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Inter-Annual and Seasonal Variability of Flows: Delivering Climate-Smart Environmental Flow Reference Values

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Abstract: Environmental flow (eflow) reference values play a key role in environmental water science and practice. In Mexico, eflow assessments are set by a norm in which the frequency of occurrence is the managing factor to integrate inter-annual and seasonal flow variability components into environmental water reserves. However, the frequency parameters have been used indistinctively between streamflow types. In this study, flow variability contributions in 40 rivers were evaluated based on hydrology, climate, and geography. Multivariate assessments were conducted based on a standardized contribution index for the river types grouping (principal components) and significant differences (one-way PERMANOVA). Eflow requirements for water allocation were calculated for different management objectives according to the frequency-of-occurrence baseline and an adjustment to reflect the differences between river types. Results reveal that there are significant differences in the flow variability between hydrological conditions and streamflow types (p-values < 0.05). The performance assessment reveals that the new frequency of occurrence delivers climate-smart reference values at least at an acceptable level (for 85–87% of the cases, $r^2 \geq 0.8$, slope ≤ 3.1), strengthening eflow assessments and implementations.

Keywords: climate-smart; environmental flows; frequency of occurrence; inter-annual and seasonal variability; one-way PERMANOVA; principal component analysis; reference values; streamflow; water allocation

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1. Introduction

Environmental flow science and management have rapidly increased the available knowledge and improved practice all around the globe [1–3], before and after the updated Brisbane Declaration and global agenda on environmental flows (eflows) [4]. Advanced methodologies in eflow assessments focus primarily on the attributes of the natural flow regime and its inter-annual and seasonal variability components built upon theoretical flow–ecology relationships [3,5–9]. Normally, the natural —or close to unimpaired— historical flow regime is seen as a reference desirable state to conserve or restore freshwater ecosystems, and hydrology-based approaches have delivered multiple reference values that range from ecologically relevant hydrological indices to percentages of the mean annual runoff (MAR) [3,6–9]. Furthermore, those reference values have been strategic inputs for many national, regional, or basin-scale programs to assess eflow requirements and track progress on environmental water allocation at a planning level as a response to recognizing the environment as a legitimate user [3,10–14]. However, such reference values are commonly used regardless of the nature of the hydrological behavior of different river types. The investigation of site-specific reference values becomes even more needed due to climate change imposing an emerging core challenge to this hydrologic-reference conceptualization: the uncertainty of non-stationarity water availability and regimes regardless of environmental water allocations [3,15–20].

In Mexico, eflow assessments are normed according to a standard that sets the ruling principles and technical procedures, applicable through a four-level hierarchical approach ranging from simple reference values, such as a percentage of the MAR (i.e., "look-up tables"), to desktop ecohydrology-based, habitat simulation, and holistic methodologies (NMX-AA-159-SCFI-2012) [9,21–24]. In this regulatory instrument, eflows are defined as the quantity, quality, flow regime, or variation of water levels to maintain epicontinental freshwater ecosystems' components, functions, and processes [21]. As in eflow science and state-of-the-art practice, such principles and procedures are grounded on the theoretical flow–ecology and flow alteration–ecological response relationships by considering a range of ecologically relevant streamflow characteristics [3,9,22–24]. The most detailed ecohydrological method was developed to cope with the non-stationarity of water availability grounded on a novel frequency of occurrence approach of two flow regime components to integrate the eflow requirements into environmental water reserves (EWR: an annual-based volume designated to remain in the environment for ecological protection) [22–24]. These are a set of ordinary low flows for hydrological conditions ranging from very dry to wet, and a flood regime based on a set of peak flow extraordinary events [24].

Nevertheless, the original method was developed for perennial rivers, and it has been implemented in ephemeral streams and intermittent rivers with the same criteria [22–24]. Local empirical knowledge provided by ecohydrologic and holistic methodologies outcomes has shown that EWRs depend on climatic and geographic influences, mainly because of the seasonal flow variability and a low baseflow buffer capacity [23]. Theoretically, non-perennial rivers exhibit higher variability than perennial rivers as a direct response to the basins' dominant climates (e.g., arid, humid, temperate, etc.), geography, and orographic effects (e.g., surface, altitudinal gradient, drainage system) [23,24]. This relationship has led to the hypothesis that runoff generation processes in ephemeral streams and intermittent rivers are more dependent on seasonal and yearly wet conditions than perennial rivers. Furthermore, climate change has not yet been fully investigated within the aims and scope of the frequency of occurrence approach, nor has the appropriateness of the current criteria for integrating eflow requirements between different streamflow types been revised [22,24]. The overall goal of this study was to fill those knowledge gaps by assessing the inter-annual and seasonal variability of flows of Mexican rivers.

The value of continuing investigating quantitative indices in flow regimes without significant human interventions strives in having a detailed reference of how they should look prior to their use as desired outcomes. Historically, this approach has been widely put into practice to limit future unsustainable water abstraction in such places, or to design regimes to achieve specific ecological functions and ecosystem services [1–3,9,22–24]. Moreover, such indices would be then useful to develop working hypotheses (i.e., flow–ecological response) based on holistic expert panels, research-driven assessments, and conduct eflow implementations to validate or adjust them in the field (i.e., adaptive management) [1–9,11,12,22–24].

The study's specific objectives are to demonstrate that (1) there are significant differences in the hydrological conditions between streamflow types. Evidence in that direction would endow Mexican environmental water science and practice with a new knowledge perspective towards climate-smart eflow assessments and resilient implementations, as well as contribute to further global discussions on addressing the non-stationarity challenge in the science community. Likewise, the findings presented provide supporting information to (2) improve the method's current criteria with new reference values of frequency factors of occurrence adjusted to climatic influence on river streamflow types, and

(3) deliver likely EWRs for water allocation for further comparisons and tracking implementation progress at a planning level.

2. Materials and Methods

2.1. Research Design

2.1.1. River Basin Selection

In order to assess the hydrological contribution influenced by regional climates, as well as the geographic and orographic effects, hydrological and climatological information from 40 river basins across Mexico was analyzed. These sites were selected based on three criteria: the variability of flows, the climate, and geographic location (Figure 1, Supplementary Material).

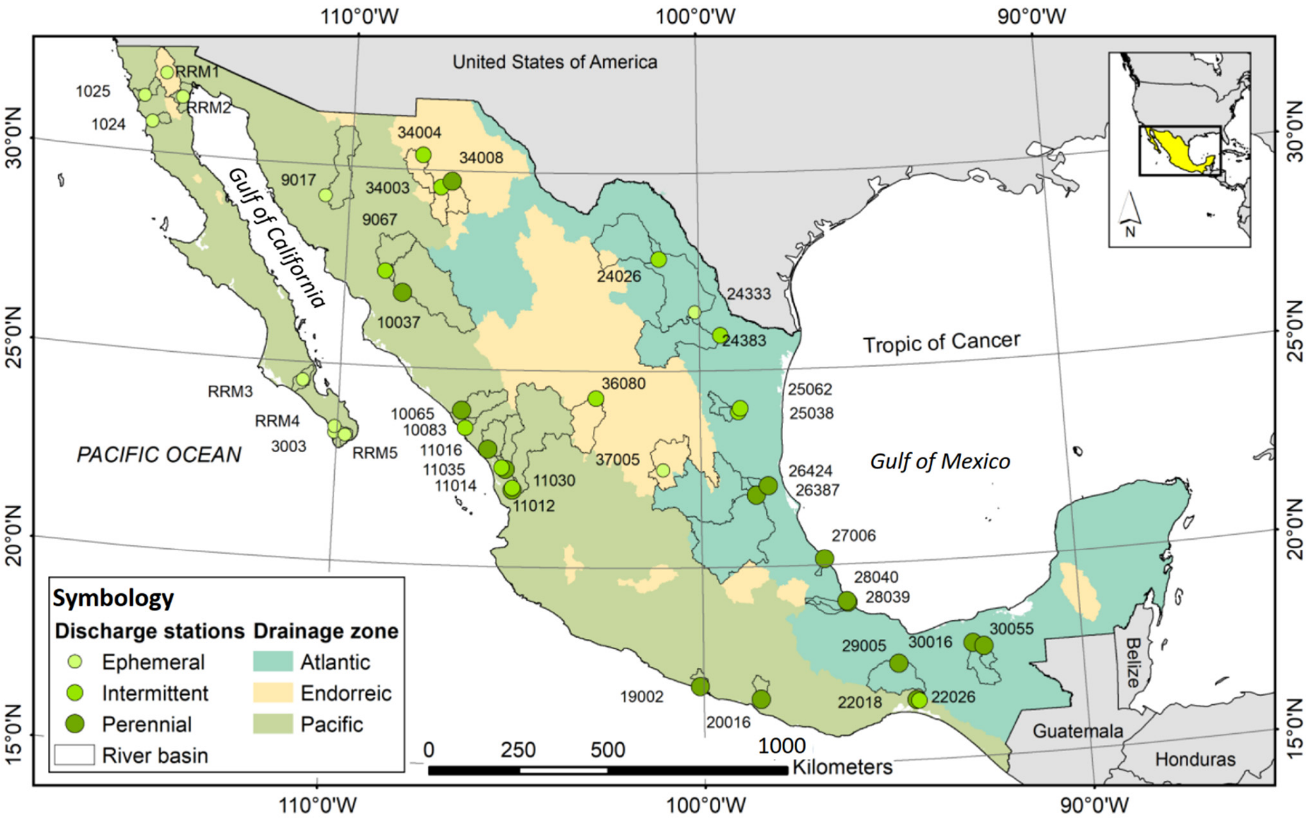

Figure 1. Location of basins, gauging stations, and codes of the study river sites per drainage zone.

First, the river sites were identified based on the mainstream flow type as a proxy of variability. All sites were classified based on the hydrological status (flow variability), which was assessed using site-specific flow duration curves at a daily scale [percentage of time that discharge volume (Q) in cubic meters per second (m^3/s) is exceeded] into three different groups following the criteria established by Equation (1) [21].

$$Streamflow\ type = \begin{cases} ephemeral, & if\ Q > 0.5 \leq 30\% \\ intermittent, & if\ Q > 0.5 > 30\% < 90\% \\ perennial, & if\ Q > 0.5 \geq 90\% \end{cases} \quad (1)$$

Climatologically, the location of the basins was based on a differentiated frequency of both droughts and floods in dry and wet seasons on the nationwide landscape according to the Tropic of Cancer. Generally, droughts are known to occur with more severe effects in northern Mexico, which regularly experiences natural water scarcity because arid or semiarid climates dominate, while floods in the southern basins are due to a higher incidence of tropical storms and hurricanes [25,26]. Geographically, the basins were classified into three categories based on the direction of the drainage system [27]: Atlantic and Pacific for those draining to the oceans or the Gulfs of Mexico or California, and endorreic for the closed system basins. This was chosen due to Mexico's geography- and orography-induced effects on the seasonal rainfall patterns, because of the limits of the Western and Eastern *Sierras Madre*—two mountain chains that run parallel to the coasts— and the Neovolcanic Axis or Transversal Volcanic System in the center [25]. River sites and drainage basin selection and geographic treatment were made based on their official delimitation [28,29].

2.1.2. Data Type, Source, and Requirements

The information used was observed streamflow at the river site. Flow record series were obtained from the Mexican Data Bank of Surface Water repository (https://app.conagua.gob.mx/bandas/, accessed on 31 March 2022) administered by the National Water Commission (CONAGUA). The information-gathering, analysis, and assessment were restricted to flow records at a daily scale for ≥ 20 consecutive years (< 10% of gaps), without the significant intervention of water infrastructure on the regime as recommended [22,24]. Given the scope of this assessment, the unregulated periods were selected based on previous work [23,24], expert knowledge, and visual inspection of the hydrographs at different times scales. Thirty-five streamflow gauging stations and five rainfall-runoff models from previous eflow studies [30,31] were used. Flow datasets varied from 1938 to 2014, the longest from the Acaponeta river (61 years), the shortest from Plutarco E. Calles, and San José-Los Pilares (20 years) (Figure 2).

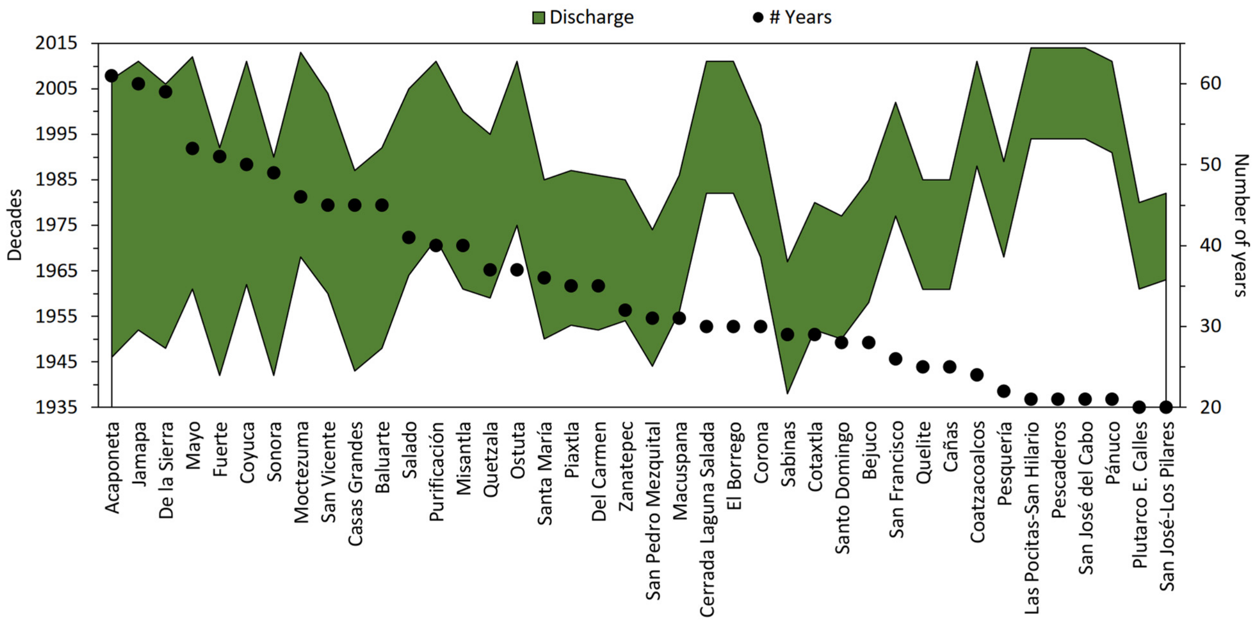

Figure 2. Periods of streamflow analysis of the river sites. Decades comprised in the left vertical axis (colored area), while the number of consecutive years in the right vertical axis (dots).

2.1.3. Analysis Techniques: Indices, Descriptive and Inference Statistics

The inter-annual and seasonal variability of flows (j = inter-annual, dry season, or wet season) were characterized as stated in the Mexican Norm for conducting eflow assessments (NMX-AA-159-SCFI-2012). This procedure consisted of the computation of the characteristic mean inter-annual flows (Q) at a monthly scale for four hydrological conditions (i = wet, average, dry, and very dry) according to the 75th, 25th, 10th and 0th percentiles of the average discharge from the selected period of records [22–24]. The corresponding months of dry and wet seasons were identified based on Equation (2), where

Q_{mmr} is the mean discharge of a given month (n = 12) according to the selected full period of records, while Q_{mar} is the mean inter-annual flows (runoff) of such a time span.

$$Season\ (S) = \begin{cases} for\ S_{dry}, & if\ Q_{mmr} < Q_{mar} \\ for\ S_{wet}, & if\ Q_{mmr} > Q_{mar} \end{cases} \tag{2}$$

Afterward, an index to assess the river's flow dependency to seasonal and yearly basin conditions was developed by identifying the hydrological contribution of wet, average, dry, and very dry conditions. This step aimed to isolate how much such conditions contribute to the seasonal and inter-annual flow variability. The procedure followed was, first, by calculating the relative contribution of the variability j (RQ_j) in the context of the maximum historical ($Q_{max} =$ 100th percentile) flow from each set of flow records, where n is the total discharge of the months representative of the condition i of the variability j (Equation (3)):

$$RQ_j = 100\ \times \frac{\sum_{i=1}^{n} Q_i}{Q_{max}} \tag{3}$$

Second, the relative contribution for each hydrological condition i (RQ_i) at each variability j (seasonal or inter-annual) was standardized from 1 to 100 (SQ_j), where n is the total relative discharge contribution from all the conditions i (Equation (4)):

$$SQ_j = 100\ \times \frac{RQ_i}{\sum_{i=1}^{n} RQ_i} \tag{4}$$

The standardized relative discharge contribution (SQ) values based on the seasonal and inter-annual variability per hydrological condition and stream type were used to assess the rivers' dependency on their hydrology, climate, and geography influence. The organization of the sets of flow records, the computation of the flow duration curves for the streamflow categorization, and the SQ values calculation were done in Microsoft Office (MO) Excel. Afterward, the outcomes were explored, analyzed, and assessed based on descriptive and inference statistics by using MO Excel and Past 3.19. Among the descriptive statistics, we computed the central (median ± 1 quartile) and full range distributions from the complete set (N = 40), and the medians of the subsets sampled per stream type (n = ephemeral 11, intermittent 12 or perennial 17). Inference statistics were performed with non-parametric tests since the SQ values showed significantly non-normal distributions (skewness of chi-squared for small-sample correction and omnibus p-normal < 0.05).

A principal components analysis (PCA) for grouping and a one-way PERMANOVA test were conducted for assessing significant differences between SQ values. The experimental design consisted of 40 observations (river site), each with 12 SQ values for seasonal (dry and wet), inter-annual variability for four hydrological conditions (wet, average, dry, and very dry), and one factor or source (independent) categorical variable with three subsets (ephemeral, intermittent or perennial). The consistency examination was limited to the two principal components (PC) because they explain 98% of the cumulative variance (PC1 = 88% and PC2 = 10%). Furthermore, the eigenvalues from PC1 lie above the confidence interval level (95% broken stick method), while the PC2 eigenvalues are near the limit (Appendix A Figure A1); the main model's outcome purpose is to reduce the analyses to the significant components. This level of confidence indicates that the SQ values are highly correlated, meaning that the higher the PC scores (eigenvectors) the higher the flow dependency to seasonal and yearly wet conditions. Thus, the PCA eigenvalues, the variance explained, and the eigenvectors for the 40 observations were critically examined in the context of the stream types, their hydrological, climatic, and geographic characteristics as follows:

- The interpretation of the PC based on the matrix of correlations, the biplot of eigenvectors, and the river sites' ordering based on the model to differentiate the flow dependency to seasonal and yearly conditions between the stream types as depicted by empirical research [22–24].
- The correlation of PC1 (significant variance *p*-value < 0.05) with independent indices of hydrological variability, in line with the previous studies [22–24]. The indices considered were the coefficient of variation (CV) and the baseflow (BFI), the former an indication of long-term variability between seasons, while the latter is representative of short-term variability [7]. Coefficients of determination were calculated according to polynomic regressions (R^2) of the PC1 by CV and BFI for the whole population and based on linear regressions (r^2) for each streamflow class. Additionally, the CV and BFI medians, ± 1 quartile, and full range are provided.
- The medians of the basins' surface (km^2) (upstream from gauged locations) [28,29], ± 1 quartile and full range, and percentage of dominant climates [32].

Similarly, the one-way PERMANOVA test was run pairwise between the SQ values of the same condition among seasonal and inter-annual variability, and the river stream classes. Together with the PCA test, it is hypothesized that (a) the ephemeral and intermittent streams exhibit higher dependency on seasonal and yearly wet conditions than perennial rivers. Moreover, (b) there are significant differences (*p*-value < 0.05) in the SQ values, and (c) this is reflected in the full spectrum of river types.

2.2. Reference Values for Climate-Smart Environmental Flows and Water Reserves

Eflows and EWRs were evaluated based on the "frequency-of-occurrence" approach developed for highly variable flow regimes in Mexico whose proof-of-concept was focused on perennial rivers [24]. The method is grounded on several time-varying hydrological conditions and individual flow events that play a key role in the performance and persistence of aquatic, semi-aquatic, and terrestrial species linked to a wide variety of rivers [3,18,33]. Likewise, frequency-of-occurrence-based management of such flow components contributes to exposing freshwater and riparian species to extreme conditions for coping with non-stationarity [8,18,24,34–36].

The procedure consisted of assessing the two main components of the flow regime according to the parametrization of their frequency of occurrence as they occur in nature [24]. First, the inter-annual and seasonal variability discharge (m^3/s) were computed for the characteristic ordinary or low flows for wet, average, dry, and very dry conditions whose natural parametrization is based on the 75th, 25th, 10th, and 0th percentiles, respectively, of the full set of records at daily and monthly scales. Conceptually, this component is based on the probability of occurrence of such conditions: wet fixed at 25% to separate ordinary flows from peak events (higher distribution tail), the average set at ± 25% around the median, so that dry (15%) and very dry (≤ 10%) are below the average range (25% lower distribution tail) [24].

To integrate the ordinary or low flow regimes of wet, average, dry, and very dry conditions into eflows, the original method provides a set of reference factors (values) grounded on the degree of deviation of the frequency of occurrence from the natural parametrization for such conditions, adjusted into a four-class management system of the desired ecohydrological status of the flow regime (environmental objectives hereafter; A = very good, B = good, C = moderate, and D = deficient). In light of the inference statistics outcomes of this study, a new set of reference values is proposed along these lines to differentiate ephemeral and intermittent streams hydrology from perennials', and to adjust the model accordingly. To date, the frequency of the occurrence model has been implemented with the same "top roof" and "ground floor" per environmental objective regardless of the weight of each of the conditions per stream type. This is because the method was developed for highly variable yet perennial rivers [24]. The multivariate assessments provide scientific evidence of greater hydrological dependency of intermittent rivers and ephemeral streams than perennial rivers. Baseline parametrization cannot continue as it was designed because the aquatic phase of intermittent rivers and ephemeral streams is not equally resilient at an ecohydrological level as in perennial rivers and, in the extreme case, it condemns them to almost or completely disappear (i.e., environmental objective class D) [3,24,33–37]. Thus, the model's "top roof" and "ground floor" parametrization need to be adjusted to avoid underestimations in non-perennial stream types. The adjustment proposed lies in the frequencies of occurrence factors for A–D classes in non-perennial rivers which are closer to the natural parametrization than in perennial rivers because they fully rely on wet years and seasons, and do not have baseflow to buffer the variability of the flow components.

In the original method, in a 10-year hypothetical time horizon, the frequency of occurrence of hydrological conditions for an environmental objective class A is set at 1, 4, 3, and 2 years for wet, average, dry, and very dry ordinary or low flows, respectively, regardless of the stream type. It is proposed to keep that for perennial rivers and adjust to 2, 4–5, 2–3, and 2 years for intermittent rivers, and 2–3, 5, 1–2, and 1 year for ephemeral streams (Table 1).

Table 1. Frequency factors of occurrence per environmental objective class for the integration of the ordinary or low flows and flood regime (Cat = categories of peak flow events at 1-, 1.5-, and 5-year return period) components into annual volumes for environmental water allocation for perennial rivers, and adjustment for ephemeral streams and intermittent rivers.

Environmental Objective	Frequency of Occurrence of Ordinary or Low Flows Per Hydrological Condition				Frequency of Occurrence of Number of Peak Flow Events		
	Wet	Average	Dry	Very Dry	Cat I	Cat II	Cat III
			Ephemeral				
A	0.25	0.50	0.15	0.10	10	6	2
B	0.15	0.45	0.20	0.20	9	5	2
C	0.10	0.30	0.30	0.30	7	4	2
D	0.05	0.25	0.35	0.35	6	3	2
			Intermittent				
A	0.20	0.45	0.25	0.20	10	6	2
B	0.10	0.40	0.30	0.20	8	4	2
C	0.05	0.30	0.40	0.25	6	3	2
D	0.05	0.20	0.40	0.35	4	2	2
			Perennial				
A	0.10	0.40	0.30	0.20	10	6	2
B	0.00	0.20	0.40	0.40	5	3	2
C	0.00	0.00	0.40	0.60	3	2	1
D	0.00	0.00	0.00	1.00	2	1	1

Similarly, for an environmental objective class B, the original reference keeps the recommended frequency of zero years in wet condition, 2 for average, 4 in dry, and 4 in very dry years in perennial rivers; for intermittent rivers, the recommended adjustment is 1, 4, 3, and 2 years, and for ephemeral streams, 1–2, 4–5, 2, and 2 years, respectively. For the environmental objective class C, in perennial rivers, the values remain at 4 and 6 years, which concentrate the frequency at dry and very dry years, respectively, whereas the adjustment for intermittent rivers is 0–1, 3, 4, 2–3 years, and for ephemeral streams is 1 year for wet condition, and 3 years for average, dry, and very dry each. For the D class of environmental objectives, unlike perennial rivers where the original method establishes permanently the very dry condition in the 10 years, in the intermittent rivers the frequency changes to 0–1, 2, 4, and 3–4 years, and for ephemeral streams to 0–1 and 2–3 years for wet and average conditions, and 3–4 for dry and very dry conditions.

The rationale for the adjustment setting is that perennial rivers exhibit baseflows that impede flow secession, i.e., 90% exceedance time based on the flow duration curve criteria used in this study, notwithstanding high values of coefficient of variation between seasons. Due to the lack of such buffer capacity in the case of non-perennial rivers, keeping the original values imply significant changes at an ecohydrological level and, therefore, a further degradation would be expected than that anticipated by the original model in the performance and persistence of aquatic, semi-aquatic, and terrestrial species [3,8,18,24,33–37]. Furthermore, the adjustment differentiates the wet conditions dependency between stream types (seasonally or annually). Then, based upon the stream type and the selected environmental objective class, the EWRs were obtained by the following of Equation (5) as it was established by the original method:

$$Q_{\mathrm{LF}} = (F_w \times Q_w) + (F_a \times Q_a) + (F_d \times Q_d) + (F_{vd} \times Q_{vd}) \tag{5}$$

where Q_{LF} is the annual discharge volume of ordinary or low flows in million cubic meters (Hm^3), F is the frequency of occurrence reference value for the hydrological condition i (factors of Table 1), Q is the discharge volume for the ordinary or low flow i, and i is the hydrological condition (w = wet, a = average, d = dry or vd = very dry).

The second flow regime component included in the original method is a set of three categories of peak flow events based on their characteristic magnitude, frequency (recurrence intervals), duration, timing, and rate of change (i.e., flood regime). Category I is set for intra-annual or high pulses (Cat I = 1-year return period), category II inter-annual to sustain the characteristic bankfull (Cat II = 1.5-year return period), and category III as a moderate magnitude (Cat III = 5-year return period), which in Mexico is the hydrologic criteria to define the river's hydraulic public space [24].

As in the ordinary or low flows component, the reference values remain the same for perennial rivers due to the general consistency previously reported [22–24]. However, in non-perennial rivers, the set of peak flow events is greatly concentrated in the wet season leading to a tendency of the highest coefficients of variation between seasons, and the lowest baseflow indices. In this sense, we propose the following adjustment for intermittent rivers and ephemeral streams to the frequency of occurrence values to integrate the eflows' flood regime component into EWRs. Based on the same 10-year hypothetical time horizon, for an environmental objective class A, the number of peak flow events should occur, mimicking their natural parametrized recurrence intervals; that is to say, 10 times for category I (high-flow pulse, once per year), 6 times in 10 years for category II (bankfull), and 2 times for category III (moderate magnitude, twice in 10 years). For an environmental objective class B, instead of 5 yearly events out of 10 years for category I, 3/10 for category II, and 2/10 for category III indicated for perennial rivers, we recommend 8/10, 4/10, and 2/10 for intermittent rivers, and ephemeral streams 9/10, 5/10, and 2/10, respectively.

For an environmental objective class C, the frequency of the events for perennial rivers remains 3/10, 2/10, and 1/10 for categories I, II, and III, accordingly, whereas for intermittent rivers it changes to 6/10, 3/10, and 2/10, and for ephemerals to 7/10, 4/10, and 2/10. In addition, for environmental objective class D, the events keep at 2/10, 1/10, and 1/10 for perennial rivers; it changes to 4/10, 2/10, and 2/10 for intermittent rivers, and ephemerals to 6/10, 3/10, and 2/10. The duration, timing, and rate of change of all the peak flow events remain as the standard given by the original method; that is to say, 75–85% of the cumulative relative frequency of the number of consecutive days that they typically last; 80–90% concerning the months of the year where such events have occurred historically (timing); and 90th and 10th percentiles for rising and fall daily flow changes (rate of change), respectively. The corresponding volumes of the flood regime to be incorporated into EWRs were calculated by the following of Equation (5) as it was designed by the original method:

$$Q_{\mathrm{FR}} = \frac{\left(F_{fI} \times D_{fI} \times Q_{fI}\right) + \left(F_{fII} \times D_{fII} \times Q_{fII}\right) + \left(F_{fIII} \times D_{fIII} \times Q_{fIII}\right)}{10} \quad (6)$$

where Q_{FR} is the annual discharge volume of the flood regime (Hm^3), F is the frequency of occurrence of the flood (f) event i (factors of Table 1), D is the duration of the peak flow event i, Q is the discharge volume (Hm^3) per day of the peak flow event i, and i is the category of the peak flow event ($I = 1$-, $II = 1.5$- or $III = 5$-year return period).

The final EWR is given by the summation of the ordinary or low flows and the flood regime volumes. EWRs were calculated for all the environmental objective classes, streamflow types, and it is expressed as a percentage of the MAR. EWRs' full and central ranges (medians ± 1 quartile) from each stream type based on this adjustment were examined separately (Adj_EWR + codes A, B, C, or D; n = ephemeral 11, intermittent 12 or perennial 17). Coefficients of determination (r^2) based on linear regressions of PC1 eigenvectors of characteristic EWR per environmental objective class were calculated for each stream type. Furthermore, the procedure for determining EWR was also calculated according to the method baseline criteria (BL_EWR+ codes A, B, C, or D; $N = 40$) to compare these results with the ones provided by the adjusted reference values outcomes.

2.3. Performance Assessment of the Reserves for Environmental Water Allocation

Along the lines of the original method proof-of-concept [24], the performance assessment of the new frequency factors of occurrence was evaluated by comparing the eflow outcomes for the implementation of the model to all the river sites based on the reference values per streamflow type, and the environmental objective class for both the adjustment proposed in this research and the baseline. However, unlike the original method, the examination of performance in both cases the adjustment and the baseline were done by comparing the outcomes of eflow calculations for the same time span considered for the streamflow gauging stations or rainfall-runoff models, against the natural parametrization of the frequency of occurrence. Moreover, the model was performed at a daily scale because of the full range of variability between the stream types, and the intrinsic hydrologic nature of non-perennial rivers which are highly dependent on sudden peak flow events that require the highest time resolution [24,33]. This guarantees such variability in the outcomes to test consistency. Figure 3 illustrates the performance assessment in three streamflow types of river sites.

Coefficients of determination (r^2) and slope values were selected as performance metrics, the first to assess the quality of the model (level of fitness), and the second to examine the level of similarity or proportion of deviation of the outcomes against the natural parametrization [24]. These metrics measure the model outcomes' precision and accuracy between the criteria for the baseline and the adjustment, respectively. While r^2 values measure the degree to which eflow modeled rates depict the same results under unchanged conditions for both criteria separately, slope values measure the proximity of such eflow modeled rates to the natural parametrization. The performance was assessed based on the following criteria: for r^2 values, good ≥ 0.9, acceptable 0.89–0.8, moderate 0.79–0.7, and low < 0.7, as in the original method. For slope values, the thresholds were set as good ≤ 2.3, acceptable 2.31–3.1, moderate 3.11–3.3, and low > 3.3, based on the outcomes' central distribution from the subset of greatest amplitude (environmental objective D). Eflows, EWRs, and performance assessments were conducted in MO Excel.

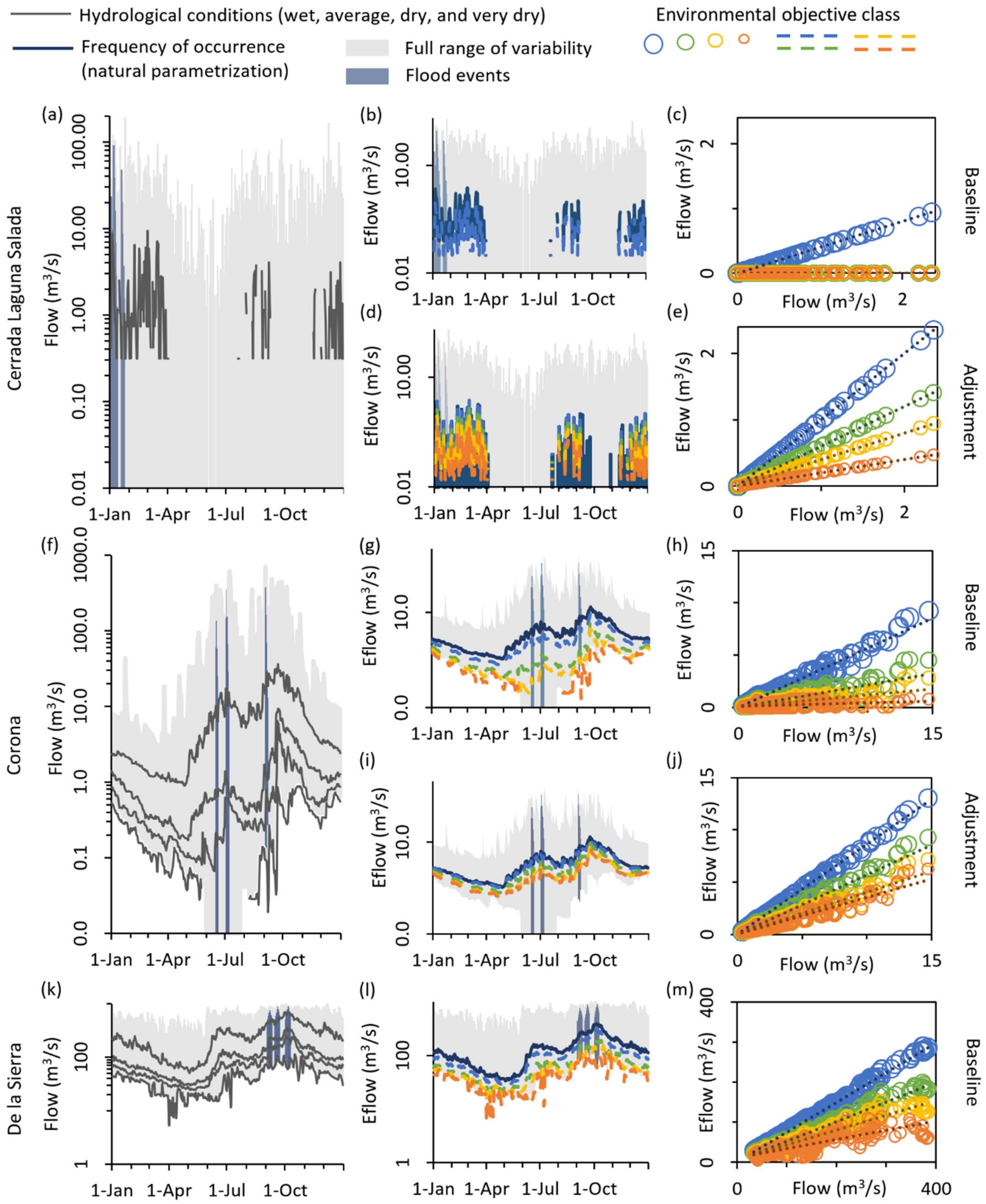

Figure 3. Performance assessment of the new frequency factors of occurrence for environmental flow allocation at three illustrative river sites, Cerrada Laguna Salada ephemeral stream, Corona intermittent river, and De la Sierra perennial river. First, wet, average, dry, and very dry conditions were computed at a daily scale for each calendar hydrological year based on each river site's complete set of flow records (hydrographs on the left; (**a**,**f**,**k**) panels; flow rate displayed at a logarithmic scale). Second, integrated environmental flows were obtained based on the reference factors (values) for both the baseline and the adjustment (Table 1) according to the environmental objective classes (Equation (5)). The regime representative of the hydrological conditions was also calculated and plotted based on the corresponding values for natural parametrization, that is to say, 25%, 50%, 15%, and 10% (hydrographs in the middle; ((**b**,**d**,**g**,**i**,**l**) panels). Third, the metrics for the performance assessment (r^2 and slope values) were calculated based on the correlation of the natural parametrization and the model outcomes per environmental objective (scatterplots on the right; ((**c**,**e**,**h**,**j**,**m**) panels). This procedure was repeated for all the study sites and critically examined for each subset and the full set of outcomes according to the performance criteria previously established.

3. Results

3.1. Hydrological Contributions per Streamflow Type: Characteristics and Relationships

The distributions of the SQ values per hydrological condition exhibit the same pattern of seasonal and inter-annual variability: the greater the water availability, the greater the range of variance (i.e., wet > average > dry > very dry) (Figure 4a). The median of the wet conditions among variabilities is 59%, while the average is 20%, dry is 14%, and very dry is 7%. Similarly, the central range is 51%, 15%, 8%, and 3% in the lower quartile, and 74%, 23%, 16%, and 11% in the upper for the wet, average, dry, and very dry conditions, respectively.

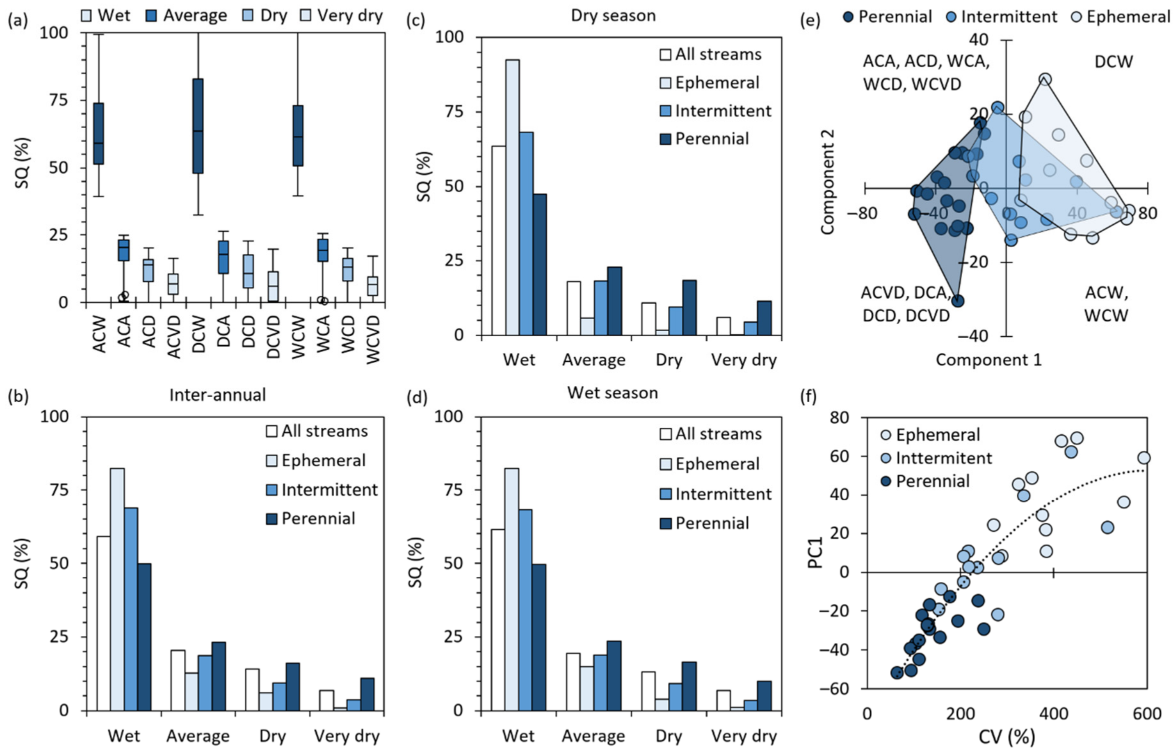

Figure 4. Exploratory data of the standardized relative discharge contribution (SQ%) and stream types relationship with the principal components and coefficient of variation index (CV%). (**a**) Central and full range distribution of inter-annual variability (A) per the hydrological condition (C): wet (W), average (A), dry (D), and very dry (VD) (nomenclature: ACW, ACA, ACD, and ACVD), dry season (DCW, DCA, DCD, DCVD), and wet season (WCW, WCA, WCD, WCVD) with outliers displayed in circles. Medians of hydrological condition per stream type of (**b**) inter-annual, (**c**) dry season, and (**d**) wet season variability. (**e**) Biplot of principal components 1 and 2 eigenvectors; and (**f**) polynomic regression between the coefficient of variation and the principal component.

However, the dry season exhibits the greatest amplitude by a condition within the central ranges (wet 48–83%, average 11–23%, dry 5–18%, and very dry 1–11%). Concerning the data outside of the central range, the highest values are depicted by the wet conditions for inter-annual and seasonal variability, reaching SQ values of > 95%. Except for the wet condition, the rest of the conditions displayed the opposite situation, <5%, two of which had outliers (average condition of inter-annual variability and in the wet season).

The median of the stream types of subsets analysis revealed similar patterns. For seasonal and interannual variability, ephemeral streams showed greater SQ values for wet conditions (82–92%) than the intermittent (68–69%) and perennial rivers (47–50%) (Figure 4b–d). Nevertheless, the magnitude of the remaining contributions was greater for perennial rivers (average 23–24%, dry 16–18%, and very dry 10–12%) than for intermittent rivers (average 18–19%, dry 9–10%, and very dry ≤ 4%) and ephemeral streams (average 6–15%, dry 2–6% and very dry ≤ 1%).

According to the PCA whose overall purpose is to reduce the analyses to the significant components based on the comprehensive ordering of the river sites per streamflow type prior to testing significance of their differences, the SQ values had a strong and positive correlation with the PC1 in wet conditions ($r \geq 0.92$), and a strong and negative one with the remaining ($r \leq -0.87$), regardless of the variability (Appendix A Table A1). In the PC2, this relationship had considerably lesser strength; however, it contributed to displaying the remaining variance at two dimensions and seemed to be season related. The PCA outcome is consistent with the descriptive analysis, the interactions between the components and the SQ values depicted a differentiated, gradient-like, climatic dependency of the river classes along the year (i.e., ephemeral > intermittent > perennial), reflected in the biplot for ordering (PC1 vs. PC2, Figure 4e), and the long-term variability index between seasons (Figure 4f). This gradient is further explained by the number of stream types based on the PC combination, the independent hydrological variability indices, the basins' surface, and the dominant climatic units upstream from the river sites (gauged locations).

All the ephemeral streams (11) and eight out of twelve of the intermittent rivers (67%) fell in the indices combination +PC1 / +PC2 and +PC1 / –PC2, and none of the perennial rivers (Table 2, Appendix A Figure A2). This set of river sites shows the greatest dependency on wet conditions regardless of the variability. On the contrary, 33% of the intermittent, and all perennial rivers (17) fell in the indices combination –PC1/+PC2, and –PC1/–PC2.

Table 2. Principal components combination (PC 1 and PC2), the coefficient of variation (CV%) and baseflow (BFI%) indices of hydrological variability, basin surface upstream from the river sites (km^2), and percentage of dominant climatic units per streamflow type.

Descriptor (Index/Metric)	Streamflow Type Ephemeral (*n* = 11)	 Intermittent (*n* = 12)	 Perennial (*n* = 17)	 All (*N* = 40)
PC combination (# basins)				
+PC1 and +PC2	5	3		8
+PC1 and –PC2	6	5		11
–PC1 and +PC2		3	7	10
–PC1 and –PC2		1	10	11
Coefficient of variation index (CV%)				
Coefficient of determ. (r^2/R^2) *	0.2473	0.5071	0.4189	0.8009
Median	384	228	130	218
Central range	339–434	207–296	111–157	134–341
Full range	271–594	154–516	64–251	64–594
Baseflow index (BFI%)				
Coefficient of determ. (r^2/R^2) *	0.0798	0.0008	0.1496	0.4021
Median	1.2	2.3	13.4	4
Central range	< 3.9	1.2–4.7	6.8–25.9	1.4–10.0
Full range	< 6.0	< 7.9	1.4–32.5	0–32.5
Surface (km^2)				
Median	2361	2891	4728	3385
Central range	1425–8748	720–8226	1849–10,653	1354–10,109
Full range	374–22,927	274–17,557	483–64,861	274–64,861
Dominant climate (%)				
Semi-warm subhumid	0.0	2.2	0.4	0.7
Semi-warm humid	0.0	0.0	8.2	4.6
Warm subhumid	0.0	2.4	14.0	8.3
Warm humid	0.0	0.0	7.8	4.4
Semi-dry semi-warm	5.8	9.7	5.8	6.7
Semi-dry warm	2.1	3.7	2.0	2.4
Semi-dry temperate	10.8	23.7	16.5	16.9
Semi-dry semi-cold	0.0	1.5	0.1	0.4

Descriptor (Index/Metric)	**Streamflow Type**			
	Ephemeral (*n* = 11)	**Intermittent (*n* = 12)**	**Perennial (*n* = 17)**	**All (*N* = 40)**
Dry semi-warm	25.4	15.0	2.7	10.4
Dry warm	19.7	0.4	0.0	4.3
Dry temperate	9.5	5.1	1.1	3.8
Very dry semi-warm	12.0	12.7	0.0	5.5
Very dry warm	8.5	0.0	0.0	1.8
Very dry very warm	0.1	0.0	0.0	0.0
Very dry temperate	3.1	0.0	0.0	0.7
Temperate subhumid	1.1	18.3	33.2	22.9
Temperate humid	0.0	0.0	1.1	0.6
Semi-cold subhumid	1.9	5.4	7.0	5.5

* Based on regressions of the PC1 and the hydrological index for the whole population (polynomic, R^2) and each river class (linear, r^2).

About the reference indices of hydrological variability (CV and BFI), the full range is also shown as a gradient with clearer distinctions in medians and ± 1 quartiles ranges. Ephemeral streams have the greatest CV ranges (full 271–594% and central 339–434%; r^2 = 0.25), the intermittent class presents an intermediate (154–516%; 207–296%; r^2 = 0.51), while the perennial rivers the shortest (64–251%; 111–157%; r^2 = 0.42). The overall correlation of PC1 with this index in the complete set of basins is positive and strong (R^2 = 0.80). In contrast, perennial rivers have BFI that ranged 1–33% (± 1 quartiles 7–26%), while in ephemeral streams and intermittent rivers it is constrained to less than 6% (4%) and 8% (1–5%), respectively, where 11 out of 23 (44%) ≤ 1% (i.e., perennial > intermittent > ephemeral). Individually, the river sites exhibit very low positive correlations ($r^2 \leq 0.15$), although together they increase (R^2 = 0.40).

In terms of the basin surface, perennial rivers cover the greatest extensions; however, there are no distinctive characteristic ranges discernable, particularly between ephemeral streams and intermittent rivers. The overlapping of these full ranges, both with the variability indices and surface, suggests that there is not a clear quantitative definition between classes, but rather a characteristic transition zone among them. In this sense, the dominant climates metric offers a more comprehensive understanding. There is a clear dominance of semi-dry, dry and very dry weather of ephemeral streams (97%) and intermittent rivers (72%), while in perennial rivers the prevalent climatic conditions are temperate subhumid, semi-dry temperate, warm subhumid, semi-warm humid, and warm humid (80%). Furthermore, as it was hypothesized, the multivariate assessment on the SQ values differences revealed a significant level both between the groups of the hydrological conditions (wet ≠ average ≠ dry ≠ very dry; p-values ≤ 0.0001), variability (inter-annual, dry, and wet seasons), and among the river classes (ephemeral ≠ intermittent ≠ perennial; p-values ≤ 0.0354) (Tables 3 and 4).

Table 3. Effects of response variables (wet, average, dry, and very dry conditions) between streamflow type and the groups of variability (inter-annual, dry, and wet season) (one-way PERMANOVA). Euclidean similarity index, permutation 9999 times.

Hydrological Condition	**Total Sum of Squares**	**Within-Group Sum of Squares**	**F**	***p*-Value**
Wet	38,460	13,520	34.12	0.0001
Average	6151	2870	21.15	0.0001
Dry	4815	1760	32.12	0.0001
Very dry	3051	846	48.19	0.0001

Table 4. Pairwise test of response variables between the groups per river type (one-way PERMANOVA). *p*-values with Bonferroni correction (Euclidean similarity index, permutation 9999 times).

River Type Pairwise	Ephemeral	Intermittent	Perennial
Wet condition of inter-annual, dry, and wet season variability			
Ephemeral		0.0177	0.0003
Intermittent	0.0177		0.0003
Perennial	0.0003	0.0003	
Average condition of inter-annual, dry, and wet season variability			
Ephemeral		0.0141	0.0003
Intermittent	0.0141		0.0003
Perennial	0.0003	0.0003	
Dry condition of inter-annual, dry, and wet season variability			
Ephemeral		0.0354	0.0003
Intermittent	0.0354		0.0003
Perennial	0.0003	0.0003	
Very dry condition of inter-annual, dry, and wet season variability			
Ephemeral		0.0336	0.0003
Intermittent	0.0336		0.0003
Perennial	0.0003	0.0003	

3.2. Environmental Water Reserves' Reference Values

The full and central ranges of the EWRs depicted distinctive thresholds among the method baseline criteria and the adjustment based on the new frequencies of occurrence where the higher the environmental objective the greater the environmental water needs (Figure 5). The full range in the baseline goes from 19–76%, 6–63%, 3–57%, and 2–52% of the MAR for the environmental objectives A, B, C, and D, respectively (Figure 5a). Regardless of the environmental objective class, the range between the first and third quartiles (i.e., interquartile range) is around 20–22% MAR with the following relative magnitudes per class: A = 41–62%, B = 23–44%, C = 14–36%, and D = 9–29%. Based on the adjustment to the frequency of occurrence reference values, the outcomes in ephemeral streams for the minimum and maximum ranged from 31–77% of the MAR for environmental objective class A, 23–61% for B class, 17–49% for C, and 12–41% for D (Figure 5b). The relative magnitudes of the central thresholds were A = 36–67% MAR, B = 31–53%, C = 26–42%, and C = 21–33% with 13–30% interquartile range. Intermittent rivers presented wider full ranges running from 28–86% MAR for an environmental objective class A, 17–71% for class B, 11–62% for C, and 10–57% for D; while the central ones varied from A = 53–70%, B = 38–53%, C = 29–43%, and D = 25–37% with a narrower interquartile range 12–17% (Figure 5c). Perennial rivers exhibited the shortest full and central ranges from all (Figure 5d): 50–76% MAR for an environmental objective class A, 33–63% for B, 26–57% for C, and 20–52% for D; A = 60–65%, B = 42–47%, C = 34–39%, and D = 28–33%, accordingly (interquartile range 5%; all classes depict outliers).

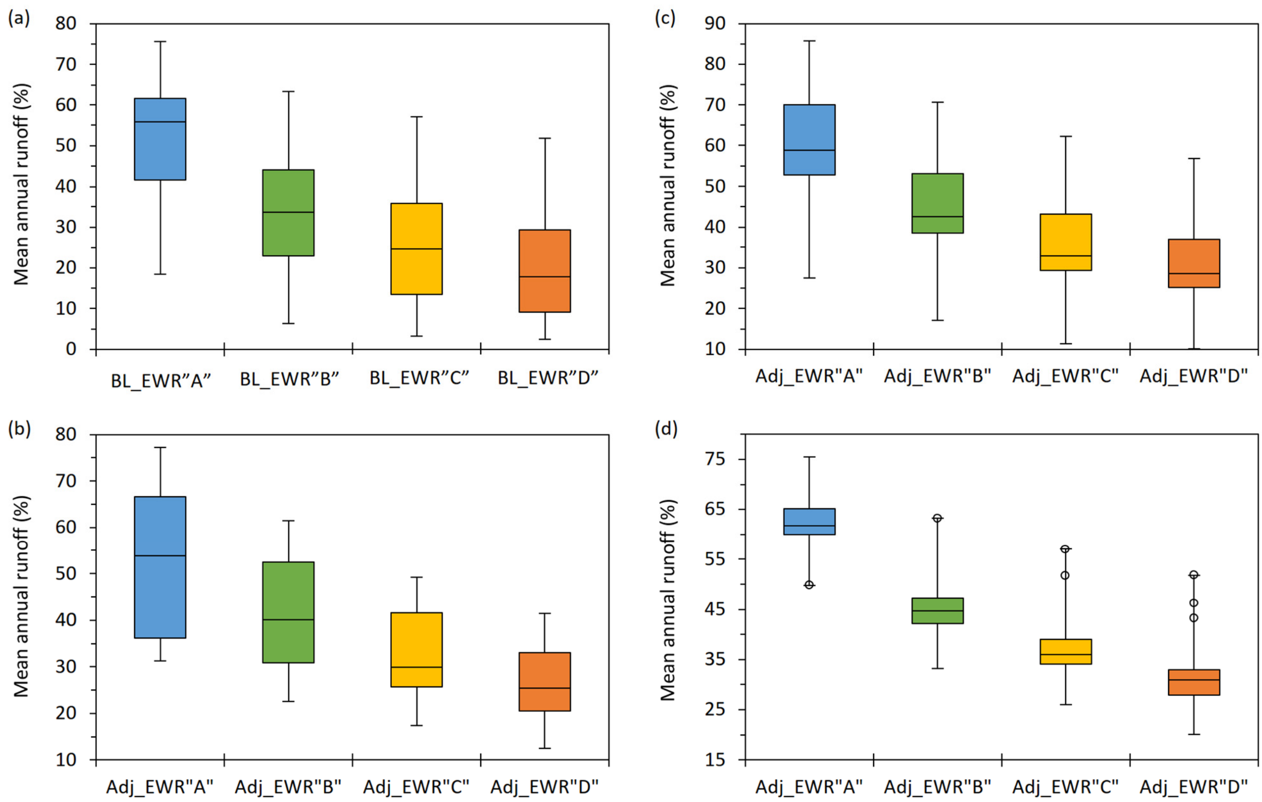

Figure 5. Central and full range of environmental water reserve volumes (EWR in percentage of the mean annual runoff) per environmental objective class (A = blue, B = green, C = yellow, and D = orange). (**a**) The method baseline (BL) criteria applied in the 40 basins, and the adjustments (Adj) based on the new criteria of frequency of occurrence reference values for (**b**) ephemeral (n = 11), (**c**) intermittent (n = 12), and (**d**) perennial rivers (n = 17; outliers displayed in circles).

3.3. Performance of the New Reference Factors for the Frequency of Occurrence

The performance of the references values of frequency of occurrence varied notably between the baseline and the adjustment; however, the latter highlights the improvement of both metrics, the r^2 and the slope values. The first aspect to note is that, except for environmental objective class A, the baseline reference values for ephemeral streams did not produce any performance outcome (r^2 nor slope values) in nine out of eleven river sites of the remaining environmental objective classes, three cases for B, six for C, and nine for D. This was because in such classes zero eflows were obtained according to the baseline reference values. Having said that, on the one hand, the baseline performed at a good level in all the river sites for the environmental objective class A ($r^2 \geq 0.9$); it achieved an acceptable level in three sites for class B (r^2 = 0.89–0.8); moderate in two for class C (r^2 = 0.79–0.7); and low in two sites for D class ($r^2 < 0.7$), in addition to the three, six, and nine cases without performance metrics previously mentioned (Figure 6). In total, the baseline reference values performed 25% at a good level, 7% acceptable, 5% moderate, and 64% low. Concerning the slope values, only three river sites for environmental objective class A performed at a good level (≤2.3; 7%), eight at an acceptable level (2.31–3.1; 18%), and at a low level in the eleven river sites for B, C, and D (>3.3; 33 cases, 75%).

On the other hand, the model's adjustment for ephemeral streams based on the coefficient of determination performed at a good level in all the river sites (100%) for all the environmental objective classes (44 cases). For the slope values, environmental objective classes A and B for all the river sites, and three cases for class C, achieved a good level of performance (25 cases, 57%). An acceptable level was found in class C of environmental objective in eight river sites (3.11–3.3; 18%), while moderate and low performance was depicted in one and ten river sites both for class D (2% and 23%, respectively).

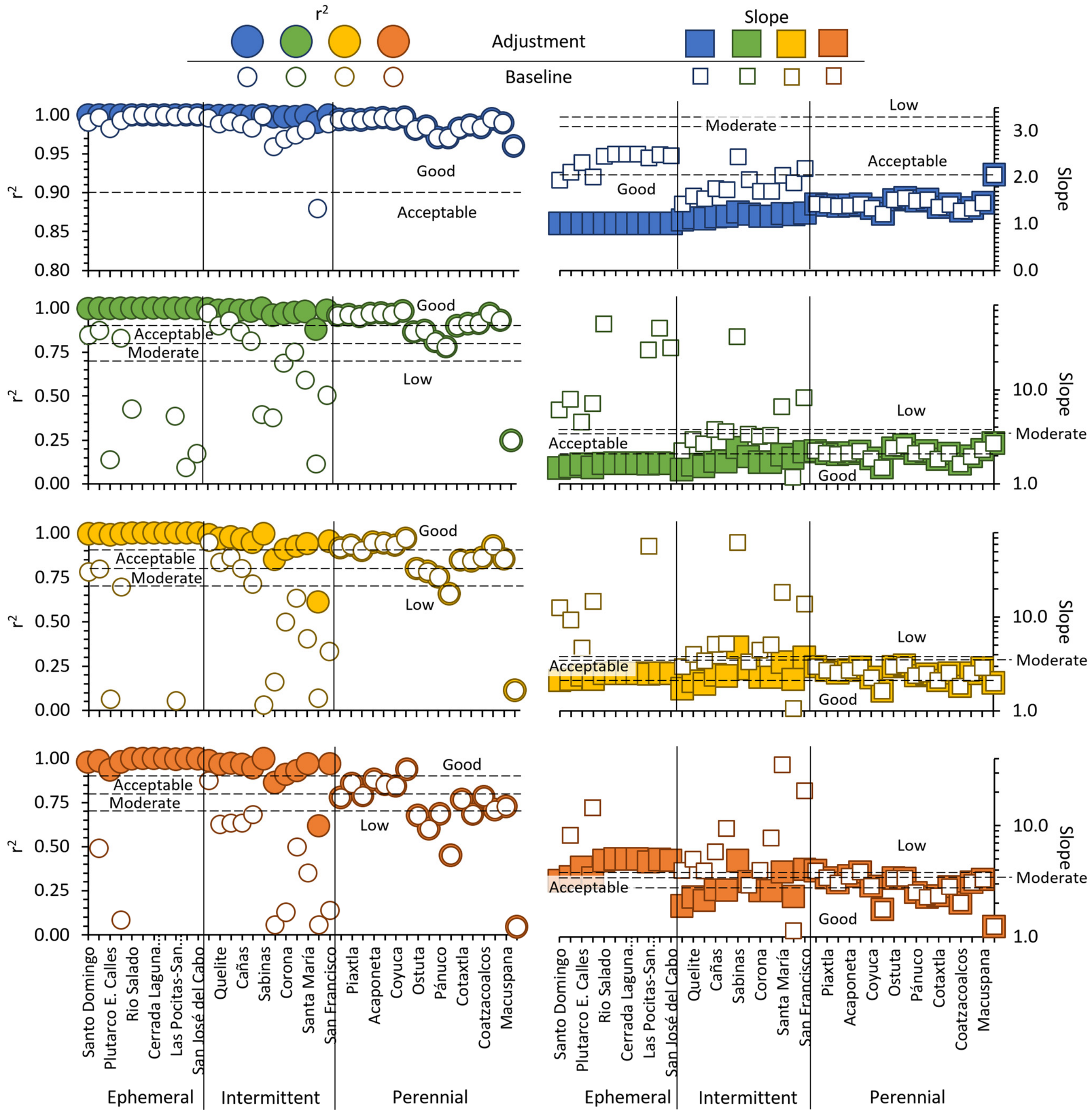

Figure 6. Performance assessment of the baseline and the new (adjustment) reference values of the frequency factors of occurrence per environmental objective class (A = blue, B = green, C = yellow, and D = orange) for environmental water allocation in ephemeral streams, intermittent, and perennial rivers. Coefficients of determination (r^2) on the left panel (circles, white baseline, and colored adjustment), and slope values on the right panel (squares, white baseline, and colored adjustment; environmental objective classes B, C, and D displayed at a logarithmic scale). Thresholds for the performance classes displayed dashed lines.

In the case of the intermittent rivers, the baseline's performed slightly better than for ephemeral streams. For this subset, the coefficients of determination depicted a good performance in eleven out of the twelve sites for an environmental objective class A, three for B, and one for C. Acceptable level of performance was found in one site for environmental objective class A, two for class B, three for C, and one for D, while two sites performed at a moderate level, one for environmental objective class B, and one for class C. The low level of performance concentrated six river sites for environmental objective class B, seven for class C, and eleven for class D; one of those did not produce any performance outcome as in the ephemerals' subset. In total, the baseline reference performed 31% of the cases at a good level, 14% acceptable, 4% moderate, and 51% low based on the r^2 values. Similarly, the slope values for an environmental objective class A showed a good level of performance in eleven river sites, two for class B, and one for classes C and D each (31% of the cases). At an acceptable level were found one river site for environmental objective class A, two for class B, and one for classes C and D (10% of the cases). The moderate level was depicted only in one site for environmental objective class B (2%), and the low level gathered twenty-seven cases (55%), seven for class B, and ten for C and D each.

About the model's adjustment for intermittent rivers, the performance based on the coefficient of determination was found at a good level in 43 of the cases (90%), all the river sites for environmental objective class A, 11 for class B, 10 for class C, and 10 for class D. Three cases depicted an acceptable performance (6%), one site for environmental objective classes B, C and D each; and only two cases a low performance (4%), one for classes C and D each. On the slope values side, 33 cases were performed at a good level (67%), all the river sites for environmental objective class A, eleven for class B, six for class C, and four for class D. Eight cases were performed at an acceptable level (16%), the remaining site for environmental objective class B, three for class C, and four for class D; two cases at a moderate level (4%), one site for classes C and D each; and five cases at a low (10%), two sites for class C and three for class D.

Finally, for perennial rivers, as there is no adjustment to the references values for the frequency of occurrence, the coefficient of determination metric depicted good performance in 38 cases (56%), the seventeen river sites for environmental objective class A, twelve for class B, eight for class C, and one for class D. Acceptable performance was found in eleven cases (16%), three sites for environmental objective class B, and four for classes C and D each; moderate in ten cases (15%), one for class B, three for class C, and six for class D; and low in nine cases (13%), one for class B, two for class C, and six for class D. About the slope values, in 39 cases the model performed at a good level (57%), the seventeen river sites for environmental objective class A, thirteen for class B, five for class C, and four for class D. Acceptable performance was found in 22 cases (32%), four for environmental objective class B, twelve for class C, and six for class D. Moderate and low performance gathered one (1%) and six cases (9%), respectively, both for environmental objective class D.

4. Discussion

The differentiating gradient of hydrological dependency ordered by the PCA is related to the streamflow type's characteristic ranges of variability between dry and wet seasons, within a year and along with successive cycles in the long term [7,22–24]. In general, the CV index resulted to be a good predictor of the river sites' wet condition dependency level: the higher the index, the greater the dependency ($r^2 = 0.80$).

A clear, quantitative, and definitive separation was found between the ephemeral streams and perennial rivers (PC1 eigenvectors from 8 to 69 vs. from –13 to –52; CV 271–594% vs. 64–251%, respectively). Such a boundary was barely distinguishable between intermittent and perennial rivers; however, it was not present between ephemeral streams and intermittent rivers. Instead, a long transitional zone with overlapping indices values was identified, a shared characteristic consistent with the dominant dry climate and the basins' surface [28,33]. This is because the streamflow setting implemented in this study was an intermediate objective to order the groups before evaluating their wet conditions dependency at an inter-annual and seasonal level. Based on such settings, there are significant differences (95% confidence level) in the response of hydrological conditions and variability between the three streamflow classes. Providing empirical and science-based evidence of such relationships has contributed to improving environmental water science and is a first step to informing eflow implementation towards climate-resilient management [3,9,18,20,22–24,37].

Detailed on-site eflow studies involving a wide variety of specialists, such as hydrologists, biologists, ecologists, water and protected area managers, raised awareness about potential underestimations of environmental water requirements in non-perennial rivers [22–24]. Even though the original method outcomes deliver ecosystem water requirements for the full spectrum of hydrological conditions, from very dry to wet, environmental water allocations reflect time-varying conditions and help to cope with the non-stationarity of the flow regime [22–24]. Eflow implementations could lead to unexpected outcomes that imply degradation in non-perennial rivers beyond sustainable limits [1–3,16,18,33]. Such empirical knowledge led us to the hypotheses tested in this research; new findings have emerged and scientifically supported the need to adjust the baseline criteria to improve the frequency factors of occurrence aiming at contributing towards climate-smart eflow management.

About the characteristic EWRs, the higher median volumes per environmental objective class vary from perennial rivers (A–D = 62–31% MAR) to intermittent (59–29% MAR) and ephemeral streams (54–25% MAR) with increasing central thresholds (interquartile range 5% perennials, 12–17% intermittents, and 13–30% ephemerals). This is because of the weighing in the new reference values of frequency factors of flow components occurrence. Such values are in line with the original method [24]; however, unlike the values provided in previous studies [11,12,22], the ones proposed in the present research differentiate between streamflow types. These were developed based on the recognition that they depend differently on hydrological conditions, inter-annual and seasonal variability, consistent with the PCA outcomes (Appendix A Figure A3), the related characteristics of each class, and the significant differences among them.

Likewise, the performance assessment on the new reference values for the frequency factors of flow components occurrence provides a clear improvement with regards to the baseline. In synthesis, the overall performance of the baseline reference values based on the coefficients of determination was at a good level in 40% of the cases between all the river sites and the environmental objective classes, 13% acceptable, 9% moderate, and 38% low. For the adjustment, the overall performance based on this metric increased to 78% at a good level, 9% acceptable, 6% moderate, and 7% low. Similarly, in terms of the slope values the model's baseline performed 36% at a good level, 22% acceptable, 1% moderate, and 41% low; whereas for the adjustment, it improved by 61% at a good level, 24% acceptable, 3% moderate, and 13% low.

As reported by the original method, the model's level of fitness (r^2 values) and similarity or proportion of deviation (slope values) of the outcomes against the natural parametrization of the frequency of occurrence of the flow components explain the differences between precision and accuracy of the adjusted reference values [24]. On the one side, the coefficients of determination depict a highly hydrological consistency (87% precision at least at an acceptable level) between the natural parametrization and the eflow regimes for the four-class system of environmental objectives based on the new factors of occurrence for wet, average, dry, and very dry conditions of inter-annual and seasonal variability regardless of the streamflow. On the other side, slopes values show that the proportion of deviation of the eflow regimes was limited to closer proximity from the natural parametrization (85% accuracy at least at an acceptable level). Despite uncertainties, these performance outcomes validate the model from a quantitative and qualitative point of view [38,39]. There are several implications of these findings.

4.1. Implications and Contributions

In comparison to the baseline, the adjustment of the frequency factors of occurrence is a significant improvement to the model because eflow implementation through water allocation systems (EWR) secures both high and low flow events in the short and long term, without underestimating such components in intermittent rivers and ephemeral streams, which are more dependent on wet conditions than perennial rivers [3,7,8,18,24,33–37,40,41]. By examining river sites per streamflow type, common patterns with significant differences arise at a hydrological level [23,33]. Capturing appropriately such differences and patterns in the parametrization of the frequency factors of occurrence reference values was a research gap [22,24]. Through the current model, we have brought on board a new setting to further study it at a desktop or on-site level, detail flow-ecology relationships or working hypotheses on ecohydrological functions [1–3,9,33], and provided a unique insight to cope with the non-stationarity challenges of the regime looking forward to climate-smart and resilient eflow implementation [24].

A second implication is that frequency-of-occurrence-based eflow regimes capture distinctively both inter-annual and seasonal variability of low flows and peak flow events, which occur throughout the country and elsewhere, regardless of the stream type, as demonstrated by the current experiment. Such variability influences changes in the basin runoff as a primary reflection of the climate along with its geology, orography, and land cover, and eventually in the composition and structure of freshwater ecosystems [17,27,33]. The original method has proved to be consistent at least at good and acceptable levels in the parametrization of the frequency of occurrence for both environmental flow components outcomes—including the extremes—between different periods of observation ($r^2 \geq 0.83$; slope ± ≤ 0.2) [24]. Although each study experiment design is different (proof-of-concept vs. significant differences in the hydrological conditions between streamflow types), the findings presented here expand such a level of consistency at a flow-daily rate. For example, in the highly variable flow regime of perennial rivers Acaponeta, Baluarte, and San Pedro Mezquital (CV = 195–251; BFI = 1.4–3.8%; 11012, 11014, and 11016 codes in Figure 1), despite a variety of trends (non-significant and significant) in the mean annual runoff between periods of observation (Figure A4, Table A2), the performance metrics at a daily scale maintain similar levels ($r^2 \geq 0.79$; slope = 1.4–3.8; Supplementary Material). If the discharge series compiles at least ≥ 20 years at a daily scale (≤ 10% of gaps) from historical or recent decades, and there is evidence that the flow regime and the basin overall structure are close to a natural state or relatively low impacted, the changes over time in discharge patterns and water availability should be reflected in the model, regardless of significant increasing or decreasing trends [24], without compromising the method's outcomes based on the new reference values.

Distinctive eflow regimes for wet, average, dry, and very dry conditions are assessed, as well as the set of peak flow events to conform EWRs [24]. These two components of the EWR are integrated based on historical though varying recurrence, facilitating discussions on dynamic implementation and governance over time instead of static, and promoting climate-resilient or adaptive water allocation systems [22,24]. EWRs, as all the variables used in river basin water balances, are regularly set at an annual scale due to planning and management in allocation systems. However, EWRs are provided based on a method that could be implemented either at a daily or monthly scale to deliver eflow prescriptions for each hydrological condition or climate scenario [24]. In the context of climate uncertainty, such prescriptions can be incorporated into water availability short-, mid-, or long-term studies according to the available water in the environment, whether from previous years or forecasted by detailed studies, and towards sustainable water future management [42,43]. EWRs for a wide array of hydrological ordinary and extraordinary conditions contribute to overcoming the eflows implementation challenge under different climate scenarios towards the maintenance of both people and ecosystems' health, as well as their resilience capacity [3,4,15–24,33,42,43].

Furthermore, at a water planning level, the reference values of EWRs expressed as a percentage of the MAR provide streamflow type frequency-based volumes adjusted to a four-class system of environmental objectives. Such reference values have been proposed based on comprehensive assessments [3,9–12] and widely used throughout the world (i.e., "look-up tables") to track progress on eflow implementation, i.e., Sustainable Development Goal 6.4.2., the "water stress" indicator and the Global Environmental Flow Information System [14], or to assess the water scarcity accounting for the gap between people's and environmental water needs [44].

The most important implication is that providing reference values based on streamflow types per environmental objective class, for both the frequency of occurrence of flow regime components and EWRs likely volumes, contribute at different levels of eflow assessments and implementation, strategic goals towards the global action agenda and the emergency recovery plan of freshwater biodiversity loss [4,45]. By explicitly including EWR scenarios for water allocation, the impacts of climate change on the water balance and the environment could be either anticipated, buffered, tracked over time, and help to adapt or mitigate transitional changes from one ecological state to another under the unavoidable future intensification of competition for the resources [3,4,15–24,42,44].

4.2. Limitations and Recommendations

The implementation of EWRs reference values (percentage of MAR) is recommended only at a water planning level and as a precautionary approach for comparison or tracking progress on eflow implementation [3,9,22–24]. For ephemeral streams and intermittent rivers, the higher the CV index between seasons, the higher reference value based on the central range analysis outcomes is recommended (i.e., 3rd, 2nd, or 1st quartile). For the case of the perennial rivers, a similar relationship is recommended although BFI-based instead: the higher the baseflow, the higher the reference value. Furthermore, examining the relationship of both indices (CV/BFI) is also advisable [7,22–24,41]. Beyond comparisons or tracking progress on eflow implementation, decision-making based on such reference values is not recommended at the water management level, in over-allocated and over-exploited rivers, nor for environmental impact assessments of water infrastructure projects. In these cases, bottom-up and detailed approaches (i.e., ecohydrology-based, habitat simulation, or holistic methodologies) should be prioritized because they are more robust and appropriate [3,9,22–24].

At a technical level, the number of ephemeral streams and intermittent rivers limits the scope of the research. This was greatly influenced by the available sets of flow records within the research design requirements; in Mexico, streamflow gauging stations tend to be in-placed in larger perennial rivers, a common global bias recently highlighted [46]. Although significant differences in the SQ% values were found based on the location of rivers concerning the Tropic of Cancer (p-value < 0.05), this was not according to drainage direction (p-value > 0.05) (Appendix A Table A3). A two-way PERMANOVA test for streamflow type and the location of rivers with regard to the Tropic of Cancer was also performed. Even though significant differences between these factors in all the hydrological conditions were found, there is not any interaction among them at a significant level; they are related (chi-square test, p-value < 0.05) (Appendix A Tables A4 and A5). These outcomes, in addition to the PCA two-dimensional grouping graphs (Appendix A Figure A5), drove the rest of the research to be streamflow type classification oriented. However, current findings suggest that more conclusive outcomes between factors could be found if the number of sample basins increases.

A more representative number of sample basins would be 80 ± 10 ideally, with 4–5 repetitions per class as considered here (ephemeral, intermittent, or perennial streamflow type; drainage direction towards the to the Gulf of Mexico in the Atlantic Ocean, Gulf of California in the Pacific Ocean, or endorreic/closed basins; and northern or southern climate). That is around twice this effort, 20 ± 2% of the country's total number [26–29]. In this sense, identifying suitable ephemeral streams and intermittent rivers is the greatest challenge, and further research on them is required. One possibility would be to expand the search to river sites at the basin headwaters, which also would increase the chance of having greater representativeness of different climates [33]. Alternatively, and perhaps more appropriately, the frequency of occurrence approach with the new reference values per streamflow type could be examined within existing frameworks for assessing people's and ecosystems' resilience based on rivers' discharge stochastic models [19,20,47]. Unlike deterministic models, stochastic models account for spatial-temporal variability of extreme events with successful outcomes towards reducing uncertainty in river basins with the influence of the Mediterranean climate [48–50].

Another limiting factor is that flow duration curves do not capture a wide range of flow cessation characteristics, which are extremely important in the development of biological and ecological processes in ephemeral streams and intermittent rivers (e.g., species dispersal and hydrological connectivity) [33,35,51]. Clearer and quantitative boundaries among the stream types could be improved by increasing the time resolution of the hydrological metrics and investigating flow–ecology relationships on which healthy aquatic, semiaquatic, and riparian or terrestrial ecosystems depend. In this sense, zero and peak flow extraordinary events with their frequency, duration, timing or seasonality, and rate of change are more appropriate [8,24,33]. So too, the low flows for different hydrological conditions at a monthly scale, together with the basins' topography, geology, land cover, and climate characteristics [3,7,9,24].

Finally, and concerning the Mexican environmental water policy and governance, a decade ago, the federal government embarked on a strategic and ambitious plan to enact environmental water for ecological protection. The overall strategy is supported by, first, a National Water Law where the environment is recognized as a legitimate user, and second, the four-level hierarchical national norm to conduct eflow assessments that has already been proved to produce robust and consistent outcomes [3,9,21–24,43,45]. However, flow regime indices references were established based on a handful of case studies. Throughout these years, new research has provided a better understanding of ecologically relevant hydrological indices, and has suggested how climate might induce shifts in them depending on river types. Such regulatory instruments are subject to continuous revisions and ratifications where adaptive management takes the opportunity to be in-placed [3,4,15–20,33,42,43,47]. Specifically, the eflows norm passes through this process every five years, the last being back in 2017 [52]. To date, the holistic ecohydrology-based desktop approach, expert panel, and on-site research-driven eflow assessments have gathered empirical and scientific valuable knowledge with the participation of more than 100 specialists in hydrology, biology, ecology, water, and protected areas managers [22–24,43]. The findings presented in this research contribute to increasing such technical robustness of the strategy through a better understanding of reference values per streamflow type to both continue developing new studies and to track progress on environmental water allocation, implementation, and governance through the upcoming management plans and the newly formed Water Reserves Monitoring Network [22–24,43].

5. Conclusions

The ecological understanding of hydrologic indices has played a meaningful role in both eflow assessments and implementations worldwide, and climate change has imposed a critical challenge to move forward from people and ecosystem's water needs based on static requirements to a more dynamic set of prescriptions capable of reflecting wider conditions' baselines. Coping with the inter-annual and seasonal variability non-stationarity of the flow regime, from very dry to wet ordinary conditions and extraordinary peak flow events, is one of the greatest challenges in eflow science and practice.

Mexico, a country with wide political, societal, and environmental conditions, faces a mix of complex climatic, ecological, and hydrological challenges representative of eflow science and practice worldwide. In the last decade, ecohydrology knowledge and eflow implementation in water allocation systems (i.e., socio-hydrology) have achieved significant progress towards setting and managing sustainable limits of water abstraction. The present research findings demonstrate that there are significant differences between streamflow types and the distinctive way non-perennial rivers depend on a range of hydrological conditions in comparison to perennial rivers.

Frequency-of-occurrence-based reference values for both eflow assessments and implementations, adjusted to streamflow type and environmental objectives of the flow regime, build on current discussions in coping with the non-stationary climate challenges by managing the set of eflow components within resilient thresholds for people and ecosystems—empirical and theoretical—and thus, socioenvironmental climate-smarter water deliveries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14091489/s1: The database for the assessment presented in this paper.

Author Contributions: Conceptualization, methodology, validation, formal analysis, investigation, writing—original draft preparation, visualization, project administration, and funding acquisition, S.A.S.-R.; writing—review and editing, supervision, S.A.S.-R., N.C.v.d.G. and M.E.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A

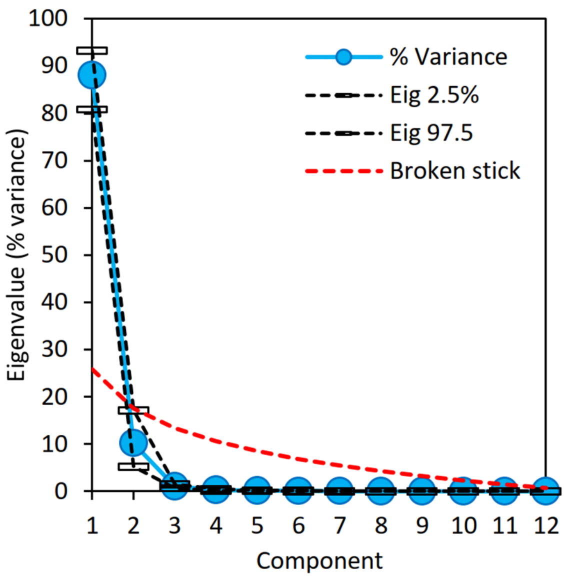

Figure A1. Percentage of variance (%) for the complete set of principal components. Principal components 1 and 2 gathered 98% of the cumulative variance (88% and 10%, respectively). The selection of such components was made based on the broken stick method (95% confidence interval).

Table A1. Matrix of correlations for the complete set of principal components.

Condition	Code	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12
Inter-annual													
Wet	ACW	0.98	–0.16	0.03	0.02	0.05	0.02	0.00	0.00	0.01	0.00	0.00	0.00
Average	ACA	–0.93	0.28	0.21	–0.08	–0.02	–0.04	–0.01	–0.04	0.02	–0.01	0.00	0.01
Dry	ACD	–0.98	0.16	–0.07	–0.02	–0.10	0.08	0.02	0.01	0.04	0.00	–0.01	–0.01
Very Dry	ACVD	–0.94	0.00	–0.31	0.06	0.00	–0.10	0.00	0.03	0.03	–0.02	0.03	0.00
Dry season													
Wet	DCW	0.92	0.38	–0.02	0.01	–0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	DCA	–0.90	–0.34	0.24	0.14	–0.02	–0.02	0.04	0.01	0.00	0.00	0.00	0.01
Dry	DCD	–0.91	–0.39	–0.04	–0.02	0.00	0.05	–0.07	0.01	0.00	0.00	0.00	0.01
Very Dry	DCVD	–0.88	–0.37	–0.23	–0.16	0.07	–0.01	0.07	0.00	0.00	0.00	–0.01	0.01
Wet season													
Wet	WCW	0.94	–0.33	0.01	–0.03	–0.04	–0.01	0.00	0.00	0.00	0.01	0.00	0.00
Average	WCA	–0.87	0.43	0.22	–0.09	0.06	–0.02	0.00	0.03	0.01	0.02	0.01	0.00
Dry	WCD	–0.93	0.34	–0.06	0.04	–0.02	0.11	0.04	–0.01	–0.01	0.01	0.02	0.01
Very Dry	WCVD	–0.92	0.14	–0.30	0.18	0.05	–0.06	–0.02	–0.03	0.01	0.04	–0.01	0.00

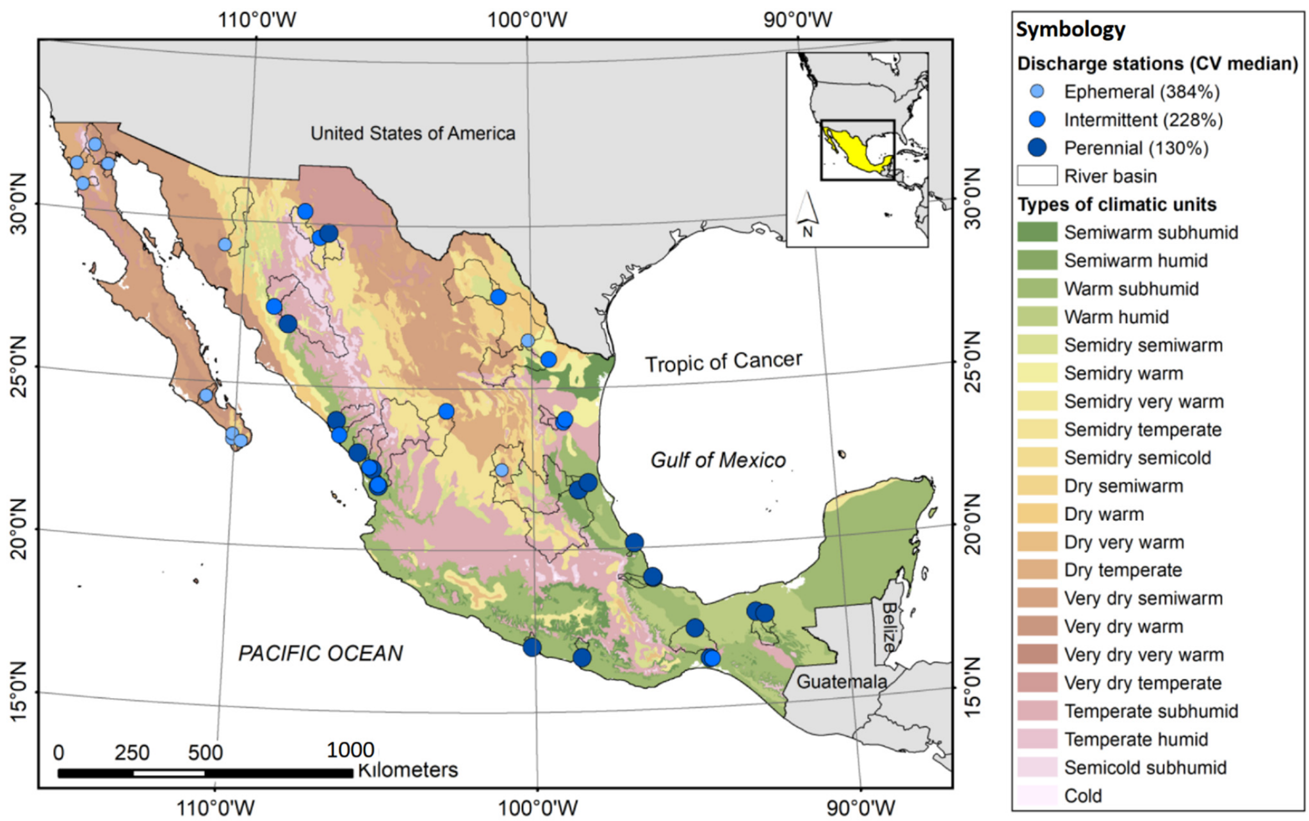

Figure A2. Location of study basins, flow type at the gauged point, the median of the coefficient of variation (CV), and types of climates based on the Köppen climatic classification system.

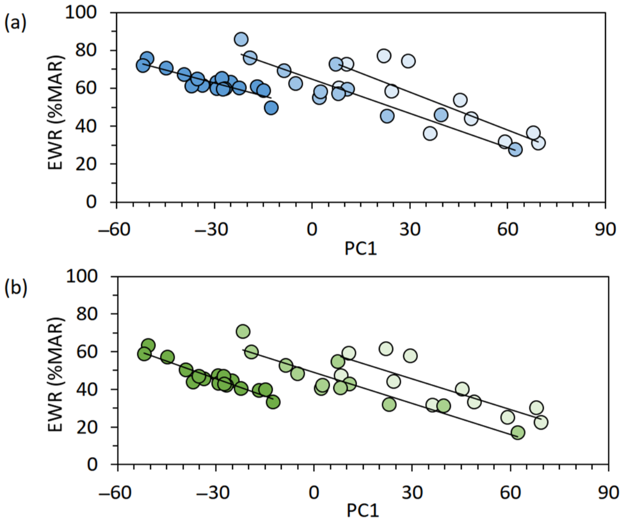

Figure A3. Linear regressions between the principal component 1 eigenvectors (PC1) and the environmental water reserves [expressed as a percentage of the mean annual runoff–EWR (%MAR)] based on the adjustment of the frequency of occurrence per streamflow type (colors gradient: lighter ephemeral, intermediate intermittent and darker perennial). The scatter plots (**a**–**d**) are displayed according to the environmental objective classes A, B, C, and D in blue, green, yellow, and orange tones, respectively.

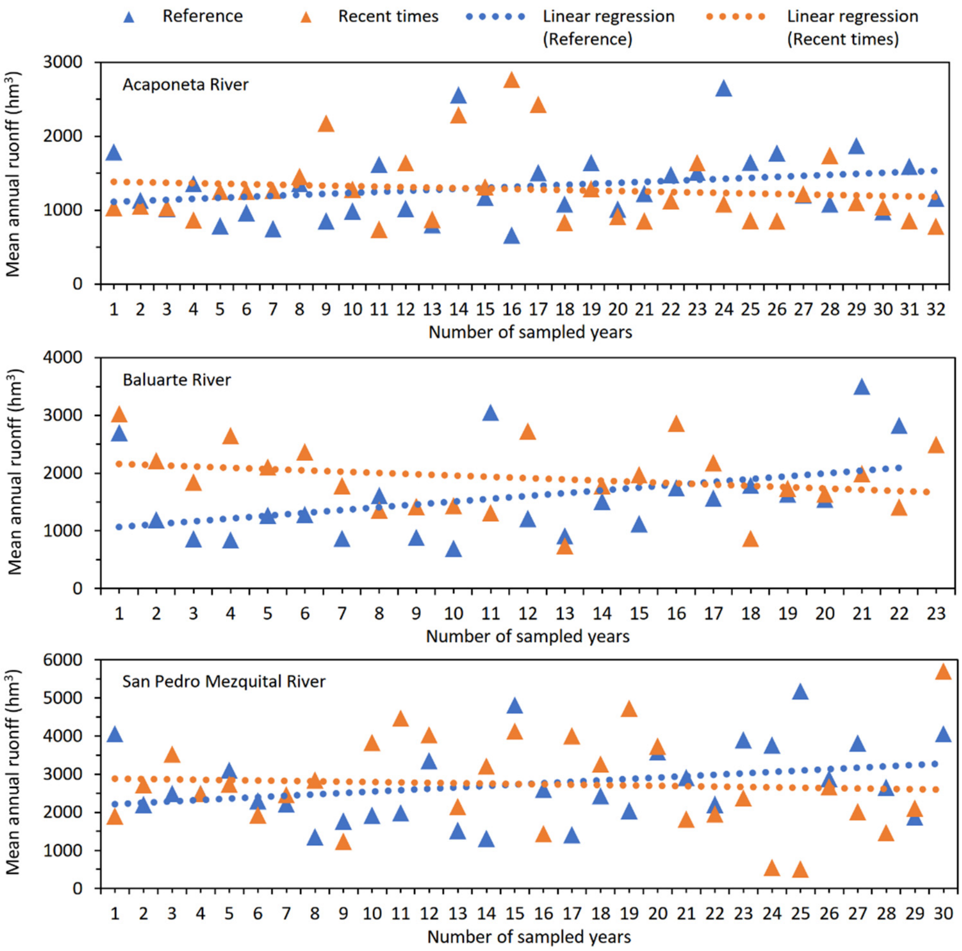

Figure A4. Trends of the mean annual runoff for two periods of observation from three highly variable flow regime rivers, Acaponeta (**top**), Baluarte (**middle**), and San Pedro Mezquital (**bottom**). Periods of observations were split into two, the first as a reference (historical) (Acaponeta 1945–

1976, Baluarte 1948–1969, and San Pedro Mezquital 1944–1973), and the second as representative from recent times (1977–2008, 1970–1992, and 1974–2003).

Table A2. The Mann–Kendall trend test and Sen's slope of the mean annual runoff based on the periods of observation of the Acaponeta, Baluarte, and San Pedro Mezquital rivers. *P*-values are displayed at no significance ($p > 0.10$), slight significative ($p < 0.10$ *), significative ($p < 0.05$ **), or strongly/very significative ($p < 0.01$ ***) levels. Tests were computed in Minitab 18.

Statistic	Mann–Kendall Z-Value	*P*-Value	Sen's Slope
Acaponeta			
Reference (1945–1976)	1.8000	0.0359 **	12.26
Recent times (1977–2008)	–0.7661	0.2278	–5.95
Complete series (1945–2008)	–0.1159	0.4539	–0.34
Baluarte			
Reference (1948–1969)	2.4814	0.0007 ***	40.28
Recent times (1970–1992)	–1.2149	0.1122	–24.77
Complete series (1948–1992)	2.2010	0.0139 **	18.28
San Pedro Mezquital			
Reference (1944–1973)	1.4630	0.0717 *	33.24
Recent times (1974–2003)	–0.4995	0.3087	–16.21
Complete series (1944–2003)	0.3125	0.3773	3.25

Table A3. Effects of response variables (wet, average, dry, and very dry conditions) between river type and variability groups (inter-annual, dry, and wet season) (one-way PERMANOVA). Euclidean similarity index, permutation 9999 times.

Hydrological Condition	Total Sum of Squares	Within-Group Sum of Squares	F	*p*-Value
Tropic of Cancer				
Wet	38,460	31,190	7.694	0.0056
Average	6151	5208	21.15	0.0001
Dry	4815	1760	6.89	0.0086
Very dry	3051	2667	5.47	0.0226
Drainage direction				
Wet	38,460	35,090	1.78	0.1684
Average	6151	5650	1.64	0.1867
Dry	4815	4392	1.72	0.1677
Very dry	3051	2786	1.76	0.1693

Table A4. Pairwise test of response variables between the groups per river type according to their location with regard to the Tropic of Cancer (one-way PERMANOVA). *p*-values with Bonferroni correction (Euclidean similarity index, permutation 9999 times).

River Type Pairwise	Northern	Southern
Wet condition of inter-annual, dry, and wet season variability		
Northern		0.0055
Southern	0.0055	
Average condition of inter-annual, dry, and wet season variability		
Northern		0.00997
Southern	0.0097	
Dry condition of inter-annual, dry, and wet season variability		
Northern		0.0041
Southern	0.0041	

River Type Pairwise	Northern	Southern
Very dry condition of inter-annual, dry, and wet season variability		
Northern		0.0191
Southern	0.0191	

Table A5. Pairwise test of response variables between the groups of rivers based on the streamflow and the Tropic of Cancer classifications (two-way PERMANOVA). Euclidean similarity index, permutation 9999 times.

Source	Total Sum of Squares	Degree Freedom	Mean Square	F	*p*-Value
Wet					
Streamflow	24,940	2	12,470	28.786	0.0001
Tropic of Cancer	6476.3	1	6476.3	14.95	0.0001
Interaction	−7682.7	2	−3841.4	−8.8675	0.9998
Residual	14,729	34	433.2		
Total	38,462	39			
Average					
Streamflow	3281.4	2	1640.7	19.917	0.0001
Tropic of Cancer	943.96	1	943.96	11.459	0.0004
Interaction	−874.7	2	−437.35	−5.3091	0.3943
Residual	2800.8	34	82.377		
Total	6151.5	39			
Dry					
Streamflow	3055.3	2	1527.6	26.159	0.0001
Tropic of Cancer	855.21	1	855.21	14.645	0.0001
Interaction	−1080.9	2	−540.44	−9.2546	1
Residual	1985.5	34	58.397		
Total	4815.1	39			
Very dry					
Streamflow	2204.4	2	1102.2	31.926	0.0001
Tropic of Cancer	383.65	1	383.65	11.112	0.0002
Interaction	−711.24	2	−355.62	−10.301	1
Residual	1173.8	34	34.525		
Total	3050.7	39			

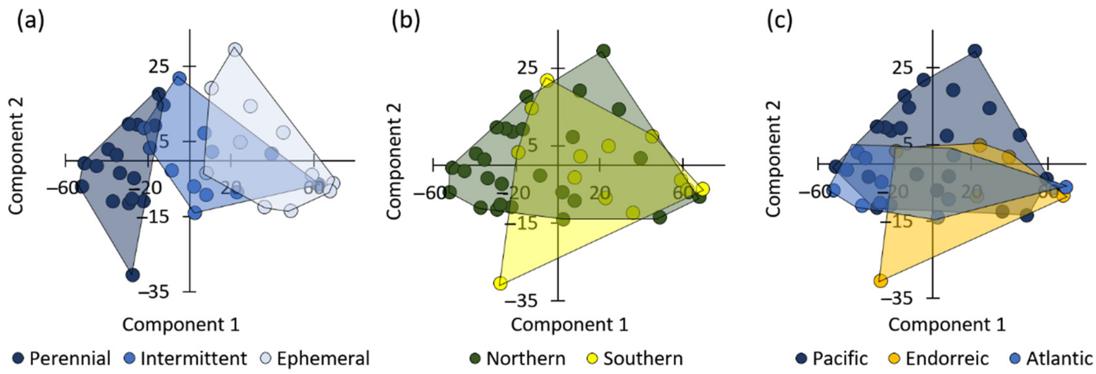

Figure A5. Biplot of principal components 1 and 2 eigenvectors per river's (**a**) streamflow type, (**b**) their location with regard to the Tropic of Cancer, and (**c**) their drainage direction.

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