) giving farmers clear information about the projected changes and possible impacts on their current practices; (ii) providing farms with the tools to make decisions about their future farming practices; (iii) providing extension and educational training about how to make these changes; and (iv) giving access to new opportunities that may arise as a result of climatic changes.

7. Conclusions

In this study, an evaluation of climate change impacts on both water supply and demand and their associated impacts on water management in the Rheraya watershed was presented. We have used the WEAP hydrology model which was calibrated with historical data, forced by present-day and future climatic conditions from the SDSM Climate Model. The SDSM simulations of future climate were obtained by forcing the model with two IPCC greenhouse gases scenarios (A2 and B2).

The results show that the average annual unmet water demand will dramatically increase in the region in the coming decades. The evaluation of the water management strategies, that are expected to offset some of the anticipated consequences of climate change by reducing stressors on Rheraya's water resources, shows that the strategies proposed by the decision makers would not be sufficient to

ensure a balance between demand and supply under the pressure of socio-economic and climate changes in Rheraya watershed. Given the imbalanced state of water resources under conditions of continued increase in demand, calibrating water demand with available supply is the most vital step to reduce the climate change effects. The effects of climate change could re-affirm the urgency to implement new policies and reforms without delay in order to make water resource management more environmentally, socially, economically and financially sustainable.

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