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Assessment of the Potential Hydrological Impacts of Climate Change in Quebec—Canada, a Refined Neutral Approach

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Abstract: There is currently much discussion as to whether probabilistic (top–down) or possibilistic (bottom–up) approaches are the most appropriate to estimate potential future climate impacts. In a context of deep uncertainty, such as future climate, bottom-up approaches aimed at assessing the sensitivity and vulnerability of systems to changes in climate variables have been gaining ground. A refined framework is proposed here (in terms of coherence, structure, uncertainty, and results analysis) that adopts the scenario–neutral method of the bottom–up approach, but also draws on some elements of the top–down approach. What better guides the task of assessing the potential hydroclimatological impacts of changing climatic conditions in terms of the sensitivity of the systems, differential analysis of climatic stressors, paths of change, and categorized response of the scenarios: past, changing, compensatory, and critical condition. The results revealed a regional behavior (of hydroclimatology, annual water balances, and snow) and a differential behavior (of low flows). We find, among others, the plausible scenario in which increases in temperature and precipitation would generate the same current mean annual flows, with a reduction of half of the snow, a decrease in low flows (significant, but differentiated between basins), and a generalized increase in dry events.

Keywords: climate change; scenario–neutral; refined approach; hydrological impact; paths of change; sensitivity analysis

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1. Introduction

The global climate has changed relative to pre–industrial times, and several lines of evidence show that these changes have had multiple impacts [1]. Estimating the effects of climate change on natural and human systems and, in turn, on numerous sectors is one of the most relevant issues on the international agenda, since it is already affecting every inhabited region across the globe [2]. This has serious consequences at all levels in the maintenance of natural resources that sustain societies and all other forms of life on Earth.

The hydrological water cycle is central to the climate, ecology, and biogeochemistry of our planet [3]. Indeed, one of the major concerns regarding climate change is related to its effects on the hydrological cycle [4–6] and, therefore, on the three principal axes of integrated water resource management: use, conservation, and water–related disasters. A large number of troubling effects (e.g., reduced water availability, alteration of ecosystems, increased risk of droughts and floods) justify efforts to assess and manage the possible impacts of climate change, despite the inherent uncertainty [7].

The assessment of the impacts of climate change on many systems has typically been studied through "top–down", scenario–led approaches that begin with anticipating future greenhouse gas concentrations to feed global climate models (GCMs), which outputs serve, once downscaled and bias–corrected [8–15], to force impact evaluation models and to analyze the evolution of the studied systems.

The vast majority of climate change impact assessment studies around the world have relied on top–down variants [12,14,16–22]. Likewise, their application has been predominant in Canada [5,23] and in the province of Québec [24–30]. These methods are well suited to global and regional long-term contexts, but remain quite impractical for site-specific water resources management studies [31]. Few anticipatory or planned adaptation decisions originate from such studies [32]. Their main limitations are that they require data tailoring to be used in impact models [33], focus on a pool of projected climate scenarios, and do not sample from the full range of climate futures [31], making their usability limited in the context of decision support [7].

As alternatives, the so–called "bottom–up" approaches aim at identifying critical conditions under which water resource systems are vulnerable. These procedures differ from top-down approaches because they do not directly assess the system response to projected climate change issues of GCMs. Instead, they focus on evaluating water resource responses to a wide range of plausible future climatic conditions [34]. These belong to the possibilistic domain, unlike the top–down approach, which belongs to the probabilistic domain. Given the context of deep uncertainty inherent in climate change, bottom–up approaches have begun to take center stage [7,32,35,36]. Bottom–up methods include information–gap decision theory [37], decision scaling, also referred to as climate–informed decision analysis or CIDA [7], risk–informed decision–making [38], and scenario–neutral approaches [32]. This study explores the latter to allow the evaluation of a wide range of climate projections, larger than typical top–down approaches, with low dimensionality and without resorting to downscaling.

The term "scenario–neutral" implies assessing the impact of a plausible range of climate changes rather than the outcome of some greenhouse gas concentration scenarios, making it scenario–neutral [32]. It refers to the generation of climate scenarios in ways other than those exclusively from projections derived from climate modeling. Its use in assessing the potential impacts of climate change on water systems is increasingly widespread [32,33,36,39–57]. It has been performed in Europe, Australia, Asia, Africa, and the United States. In Canada (Québec), a recent study [58] evaluates the difference in climate sensitivity of the hydrology of two contrasted catchments.

Neutral scenario approaches resort to various methods to generate exploratory scenarios of the future climate. The change factor method (also referred to as 'simple scaling', 'delta method', or 'perturbation method') has been selected for the present study. It has been used in several studies to issue perturbed meteorological series [21,22,32,46,54,55,59]. Even though the change factor method is not suitable for accounting for changes in many attributes such as intermittency, autocorrelation, and extremes, or for complex combinations of changes [45], when the scenario–neutral space is coupled with climate projections issued from climate modeling, it becomes possible to understand the likelihood and to identify the possible timing of the changes [60,61].

The overarching aim of this paper is to understand how changes in climatic variables are translated on hydroclimatological components of interest, specifically mid and low–flow conditions, the latter under a differential analysis of the basins, rarely evaluated in the context of the impact of climate change [62]. The study was carried out in six basins located in the province of Québec (Canada) through a simple, but refined framework that uses the delta change of the neutral approach to generate climate scenarios that feed the impact model and concludes with the analysis of the system's performance (the six basins). The results are also evaluated in terms of the system's sensitivity, differential analysis of climatic stressors, the categorized response of the scenarios (past, changing, compensatory, and critical conditions), and paths of change. The outcomes showed a regional behavior (of hydroclimatology, annual water balances, and snow) and a differential behavior (of low flows). Various scenarios of interest were identified, which are particular to each selected performance indicator. This offers a novel perspective for the study area in terms of the contributions that the results represent in the advancement of climate risk management.

2. Materials and Methods

2.1. Study Area and Data

Six natural regime catchments tributaries of the large St. Lawrence River basin, located in Quebec, Canada (Figure 1), were chosen for this study. Their main characteristics are given in Table 1. The catchment areas vary from 512 to 761 km^2. Five basins have gentle slopes (4–9% gradient), and only the 052805 catchment has a moderate slope (13.4%). The total precipitation (P) ranges from 1000 to 1260 mm/year, a substantial part of which accumulates as seasonal snowpack (October–April) and the rest as rainfall (mostly May–September). The highest monthly precipitation occurs in July. The second highest precipitation is in October, slightly less than in July. The lowest monthly precipitation is in February, but overall, precipitation is quite uniform (changes are small and gradual from one month to the next). The mean annual temperature (T) ranges from 3 °C to 5 °C, with the maximum monthly mean in July and the minimum monthly mean in January (Figure 2). Snowfall is very similar in all catchments, ranging from 190 to 225 mm/year (snow water equivalent or SWE). The evapotranspiration (ET) varies from 435 to 570 mm/year. ET and SWE are estimated by the model.

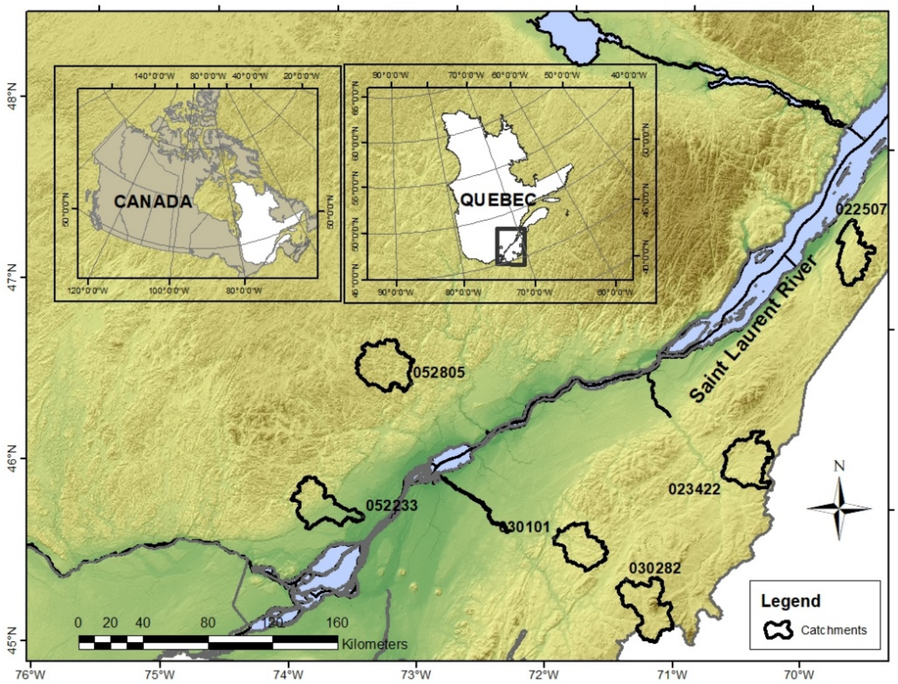

Figure 1. Localization study area.

Table 1. Main catchment characteristics and climatology. P: total precipitation. T: mean annual temperature. ET: evapotranspiration. SWE: snow water equivalent.

ID	Name	Area (km^2)	Forest Land Cover (%)	Slope (%)	P (mm)	T (°C)	ET (mm)	SWE (mm)
022507	Du Loup	512	77	5.9	1000	3.0	435	219
023422	Famine	695	75	4.1	1160	3.6	482	225
030101	Nicolet Sud–Ouest	549	60	5.8	1170	5.0	557	191
030282	Au Saumon	736	79	7.9	1260	4.4	549	204
052233	L'Achigan	633	59	6.4	1110	5.1	573	219
052805	Du Loup	761	83	13.4	1030	3.0	485	210

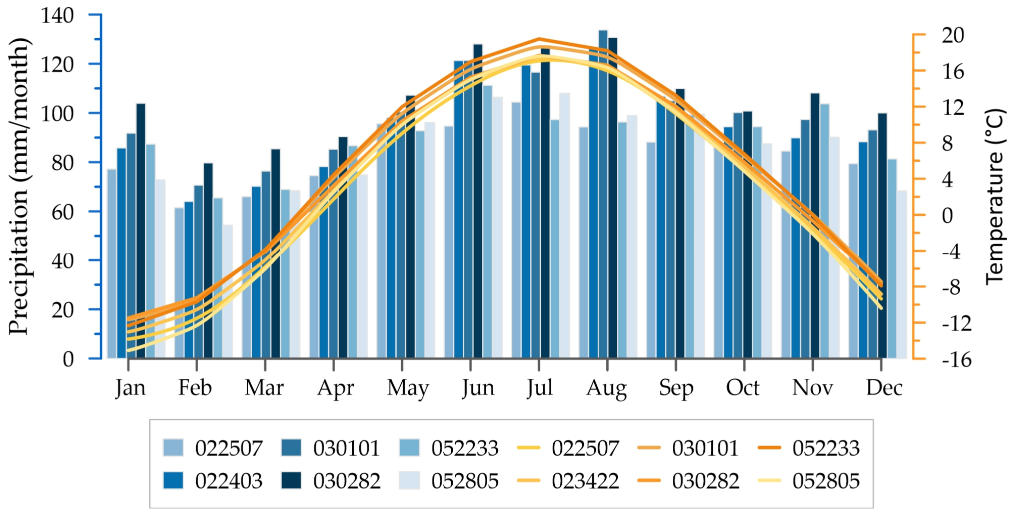

Figure 2. Monthly precipitation and temperature averages of all basins.

Streamflow usually peaks in April when the snowpack melts. A second, but smaller peak occurs in mid–autumn when the evaporation rate lessens, and the snowpack has yet to take form. Although annual minimum flows occur during the coldest months of winter, low flow conditions also occur in mid–summer when evapotranspiration peaks. The dominant land use in four catchments is Forest (59–83%), while the 030101 and 052233 catchments are an important part of agricultural and urbanized lands (32% and 35%, respectively) [63].

Daily observations of temperature and precipitation are available as gridded data after kriging observations at 0.1° resolution and cross–checking the quality of the estimated data. Selected watersheds are located in zones with the best data quality, given the high density of the network of gauging stations [64]. Flows (taken from the Quebec hydrometric network) and T and P observations were provided by [64]. A burned 50 m digital elevation model (DEM; resampled to 500 m) and land use information are provided by Quebec Ministère de l'Environnement et de la Lutte contre les Changements Climatique [65]. Soil textures are assessed based on percentages of clay, silt, and sand provided by [66].

2.2. Methodology

An assessment of the effects of changing climatic conditions, including past and future scenarios, on the hydroclimatology of a set of catchments in Quebec, Canada, located in different zones of the province, was carried out using the neutral approach proposed by [32]. Here, we propose a refined version at the system modeling stage (calibration focusing on the evolution of medium and low flow conditions) and at the performance evaluation stage (with a rigorous selection of performance metrics and a novel analysis of the response of the systems). This analysis is carried out within the possibilistic domain, focusing on the evolution of the water regime through a selection of hydrological and hydroclimatic indices and indicators. The methodological configuration of the proposed refined neutral approach is illustrated in Figure 3, which is shown in the context of the framework of the design of climate change adaptation measures. It consists of three stages: the generation of system forcings, modeling of potential impacts, and evaluation of system performance.

Forcing generation.

The generation of forcings (the climatic variables used for the stress test) begins with the definition of an exposure space (all the scenarios of interest to be evaluated), for which the perturbation method, the variables to be analyzed, their limits, and the rate of change (delta) of the variables must be defined. To obtain the forcings, we used the delta method of the neutral approach, a constant and incremental annual change that uses a reference climatology (30–year averages of the climatological variables that represent current conditions). Daily temperature and total precipitation from 1985 to 2014 (30 years of recent validated data) were used.

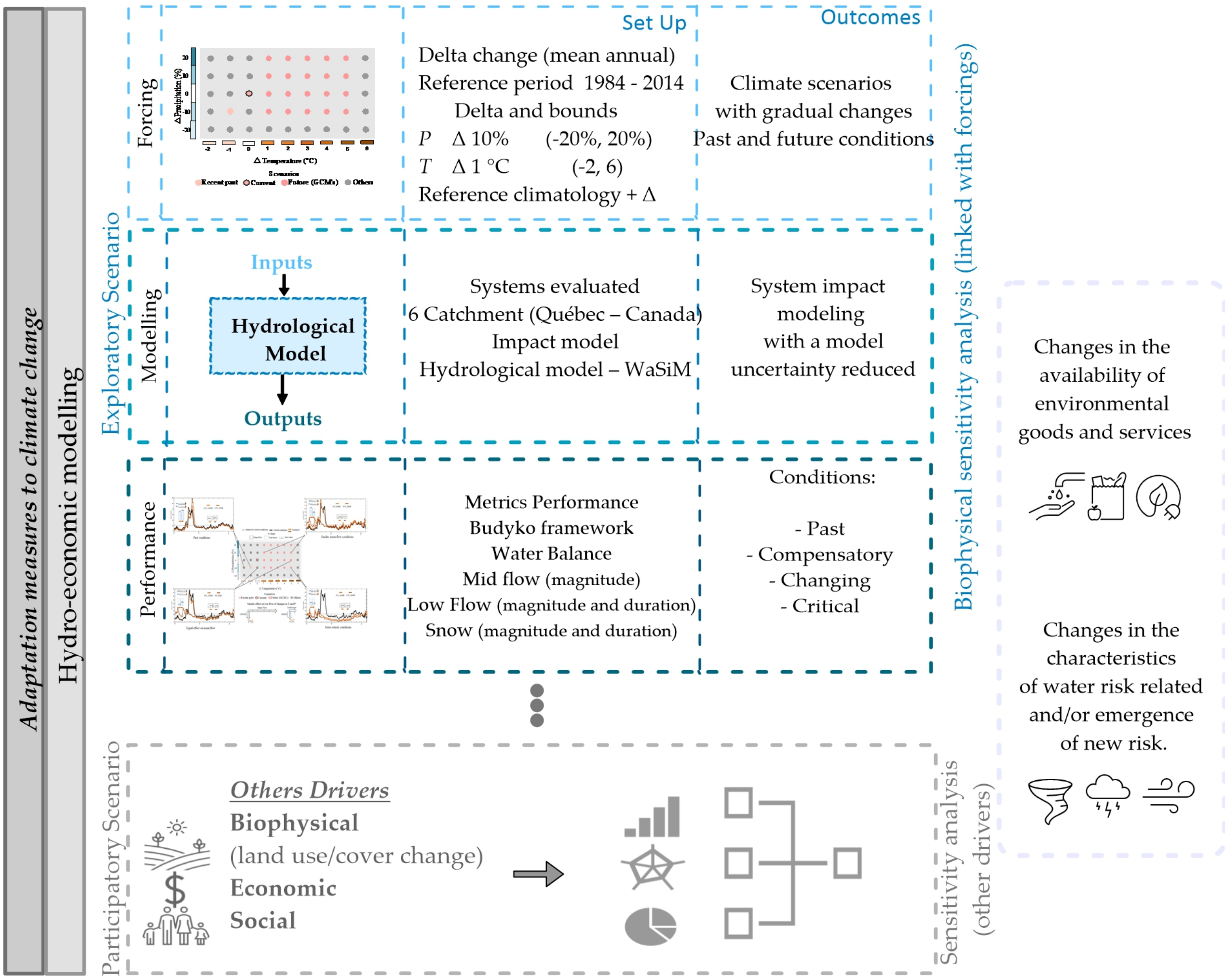

Figure 3. Modeling set up. The design of adaptation measures includes hydro–economic modeling composed of exploratory and participatory scenarios. In the former (in blue), three consecutive processes are shown in the rows: forcings, modeling, and performance, and in the middle and right–hand columns, respectively, the configuration and results obtained in this study. These three steps together constitute a sensitivity analysis of one of the biophysical components of the systems. In the lower part (in gray), the second scenarios are listed, which involve other biophysical components as well as the socioeconomic components that analyze the system's vulnerability to other drivers. Finally, the central issues addressed by climate change adaptation are summarized on the right side (in purple).

The available projected values (based on the Coupled Model Intercomparison Project —CMIP5) of the changes in precipitation and temperature in Quebec [67,68] were used as a reference to define the limits of the exposure space. These limits were extended beyond the highest and lowest values projected for 2050 in the aforementioned studies, including the evaluation of past conditions, since the beginning of the century. To generate each climatic scenario, we start from the reference climatology (30–year averages of observed T and P data) and an additive perturbation (Equation (1)) is used for temperature in increments of 1 °C (from −2 °C to 6 °C) and a multiplicative perturbation (Equation (2)) in increments of 10% for precipitation (from −20% to 20%). In this step, all scenarios of the exposure space are obtained and provided to the hydrological model.

$$Tmod = Tobs + \Delta T \quad (1)$$

$$Pmod = Pobs * (1 + \Delta P) \quad (2)$$

where *Tmod* is modified temperature, *Tobs* is observed temperature, and ΔT is the temperature delta, all in °C in increments of 1 °C. *Pmod* is modified total precipitation, *Pobs* is observed precipitation, both in mm, and ΔP is the precipitation delta, expressed as a fraction and in 10% increments, e.g., for a 20% decrease in precipitation, ΔP is −0.2.

Modeling of potential impacts.

To assess the potential impacts of changing climatic conditions, a robust impact model (in this study, a hydrological model) that is a representation of the behavior of the systems studied, which has already been used successfully for the same study area [63,69] as well as in another neutral scenario study [33], was used. To minimize the uncertainties associated with the impact model, an optimal calibration strategy was applied to avoid poor and biased simulations after a change in climate [70], which included: the selection of the type of technique and algorithm of optimization [71], of the objective functions [72], and of the model performance metrics [73,74]. In this second step, the response of the systems to the forcings (generated in the first step) are simulated through the impact model, which generates the variables used in the calculation of the impact indices and indicators as outputs.

Hydrologic model.

The physically based hydrological model WaSiM–ETH [75], in its version Richards–9.02.00, was adopted for hydrological simulation (here called the impact model) at a daily time step, using daily temperature and precipitation time series as inputs. The spatial domain is a 500 × 500 m^2 raster. Spatial interpolation applies Thiessen for temperature and inverse distance weighting for precipitation. Snow accumulation and snowmelt were modeled using a degree–day factor method [76], and the Hamon equation was used for evapotranspiration [77]. The soil–water balance was estimated using the Richardson equation within the unsaturated zone.

Calibration and validation.

Eight free model parameters were calibrated with a multi–objective optimizer, called Pareto–archived dynamically dimensioned search (PA–DDS) [78], with 500 runs to identify the optimal parameter sets, using observations for the period 1980 to 1989 to calibrate and the baseline period 1990 to 1999 to validate. After testing several objective functions in combination with other different variants (flow transformation) typically used to represent better low flow [79–81], the objective functions KGE–KGE square root ($Q^{0.5}$) were selected, which showed a better representation of mid and low flow.

To evaluate the hydrological model performance, three statistical indicators were used: Kling–Gupta efficiency (KGE, [82]; Equation (3)), the root–mean–square error normalized by the mean of the flows (NRMSE; Equation (4)), and the percent bias (PBias; Equation (5)). PBias absolute values less than 10% are considered very good performance, and 10% to 15% a good performance [83]; a negative value indicates an underestimation and a positive value, an overestimation. *KGE* values range between −∞ and 1, of which 1 is a perfect fit [84]. To compare the *RMSE* values across different catchments, the metric is divided by the mean of the observed values over the period evaluated [85].

$$KGE = 1 - \sqrt{(r-1)^2 + (\propto -1)^2 + (\beta - 1)^2} \quad (3)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (Q_s - Q_o)^2\right]^{1/2} \quad (4)$$

$$PBias = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_s)}{\sum_{i=1}^{n}(Q_o)} \quad (5)$$

where n is the number of samples, r is the correlation coefficient (observed and simulated values), α is the ratio between the standard deviations, β is the bias, Q_o is the observed values, and Q_s is the simulated values.

Assessment of the system performance.

To assess the system performance to the stress tests, an indicator–based analysis was carried out in four stages. First, the criteria for the selection of indicators are defined: (1) area of application, in this case, water resources management, specifically for mid and low–flow conditions; (2) correspondence between the resolution and type of the perturbation (nature of the neutral approach method used to generate the forcings); (3) representativeness of the hydrological processes and components of interest; (4) indicators appropriate for climate change impact studies; (5) relevancy for cold regions; and (6) complementary to the evaluation of the other drivers (participatory scenarios). Second, a set of candidate indicators are selected by the previously established criteria, not shown here for conciseness. Third, all candidate indicators were calculated using the outputs of the impact model to evaluate every single climate scenario of the exposure space. Fourth, an analysis of the results obtained with each candidate indicator was carried out to select a limited number of key indicators. This task involved discarding indicators that provided redundant information and identifying the most representative indicators for each system performance category.

Finally, different categories of performance evaluation indices and indicators were chosen. Selected components of the water cycle include: ratio inputs/outputs, total precipitation/total evapotranspiration [62,86,87]; the Budyko framework, the relationship between aridity and evaporation indices [88–90]; total snowfall, maximum solid precipitation during the winter [91,92]; and number of snowy days [91,92]. Mid–flow conditions: mean annual flow [86,93–95]; low–flow conditions: 7–days low–flow value with a 2–year return period (7Q2; [81,91,92]). Duration of hydrological events of interest [62,96]: short dry events—SDE (events of two consecutive weeks with flows below 7Q2 of the current conditions), medium dry events—MDE (events of four consecutive weeks with flows below 7Q2 of the current conditions), with the last two indicators being the sum of the events for 30 years [91]. The values of the indicators correspond to the averages of the period evaluated, 30 years, except for the indicators of dry events. All indicators corresponding to low flow conditions are calculated in the summer period (May to October). As a result of this third and final step, the categorized indices and indicators are obtained that allow an exploratory analysis of the evolution of the water systems studied in a changing climate.

3. Results

3.1. Exposure Space

Figure 4 shows the exposure space, which, as its name indicates, is the space comprising each of the scenarios to which the systems are exposed (described in the methodology section and summarized in Figure 3), representing the climatic conditions in terms of changes in temperature and precipitation of the recent past in the year 1948 [68,97] and a variety of future scenarios comprising the scenarios projected by the climate models [68] of the evaluated horizon.

3.2. Performance of the Hydrological Model

The selection of the objective functions used to calibrate and validate, as well as the performance metrics of the model, were focused on an adequate representation of mid and low–flows. The multi–objective optimization shows the best results in all six catchments with the KGE–KGE square root ($Q^{0.5}$) functions having been employed to calibrate both flow conditions [98], with even better performance than transformed inverse on flows, reported as other optimal objective function for calibrating low–flows [79,80]. Two objective functions are used to adequately represent both low and mid flow in the same set of parameters. The results of the hydrologic model performance in each catchment are shown in Table 2.

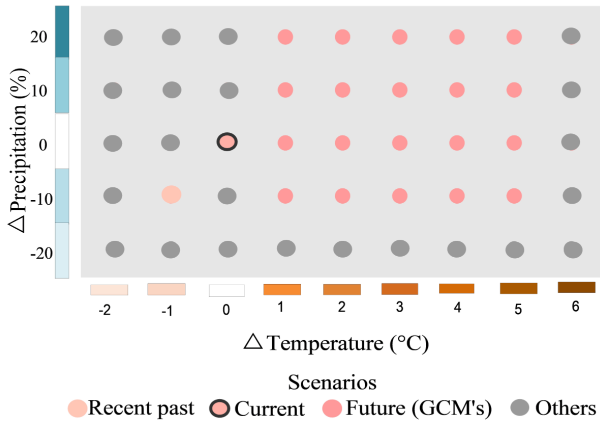

Figure 4. Exposure space. The salmon circle with a black border represents current conditions, the pale salmon circle represents the recent past, the dark salmon circles represent projected scenarios from GCM, and the gray circles are other scenarios. The Y–axis shows precipitation changes in percent (%), and the X–axis shows temperature changes in °C.

Table 2. Calibration and validation outcomes. KGE: Kling–Gupta efficiency. NRMSE: root–mean–square error normalized by the mean of the flows. PBias: percent bias.

ID	Calibration			Validation		
	KGE	**NRMSE**	**PBias (%)**	**KGE**	**NRMSE**	**PBias (%)**
022507	0.86	0.78	−0.35	0.81	0.72	4.61
023422	0.82	0.87	2.96	0.82	0.94	−2.46
030101	0.80	0.92	2.03	0.73	0.90	11.9
030282	0.79	0.87	2.79	0.67	0.89	14.0
052233	0.88	0.76	0.27	0.81	0.91	4.20
052805	0.89	0.55	1.07	0.84	0.61	3.72

3.3. System Performance Outcomes

The results that reveal the performance of the system, through the evaluation of several indices and indicators, under different climatic scenarios are presented in the following order: a macro view involving climatology and hydrology through the Budyko framework, a global hydrological response of the basin through the water balance, and the mean flows. Likewise, the most representative conditions and components of the hydrological cycle of the pluvial and snow periods are evaluated, which are, respectively, low–flows and snow.

Hydroclimatological changes. The Budyko framework has been employed to associate climate variables with hydrological variables through two indexes: the evaporative index—EI, the ratio between actual evapotranspiration—E (that is ET) and precipitation (P), and the aridity index—AI, the ratio between potential evapotranspiration (E_p) and precipitation. All variables with which the Budyko indices were calculated are generated by the hydrological model. The results obtained for all the scenarios in each of the basins are presented in Figure 5. The points on the lower left correspond to the scenarios of past conditions (lower left of the exposure space), the current conditions are in the position EI~0.45 and AI~0.56, and the points on the far right correspond to the less favorable scenarios of higher temperature and lower precipitation (lower right corner of the exposure space). The past and current hydroclimatological conditions are located at a very close point. Under all of the evaluated scenarios, all basins remain in the humid hydroclimatic classification. However, three basins (030101, 052233, and 052805) move from the energy–limited zone to the water–limited zone under the higher temperature and lower precipitation scenarios (the scenarios corresponding to the lower right corner of the exposure space).

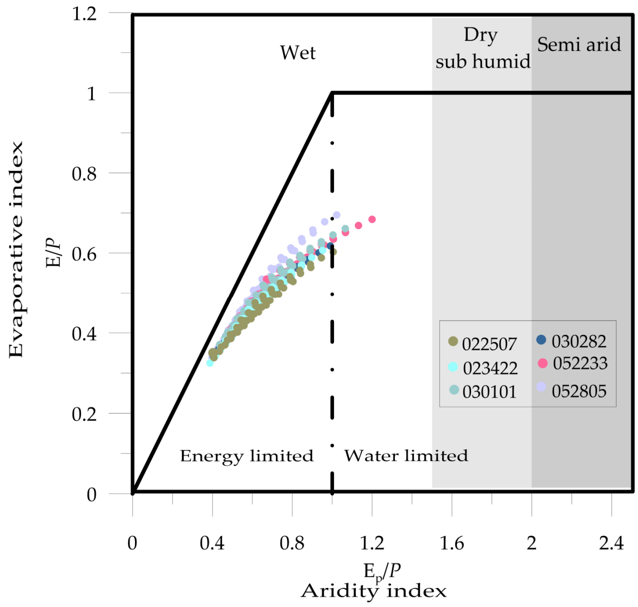

Figure 5. Budyko framework. The Y–axis represents the evaporative index, and the X–axis the aridity index. The response of each basin is represented by the colors shown in the box at the bottom right. From left to right, the climatic zones are shown: humid, dry sub–humid, and semi–arid in white, light gray, and dark gray, respectively. The vertical dotted line marks the division for energy–limited and water–limited zones.

Global catchment performance. Figure 6 illustrates the behavior of each catchment in terms of water balance for two groups of scenarios: those only associated with temperature changes (left part of the figure) and those only associated with changes in precipitation (right part of the figure). Here, the watershed response is evaluated as the changes in the input–output relationship of the water balance in each basin regarding changes in the mean annual temperature and for changes in the percentage of total annual precipitation, i.e., the response of the systems to each of the forcing factors separately. In basins 030101, 052233, and 052805, the gradient of change in the water balance due to temperature is more pronounced than in the other catchments.

Mid–flow conditions and snow: Figure 7 presents the response of basin 022507, which is representative of the behavior of the six basins since the results of the changes in the interannual mean flows (QInAnn), the interannual snowfall (SnInAnn), and the interannual mean number of snow days (SnD) were similar in all six basins. The analysis was performed through four groups of evaluation of the response of the systems to changes in the forcings, in which the main findings are synthesized in terms of key scenarios to understand different system conditions.

Past conditions: In the upper left are shown two scenarios (ScPast1: −2 °C, −10% P and ScPast2: −1 °C, −10% P) representing the recent past conditions of the studied basins. According to [66], the temperature increase between 1950 and 2012, for the basin 022507 was about 1 °C, for the other basins was about 2 °C, and the precipitation increase for all basins was close to 10%. For ScPast1, the change in QInAnn is −9%, for ScPast2 it is −12%, and the changes in SnD are 6% and 12%, respectively. The changes in SnInAnn are 2% and 10%. All variables increased in both scenarios.

Compensatory conditions: The upper right–hand side shows two scenarios (ScComp1: 1 °C and 10% P and ScComp2: 5 °C and 10% P) that represent the compensatory conditions for SnInAnn and QInAnn, respectively. In this case, the future conditions under which the same values of the current conditions of these two variables would be maintained. In the ScComp1 scenario, SnInAnn is unchanged, QInAnn increases by 12%, and SnD shows a slight decrease of −6%, while in the ScComp2 scenario, QInAnn is unchanged, SnInAnn is halved, and SnD is reduced by −34%. Although the differences in the changes in QInAnn between these two scenarios are minor, the changes in the hydrograph are considerably different since, under the ScComp2 scenario, the spring's highest flow peak disappears.

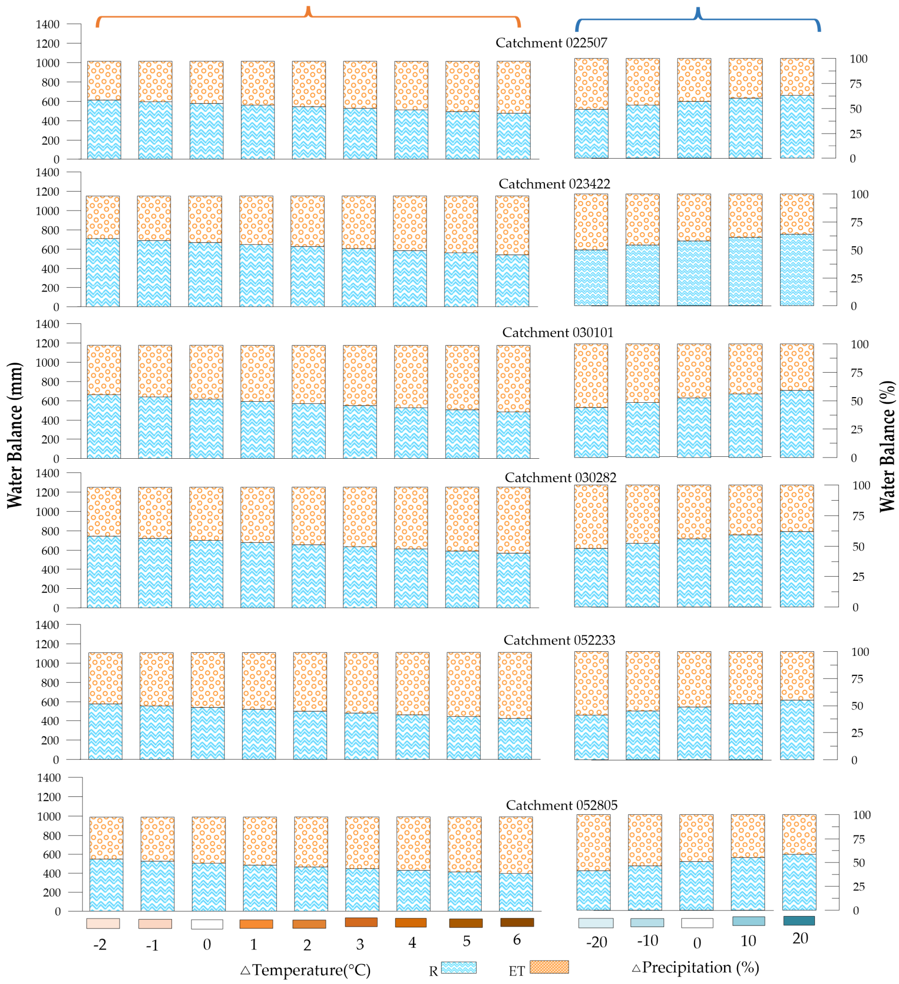

Figure 6. Water balance. Each bar represents the total multiannual precipitation for each watershed. The orange fraction of each bar represents evapotranspiration (ET) and the blue fraction represents runoff. The figure is divided into two parts, the first corresponding to constant precipitation (current conditions) and changes in temperature (presented in the left part of the figure, those included in the orange key) and the second corresponding to a constant temperature (current conditions) and changes in precipitation (presented in the right part of the figure, those included in the blue key). On the left, the figure shows the water balance in mm to represent the total precipitation values of each basin; on the right, the water balance is presented in percentages so that they are graphically comparable with the results of the balances associated with the change in temperature.

Changing conditions: Scenarios with equal changes in QInAnn, a decrease of −15% (ScChang1: 0 °C and −10% P and ScChang2: 5 °C and 0% P), are shown on the lower left; however, the distribution of flows throughout the year, as seen in the hydrograph, are completely different. While in ScChang1, where the decrease in QInAnn is only attributed to the 10% decrease in precipitation, the shape of the hydrograph is maintained, but with a slight decrease in flow during the spring flood, with a marginal reduction in SnD and a small −12% reduction in SnInAnn. In ScChang2, the same decrease in QInAnn is only associated with the 5 °C increase and generates a drastic change in the hydrograph without the large spring flood, but with increased flows during the winter period, with a reduction in both SnD and SnInAnn of −35% and −58%, respectively.

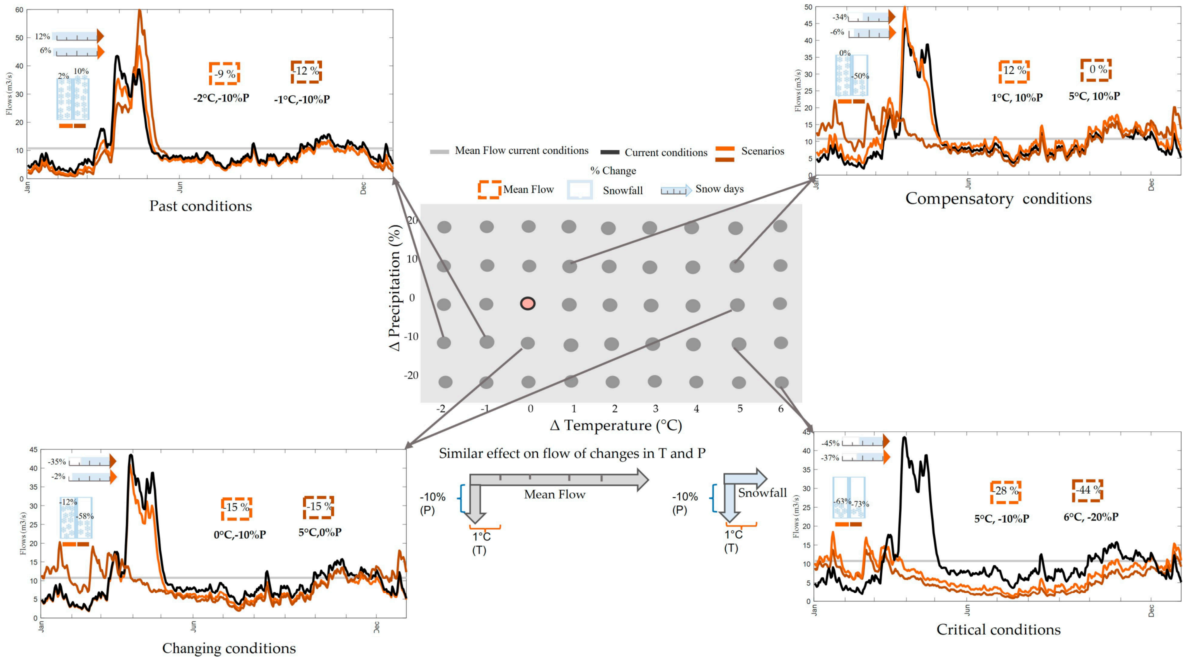

Figure 7. Mid–flow conditions and snow. In the center of the figure is the exposure space (explained in Figure 4), where arrows indicate which pairs of scenarios are referred to in each of the hydrographs. Below, represented by thick arrows, are the equivalent changes or compensatory scenarios in the vertical sense precipitation and in the horizontal sense temperature of the mean annual flows (gray) and snowfall (blue). Each graph shows the interannual hydrograph of recent conditions (black line) and of two evaluated scenarios (shown in orange colors, the darker one being the one with higher temperature and lower precipitation). The gray line represents the average flows of the current conditions. The values within the graph correspond to the percent change of each scenario concerning the current conditions. Within the dashed line boxes are the values of the changes in mean flows for each scenario. The percentage change of snowfall is represented by the light blue bars, where the white part represents the loss of snow and the part with snowflakes is the amount that remains. The percentage change of snow days is represented by the pencils, where the color of the tips represents the scenario to which it belongs, the light blue part represents the percentage of days with snow, and the white part is the decrease in days with snow.

Critical conditions: Two scenarios are shown at the bottom right (ScCtri1: 5 °C and −10% P and ScCrit2: 6 °C and −20% P), representing the critical conditions (two of the least favorable scenarios evaluated, higher temperature and lower precipitation). ScCtri1 shows a very important decrease in QInAnn of −28%, in which there is a significant reduction in SnInAnn and SnD, −37% and −63%, respectively. ScCrit2 represents the most critical conditions of all scenarios evaluated, in which the reductions in QInAnn, SnD, and SnInAnn are −44%, −45%, and −73%, respectively.

Low flow conditions: Unlike the average conditions, the response in terms of low flows was not similar in all of the basins, therefore an analysis is detailed for each of them, for which a threshold of interest was defined, in this case, established by the MDDELCC as limiting river water withdrawals by municipalities to 15% of 7Q2 [99]. Table 3 presents the scenarios under which there is a reduction of about 15% of 7Q2 and the short dry events—SDE (sum of events for 30 years of two consecutive weeks with flows below 7Q2 of the current conditions) and medium dry events—MDE (sum of events for 30 years of four consecutive weeks with flows below 7Q2 of the current conditions). In catchments 022507, 023422, and 052805, this threshold is reached under the same three scenarios; however, there is a difference in the increase in short and medium dry events. This same threshold is reached in watershed 030101 in two scenarios (different from those mentioned above), but with a greater number of dry events. Finally, in watersheds 030282 and 052233, this threshold occurs in only one scenario, different for each one. It was found that in the 052233 basin, there is the greatest increase in short dry events. There was a significant increase in medium dry events in none of the basins.

Table 3. Scenarios of low flow target conditions (−15% 7Q2) and dry events. The additional SDE and MDE columns are the additional number of events concerning the number of current events. The Scenario Target (−15%7Q2) column shows the scenarios from the closest to the farthest, from left to right, in which this threshold could be reached. SDE: short dry events. MDE: medium dry events.

ID	Scenario Target (−15%7Q2) (T, P)			Current SDE	Additional SDE			Current MDE	Additional MDE		
022507	1 °C, 0%	3 °C, 10%	5 °C, 20%	3	1	2	2	0	1	1	0
023422	1 °C, 0%	3 °C, 10%	5 °C, 20%	4	1	2	2	1	0	0	0
030101		2 °C, 0%	6 °C, 10%	7		3	4	0		1	1
030282			1 °C, 0%	2			2	0			0
052233			4 °C, 0%	1			10	0			1
052805	1 °C, 0%	3 °C, 10%	5 °C, 20%	9	1	1	1	0	0	2	0

Table 4 presents the performance under low flow conditions concerning three of the scenarios evaluated under mid flow conditions (compensatory, changing, and critical), which was carried out through the indicators: percentage (%) change in 7Q2 (of each scenario concerning current conditions), SDE, and MDE. Under a compensatory scenario under mid flow conditions in which the flow remains at the same values (0% QInAnn), the redu ction in low flows ranges from −6% in basin 052233 to −35% in basin 030282, with the other basins showing responses ranging between these values. The basin with the greatest increase in SDE and MDEs is 052805, and the basin with no increase in these indicators was 052233. In the scenario of changing conditions (−15% QInAnn), the reduction in low flows ranges from −19% in basin 052233 to −47% in basin 030282, and the other basins with responses ranging between these values. The basin with the highest increase in SDE and MDE is 052805 and the basin with the lowest increase in these indicators is 030282. Regarding the critical scenario under mid flow conditions (−28% QInAnn), the reduction in low flows for basin 052233 is −28%, and for the other basins, it is close to −50%, with all basins ranging between these values. The basin with the highest increase in SDE and MDE is 052805 and the basin with the lowest increase in these indicators is 023422.

Table 4. Performance of low flow conditions under mid flow conditions: compensatory, changing, and critical, respectively. The additional SDE and MDE columns are the additional number of events concerning the number of current events (shown in Table 3). QInAnn: interannual mean flows.

ID	Scenario (0% QInAnn) (5 °C T, 10% P)			Scenario (−15% QInAnn) (5 °C T, 0% P)			Scenario (−28% QInAnn) (5 °C T, −10% P)		
	% Change 7Q2	Additional		% Change 7Q2	Additional		% Change 7Q2	Additional	
		SDE	MDE		SDE	MDE		SDE	MDE
22507	−27	5	1	−40	13	4	−49	18	7
23422	−27	7	0	−40	12	0	−49	16	0
30101	−8	1	1	−27	13	4	−44	23	12
30282	−35	6	1	−47	7	2	−54	18	4
52233	−6	0	0	−19	14	1	−28	25	3
52805	−31	7	4	−45	20	10	−53	30	17

4. Discussion

To put the results in context, it is necessary to first summarize the set of assumptions on which this study is based. The uncertainty analysis focused on reducing the uncertainty associated with the impact model by selecting a robust one and performing a thorough calibration focused on improving its performance to assess the response of systems to climate change for the specific purposes of this study: medium and low flow conditions.

The sensitivity analysis is based exclusively on system forcing; therefore, other external stressors on water resources are not considered. The potential impacts of changes in climatic conditions are studied with the help of the delta neutral approach method, which only uses the annual mean values of the system forcings to generate all scenarios of the exposure space. The top–down approach is used in two stages: as a guide for defining the limits of the exposure space and to obtain an idea of when changes in specific scenarios may occur.

The results generated in this study are divided into two main groups: those that describe regional behavior and those that describe differential behavior in each basin under the same climate change scenarios. The main findings are described below according to each group.

The indices and indicators for which all basins showed similar results are presented here: the Budyko framework, water balances, mean interannual flows, and snow duration and magnitude. The Budyko framework describes changes in climatic zonation in terms of aridity indices and the evaporation index, where higher EI values represent a decrease in runoff and higher AI values indicate warmer and drier zones. Under the most likely scenarios (dark salmon dots in the exposure space), the catchments move within the energy–limited zone; however, under the least favorable likely scenario (6 °C and −10% P), catchments 052233 and 052805 cross the point in Budyko space that divides the energy–limited zone to the water–limited zone.

To disaggregate the information provided by the Budyko framework (understood as the distribution of water inputs and outputs within its climatic context), that is, the water balances of the scenarios corresponding to changes in temperature, but under current precipitation conditions and the opposite case, the changes in precipitation under current temperature conditions were analyzed. Here, it was identified that the change in runoff associated with each precipitation delta is equivalent to the effect of five temperature deltas, i.e., the runoff losses relating to a 10% decrease in precipitation are equivalent to the losses associated with a 5 °C increase (Figure 6).

A more detailed analysis of the water balance of all scenarios was carried out through the response of the mean interannual flows, which were analyzed jointly with snowfall and snowy days. For this purpose, four groups of scenarios were defined. Past conditions: under a colder climate and with less precipitation, snowfall and SnD are higher in both scenarios evaluated, which mainly highlight a decrease in runoff in the winter period and a slight shift (delay of a few days) of the time of year in which the spring peak flow occurs. Changing conditions show a large contrast between them with the same percentage change over QInAnn (−15%); under the scenario of losses associated with temperature increase (5 °C), there is a large change in the distribution of water throughout the year, an increase in runoff during the winter, and a disappearance of the typical spring peak flow, where the snowfall is reduced to 2/5. In contrast, the changes associated with the decrease in precipitation show a generalized decrease in flow values, but the shape of the hydrograph is maintained, and the decrease in snowfall is about 1/5 and the SnD 1/10 of the decrease of these variables in the temperature increase scenario. In terms of compensatory conditions, in the scenario in which the QInAnn has the same values as the current conditions, i.e., in which a 10% increase in precipitation compensates for the losses associated with the temperature increase (5 °C), the spring peak flow disappears, the snowfall is reduced by half, and the SnD decreases by one third. The snowfall compensatory scenario, in which a 10% increase in precipitation compensates the losses associated with the temperature increase (1 °C), shows a slight rise in QInAnn and a small decrease in SnD. Critical conditions: this last group shows the most critical probable and possible evaluated scenarios in which the spring peak flow disappears and the flows decrease considerably during most of the year, except during the winter season, and for the probable scenario, the snowfall and the SnD are reduced to 2/5 and 2/3, respectively.

Focusing one last time on the summer period, we analyze the differential behavior of the basins studied before a threshold value (the maximum percentage of flow that can be captured during the summer period), in which a varied response of the basins is identified since this threshold is reached in one, two, or three scenarios. The two basins in which this threshold is reached in the most distant scenarios are 052233 and 030101, and it is in these same basins that there is a greater increase in short dry events under the scenarios in which the threshold is reached. The increase in medium dry events for this threshold in all basins was not significant.

Equivalences between the scenarios selected to analyze the mid flow and snow conditions (changing, compensatory, and critical conditions) and their respective correspondence with the response of low flows to each of those scenarios were also evaluated. Here, for each pair of scenarios selected for these conditions, only the likely scenarios are analyzed. The compensatory scenario (0% QInAnn) represents a decrease in low flows for all basins with very dissimilar values, where the largest reduction (−31%) occurs in basin 030282. For the case of changing conditions (−15% QInAnn), there is an even more pronounced decrease in low flows, reaching, in the worst case, a little more than three times (−47%) for basin 030282. In the other basins, the response continues to be varied, although not as dissimilar as in the case of compensatory conditions. Under critical conditions (−28% QInAnn), the response in the basins is much more similar (except in basin 052233, where the reduction in low flows is significantly lower); however, also for this scenario, the worst conditions (−54%) occur in the same basin, basin 030282. No correspondence was found between a greater decrease in low flows in one basin concerning another, with a greater increase in the number of dry events, i.e., that for a given scenario, the reduction in flow is greater than in another, does not necessarily mean that there are also more dry events in the basin where the reduction was greater. The basin with the greatest increase in dry, short, and medium events is 052805. In all scenarios evaluated, two basins 022507, and 023422, showed very similar behavior in terms of changes in the magnitude of low flows, although with differences in the duration of dry events.

The framework proposed for assessing the potential impacts of climate change is based on the evaluation of the system's behavior to changes in the drivers—in this case, the inputs—until substantial changes or points of failure of the system are found. The analysis ranges from hydroclimatology to annual hydrological changes (balances and mid–flows). It includes the hydrological components of the snow and pluvial periods (low flows), the latter under a differential analysis of the basins. In addition, the particularities of cold regions are taken into account.

In this study, the uncertainty analysis is focused on the two main sources of uncertainty associated with the impact model (structural and parametric). The first is addressed through the selection of a robust model and the second through a thorough calibration. Both uncertainties are reported in the literature as relevant in climate change impact modeling [23,70] and especially when evaluating summer flows [81,100]. The hydrological model has also been successfully employed in several climate change studies [33,101–103]. The other main sources of uncertainty related to the climate variables is represented by a sensitivity analysis.

Several studies on the potential impacts of climate change on water systems in Canada [28,104], and specifically in the province of Quebec [23,25,105], use a set of climate projections from GCMs to assess the response of water systems to these point scenarios and are evaluated mainly through the estimation of water balance variables and the amount of snow. A recent study in Quebec [106] also employs GCM scenarios, but in a sensitivity analysis context, which uses flow, snow, and soil moisture as system performance metrics.

In contrast, the present study evaluates a wide range of scenarios, including past and future, as well as possible and probable scenarios. In addition, it identifies not only the potential scenarios of interest, but also analyzes the sensitivity (in different hydroclimatic and hydrological contexts and for different periods), the degree of influence of each climatic forcing (according to the rates of change selected for each climatic variable), and a categorized response of the scenarios (past, changing, compensatory, and critical conditions). The paths of change, the correlation between changes in climate variables and each system performance metric (regional analysis) and for each basin (differential analysis regarding low flows), are also defined.

The neutral approach adopted here is a simpler methodology compared to the top–down approach that allows the exploration of a large number of climate scenarios at a lower cost. Through this, it is possible to identify the response of the studied systems to a different threshold level of impact and new climate scenarios provided by GCM. This is without the need to re–run the impact model simulations and without recalculating the system performance, as is required in the top-down approach. The progress achieved in this study in relation to the hazard assessment and sensitivity analysis of water systems to climate change is focused on the refinement of the impact modeling and system performance evaluation stages (with a novel and detailed presentation of the results) that obtains more and especially varied information from the hydroclimatic indices and indicators used, their interrelationships, the different classifications, and the possibility of revisiting the results generated when new information is available.

5. Conclusions

There are different ways of estimating the potential impacts of changing climatic conditions on water systems. In this study, we have selected one of them, with soundness, coherence, and clarity as principles, involving the available information and extracting as much information as possible, but always in accordance with the methodologies and resolutions used here. The delta change method of the bottom–up approach is adopted, but certain elements of the top–down approach are also used (the limits and horizons of the climate projections issue of global climate models) to better guide the identification of the scenarios of interest (responding to different criteria). The results obtained provide a big picture of the problem, with the inherent limitations of delta change, of the perturbation technique (in that it only takes one statistical attribute of the climate variables and with no assessment of the likelihoods of every scenario).

The application of the refined version of the neutral approach proposed here contributes mainly to (1) obtaining an analysis of the behavior of the systems from different angles; (2) performing an exploratory analysis of the possible changes that the systems could undergo; (3) carrying out different types of diagnostics strongly related to the variable being evaluated and its respective threshold; (4) knowing how systems transition in the face of gradual changes; (5) identifying potential scenarios of interest, which can be very varied for each system; (6) having a differential analysis of climatic stressors.; and (7) identifying the variables for which there is no uniformity in the response to the same scenarios. All of this is in addition to the improvements in the methodological part of the framework for evaluating the potential effects of climate change on the systems evaluated (mentioned in previous sections).

More detailed analyses of changes in low flows would be desirable, given the complexity of the response of this hydrological variable, which is closely related to other factors such as geology and soil moisture, among others. Expert support could also be used to assign probabilities to the scenarios identified as being of interest once the modeling stages of the exploratory and participatory scenarios (in which all of the physical and socioeconomic drivers that condition the availability of water for its different uses are involved) have been completed. In later stages, these analyses could be complemented by including new thresholds for each variable, defined by the stakeholders, involving the other biophysical and socioeconomic changes.

The study presented here seeks to guide the following stages of hydro–economic modeling through a simplified, but refined version of the assessment of the potential impacts of climate change by generating more information (with a concatenated results analysis structure that explores the results obtained to the maximum) and better tools (the refined impact assessment framework implemented here). Assumptions in the sensitivity assessment and the uncertainty analysis are specified to provide greater clarity for future work based on this study, thus advancing the following tasks for the identification and subsequent implementation of measures for adaptation to climate change in water systems. This study undoubtedly constitutes a significant advance toward the design of adaptation plans (which is the next step after hydro–economic modeling) both for the basins studied and for other cold regions with similar hydroclimatic characteristics.

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