

Water availability as a limiting factor and optimization of hydropower generation as an adaptation strategy to climate change in the Sinú-Caribe river basin

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RESUMEN

Se aplicó el Modelo de Evaluación y Planificación del Agua (WEAP, por sus siglas en inglés) 2.1 a la cuenca del río Sinú-Caribe en Colombia para crear varios escenarios de referencia y de estrategias de adaptación. Dichos escenarios incluyen el análisis del suministro de agua, el uso y la demanda así como proyecciones futuras teniendo en cuenta los potenciales impactos de los efectos del cambio climático sobre los recursos hídricos. El análisis de la disponibilidad de agua como factor limitante en el balance entre la oferta y la demanda de los sectores productivos y actividades en la cuenca del río Sinú-Caribe en Colombia, muestra que la oferta requerida se podría aumentar y por lo tanto la demanda insatisfecha aumentaría más rápidamente bajo condiciones de cambio climático. Los índices de escasez definen sus puntos críticos en el balance oferta-demanda al año 2074 en el escenario actual o de referencia y al año 2066 contemplando el cambio climático. Igualmente se elaboraron escenarios de optimización para la generación de energía hidroeléctrica en los meses más críticos del año, mostrando cómo las estrategias de manejo de los recursos hídricos pueden mitigar los efectos adversos del cambio climático.

ABSTRACT

The Water Evaluation and Planning Model (WEAP) 2.1 was applied to the Sinú-Caribe river basin in Colombia to create several baseline and adaptation strategy scenarios for water supply, use and demand, and to make projections for the future including the potential impacts of climate change. The analysis of water availability as a limiting factor in the supply-demand balance of the productive sectors and activities in the Sinú-Caribe river basin in Colombia shows that the supply requirement would increase and thus unmet demand would increase more quickly under climate change conditions. The scarcity indexes define the critical points in this balance by the years 2074 under current or baseline conditions and 2066 with climate change. Optimization scenarios for hydropower generation for the critical months of the

year were also generated and show how water resources management strategies can mitigate the adverse effects of climate change.

Keywords: Supply requirement, management strategies, scarcity index, unmet demand.

1. Introduction

The Fourth Evaluation Report of the Intergovernmental Panel in Climate Change (IPCC, 2007a) concludes that man-made global warming is due mainly to greenhouse gas emissions, especially CO₂. During the last century, the concentration of carbon dioxide in the atmosphere increased from 278 ppm in the pre-industrial era to 379 ppm in 2005, and the average global temperature rose 0.74 °C.

This increase in the rate of global warming has taken place during the last 25 years, and according to historical records, 11 of the 12 hottest years have occurred in the last 12 years. The IPCC report presents detailed estimated projections for the 21st century, which indicate that the Earth's temperature could increase 3 °C by the year 2100, based on results from world average models for A2 and A1B scenarios, and that the average world temperature for that year could increase between 1.8 °C (based on low B1 scenario) to 4 °C (based on high A1FI scenario) (UNFCCC, 2008).

It is estimated that greenhouse gas emissions could rise from 25 to 90 % in the year 2030 compared to the year 2000 and even an increase of 1 to 2.5 °C would have drastic effects, including the reduction of crops in tropical zones, the risk of famines, the propagation of diseases such as malaria, and an increase in the risk of extinction of 20 to 30% of all plant and animal species (IPCC, 2007a).

It is forecasted that in the subsequent decades, even with relatively small average temperature increases, billions of people, especially those in developing countries, will face water and food shortages. It is also expected that floods, droughts and heavy precipitation will increase. Changes in some types of extreme phenomena have already been observed especially on human systems and low coastal systems; for example, there has been an increase in the frequency and intensity of heat waves and heavy precipitation on most regions of the world (IPCC, 2007b).

In the course of this century, millions of people who live in the watersheds of the Himalayas and the Andes could face an increased risk of flooding due to the melting and loss of glaciers followed by drought and the scarcity of water once these glaciers disappear (IPCC, 2007b).

Africa's climate is expected to be more variable, with more frequent and severe extreme meteorological phenomena which pose a higher risk to health and life. These phenomena include drought and floods in new areas (Few *et al.*, 2004; IPCC, 2007b) and flooding due the rise in the sea level in coastal zones of that continent (Nicholls 2004; McMichael *et al.*, 2006). According to the IPCC report, by the year 2020, up to 250 million people in Africa could be exposed to increased hydrological stress. Africa will face more water shortages, with the possible consequence of an increase in conflicts over water, due to the fact that there is a complex transboundary system in almost all 50 river basins in Africa (Ashton, 2002; De Wit and Jacek, 2006).

In Latin America, it is expected that by mid 21st century, the increase of temperature, and therefore, the reduction of soil moisture will generate a gradual substitution of tropical rainforest by savannas in the eastern Amazonia. Vegetation of semi arid regions will be substituted by vegetation of arid regions, and major biodiversity losses will take place with the extinction of species in

many tropical regions of Latin America. The yield of some crops will decrease, and with that, livestock production will also decrease, and this will have a negative impact on food production, and therefore, more people could experience hunger. Also, changes in precipitation patterns and the disappearance of glaciers will considerably affect the availability of fresh water for human consumption, for agriculture, and for hydropower generation (IPCC, 2007b).

According to several regional reports, the Andean glaciers could disappear in this century, with grave consequences for human life, production and subsistence means and ecosystems. In the course of this century, millions of people in Bolivia, Chile, Ecuador and Perú who live in the watershed of the Andes and depend on the seasonal melting of the glaciers for water supply and hydropower generation could face an increased risk of flooding due to the melting and loss of glaciers followed by drought and the scarcity of water once these glaciers disappear. The resulting water shortages would reduce the amount of hydropower generated (Mayr, 2006; IPCC, 2007b; UNEP, 2007).

The impact of these climate changes on water resources involve not only changes in the quantity, quality and recharge of the flow, but also by the characteristics of the system and the pressures on it, the way the system is managed and the adaptations to climate change that are applied. It is possible that other non-climate changes, such as the loss of biotic-physical regulators of the hydrologic cycle (like losses of physical, chemical, and mechanical properties of soils, changes in the structure of flora and fauna, and losses or changes in land cover), deforestation, the expansion and mismanagement of agriculture in unsuitable land, and the location of inadequate infrastructure would have a larger impact than those caused by climate change itself. More stressors on the system would increase its vulnerability to climate change, but management adaptations would reduce that vulnerability. Systems not subject to management would surely be the most vulnerable to climate change (IPCC, 2001b; UNFCCC, 2008).

For water resources, the variability in the hydrologic cycle induced by climate change poses new challenges in planning and management. The development of adaptation strategies to address the diverse additional uncertainties requires a comprehensive, integral and multidimensional focus; given the role that water plays in maintaining human life, society and the ecosystems they depend on. Methods of administration of water resources, particularly those that utilize integrated management, can be applied to adapt the hydrologic effects of climate change and new uncertainties, in order to diminish their vulnerabilities (IPCC, 2001b).

The intrinsic characteristics of integrated water resources management (IWRM) make it the ideal framework for the evaluation, design, execution and supervision of the strategies of adaptation of water resources to the effects of climate change. The IWRM method is a systematic planning and management approach that considers a series of processes and supply-demand actions, incorporating the participation of key actors or stakeholders in the decision-making process. It also facilitates adaptive management by means of monitoring and continuous revision of the water resources situation (UNFCCC, 2006).

The Water Evaluation and Planning Model, WEAP 2.1. (Sieber and Purkey, 2007), developed by the Stockholm Environment Institute (SEI), is a tool used to achieve effective IWRM. It integrates a range of hydrological physical processes with the administration of demand and infrastructure in a continuous and coherent manner, providing the analysis of multiple scenarios, including alternative climates, the anthropogenic changes causing stress such as variation in land use, changes in municipal and industrial demands, alternate operating regulations and the points of diversification of the changes (UNFCCC, 2005).

Since Colombia is as vulnerable as any country to the possible effects of climate variability described previously, this study presents an analysis of water availability as a limiting factor to different economic activities and productive sectors. Strategies of adaptation and/or optimization for the generation of hydropower are presented along with their effects on the supply-demand balance in the Sinú-Caribe river basin, integrating different tools and applying the WEAP model.

2. Methodology

For the purpose of this article, data have been used from previous reports by Ospina (2009) and Ospina *et al.* (2009) of the supply-demand balance of water resources, and the generation of hydropower in the Sinú-Caribe river basin. These data include: annual renewable water resources, water demand for different uses and by different sectors, water demand coverage, water demand required, unmet water demand, water storage volumes, and hydropower generation at the Urrá 1 dam, taking into account current conditions and projections of possible climate change effects on water resources, especially changes on precipitation, temperature, and evaporation, expressed by changes in streamflows and water volumes.

The current net natural supply of water resources is determined along with the supply under current climate change conditions, using as limiting factors (K_s) the maximum amount of water that can be provided under Colombian legislation (10% of the natural net supply) in both cases. Using data from the aforementioned articles, models of supply requirement (SR) and supply yield (SY) are adjusted in terms of time, assuming SR as real demand and SY as coverage of that demand.

Thus, the current and projected unmet demand can be determined and the effect of a possible adaptation scenario is analyzed. In addition, according to reports of the Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM, 2000-2001) the scarcity index (SI) can be calculated by obtaining the ratio between the demand and the supply, which is assumed to be the current net natural supply K_a and the projected supply under climate change conditions K_{cc} .

Since the river basin is involved in the generation of hydropower and in order to mitigate and/or improve the negative projected effects on this generation of energy, several scenarios are created with various strategies, which are then used to determine the influence of these strategies on the unmet demand (UD) in the region, considering specifically the most critical months of the year from February to April. The proposed strategy is simulated by generating a new demand site in the study region called “pumping”, whose purpose is to extract water from a source downstream from the dam and supply that water upstream or at the dam site (see Fig. 1).

3. Analysis and results

The study area is located approximately between 7 and 10° N latitude and 75° and 77° W longitude in NE Colombia. In Figure 1, the location and principal demand sites are presented, including the Urrá 1 reservoir and the future pumping station.

In Tables II, III, IV and V, and Figure 2, the variables and data obtained in studies by Ospina (2009) and Ospina-Noreña *et al.* (2009a, 2009b) are summarized. Detailed information can be found about the models of climate change, methodology, tools used, construction of scenarios as well as the different analyses and interpretation of the data used for the Sinú-Caribe river basin.

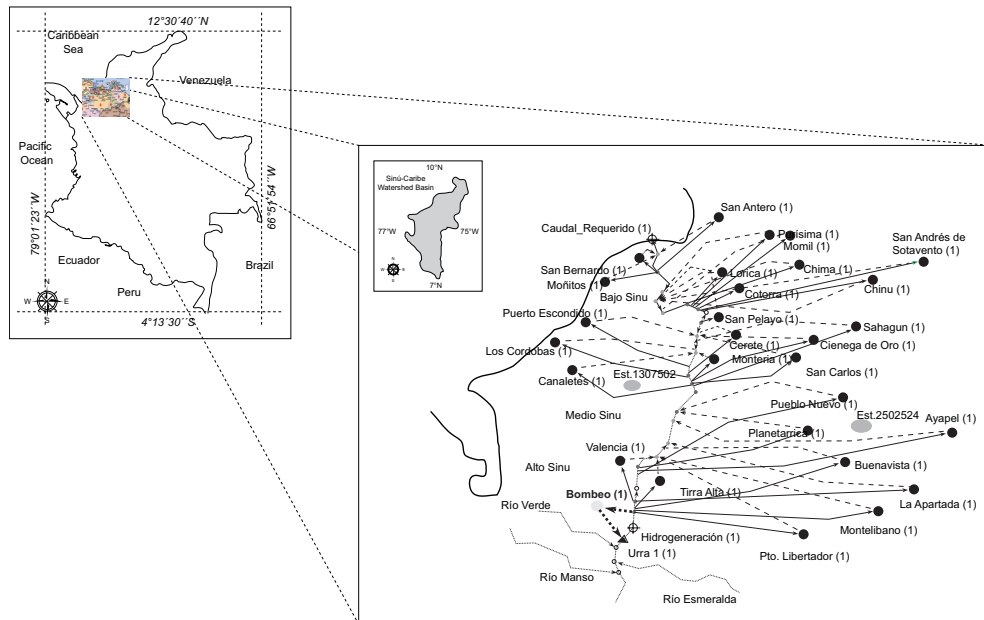


Fig. 1. Study area location and principal demand sites. Continuous lines represent provisions of water to the demand centers. Dashed lines represent water returns to the source. Black points represent demand centers. Dotted lines and circle represent the pumping system. The number between parentheses corresponds to the priority established for that water demand, (1) for all centers in this case.

It is clear from the information shown in those tables and figures that all the models and scenarios project negative effects on flow in the basin, on the volume of water stored in the reservoir and on the generation of hydropower by the end of the 2010-2039 period. The projected supply yield for the different scenarios for the year 2039 is presented to cover the supply requirement or demand for the same year (636.1 millions of cubic meters -MCM- for all scenarios, see Table V) and the ratio for unmet demand is specified for each case. The new scenarios developed in this report are based specifically on the current or baseline scenario and the future weighted average scenario (see Table III), for the purposes of the proposed analyses.

Table I presents some of the characteristics of the various scenarios of greenhouse gas emissions presented in Table II, which, according to IPCC (2001), are the basis for the evaluation of climatic and environmental consequences of future emissions, which are in turn used to implement mitigation strategies and adaptations actions to climate change. These scenarios represent emissions as a result of suppositions about the development of the planet in terms of economy, population and technological growth.

The average weighted flow scenario, which appears in Tables III, IV and V, was created by the application of weight to the flow volume for each of the models in Table II and by the standardization of the sum of these models, taking into account the change in the variables Tmax (maximum temperature) and PCP (precipitation) projected for the different scenarios. The flows of the models which showed the largest increase in Tmax and the greatest decrease in PCP were given more or less weight, then added and divided by the sum of the weighted factors (See Table II).

Table I. Socioeconomic development scenarios -SRES- (IPCC, 2001a).

Scenario	Description
A1	Rapid economic growth, population growth peaks mid-twenty-first century, market mechanisms dominate the economy. Subdivisions: A1FI: fossil fuel-dependent; A1T: non-fossil energy sources; A1B: not relying heavily on any single energy source.
A2	Self-reliant economies, preservation of local identities, continuously increasing population, economic development is primarily regionally oriented.
B1	Use of clean, efficient technology; reductions in material intensity; global solutions to economic, social and environmental sustainability, including improved equity; population peaks in mid-twenty-first century.
B2	Local solutions to economic and environmental sustainability; continuously increasing global population at a lower rate than A2; less rapid and more diverse technological change than in the A1 and B1 scenarios.

Source: Turnpenny *et al.*, 2002

Table II. Weights for the calculation of average weighted flow.

Model/experiment ^a	Weight
CCSRNIES_A21	1
CSIROMK2B_A21	1
CGCM2_A21	2
CGCM2_A22	2
CGCM2_A23	2
HadCM3_A21	4
HadCM3_A22	3
HadCM3_A23	2
Total	17

^aA21, A22, and A23 refers to experiment 1, 2, and 3 for the A2 scenario.

Table III. Current stream flows and corresponding stream flows for the weighted average scenario for the entire river basin, for the period 2010-2039.

Month	Current/baseline stream flow (m ³ /s)	Weighted average stream flow (m ³ /s)
January	267.2	272.9
February	203.4	162.7
March	200.7	156.7
April	350	208.3
May	642.2	655.5
June	739.3	555.7
July	765.1	513.3
August	701.9	582.5
September	669.7	458.4
October	715.7	575.4
November	633.5	498.4
December	443.8	428.3
Average	527.7	428.3

It was taken into account the expected changes in maximum temperature and precipitation, due to the fact that the model that was used to calculate the stream flows, only considered these two variables (Ospina, 2009; Ospina, *et al.*, 2009a).

The weighted average scenario was established applying the criterion of avoiding the most adverse effects that can be found. In other words, for those models that project greater increase in T_{\max} and greater decrease in PCP, higher weights are given, and vice versa.

Here it is important to point out, that conscious the uncertainty associated to the different scenarios socioeconomic conditions, climate, and data bases; among others. The weighted average scenario was proposed precisely as a scenario that encompasses all the expected projections, according to the different models, and tries to manage, or considers such uncertainty.

Table IV. Projected annual changes in storage volume in reservoir Urrá 1 and electrical power generation.

Model/Variable	Volume stored in reservoir			Electrical power generation		
	MCM	% change ^a	% change_MTV ^b	GWh	% change ^c	% change ^d
CCSRNIES_A21	1418.9	-2.3	-12.9	1408.4	-0.7	-16.5
CSIROMK2B_A21	1424.7	-1.9	-12.6	1258.8	-11.3	-25.4
CGCM2_A21	1353.2	-6.9	-17	1408.2	-0.8	-16.5
CGCM2_A22	1340.2	-7.8	-17.8	1224.8	-13.7	-27.4
CGCM2_A23	1360.1	-6.4	-16.6	1229.2	-13.4	-27.1
HadCM3_A21	1022	-29.7	-37.3	920.1	-35.2	-45.5
HadCM3_A22	1161.3	-20.1	-28.8	1051.6	-25.9	-37.7
HadCM3_A23	1300.7	-10.5	-20.2	1378.3	-2.9	-18.3
HadCM3_A2_SDSM	1439	-1.1	-11.7	1427.2	0.6	-15.4
Statistical	1151.2	-20.8	-29.4	1032.7	-27.2	-38.8
Weighted average	1258.9	-13.3	-22.8	1189.2	-16.2	-29.5
Reference or baseline	1452.8	0	-10.9	1418.9	0	-15.9

Source: Adapted from Ospina *et al.*, 2009a.

^a Compared to reference/baseline scenario, equal to 1452.8 millions of cubic meters (MCM).

^b Compared to MTV: maximum technical volume, equal to 1630 millions of cubic meters (MCM).

^c Calculation in terms of the reference/baseline scenario, equal to 1418.9 gigawatt hour (GWh) per year.

^d Calculation in terms of maximum generation capacity, equal to 1687.2 GWh/yr.

Table V. Projected water supply yield and unmet demand for the period 2010-2039, for all water uses and sectors, for the entire river basin.

Model/Variable	Supply yield MCM	Unmet demand MCM
CCSRNIES_A21	614.1	22.0
CSIROMK2B_A21	618.6	17.5
CGCM2_A21	578.7	57.5
CGCM2_A22	598.0	38.1
CGCM2_A23	604.9	31.2
HadCM3_A21	477.0	159.1
HadCM3_A22	537.7	98.4
HadCM3_A23	555.3	80.8
HadCM3_A2_SDSM	619.4	16.7
Statistical average	402.3	233.9
Weighted average	563.3	72.8
Reference or baseline	188.2	1.9

Source: Adapted from Ospina *et al.* (2009b).

Trying to obtain the best management of the uncertainty mentioned above, with the objective of reaching the most realistic and approximate results possible, it was sought that all the models, or the relationships found among the different variables necessary for doing this study, were statistically significant to a confidence level of 95%. In addition, after finding the estimated values, caution

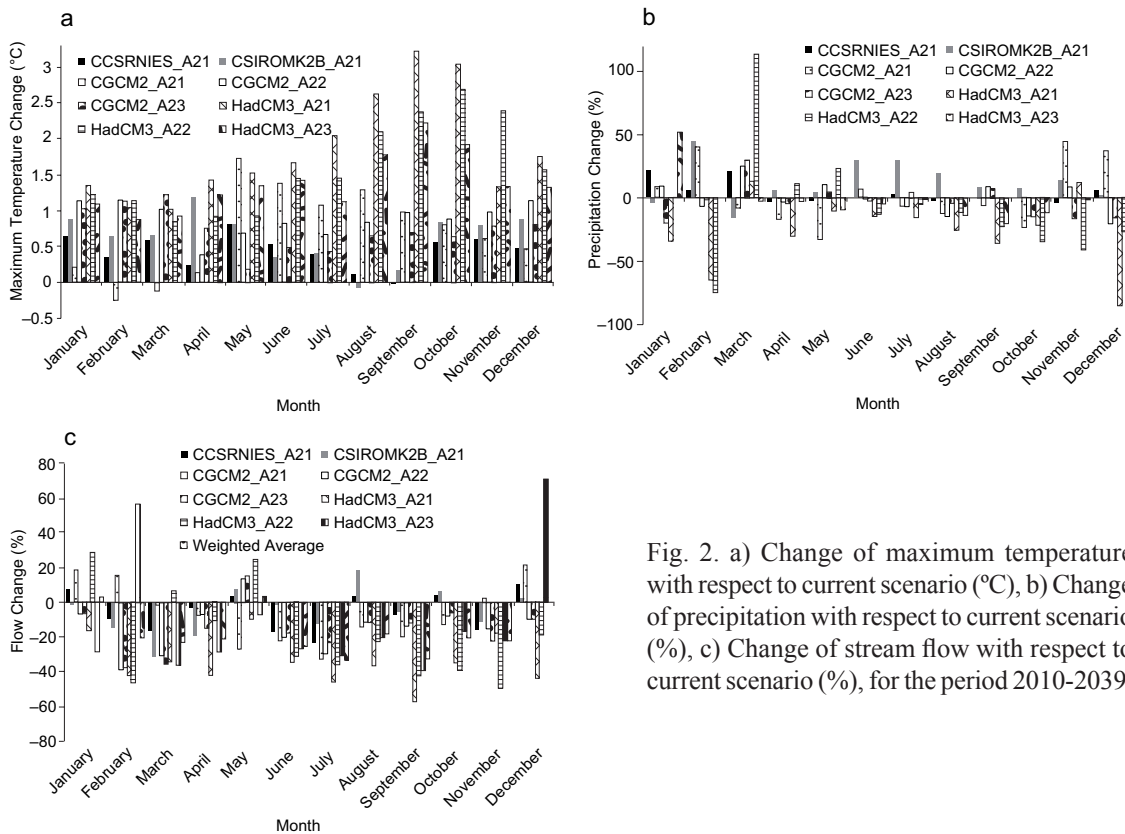


Fig. 2. a) Change of maximum temperature with respect to current scenario (°C), b) Change of precipitation with respect to current scenario (%), c) Change of stream flow with respect to current scenario (%), for the period 2010-2039.

was taken that there were no differences statistically significant to a confidence level of 95% of the mean, median, standard deviation, and distribution among the observed and estimated data, which gave a high degree of safety and certainty to the results shown in this paper. Further information about these concepts can be found in Ospina (2009) and Ospina *et al.* (2009a).

As shown in the above tables and figures, water availability can become a limiting factor (K) in the region, in terms of meeting the needs of the population, economic sectors and productive activities and this limitation will become more severe as the estimated climate changes take place. For this reason, the influence that over time water supply can have as a limiting factor in the baseline and climate change scenarios in some variables of the supply-demand ratio in the region is analyzed in the following section.

3.1 Water resources as a limiting factor

As mentioned in the methodology section, the extractable flow from a river basin in Colombia has been established at 10% of the net supply, which currently would be 1664.2 MCM and 1350.7 under projected climate change scenarios for 2010 to 2039 (see Table III, baseline scenario and weighted average scenario), that is, the values of K_a and K_{cc} respectively and the maximum possible SY.

With the values obtained of SR and SY from WEAP, the models were adjusted for the purpose of having a longer projection in time, after 2039, because the outcomes from WEAP in this case only evaluated the period 2010-2039. The models chosen were:

$$SR = 188.7e^{0.04t} \quad (1)$$

$$SY = 0.288t^2 + 4.024t + 179.0 \quad (2)$$

Both models provide a good adjustment and an R^2 of 99.9%. The percentage of the unmet demand was calculated taking in to account that the SR is the supply requirement or demand and SY is the supply yield or coverage of that demand.

Even though climate projections up to 2069 and 2099 were available, it was decided to generate climate projections based on equations 1 and 2, which take into account the output from WEAP where its results consider the population projections, rate of change of domestic, industrial and commercial consumption in the Sinú-Caribe river basin, and the percentage of losses in the supply system, among others. In addition, it was intended to do a coherent analysis of the 50-year economic life span of the dam, where the adaptation strategy was proposed.

Figure 3 represents the ratio of the required supply and the UD, taking into account the limiting factors of the water resources and the baseline scenario. A baseline adaptation scenario is also presented, in which the initial condition of the required supply is reduced by 20%, which leads to the same reduction in the supply yield.

The 20% reduction is a hypothetical value, which is possible and feasible if small changes are made with regard to a more efficient water use (a reduction in consumption from the current 35 to 30%, for instance), a decrease in water losses in the systems from 15 to 10%, and the installment of more efficient water devices for another 5%.

By following the curve of Figure 3 referring to the supply requirement or demand in the baseline scenario (SR), it is found that the unmet demand rises as it nears the limiting factors

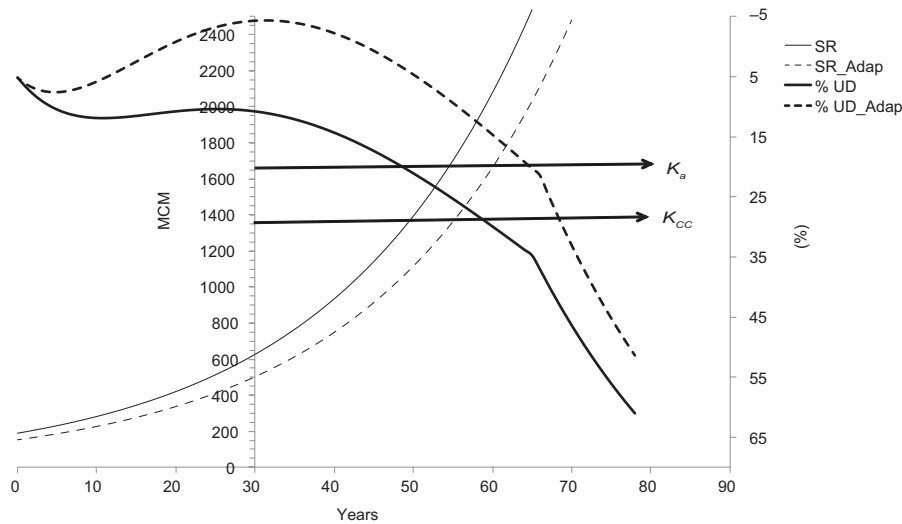


Fig. 3. Limiting factor for the projection of supply requirement – unmet demand, baseline scenario (SR, % UD) and baseline with adaptation scenario (SR_Adap, % UD_Adap).

and the K_{cc} would be reached around the year 2059 and the K_a in 2064. That is, the required supply would equal the maximum amount of water available approximately 5 years earlier due to the effects of climate change. In addition, the point of intersection of SR with the K_s , marks the beginning of a marked increase in the UD. The 0 on the horizontal axis of the graph represents current conditions (2009).

As the initial condition of the supply requirement is reduced by 20%, there is a displacement of this demand to the right (SR_Adap) of approximately 5 years at the points of intersection, and an important reduction in the UD, which counteracts and improves the effects of climate change to a certain extent (Table VI).

Table VI. Summary of the effect of climate change in time on SR and UD.

Limiting factor/Variable	Intercept year		Unmet demand (UD) %	
	SR	SR_Adap	SR	SR_Adap
K_{cc}^*	2059	2064	21.1	4.6
K_a^*	2064	2069	25.4	9.3

*Constants are assumed for the purpose of the corresponding comparisons; however, the climatic projections indicate much more adverse effects as time passes in the region. Therefore, the limiting factors would be gradually fewer, and would establish in turn new conditions or analysis scenarios.

A similar behavior of the UD is observed when the SY nears the determined limiting factors, the points where the UD starts to rise at a much faster rate. As seen in Figure 4, the SY is very similar in both scenarios and tends to converge in time, but the difference in the UD is significant.

By following the curves of SY in Figure 4, it is clear that under current conditions, the K_a would be reached around the year 2074, at the point where the UD in the baseline and adapted baseline scenarios is 34.8 and 20.2%, respectively, and where the increase in the UD is accelerated, while the K_{cc} would be reached in the year 2066 (8 years earlier), with an UD in the baseline scenario of 27.1% and in the adapted baseline scenario of 11.4%. If from this point on the SY becomes constant (K_{cc}) and thereby the increase in the UD is accelerated, by 2074 there would be a UD of 46.8% and 33.6% in the baseline and baseline adaptation scenarios, respectively, that is, above the values found in current conditions in terms of the net natural supply.

As mentioned in the methodology section, according to studies by the IDEAM, the SI can be calculated by obtaining the ratio between the demand and the supply. For the purposes of this study, the SR is assumed to be current or baseline (K_a) and projected demand under climate change (K_{cc}). The results of this ratio in percentages are found in Figures 5 and 6.

According to the IDEAM (2000a), five categories can be determined for this ratio: not significant (<1%, demand not significant with respect to supply), minimal (1-10%, very low demand), medium (11-20%, low demand), medium high (21-50%, considerable demand) and high (> 50%, high demand).

Up to the year 2001, the SI in the river basin was classified in the minimal category, that is, between 1 and 10%. According to the values shown in the above figures, the scarcity index

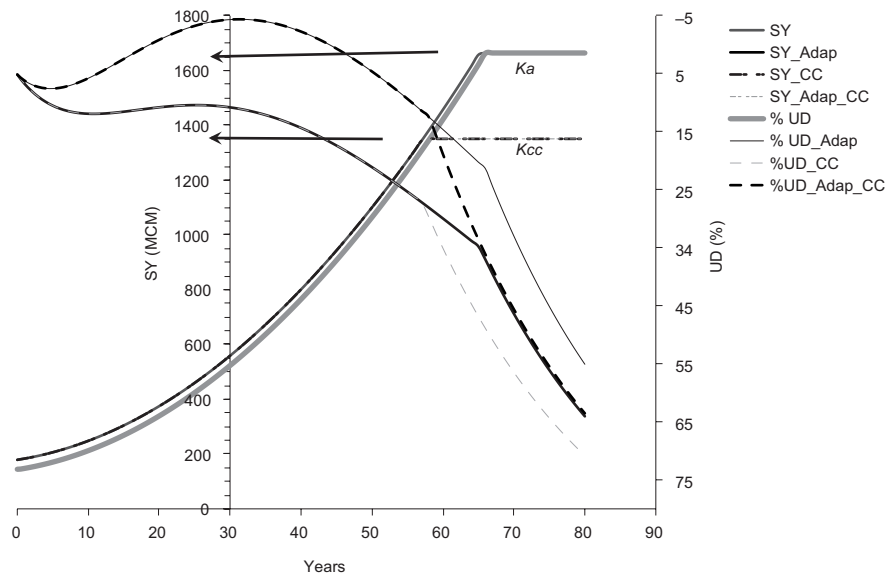


Fig. 4. Water availability as a limiting factor for the projection Supply Requirement-Unmet Demand, baseline scenario (SY, % UD) baseline adaptation scenario (SY_Adap, % UD), baseline with climate change (SY_CC, % UD_CC) and adapted baseline with climate change scenario (SY_Adap_CC, % UD_Adap_CC).

would not move up to the medium category until the year 2023 in the baseline scenario under current conditions Ka, and until the year 2018 in the baseline scenario with climate change Kcc conditions, and not until 2029 and 2024 respectively, in the adaptation scenario. In the latter case, the SI would be categorized as medium high, until it reaches the high category in the 2040s (see Figures 5 and 6).

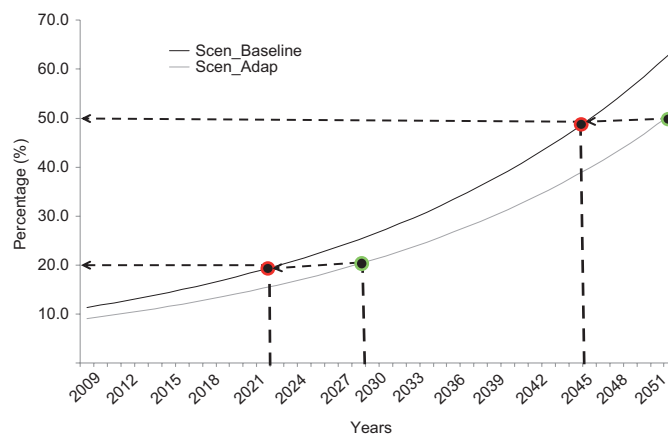


Fig. 5. Evolution of Scarcity Index over time. Calculation made with demand equal to Ka . Black lines refer to Supply Requirement (SR) for the baseline scenario (Scen-baseline). Gray lines refer to Supply Requirement (SR) with adaptation strategy (Scen-adap).

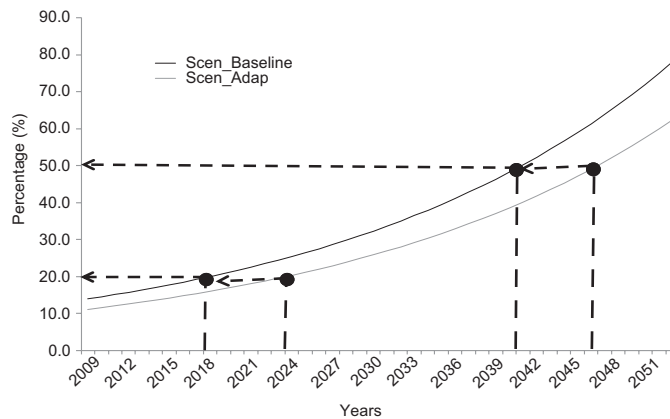


Fig. 6. Evolution of Scarcity Index over time. Calculation made with demand equal to K_{cc} .

3.2. Effects of optimization of hydropower generation on the supply-demand balance in the Sinú-Caribe river basin.

In order to obtain a better approximation of water use in the region of the Sinú-Caribe river basin, and to integrate the main productive sectors and activities, several scenarios are generated to mitigate and/or improve the negative effects projected on hydropower generation; with these scenarios it is also possible to observe the influence of the strategies on the unmet demand previously stated, with specific intervention in the most critical months of the year (February-April), when Ospina (2009) found a significant reduction in hydroelectric energy generation.

To create these scenarios, a new demand site called “pumping” is generated, whose purpose is to extract water downstream from the dam and provide water upstream or at the dam site (Fig. 1). These scenarios are generated with the weighted average, taking into account differing quantities of water to be recycled in three months and differing start dates for pumping. The criteria used to estimate the amount of water to be pumped was the difference between the current flows and those projected in the weighted average scenario for the three most critical months ($100 \text{ m}^3/\text{s}$), compared to the effect of a larger volume ($150 \text{ m}^3/\text{s}$) on the previous difference and a water loss of 10% in the process (Table VII).

Table VII. Values for the generation of optimization scenarios for hydropower.

Mo./Sc.	Flow ($100 \text{ m}^3/\text{s}$)		Flow $150 \text{ (m}^3/\text{s)}$	
	Pumping (%) ^b	Pumping 1 (%) ^a	Pumping 2 (%) ^b	Pumping 3 (%) ^a
January	20	0	20	0
February	40	26.4	40	26.4
March	40	28.5	40	28.5
April	0	45.1	0	45.1

^a Real percentage of the difference in flows.

^b Hypothetical percentages of the flow to be pumped.

In Figures 7 and 8, a substantial improvement in the storage volume in the dam can be clearly seen, and the resulting generation of energy. By carefully examining the scenarios Pumping and Pumping 1 or Pumping 1 and Pumping 2 and Pumping 3, it is evident that the beginning of the pumping activity and the percentage or quantity of water pumped are fundamentally important, which suggests at the same time the high sensitivity of hydropower to the change in the storage volume of the reservoir. Therefore, the storage volume cannot be allowed to reach critical levels for hydropower generation and pumping must begin before these critical levels are reached.

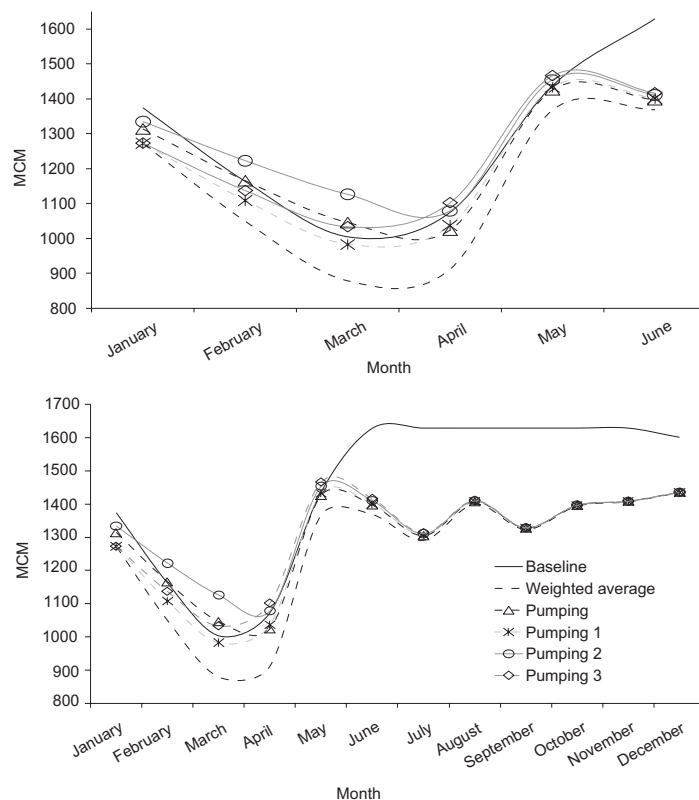


Fig. 7. Storage volume in reservoir under adaptation and/or mitigation scenarios.

The effects of these scenarios on the unmet demand in the river basin are shown in Figure 9. All the scenarios show a decrease in this variable, especially those where the pumping is started in January. It is important to note that in this case, the new demand site (Pumping) acts as a flow regulator and could also function to extract water to another site in case of extreme precipitation events in some months. According to projections (Fig.10), a major increase in the number of extreme events of precipitation is expected by the end of the century, thereby the flow regulation may avoid many disasters downstream, which have occurred previously.

It is also important to highlight that in scenarios not presented here, where pumping is more than 150 m³/s, the UD starts to appear where it does not previously exist (January-April) and increases significantly with respect to the weighted average scenario, although hydropower generation is

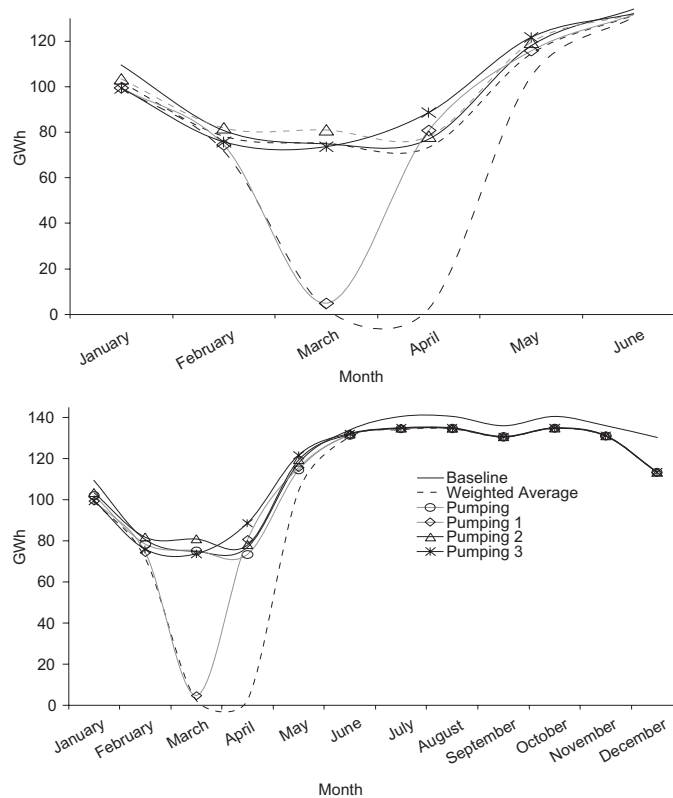


Fig. 8. Hydropower generation under adaptation and/or mitigation scenarios.

greater and reflects values superior to current ones. This should be analyzed in more detail since this situation could incite or foster conflicts between the productive sectors.

The concepts expressed above point out that the quantity of water to be pumped, and the schedule for starting such pumping, are two major factors when considering optimization of hydropower generation, as a strategy of adaptation.

Figure 11 shows the annual average changes in the generation of electricity, the storage volume in the reservoir and the unmet demand in the river basin, under hydropower optimization scenarios for the period 2010-2039.

Taking into account these figures, the best scenario would be that of Pumping 2, which results in a decrease in the baseline scenario of only 3.1 and 8.7% in hydropower generation and stored volume, respectively, and a significant decrease of 15.1% in the unmet demand in the weighted average scenario.

4. Conclusions

Water as a limiting factor in the Sinú-Caribe river basin highlights the fact that modifications in climatic-hydrological variables caused by climate change will have significant adverse effects on the physical and the biotic, like losses of physical, chemical, and mechanical properties of soils, changes in the flora and fauna structures, losses or changes in land cover and the economic and

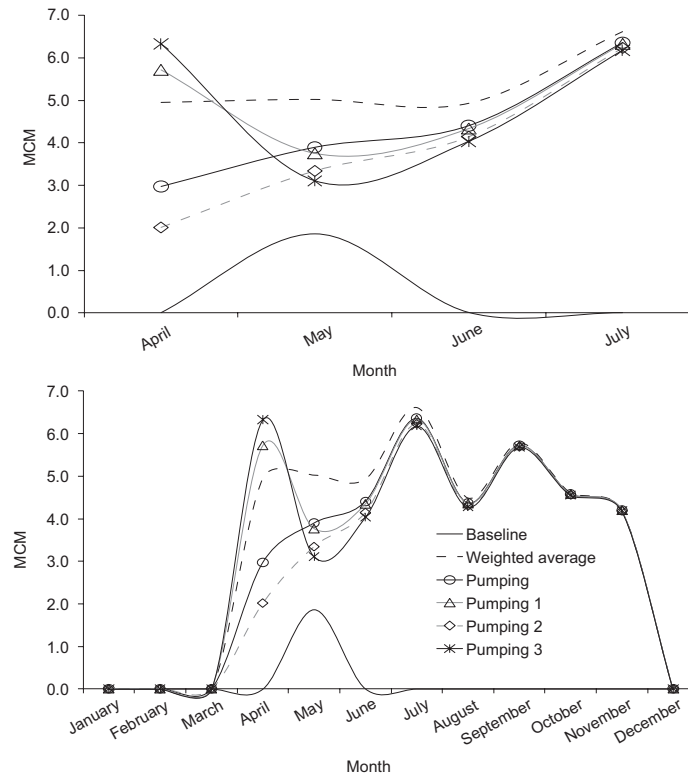


Fig. 9. UD in the Sinú-Caribe river basin, taking into account the optimization scenarios for hydropower generation.

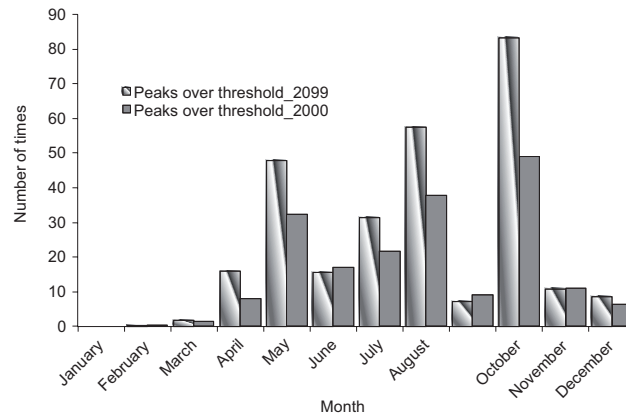


Fig. 10. Times that the 50 mm precipitation threshold is surpassed in the Sinú-Caribe, River Basin, 1975-2000 and 2070-2099, A2 scenario. Source: Ospina-Noreña *et al.*, 2009.

socio-cultural sectors of the region. According to the projections of the diverse variables that make up the analysis of supply-demand of water resources in the study area, it is estimated that for the period of the 2060s, the flow capacity of the river basin will be at a critical point, which could foster and incite serious regional conflicts. However, the negative effect on other elements of the analysis such as the scarcity index (SI) could occur much earlier.

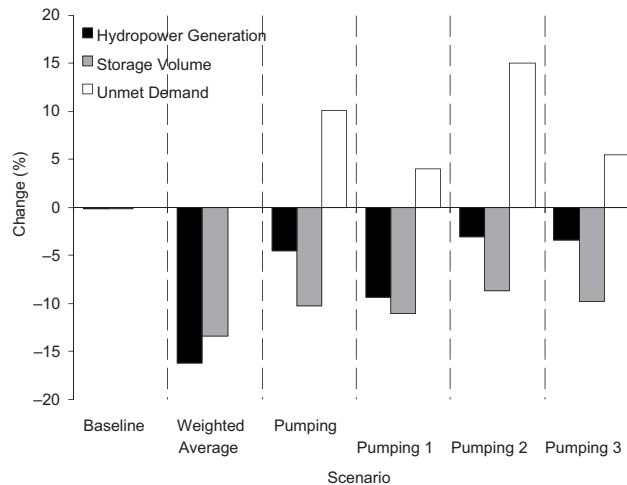


Fig. 11. Changes in hydropower generation, storage volume and unmet demand. Unmet demand: calculation made in the weighted average scenario, with the invested sign to better visualize the improvement in the UD, that is, a higher demand is met.

It was found that the projections of the supply requirement (SR) and the supply yield (SY) could be modified in two ways: 1) by changing the initial or current conditions of water demand, and therefore supply, which could be made through regulations, higher efficiency in the supply and return infrastructure, management of water use strategies, and change in priorities, among others, and 2) by modifying the rates of change, which could be made by intervening the projections of the different variables involved in the demand, like the population growth, and increase in domestic, agriculture and commercial water use.

The proposed adaptation scenarios show that intervention in the initial conditions or in the rates of change of the demand at any time are beneficial and counteract in some way the adverse effects of climate change. However, this only saves some time, making it necessary to move forward with other studies on the adaptation and mitigation of the impact of climate change, including characterization and response to the different physical and biotic factors in terms of possible changes in the region, territorial legislation, and sectorization of agriculture and cattle ranching in areas appropriate for these activities.

Based on the projections for the different scenarios, the current conditions of the degree of aridity and degradation in terms of biotic-physical factors of the river basin and the scarcity and stress on water resources will exacerbate with time. In this sense, the conservation of forests, vegetation and other elements of hydrological regulation, as well as the recuperation and reforestation of degraded and viable forestry areas, must be undertaken along with studies to redistribute productive agricultural areas and the prevention of their expansion.

The strategies chosen for the optimization of hydroelectric energy generation in the most critical months provide a positive alternative to mitigate the projected adverse effects of potential climate changes in the region, given that they result in less decrease in the electrical energy generated and a greater storage volume of the reservoir, in comparison to the baseline scenario, in addition to a lesser unmet demand in the weighted average scenario. The optimization of electrical energy strategies

show that it is fundamental to determine with a high degree of precision the exact quantities and timing of the flow to be pumped, so that the supply-demand ratio of the different sectors and/or downstream activities improves or is maintained, otherwise, it becomes a negative factor in this ratio, starting or causing diverse conflicts over water resources.

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