Determining Mexican climate-adaptive environmental flows reference values for people and nature

A hydrology-based approach for preventive environmental water allocation

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Determining Mexican climate-adaptive environmental flows reference values for people & nature

A hydrology-based approach for preventive environmental water allocation

Sergio A. Salinas Rodríguez

Propositions

accompanying the dissertation

Determining Mexican climate-adaptive environmental flows reference values for people and nature

A hydrology-based approach for preventive environmental water allocation

by

Sergio Alberto SALINAS RODRÍGUEZ

1. Uncertainty lies between knowledge and the unknown.
2. In freshwater ecosystems conservation, hydraulic modeling is the most effective interface that connects knowledge and practice to produce science-based outcomes.
3. Long-term stream discharge and societal agreement about its desired ecohydrological state are the only information requirements for preventive environmental water allocation at a reasonable level of certainty. (This dissertation)
4. Climate-smart environmental flows depend on the stratification of long-term hydrological variability, the frequency of occurrence of different climatic conditions, trends, metrics, flow type and societal dependency to water availability. (This dissertation)
5. The implementation of the environmental flow components based on their probability of occurrence keeps socio-environmental systems resilient to long-term climate shifts. (This dissertation)
6. Long-term changes drive living organisms' adaptation strategies. Resistance of status-quo of human consumption patterns is useless, resilience is smarter.
7. Smart nature protection is conserving or restoring ecosystem's adaptive-capacity to anthropogenic change while increasing the awareness among policy makers of uncertainty about human consumption patterns.
8. Decisions are made with or without information. A precautionary approach, long-term monitoring, and adaptive management increase resilience in the face of uncertainty.
9. Understanding and explaining life is not as important as experiencing it. Life is an ever evolving experimental design that makes learning-by-doing worthwhile.
10. Aldous Huxley's quote "experience is not what happens to a man; it's what a man does with what happens to him" is powerful and inspirational for personal development and science practice.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors prof.dr.ir. N.C. van de Giesen and prof.dr. M.E. McClain.

Determining Mexican climate-adaptive environmental flows reference values for people and nature

A hydrology-based approach for preventive environmental water allocation

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Dissertation

for the purpose of obtaining the degree of doctor at Delft University of Technology by the authority of the Rector Magnificus prof.dr.ir. T.H.J.J. van der Hagen, chair of the Board of Doctorates to be defended publicly on Tuesday 18 June 2019 at 12:30 o'clock

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To Jessica, my beloved life partner.

Contents

Summary

Environmental flows science has significantly advanced in the last decades. In Mexico, a standard for environmental flow assessments was recently published as a regulatory instrument to support water planning and management based on state-of-the-art knowledge and practice. Through its implementation, environmental water allocations have been made, and expected to continue, for securing a sustainable balance between water use and freshwater ecosystems protection for up to 50 years. However, the appropriateness of the technical procedure in a climate change context has not been investigated. Do the environmental flows cope with the non-stationary challenge of the flow regime and the water availability shifts in the long term? This research focuses on the assessment of the inter-annual and seasonal variability of the Mexican rivers flow regimes to determine climate-adaptive reference values for environmental flows and water allocations.

In the first stage, the research focuses on the overall strategic approach for conducting environmental flow assessments and promoting early implementation. Results at 25 reference sites from two different methodologies, hydrology-based desktop and holistic with on-site information, are analytically evaluated. The strategic implementation of the methods revealed a reasonable level of consistency in 72% of the study sites (environmental water reserves coefficient of variation ≤ 10%). The remaining difference is attributed mainly to a better reflection of the natural dry episodes by the hydrology-based method. In 94% of the cases, the environmental water reserves are feasible to implement at the water planning level.

The environmental flows hydrology-based method developed for the Mexican rivers, its ecohydrological foundations, consistency of results, and hydrological validations is assessed in-depth in seven case studies. Two different time sections of the total period of records from each rivers' streamflow were evaluated. The first was considered a reference for validation, and the second was subjected to assessment. The results depicted an overall consistency level ($R^2 \geq 0.9$ in 78% of the performance indicators). The main contribution of this method consists of novel frequency-of-occurrence approach for evaluating two major flow regime components for coping the non-stationary climate challenge: low flows from ordinary wet, average, dry and very dry conditions, and a flood regime of peak flow extraordinary events. Environmental water requirements are adjusted to a four-tiered environmental objective class system. Potential flow-ecology relationships are exemplified for on-site ecological validation in intermediate, full detailed assessments, and for long-term monitoring.

The following step consisted of assessing the magnitude of the hydrological contributions of wet, average, dry and very dry conditions from the inter-annual and seasonal variability. Forty Mexican rivers were selected based on their climate,

geographic and hydrological representativeness. The rivers were classified based on mainstream flow type [ephemeral (11), intermittent (12) or perennial (17)]. Climate and geography were considered based on two separate classifications. First, with regard to the Tropic of Cancer to cover the incidence of climatic extreme events such as droughts (northern = 13) and floods (southern = 27). Second, according to exorreic (Atlantic or Pacific [13 and 21, respectively]) or endorreic (6) drainage. Full and central range distribution descriptive statistics, principal component analysis, and one-way PERMANOVA inference statistics were used to assess similarities and differences. The hydrological classification based on flow type reflected the most comprehensive hydrological condition dependency [(ephemeral > intermittent > perennial; differences at 95% confidence level (p-values < 0.05)], consistent with independent flow variability indices and dominant climates.

In the final stage of the research, the impact of climate change was assessed in the set of previously selected rivers. Mann-Kendall trend tests were conducted in river discharge and basin rainfall from at least 20 and 25 consecutive years. Regardless of the flow type and the basin location, significant increasing and decreasing trends were found at least at 90% confidence level (p-values < 0.10). Hydrology-based environmental flows and water reserves were calculated as stated by the method's current baseline, and according to an adjustment to the frequency of occurrence criteria as a reflection of dependency from each flow type to the hydrological conditions. The performance assessment of the reference values was focused on the basins water availability impact revealed no significant difference between the baseline and the adjustment.

The stratification of flow type dependency to different inter-annual and seasonal variability is key in environmental flow assessments. The frequency of occurrence of the environmental flow components is a significant contribution to environmental water science and practice towards climate-smart long-term implementation. The uncertainty of flow regime variability in a climate change context imposes great challenges in water availability for both people and nature. By coping with such variability under different climate scenarios, and explicitly integrating them in environmental flow assessments based on a probability of occurrence approach provide ecosystem-based climate-adaptive water allocations.

Applications of these reference values go from preventive water planning and management to research-driven for flow-ecology relationships in-depth assessments. "Rules of thumb" or volumes look-up tables, advanced *holistic (eco)hydrologic desktop* methods, intermediate and full detailed assessments are benefited. These levels of analysis do not exclude but complement each other. They provide strategic frameworks for environmental flows implementation, urgently needed to protect or restore freshwater ecosystems and the related environmental services.

Samenvatting

De wetenschappelijke kennis over rivierafvoeren voor milieudoelen (milieu-afvoeren) is de afgelopen jaren aanzienlijk toegenomen. In Mexico is onlangs een nieuwe norm voor de bepaling van milieu-afvoeren gepubliceerd als een regelgevingsinstrument ter ondersteuning van waterplanning en -beheer op basis van de meest geavanceerde kennis en praktijk. Door toepassing van deze norm is er water gereserveerd voor milieudoeleinden ten einde een duurzaam evenwicht te verzekeren tussen enerzijds watergebruik en anderzijds bescherming van zoetwaterecosystemen voor een periode tot 50 jaar. Naar verwachting zal deze praktijk voortgezet worden. Er is echter niet onderzocht of de technische procedure ook toepasbaar bij klimaatverandering. Voldoen de milieu-afvoeren nog wel als de rivierafvoeren sterk fluctueren en de beschikbaarheid van water op de lange termijn afneemt? Dit onderzoek richt zich op de variatie in rivierafvoeren tussen verschillende jaren en seizoenen om klimaatadaptieve referentiewaarden voor milieu-afvoeren en waterreserveringen te kunnen bepalen.

De eerste fase van het onderzoek richtte zich op de holistische strategische aanpak voor het bepalen van milieu-afvoeren en het bevorderen van vroegtijdige toepassing. Op 25 referentielocaties zijn twee verschillende methoden toegepast, één die alleen gebruik maakt van bestaande hydrologische data en een tweede holistische methode waarbij ter plekke informatie werd verzameld. De resultaten zijn geanalyseerd en geëvalueerd. Voor 72% van de locaties waren de resultaten redelijk consistent (variatie in milieu-afvoeren ≤ 10%). Het resterende verschil kan grotendeels verklaard worden doordat natuurlijke droogteperiodes beter in de hydrologische methode zitten. In 94% van de gevallen zijn de waterreserveringen voor milieudoeleinden toepasbaar op planniveau.

De hydrologische methode voor de bepaling van milieu-afvoeren voor de Mexicaanse rivieren, de ecohydrologische basis van deze methode, de consistentie van de resultaten en de hydrologische validatie zijn in zeven case studies in detail geëvalueerd. Uit de totale periode waarover afvoerdata beschikbaar zijn, zijn telkens twee kortere periodes geselecteerd. De eerste periode is beschouwd als basis voor validatie en de tweede is geevalueerd. Het algemene consistentieniveau was hoog (R^2 ≥ 0.9 voor 78% van de prestatie-indicatoren). De belangrijkste innovatie van deze methode is de nieuwe frequentie-van-voorkomen benadering voor het evalueren van twee componenten van het afvoerregime die van groot belang zijn voor de aanpak van de non-stationaire klimaatuitdaging: lage afvoeren onder normaal natte, gemiddelde, droge en zeer droge omstandigheden; en piekafvoeren onder buitengewone omstandigheden. De vereiste milieu-afvoeren hangen af van de milieudoelen, die in vier klassen verdeeld zijn. De potentiële afvoer-ecologie relaties worden geïllustreerd

aan de hand van gemiddelde en uitgebreide ecologische evaluaties in het veld en lange-termijnmonitoring.

De volgende stap bestond uit de bepaling van de hydrologische bijdragen van natte, gemiddelde, droge en zeer droge omstandigheden aan de variabiliteit tussen jaren en seizoenen. Veertig Mexicaanse rivieren werden geselecteerd op basis van hun klimaat, geografische en hydrologische representativiteit. De rivieren werden geclassificeerd op basis van het afvoertype [slechts nu-en-dan afvoer (11), wisselend afvoer (12) of permanente afvoer (17)]. Voor klimaat en geografie werd gekeken naar de locatie ten noorden (13) of ten zuiden (17) van de Kreeftskeerkring vanwege het voorkomen van klimaatextremen zoals droogte ten noorden en overstromingen ten zuiden van de Kreeftskeerkring. In de tweede plaats werd gekeken naar de exorreïsche afvoer naar de Atlantische Oceaan (13) of de Grote Oceaan (21) of endorreïsche afvoer (6). Om overeenkomsten en verschillen vast te stellen werd de volledige en centrale bereikverdeling beschreven en werd principal component analyse en one-way PERMANOVA deductiestatistieken toegepast. De hydrologische classificatie op basis van afvoertype toonde de meest omvattende afhankelijkheid van hydrologische omstandigheden [slechts nu-en-dan afvoer, wisselend afvoer of permanente afvoer; 95% betrouwbaarheidsniveau (p-waarden < 0.05)], consistent met onafhankelijke afvoervariabiliteit en het dominante klimaat.

In de laatste fase van het onderzoek werd de invloed van klimaatverandering op de eerder geselecteerde rivieren beoordeeld. Hiervoor zijn Mann-Kendall-trendtesten uitgevoerd op de rivierafvoeren en de neerslag van minimaal 20 respectievelijk 25 opeenvolgende jaren. Onafhankelijk van het afvoertype en de locatie van het stroomgebied, werden significante stijgende en dalende trends gevonden op 90% of hoger betrouwbaarheidsniveau (p-waarden < 0.10). Hydrologisch-gebaseerde milieu-afvoeren en waterreserveringen zijn berekend op basis van de huidige baseline van de methode en met aanpassing van de frequentie van voorkomen als gevolg van de afhankelijkheid van elk afvoertype van de hydrologische omstandigheden. De prestatiebeoordeling van de referentiewaarden richtte zich op de impact van de beschikbaarheid van water en gaf geen significant verschil te zien tussen toepassing van de baseline en de aanpassing.

De stratificatie van de afvoertype-specifieke afhankelijkheid van de verschillende variaties tussen jaren en seizoenen is van centraal belang voor de vaststelling van milieu-afvoeren. De frequentie waarmee de componenten van de milieu-afvoeren voorkomen, levert een belangrijke bijdrage aan zowel de wetenschappelijke kennis over milieu-afvoeren en de praktijk met het oog op lange-termijn klimaatslimme toepassing. De onzekerheden met betrekking tot afvoervariatie bij klimaatverandering vormen een grote uitdaging voor de beschikbaarheid van water voor mens en natuur. Het omgaan met afvoervariatie in verschillende klimaatscenario's en het expliciet integreren van de variatie in de bepaling van milieu-afvoeren op basis van een frequentie-van-optreden benadering, resulteert in ecologische klimaatadaptieve waterreserveringen.

Toepassingen van deze referentiewaarden strekken zich uit van preventieve waterplanning en -beheer tot diepgravende onderzoeksgedreven evaluaties van de afvoer-ecologie relaties. "Vuistregels" en opzoektabellen, geavanceerde holistische (eco)hydrologische desktopmethoden en gemiddelde en uitgebreide beoordelingen hebben allemaal hun nut. Deze analyseniveaus sluiten elkaar niet uit, maar vullen elkaar aan. Zij bieden een strategisch kader voor de toepassing van milieu-afvoeren, die dringend nodig zijn voor de bescherming en het herstel van zoetwaterecosystemen en de milieudiensten die deze leveren.

1
Introduction

1.1 The need for environmental flows assessment science

Globally, freshwater ecosystems occupy approximately 1% of Earth's surface and support around 10% of all known species (Abramovitz, 1996; McAllister Hamilton & Harvey, 1997; Dudgeon et al., 2006; Balian, Segers, Lévêque & Martens, 2008). By virtue of their location in the landscape, they connect terrestrial and marine ecosystems and provide vital ecosystems services to the wealth and subsistence of human communities [Millennium Ecosystem Assessment (MEA), 2005; United Nations Environment (UN Environment), 2017]. Rivers and their associated floodplains, aquifers, lakes and wetlands depend on the local and regional climate, geology, and landscape (e.g. orography and vegetation) to generate runoff on the basin (Cotler Ávalos, Garrido Pérez, Luna González, Enríquez Guadarrama & Cuevas Fernández, 2010; Costigan et al., 2017; Capon et al., 2018). The characteristic regime of flow and water levels in freshwater ecosystems is key for water, food, and energy provisioning to humankind, as well as other regulating, supporting and cultural services (MEA, 2005; Arthington, 2012; Costigan et al., 2017; Gilvear, Beevers, O'Keeffe & Acreeman, 2017; UN Environment, 2017).

However, it is widely known by the scientific community that freshwater ecosystems are way most threatened by anthropogenic impacts than the terrestrial and marine ones. This is mainly due to the fact of water overexploitation, pollution, flow modification, habitat degradation and loss, invasive exotic species, and more recently by climate change [Dudgeon et al., 2006; Vörösmarty et al., 2010; World Wide Fund for Nature (WWF), 2018]. Environmental flows assessment science (or environmental water science) emerged to quantify linkages between hydrological processes, components and ecological variables to support environmental water allocations as a river basin management tool for protecting or restoring freshwater ecosystems (Poff & Matthews, 2013; Poff, Tharme & Arthington, 2017). Despite the progress achieved by this complex hydro-ecological understanding, there is no global record of implementation (Arthington et al., 2018a). The major obstacles on the ground include lack of political will and public support, constraints on resources, knowledge and capacity, institutional barriers, and conflicts of interest (Le Quesne, Kendy & Weston, 2010; Harwood et al., 2017). There is still an urgent need for a greater effort (Richter, 2010; Richter, Davis, Apse & Konrad, 2012; Acreman et al., 2014ab).

One strategic way to embrace the challenge to overcome the obstacles found for assessing and setting freshwater ecosystem requirements is their context understanding and purpose, *is it for conservation or restoration?* Acreman et al. (2014a) state that in general environmental flows may be achieved, from the one side, by limiting alterations from the natural flow baseline to maintain diversity and ecological integrity (precautionary approach for natural and semi-natural rivers). On the other side, by designing regimes to achieve specific ecological and ecosystem service outcomes better suited for modified and managed rivers. That is to say, the first a top-down while the second a bottom-up approach.

Hierarchical-method frameworks based on a case context and purpose, from simple to complex and from conservation to restoration, offer a balance between technical specifications, research needs, the level of certainty required, and the level of resources available to advance in environmental flow implementation (Le Quesne et al., 2010; Kendy, Apse & Blann, 2012; Opperman et al., 2018).

1.2 Research background

In Mexico, the first documented environmental flow assessments were conducted in the 1990s by the Mexican Institute of Water Technology in heavily water-exploited rivers (Alonso-Eguía Lis, Gómez-Balandra & Saldaña-Fabela, 2007). Together with the global concern, these assessments raised awareness of ecosystem water requirements and triggered discussions for developing a nationwide standard as a regulatory instrument (*Norm*) to support the water management, based on the environmental water science (Alonso-Eguía Lis et al., 2007; Barrios-Ordóñez et al., 2015).

In 2007, the first draft of a standard for determining environmental flows was concluded and discussed for approval based on the Montana method (Tennant, 1976), a hydrology-based approach adapted to the Mexican conditions (García, González, Martínez, Thala & Paz-Soldan, 1999). The project did not succeed due to the fact of the obstacles still present (Le Quesne et al., 2010; Harwood et al., 2017; Arthington et al., 2018a), in particular, because of it was presented as an obligatory public policy, and the lack of knowledge and capacities to conduct assessments on the ground.

By 2011, a second project was presented, improved by the available state-of-the-art environmental water science and practice. It was based on more on-site environmental flow assessments gathered by national and international scientists, government agencies, and non-government organizations (Barrios-Ordóñez et al., 2015). In 2012 the standard was published in the Official Journal of the Federation as a voluntary regulatory instrument –yet legally binding to the obligatory water availability standard– to increase knowledge and build capacities for its implementation in a learning-by-doing model, and to eventually raise its rank to an obligatory public policy (Secretaría de Economía, 2012; Barrios-Ordóñez et al., 2015).

The environmental flows standard focuses on principles of river hydrology, ecology, and precautionary natural resources management. It is a flexible and iterative three-to-four-level framework for selecting the appropriate methodology based on the environmental flow needs (Le Quesne et al, 2010; Barrios et al., 2011; similar to Opperman et al., 2018). Hydrology-based for water planning (level zero) and management (level 1). Hydrobiological (habitat simulation models) or holistic for detailed intermediate assessments in cases with exceptional natural values (level 2). And holistic detailed assessments complemented by hydrobiological models (level 3) in the case of research-driven purposes (i.e. water infrastructure projects) (Figure 1.1).

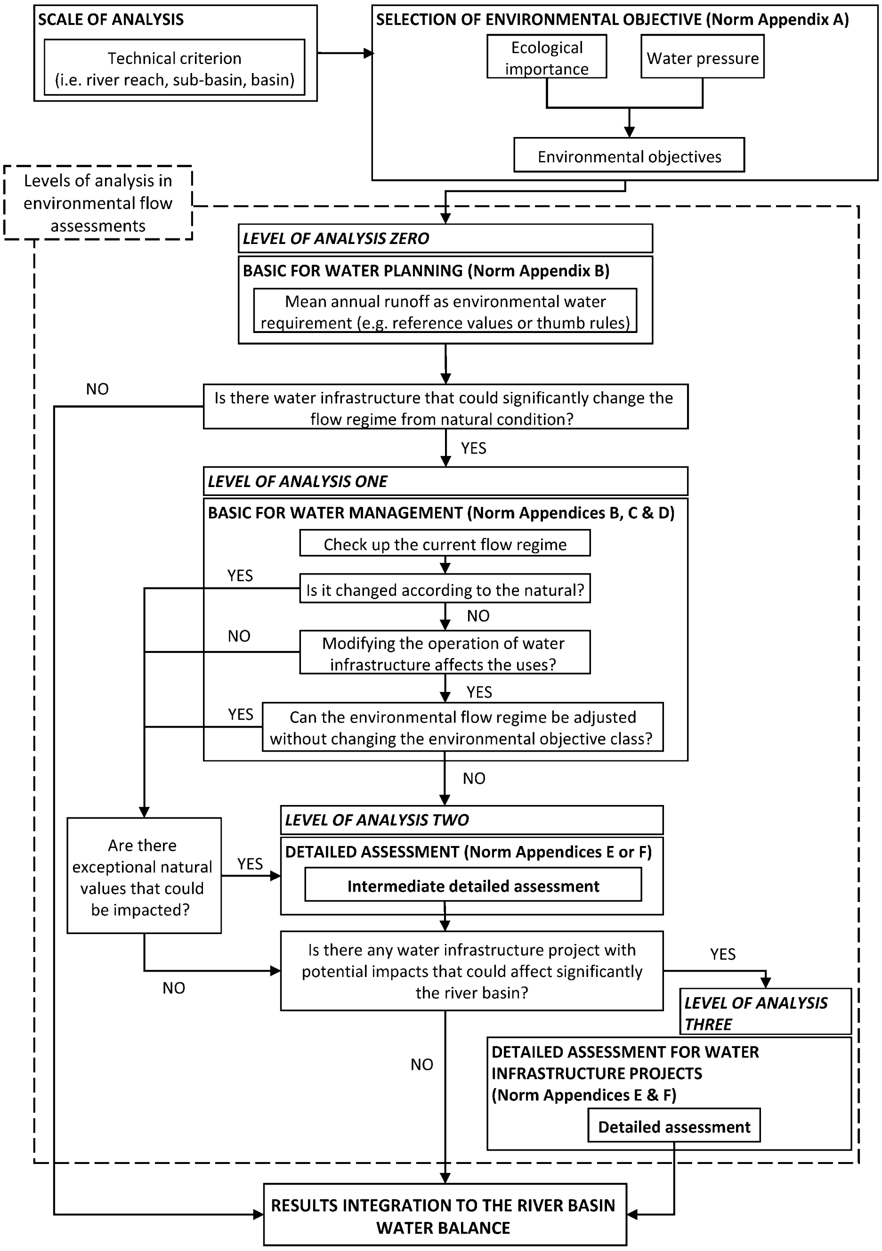


Figure 1.1. Three-to-four-level framework of the Mexican standard for determining environmental flows (based on Barrios et al., 2011).

Based on the environmental flows standard strategic implementation, the Mexican government set environmental water allocation initial targets (189 river basins by 2018) as a cross-section climate change adaptation measure in public policies [Secretaría de Gobernación (SEGOB), 2013 and 2014ab; Barrios-Ordóñez et al., 2015]. On one side, allocating water for the environment in healthy, unstressed systems secures sustainable planning and management due to the fact that once titles are issued, the flow regime and freshwater ecosystems start to degrade because of the water usage, and is very difficult to bring the system back in balance (Acreman et al., 2014ab; Barrios, 2014; Horne, O'Donnell & Tharme, 2017).

On the other hand, by protecting the amount of water designated to remain in the environment, water allocation systems keep a buffer zone to deal with climate uncertainty (Barrios, 2014). Environmental water implementation through allocations systems is key to reduce vulnerability and maintain long-term climate-adaptive capacity, for both people and nature, before water availability shifts (Salinas-Rodríguez, López Pérez, Barrios Ordóñez, Wickel & Villón Bracamonte, 2013). This is the cornerstone for ensuring the environmental services associated with the flow regime (MEA, 2005; Arthington, 2012; Costigan et al., 2017; Gilvear et al., 2017), and supports environmental flows management as an ecosystem-based adaptation measure to climate change.

This research was conceptualized based on the unique opportunity for implementing the standard in a systematic and synchronized way throughout the country. It focuses on planning, management, and intermediate analysis levels of environmental flow assessments. The findings are expected to contribute to the current knowledge of the Mexican environmental water science and to strengthen its practice for setting preventive water allocations in a climate change context.

1.3 Science questions

The overall goal of this thesis is to determine Mexican climate-adaptive environmental flows reference values for people and nature. For this purpose, the following objectives and research questions are formulated:

Objective 1. To present the foundations of the standard for determining environmental flows and the implementation strategy in pilot basins to assess the consistency of results from two different methodologies: (i) a hydrology-based desktop study, and (ii) a holistic or "ecosystemic" study based on field surveys and expert panel assessments.

- *How is the Mexican standard structured and implemented?*
- *What is the performance and level of consistency between the methods outcomes?*

- *Are the hydrology-based method outcomes validated by the holistic ones?*
- *What are the advantages, contributions, and limitations of the strategy?*

Objective 2. To present in detail the hydrological method for determining environmental flows, its ecohydrological foundations, and the novel frequency-of-occurrence approach for integrating and adjusting two major flow regime components into environmental water volumes: (i) low flows for a variety of hydrological conditions, and (ii) a flood regime with peak flow events from different magnitudes.

- *What are the benefits and challenges of the hydrology-based method developed for the Mexican rivers?*
- *What is the hydrological performance and level of consistency in different rivers?*
- *How is this useful for building flow-ecology relationships, on-site ecological validation and monitoring, and for coping the non-stationary climate challenge?*
- *What are its advantages and limitations?*

Objective 3. To assess different river basin classifications in order to find the most appropriate for (i) adjusting the frequency of occurrence criteria based on the rivers dependency of wet years or season condition; (ii) conducting in-depth trend analysis tests in discharge and rainfall, and (iii) hydrology-based environmental flow assessments.

- *Which river classification (geography, climatic or hydrology-based) reflects the inter-annual and seasonal variability heterogeneity of flows from the Mexican rivers?*
- *Do all hydrological conditions contribute to the same extent to the rivers full range of variability?*
- *Which type of river exhibits the highest dependency to wet years or season condition?*

Objective 4. To assess the climate change impact on the discharge and basins rainfall historical and recent trends for providing new reference values of (i) frequency of occurrence of the flow regime components based on differentiated climatic conditions; and (ii) the likely volumes for environmental water allocations.

- *Are there significant trends in the rivers discharge and basins rainfall class?*
- *What would be the suitable frequencies of occurrence criteria per river class and their likely reference values for environmental water allocation in the context of long-term availability shifts?*

1.4 Thesis outline

The thesis has four main chapters in order to address the overall goal, the research questions, and objectives. In chapter 2, the environmental flows standard foundations and its implementation strategy –a National Water Reserves for the Environment Program– are described. The results of two methodologies in 25 reference sites from eight pilot basins are analytically evaluated. A performance assessment is carried out focused on the process and early achievements.

Chapter 3 presents a detailed environmental flows hydrology-based desktop method developed for conducting assessments explicitly coping with the flow regimes' non-stationarity climate challenge. It includes an in-depth review from relevant literature on hydrological methodologies, their limitations, challenges, and opportunities in the Mexican natural resources management context. The new method's ecohydrological foundations are deeply examined, implemented and its performance assessed in seven rivers that discharge into a coastal wetland of international importance as a case study. Results of the method are critically analyzed and discussed in terms of its usefulness for building flow-ecology relationships as well as its advantages and limitations in strategic environmental water allocations.

In chapter 4, the magnitude of the hydrological contributions of wet, average, dry and very dry conditions from inter-annual and seasonal variability are assessed in 40 rivers classified by flow type, climate, and geographic location. Results of the grouping are examined in terms of their theoretical consistency prior to selecting the most comprehensive classification. A significance test on the hydrological conditions contributions per type of variability and river is conducted and the findings are discussed.

The final results of the research are presented in chapter 5. Here, a trend analysis of discharge and rainfall is carried out. Furthermore, the new frequency of occurrence criteria for integrating the flow regime components is proposed in light of the magnitude of the hydrological contributions of wet, average, dry and very dry conditions from inter-annual and seasonal variability per river type. The adjustment of the frequency of occurrence criteria is made in line with the original method conceptual basis. Hydrology-based environmental flow and performance assessments are conducted according to the current criteria and based on four scenarios. Reference values for both the new frequencies of occurrence criteria and the volumes for environmental water allocations are examined. Their implications and contributions for the Mexican environmental water science and practice are discussed as well as their limitations and recommendations.

Finally, the research conclusions, implications and a general outlook are summarized in chapter 6.

2

Mexican environmental water science, management and policy

This chapter focuses on the presentation of the National standard for determining environmental flows, its implementation strategy for the National Water Reserves for the Environment Program, and its results in 25 reference sites based on assessments conducted from 2012 to 2015 using hydrological and holistic methodologies. An analytical evaluation revealed an overall consistency between the Norm's environmental objectives (baseline) and the current ecological conditions on-site for 80% of the cases (96% over high confidence rating). Furthermore, in 72% of the reference sites the coefficient of variation among the reserves was below the last quartile range limit (< 11%), while those remaining above are attributed to a difference in the methods' hydrologic scope. The recommended volumes for environmental allocation are feasible for implementation under the current water availability conditions in the 94% of the river basins.

This chapter is based on:

Salinas-Rodríguez S.A., Barrios-Ordóñez J.E., Sánchez-Navarro R. and Wickel A.J. (2018). Environmental flows and water reserves: Principles, strategies, and contributions to water and conservation policies in Mexico. *River Research and Applications, 34*(8):1057-1084. DOI: https://doi.org/10.1002/rra.3334.

2.1 Introduction

The natural flow regime in aquatic ecosystems plays a critical role in sustaining ecological functions, processes, and services, and the ecological consequences of its alteration are well recognized (Poff et al., 1997; Richter, Baumgartner, Wigington & Braun, 1997; Bunn & Arthington, 2002; Davies & Jackson, 2006; Poff & Zimmerman, 2010; Acreman et al., 2014a; Poff et al., 2017). The quantity, quality, and timing of water required to preserve ecological functions and environmental services are generally identified as environmental flows (or “e-flows”). Their implementation in public policies such as *environmental water reserves* (EWR) –a volume based on the environmental water science– is an allocation mechanism to manage rivers in a more ecologically and socially sustainable way under current and future water usage, and freshwater biodiversity degradation rates (Acreman et al., 2014a; Horne et al., 2017; Poff et al., 2017).

In Mexico, an EWR is an annual volume of water that is allocated, by presidential decree, to benefit the environment and ecological protection of a river basin. It is established for a duration of up to 50 years and defines the usage of remaining water available in its geographical territory. The Mexican Environmental Flows Norm (NMX-AA-159-SCFI-2012) officially establishes the procedure and technical standards (onwards referred as eFlowsNMx) to determine this volume of water.

In 2012, the national water agency launched a National Water Reserves for the Environment Program (NWRP) focusing on 189 river basins –based on their water availability, low demand from current water users, and high biological richness and conservation values [Comisión Nacional del Agua (CONAGUA), 2011]– as a strategy to implement EWRs. Unlike other national-scale approaches around the globe, the Mexican NWRP aims to establish EWRs in targeted basins to capitalize on their favorable conditions of conservation potential while building a network and strengthening capacities in the e-flows standard implementation. These are fundamental aspects for a second phase of the program, which will focus on basins already facing intense pressure on their water resources (Barrios, 2014; Horne et al., 2017).

In this chapter, we present and discuss the implementation strategy of the eFlowsNMx developed in this program and its results in pilot projects from 2012 to 2015 (phase I). An analytical assessment of consistency between environmental objectives (national baseline *vs*. field evaluation) and EWRs determined using hydrological and holistic methodologies was conducted in 25 reference sites across 54 river basins throughout the country. The performance of the NWRP was examined in terms of progress towards the enactment of EWRs decrees.

2.2 Background: Water resources, conservation, and early assessments

The Mexican National Water Commission (CONAGUA) is the federal agency in charge of managing water resources in 757 river basins and 653 aquifers, located in 13 hydrological regions throughout the country. For each basin, there is an official water availability study published in the Official Journal of the Federation. According to recent publications, Mexico's total renewable water is 446.7 km^3/year, of which 85.6 km^3/year have been allocated to be used [Comisión Nacional del Agua (CONAGUA), 2016a. While these numbers indicate low water stress (19%) at the national level, at the scale of hydrological regions there are parts of the country that experience severe water stress (> 40%). Large natural differences in climate and its variability exist between the arid North and Center of the country, and the humid, tropical South, with water stress and over-allocation of water resources concentrated in the first.

In terms of conservation, the country has a system of 182 federal protected areas (PA) with a combined surface area of approximately 908,395 km^2 (10.8% and 22.1% of Mexico's terrestrial and marine territory, respectively). Seventy-nine PAs are completely or partially designated as wetlands of international importance [Comisión Nacional de Áreas Naturales Protegidas (CONANP), 2017]. However, recent official reports indicated strong negative trends associated to pollution of water bodies, levels of depletion, invasion by exotic species, changes in natural land cover and development of dams and other water management infrastructure (Contreras-Balderas, Almada-Villela, Lozano-Vilano & García-Ramírez, 2003; Baena, Halffter, Lira-Noriega & Soberón, 2008; Valderrama-Landeros et al., 2017).

The first e-flow assessments (EFA) in Mexico appeared in the early 1990s. Applications of hydrological, hydraulic, habitat simulation and holistic methodologies raised awareness of ecosystem water requirements and paved the way towards the development of a national standard for integrated water and conservation planning and management (Alonso-Eguía Lis et al., 2007). Among the first EFA at basin level that demonstrated the ecological significance of water and its social recognition for the establishment of EWRs are the studies of the Conchos, Copalita-Zimatán-Huatulco and San Pedro Mezquital rivers developed by the alliance between the World Wildlife Fund (WWF) and the Gonzalo Río Arronte I.A.P. Foundation (FGRA) from 2004 to 2010 (Barrios, 2014).

Additionally, key institutions such the Mexican National Commission for the Knowledge and Use of Biodiversity and the National Institute of Ecology and Climate Change (former National Institute of Ecology) developed official national scale assessments such as the Conservation Priorities and the Eco-hydrological Alteration State in Mexican River Basins (Aguilar, Kolb, Koleff & Urquina Haas, 2010; Garrido, Cuevas, Cotler, González & Tharme, 2010).

These earlier experiences contributed to the development of the eFlowsNMx (Secretaría de Economía, 2012). Since its publication, researchers from universities and the Mexican Institute of Water Technology have conducted e-flow assessments to determine the amount of water for the environment and demonstrated the utility of the eFlowsNMx as a regulatory instrument (De la Lanza Espino, Carbajal Pérez, Salinas Rodríguez & Barrios Ordóñez, 2012; De la Lanza Espino, Salinas Rodríguez & Carbajal Pérez, 2015; Gómez-Balandra, Saldaña-Fabela & Martínez-Jiménez, 2014).

2.3 Methodology: Environmental flows norm principles and strategic practice

The eFlowsNMx aims to find a balance between water use and conservation, and provides a standardized strategic approach for conducting e-flow assessments, which consists of:

- Setting suitable water and conservation management objectives (onwards referred to as environmental objectives) to deal with current and future water demands, ecological status and risks in water management, avoid conflicts over water availability between the environment and other users, particularly during water scarcity episodes (King, Tharme & de Villiers, 2000; Bunn & Arthington, 2002; Davies & Jackson, 2006; Poff & Matthews, 2013).
- Assessing the e-flows requirements based on the analysis of the natural and current flow regime components of intra and inter-annual variability, as well as the related ecological functions, processes and environmental services to achieve a specific ecological status (Poff et al., 1997; Richter et al., 1997; Mathews & Richter, 2007; Poff & Zimmerman, 2010).
- Delivering science-based outcomes to decision makers in order to be able to determine the amount of water to be allocated as an environmental reserve volume, which should be linked to achieving a particular ecological target condition.

In general, this process follows what is considered the common thread in state-of-the-art e-flows science, practice, and policy (Acreman et al., 2014b; Horne et al., 2017; Poff et al., 2017).

2.3.1 Implementation strategy for determining environmental flow requirements

Environmental objectives

Environmental objectives or desired ecological status are established based on two factors in a river basin (Figure 2.1). The first factor is the *ecological importance* of an ecosystem, which is established based on a generic ecological status assessment that combines biotic aspects, ecological integrity condition and expected state of ecohydrological alteration of the components and attributes of the flow regime. The second factor is the human pressure on water resources, where *water pressure* is defined as the ratio of allocated volume for all uses divided by its availability. This factor is considered an independent variable in environmental water allocation, due to its importance for water management as a proxy of societal objectives in meeting water demand, current and under projected development conditions.

Environmental objectives are selected based on a matrix with four classes (A, B, C and D), according to a combination of water pressure and ecological importance levels as a practical implementation of conceptual flow-ecology and flow alteration-ecological response relationships (Poff & Zimmerman, 2010; Poff & Matthews, 2013; Acreman et al., 2014b). The extremes of these classes range from a very good desired or optimal ecological status (A) to a deficient ecological status (D).

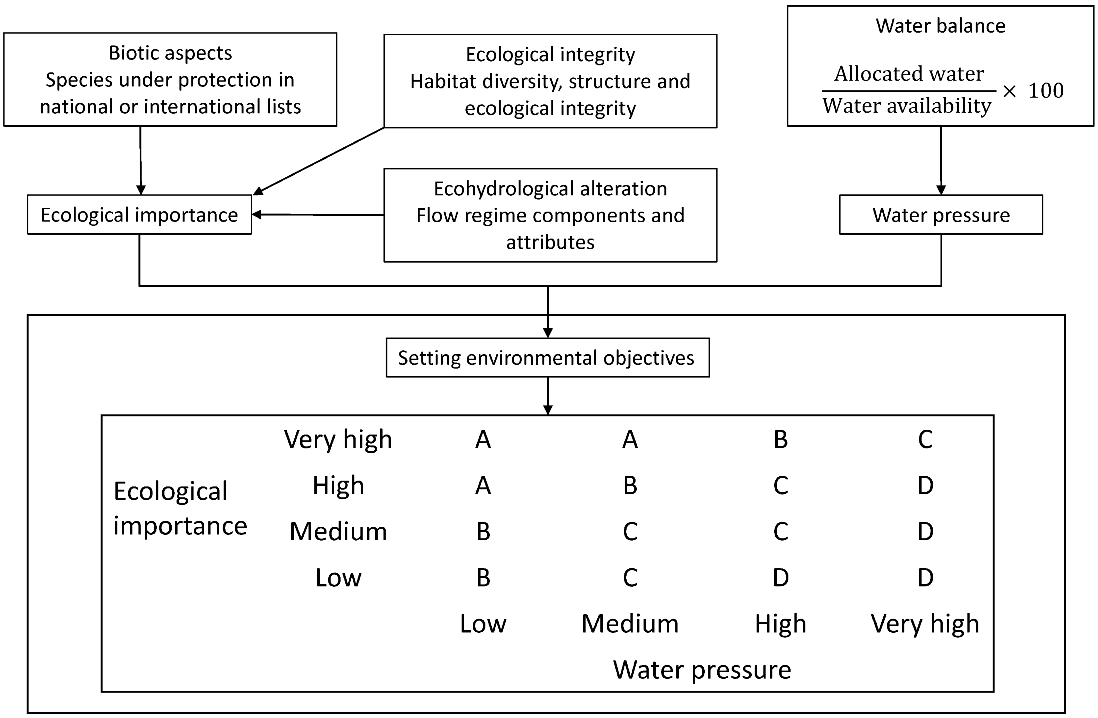


Figure 2.1. Process for setting environmental objectives based on the ecological importance and water pressure factors.

Methodologies for assessing environmental flows

The norm allows determination of e-flow requirements based on any of the methodologies commonly grouped according to the type of their approach: *hydrological*, *hydraulic*, *habitat simulation* or *holistic* (Poff et al., 2017). In the context of the NWRP, e-flows were determined based on the implementation of two different methodologies. One is a desktop hydrological approach originally developed by the alliance of the World Wildlife Fund and the Fundación Gonzalo Río Arronte I.A.P. to determine e-flow requirements in the San Pedro Mezquital river basin (Sánchez Navarro & Barrios Ordóñez, 2011). The second is a holistic approach, adapted from the Building Block Methodology (King et al., 2000) to the Mexican context.

These methodologies were mainly selected due to their suitability for water planning and management. In the implementation of the methodologies, e-flows aim to encompass (1) an ordinary seasonal flow pattern considering intra-annual (seasonality) and inter-annual variability (hydrological conditions); and (2) a flood regime with at least three flow magnitude categories typified according to their recurrence interval (frequency): intra-annual, low and moderate inter-annual with corresponding attributes of duration, timing and rate of change (Table 2.1). The previous flow components allow guiding the ecohydrological working hypotheses to understand flow-ecology and flow alteration-ecological response relationships, usually based on specialized literature and validated in the context of an expert panel in interdisciplinary workshops for developing e-flow recommendations (Poff & Zimmerman, 2010; Acreman et al., 2014ab).

Table 2.1. Flow regime components and metrics according to the hydrological and holistic methods of the Mexican Environmental Flows Norm (NMX-AA-159-SCFI-2012).

Method	Flow regime component	Metrics
Hydrological	Intra-annual and inter-annual variability	Mean monthly flows in cubic meters per second of percentiles 75th, 25th, 10th and 0th as representative of wet, average, dry and very dry annual conditions, respectively.
Holistic	Intra-annual and inter-annual variability	Mean seasonal flows in cubic meters per second based on percentiles ranges 50th – 25th and 25th – 0th as representative of average and dry annual conditions, respectively.
Hydrological and holistic	Flood regime	Category I. Intra-annual flood magnitude in cubic meters per second typified by a frequency of one-year recurrence interval. Category II. Low inter-annual flood magnitude in cubic meters per second typified by a frequency of one-year and a half recurrence interval. Category III. Moderate inter-annual flood magnitude in cubic meters per second typified by a frequency of five-year recurrence interval.

Implementation strategy

Between 2012 and 2015 eight pilot zones were selected and e-flow assessments conducted with both hydrological and holistic methodologies (Figure 2.2): The Colorado, Piaxtla, Acaponeta, San Pedro, and Chamela zones located in western Mexico; Copalita in the south of the country, all discharging into the Pacific Ocean; and the Sierra Gorda and Papaloapan zones in the center flowing to the Gulf of Mexico.

Regional academic groups were formed to cover all the areas of expertise required for the holistic approach. Water managers from CONAGUA and representatives from the Mexican Commission of Natural Protected Areas (CONANP) participated in the assessment workshops.

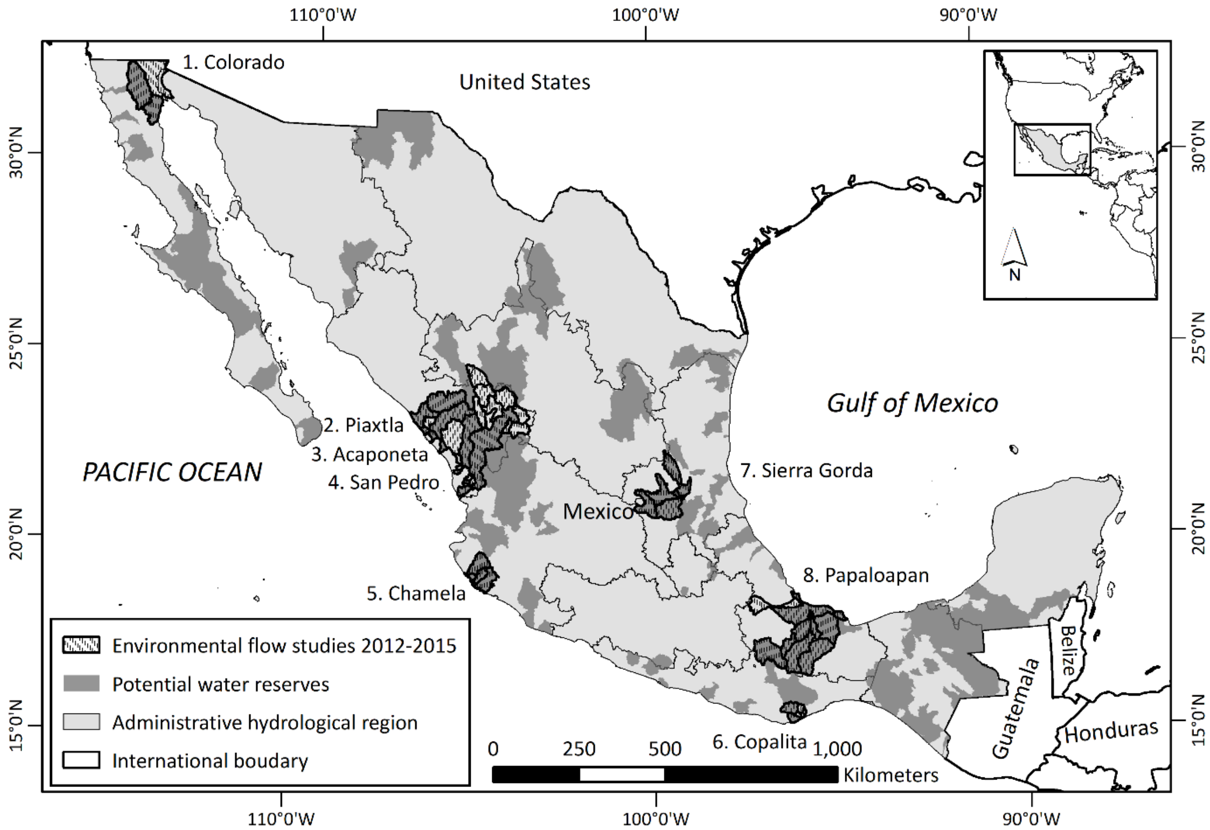


Figure 2.2. Potential water reserves and pilot zones for environmental flow assessments in 2012 – 2015 of the National Water Reserves for the Environment Program.

The workshops for the general approach (Figure 2.3) were conducted at two different levels:

- National-scale, to present the norm, its objectives, technical guidelines, and procedures, in particular within the holistic method to discuss and agree on a work plan and fieldwork protocols for this assessment. Additionally, the hydrological approach was applied as a capacity-building, hands-on workshop directed to hydrologists and water managers.
- Basin-scale, where the holistic method was applied in each pilot zone with two field surveys (dry and wet season). Hydrological information at a daily scale was taken from the National Data Bank of Surface Water repository (ftp://ftp.conagua.gob.mx/Bandas/), or rainfall-runoff models were developed [Sonoran Institute Mexico A.C. (SIM), 2015].

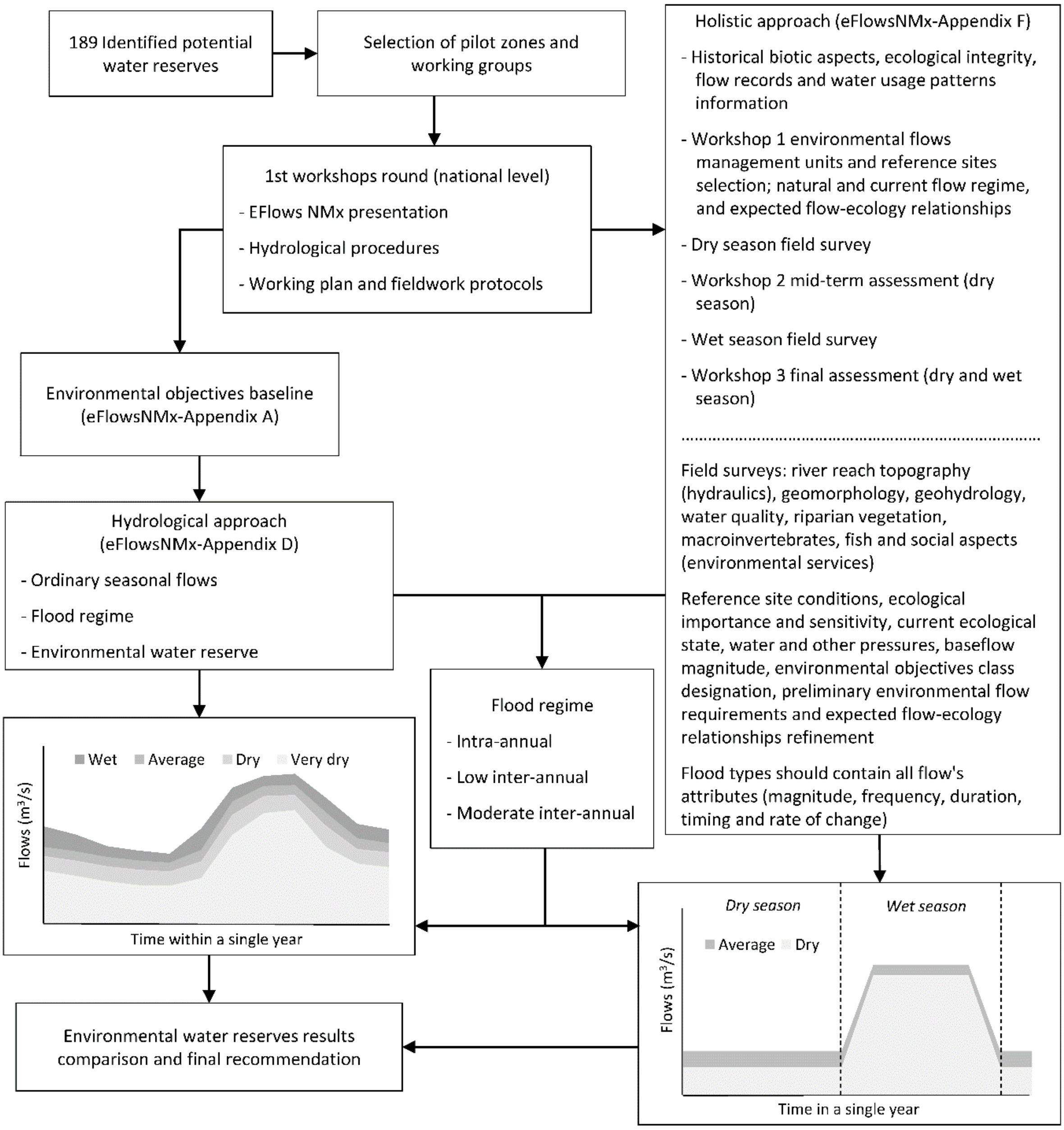


Figure 2.3. General strategy implemented in the environmental flow assessments of the National Water Reserves for the Environment Program. Conceptual hydrograms represent the environmental flow regime at monthly scale in the hydrological approach (bottom left), and seasonal scale in the holistic approach (bottom right). Tones of gray represent the ordinary flow conditions obtained using the hydrological approach (wet, average, dry and very dry years) and the holistic methodology (average and dry years).

For the implementation of the hydrological approach, the environmental objectives provided by the eFlowsNMx were adopted as a baseline. In the case of the holistic methodology, 25 reference sites were selected. These sites were defined as river reaches or streams with available hydrological information (daily flow records from gauging stations or rainfall-runoff models) and with homogenous characteristics of ecological importance and water pressure.

The ecological importance factor of each site was assessed based on the guidelines provided by King et al. (2000). Details from the reference sites in terms of biotic (*ecological importance and sensitivity*), ecological integrity and ecohydrological alteration (*habitat integrity*) conditions or subfactors were discussed and agreed by the expert panel considering the following aspects and scoring system:

- Ecological importance and sensitivity. It was assessed based on the following biotic determinants: rare, endangered, unique or intolerant biota, species or taxon richness. The diversity of aquatic habitat types or features, refuge values or habitat types, the sensitivity of habitat to flow changes. Sensitivity to flow-related water quality changes, migration route or corridor for instream and riparian biota, and protected areas including Ramsar sites. A four or five-point rating classes (0 – 4) was used depending on each determinant, where zero or one means none or marginal (low), two moderate, three high and four a very high relative importance or sensitivity.
- Habitat integrity. It is based on the assessment of two separate groups of modifiers with a specific set of indicators. First, the ecological integrity with signs of modification in the rivers' geomorphology, water quality, vegetation, and fauna (macroinvertebrates and fish). Second, the ecohydrological alteration such as water abstraction or flow components modification (hydrology and geohydrology). A four-point rating class (1 – 4) was used: one means completely modified, two moderately modified, and three with few modifications and four natural or without significant changes. In this case, no data means not present and therefore not relevant for the assessment (e.g. fish in ephemeral streams).
- The final (overall) ecological importance was set based on the median from individual subfactors: one implies low, two medium or moderate, three high and four very high ecological importance and confidence ratings. Environmental objectives were set according to its combination with the water pressure factor (Figure 2.1).

In addition to the information surveyed on-site, historical species presence, conservation status, and experts or local knowledge were also considered [Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), 2016].

2.3.2 Environmental flow regimes and water reserves volumes

Monthly and seasonal regimes of yearly flow conditions, in addition to the flood regime, were synthesized from both the hydrological and holistic approaches into the annual volumes of EWRs, and their coefficient of variation was calculated to analyze their differences.

In order to understand the scope of these results and their consistency, flow variability indices of the natural regimes were calculated and analyzed based on the proposed by Hughes & Hannart (2003) and Hughes, Desai, Birkhead & Louw (2014), adapted to the norm's outcomes. These include the mean annual runoff (MAR) and mean annual baseflow (MABF). A coefficient of variation index (CV) as an indication of long-term variability of wet and dry seasons. It is calculated, first, based on the coefficient of variation for all monthly flows for each calendar month; and second, by summing the three main months of both seasons from such monthly coefficients averages. A baseflow index (BFI) representative of short-term variability of flows (ratio of the MABF to the MAR), and their logical combination (CV/BFI) for an overall index of variability (CVB). Finally, the EWR volumes were evaluated to confirm that they do not affect existing water rights. For this purpose, EWR volumes were compared with the current water available for potential environmental allocation (total volume for environmental use, water committed downstream and water availability), as established by the water balance agreements currently in place [Comisión Nacional del Agua (CONAGUA), 2016b].

2.4 Results and discussion

2.4.1 Water and conservation management objectives

Generally, a strong consistency was found between the environmental objectives baseline and the outcomes of the holistic method applied at an individual basin scales (Table 2.2). The on-site assessment revealed 17 cases with a very high ranking in ecological importance, seven ranked high, and one ranked medium, in comparison to 12, 11 and two from the baseline, respectively. According to the environmental objectives baseline classification, the desired ecological status of 22 out of 25 basins (88%) ranked as very good (class A), two ranked as good (B), and one as moderate (C); while based on the holistic approach, 21 basins (84%) were determined to have a very good (A) and four showed a good (B) ecological status.

In 20 basins (80%), the environmental objective baseline was confirmed by the holistic assessment, while five revealed a different current ecological condition. The units Verde 3, Papaloapan and Jamapa-Cotaxtla showed a loss of ecological integrity due to ecohydrological alteration; while Trinidad and Blanco presented a very good or good biotic, ecohydrological and ecological integrity conditions (Table 2.3).

One last remark from the on-site assessment is that 17 basins were assessed with a very high confidence rating score (3.5 – 4.0) of ecological importance, seven with high (2.5 – 3.0), and only one with medium or moderate (2.0). This result, as well as the consistency between the environmental objectives, is due to the strategic selection of pilot basins. From the 25 reference sites, all are potential water reserves with the only exception of Blanco that is under very high pressure over water demand (193%).

2.4.2 Water reserves volumes and flow regime characteristics

EWR volumes among basins and pilot zones were predictably diverse. For the hydrological and the holistic method, respectively, they ranged from 6.5 or 7.8 million cubic meters per year (Mm^3/year) in El Borrego (arid basin) to 27,305 or 29,874 Mm^3/year in Llanuras del Papaloapan (humid tropical), mostly due to their geographical location and climatic conditions (Table 2.4).

In terms of EWR volumes coefficient of variation between both methods, there were found values ranging 1.6 – 33.2% across the full range of distribution, with 13 out of 25 basins in the first two quartiles (≤ 6.4%), five in the third (6.9 – 10.2), and seven above (11.1 – 33.2%, Jamapa-Cotaxtla, El Borrego, Presidio 2, Trinidad, Cuitzmala, Cerrada Laguna Salada and Verde 3). This variation of volumes is explained by two reasons.

First, due to a difference in the hydrologic scope or temporary resolution among methods (monthly *vs*. seasonal; Appendix A1). Basins in arid or tropical regions from western Mexico exhibit higher seasonal variability (CV > 110%), some with remarkable differences between ordinary high and low flows magnitudes. These streams show the lowest baseflow buffer capacity (BFI ≤ 11%) and the highest overall CVB index from 14.9 to 655.7 (Figure 2.4).

Together, these results indicate that these basins could tend to be affected regularly by droughts (Hughes & Hannart, 2003; Hughes et al., 2014). In these regions, the hydrological approach encompassed natural dry episodes better, which is consistent with the metrics of flow regime components (percentiles 10^{th} and 0^{th} at monthly scale hydrological *vs*. 25^{th} – 0^{th} holistic at seasonal).

About the second cause, the expert panel evaluated EWR volumes within the on-site assessment for a different class of baseline environmental objectives, in coherence with the current ecological status and following a more accurate desired condition. In this case, Papaloapan and Blanco have the major baseflow contribution (BFI > 40%) and the lowest overall variability in its flow regime (CVB < 1.3); therefore, these rivers did not present meaningful variability in EWR volumes.

With regard to the feasibility of EWRs under the current basins' water allocation, most of the recommended volumes are lower than the currently available water for potential environmental allocation. Exceptions are Copalita 1 unit which has a deficit in EWR (17 Mm^3/year) and San Nicolás A (303 – 424 Mm^3/year). These deficits are because of significant differences between the calculated MAR from gauging stations used in the e-flow assessments and the amounts officially recognized in the water balance agreements, where the MAR is based on annual-scale rainfall-runoff models for the last 20 years. These differences should be analyzed in more detail (e.g. recent flows and rainfall records from gauging stations within these or neighboring basins).

Table 2.2. Environmental objectives baseline and on-site assessments using the holistic method. Scoring system: 1 = low, 2 = medium, 3 = high and 4 = very high importance for biotic aspects; and 1 = completely modified, 2 = moderately modified, 3 = few modifications and 4 = natural or without significant changes for ecological integrity and ecohydrological alteration conditions.

Pilot zone	River basin	National baseline			
		Water pressure (percentage)	Water pressure (class)	Ecological importance	Env. objective class
Colorado	Cerrada Laguna Salada	0.1	Low	Very high	A
	El Borrego	0.0	Low	Very high	A
Piaxtla	Piaxtla 2	0.6	Low	Very high	A
	Quelite 2	0.4	Low	High	A
	Presidio 2	0.2	Low	Medium	B
Acaponeta	Acaponeta 1	1.7	Low	High	A
San Pedro	San Pedro Des.	8.2	Low	Very high	A
Chamela	San Nicolás A	2.2	Low	Very high	A
	Purificación	8.1	Low	Very high	A
	Cuiztmala	1.7	Low	High	A
Copalita	Copalita 1	0.3	Low	Very high	A
Sierra Gorda	Santa María 3	4.2	Low	Very high	A
	Verde 3	6.1	Low	High	A
	El Salto	6.2	Low	High	A
	Tampaón 1	2.3	Low	High	A
Papaloapan	Valle Nacional	0.1	Low	High	A
	Papaloapan	0.3	Low	Very high	A
	Playa Vicente	0.1	Low	High	A
	Tesechoacán	0.0	Low	High	A
	Trinidad	0.1	Low	Medium	B
	San Juan	7.2	Low	Very high	A
	Llanuras del Papaloapan	0.1	Low	Very high	A
	Grande	7.3	Low	High	A
	Blanco	193.1	Very high	Very high	C
	Jamapa-Cotaxtla	0.0	Low	High	A

Table 2.2. *Continue*.

On-site assessments					
Biotic aspects	Ecological integrity	Ecohydrological alteration	Overall confidence rating score (median)	Ecological importance	Env. objective class
4.0	4.0	3.5	4.0	Very high	A
2.0	4.0	4.0	4.0	Very high	A
4.0	3.0	4.0	4.0	Very high	A
3.5	3.0	4.0	3.5	Very high	A
4.0	3.0	2.5	3.0	High	B
4.0	4.0	4.0	4.0	Very high	A
4.0	3.0	4.0	4.0	Very high	A
4.0	4.0	4.0	4.0	Very high	A
4.0	3.0	3.0	3.0	High	A
4.0	4.0	4.0	4.0	Very high	A
4.0	2.0	4.0	4.0	Very high	A
4.0	4.0	4.0	4.0	Very high	A
4.0	2.0	2.5	2.5	High	B
4.0	4.0	4.0	4.0	Very high	A
4.0	3.0	4.0	4.0	Very high	A
4.0	4.0	4.0	4.0	Very high	A
2.0	2.0	2.5	2.0	Medium	B
4.0	3.0	4.0	4.0	Very high	A
1.0	3.0	4.0	3.0	High	A
4.0	3.0	4.0	4.0	Very high	A
4.0	2.0	4.0	4.0	Very high	A
4.0	1.0	3.0	3.0	High	A
1.0	3.0	4.0	3.0	High	A
4.0	3.0	4.0	4.0	Very high	A
4.0	2.0	3.0	3.0	High	B

Table 2.3. Detail assessment in biotic determinants (ecological importance and sensitivity: 0 or 1 = non or marginal, 2 = moderate, 3 = high and 4 = very high), ecological integrity and ecohydrological conditions (1 = completely modified, 2 = moderately modified, 3 = few modifications and 4 = natural or without significant changes) in pilot river basins reference sites using the holistic method.

River basin	Ecological importance and sensitivity									
	Rare and endangered biota	Unique biota	Intolerant biota	Species or taxon richness	Diversity of aquatic habitat types or features	Refuge value of habitat types	Sensitivity of habitat to flow changes	Sensitivity to flow-related water quality changes	Migration route or corridor for instream and riparian biota	Natural protected areas or Ramsar sites	Score (median)
C. Laguna Salada	4	4	4	2	4	4	2	4	4	4	4.0
El Borrego	4	2	0	2	1	1	2	4	0	4	2.0
Piaxtla 2	4	4	4	4	4	4	3	3	3	4	4.0
Quelite 2	4	4	4	3	4	3	3	3	3	4	3.5
Presidio 2	4	4	4	4	4	4	4	2	2	4	4.0
Acaponeta 1	4	4	4	4	4	4	4	3	4	4	4.0
San Pedro Des.	4	4	3	4	3	4	4	3	4	4	4.0
San Nicolás A	4	3	4	4	4	4	4	4	4	4	4.0
Purificación	4	3	4	4	4	4	4	4	4	4	4.0
Cuiztmala	4	3	4	4	4	4	4	4	4	4	4.0
Copalita 1[†]	4	3	2	3	3	2	2	3	2	4	4.0
Santa María 3	4	4	4	2	4	4	4	4	4	4	4.0
Verde 3	4	4	3	2	2	4	4	4	4	0	4.0
El Salto	4	4	4	4	4	3	4	4	4	3	4.0
Tampaón 1	4	4	4	4	3	4	4	4	4	4	4.0
Valle Nacional	4	4	4	4	4	4	4	3	4	0	4.0
Papaloapan	2	2	2	2	2	2	2	3	1	0	2.0
Playa Vicente[†]	4	4	4	2	4	2	2	2	1	0	4.0
Tesechoacán	0	1	2	2	1	1	1	1	0	4	1.0
Trinidad[‡]	0	4	4	2	3	3	3	2	0	0	4.0
San Juan[‡]	1	4	4	2	3	3	3	3	2	0	4.0
Ll. del Papaloapan[†]	4	3	4	2	4	2	2	3	0	4	4.0
Grande	0	1	1	1	1	1	1	1	0	4	1.0
Blanco	4	4	4	3	4	4	3	3	2	4	4.0
Jamapa-Cotaxtla[†]	4	4	4	3	4	4	3	3	3	0	4.0

Note: Highest score possible in ecological importance and sensitivity, due to the presence of species under protection at the national level (†) or unique biota (‡).

Table 2.3. *Continue*.

Ecological integrity						Ecohydrological alteration		
Geomorphology	Water quality	Vegetation	Macroinvertebrates	Fish	Score (median)	Hydrology	Geohydrology	Score (median)
4	4	4	2		4.0	4	3	3.5
4	4	4	1		4.0	4	4	4.0
2	3	3	2	3	3.0	4	4	4.0
3	3	2	3	4	3.0	4	4	4.0
3	4	3	2	2	3.0	3	2	2.5
4	4	2	4	3	4.0	4	4	4.0
2	3	3	3	3	3.0	4	4	4.0
4	4	2	4	4	4.0	4	4	4.0
4	3	3	3	2	3.0	3	3	3.0
4	3	3	4	4	4.0	4	4	4.0
1	3	2	3	1	2.0	4	4	4.0
4	4	4	4	3	4.0	4	4	4.0
3	3	2	2	2	2.0	2	3	2.5
3	4	3	4	4	4.0	4	4	4.0
4	3	3	4	3	3.0	4	4	4.0
4	3	4	4	4	4.0	4	4	4.0
2	2	2	2	2	2.0	2	3	2.5
4	2	3	2	3	3.0	4	4	4.0
4	2	3	2	3	3.0	4	4	4.0
4	3	3	3	3	3.0	4	4	4.0
3	2	3	2	2	2.0	4	4	4.0
3	1	3	1	1	1.0	3	3	3.0
3	2	3	2	3	3.0	4	4	4.0
4	2	4	3	3	3.0	4	4	4.0
3	2	2	2	2	2.0	3	3	3.0

Table 2.4. Hydrological and holistic environmental water reserves volumes, natural flow regime characteristics and volume of water availability for environmental allocation in the reference sites of the pilot river basins. SD = Standard deviation, AVG = Average, CV = Coefficient of variation, MAR = Mean annual runoff, CV = Coefficient of variation index, MABF = Mean annual baseflow, BFI = Baseflow index, and CVB = Overall index (CV/BFI) of flow variability. Volumes are shown in millions of cubic meters per year.

Pilot zone	River basin	Environmental water reserve				
		Hydrological (Mm^3)	Holistic (Mm^3)	SD	AVG (Mm^3)	CV (%)
Colorado	C. Laguna Salada	21.9	31.3	6.7	26.6	25.1
	El Borrego	6.5	7.8	0.9	7.2	13.1
Piaxtla	Piaxtla 2	889.5	826.8	44.3	858.2	5.2
	Quelite 2	61.2	63.3	1.5	62.3	2.4
	Presidio 2	327.7	404.0	54.0	365.9	14.7
Acaponeta	Acaponeta 1	829.4	860.0	21.7	844.7	2.6
San Pedro	San Pedro Des.	1,711.0	1,920.0	147.8	1,815.5	8.1
Chamela	San Nicolás A	776.0	897.0	85.6	836.5	10.2
	Purificación	388.0	428.0	28.3	408.0	6.9
	Cuiztmala	157.0	204.0	33.2	180.5	18.4
Copalita	Copalita 1	584.0	554.0	21.2	569.0	3.7
Sierra Gorda	Santa María 3	584.0	571.0	9.2	577.5	1.6
	Verde 3	192.0	119.0	51.6	155.5	33.2
	El Salto	467.0	499.0	22.6	483.0	4.7
	Tampaón 1	2,997.0	3,225.0	161.2	3,111.0	5.2
Papaloapan	Valle Nacional	2,306.0	2,549.0	171.8	2,427.5	7.1
	Papaloapan	14,672.0	15,358.0	485.1	15,015.0	3.2
	Playa Vicente	4,413.0	4,878.0	328.8	4,645.5	7.1
	Tesechoacán	4,821.0	4,545.0	195.2	4,683.0	4.2
	Trinidad	4,275.0	5,272.0	705.0	4,773.5	14.8
	San Juan	6,961.0	6,584.0	266.6	6,772.5	3.9
	Ll. del Papaloapan	27,305.0	29,874.0	1,816.6	28,589.5	6.4
	Grande	765.0	807.0	29.7	786.0	3.8
	Blanco	1,489.0	1,602.0	79.9	1,545.5	5.2
	Jamapa-Cotaxtla	1,341.0	1,146.4	137.6	1,243.7	11.1

Table 2.4. *Continue*.

Flow variability indices					Environment water availability (Mm^3)
MAR (Mm^3)	MABF (Mm^3)	CV (%)	BFI (%)	CVB	
56.9	3.1	274.2	5.4	50.6	59.6
17.4	0.5	325.1	2.6	123.1	17.5
1,460.1	55.2	138.6	3.8	36.6	1,405.0
101.6	0.4	272.9	0.4	655.7	153.4
997.8	30.7	379.7	3.1	123.6	975.1
1,310.8	50.4	250.8	3.8	65.3	1,357.3
2,708.3	95.7	195.4	3.5	55.3	2,640.2
1,210.0	26.1	111.6	2.2	51.8	472.6
540.5	7.5	110.7	1.4	79.4	458.3
296.8	33.9	170.3	11.4	14.9	229.8
941.6	208.3	122.2	22.1	5.5	566.6
944.9	319.8	135.9	33.8	4.0	600.8
367.4	72.4	147.5	19.7	7.5	195.8
801.4	151.6	108.5	18.9	5.7	815.8
5,372.8	1,264.4	117.3	23.5	5.0	4,461.3
3,279.5	635.5	87.9	19.4	4.5	3,797.7
18,434.6	9,064.2	64.2	49.2	1.3	19,597.8
6,012.0	1,338.4	65.8	22.3	3.0	6,120.0
5,365.4	1,232.8	53.0	23.0	2.3	6,614.3
6,352.0	1,310.5	51.4	20.6	2.5	6,329.0
8,088.9	2,169.6	74.0	26.8	2.8	8,510.4
38,767.7	9,385.5	79.5	24.2	3.3	40,518.1
1,209.9	178.0	100.6	14.7	6.8	819.8
1,750.0	752.9	45.0	43.0	1.0	2,081.2
1,886.6	437.0	68.3	23.2	2.9	1,849.2

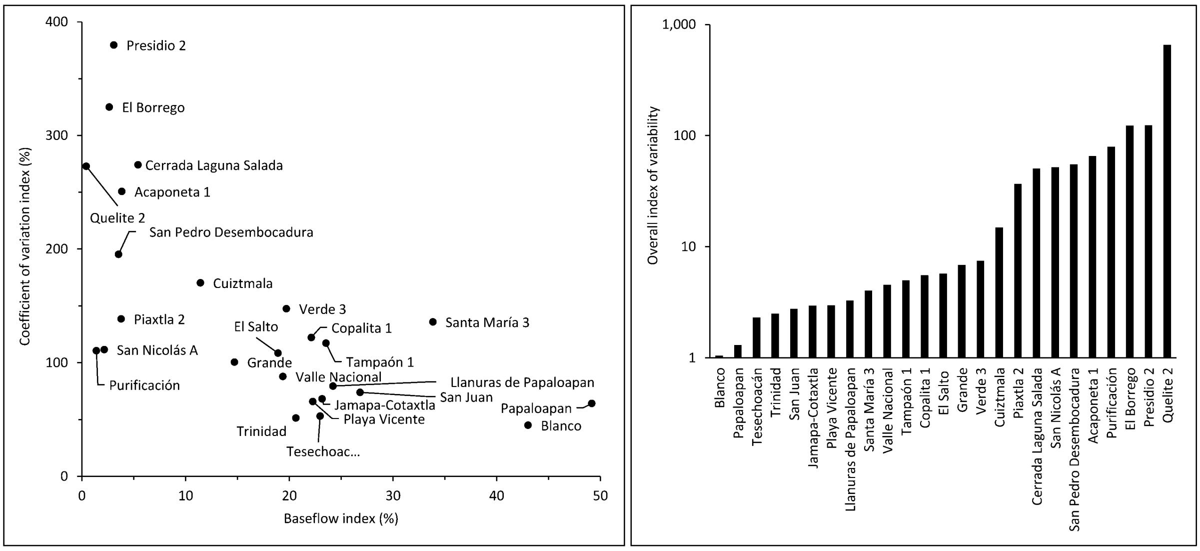


Figure 2.4. Relationship between short and long-term seasonal flows (left) and the overall index of variability (right) in reference sites across pilot river basins.

2.4.3 Recommendations for flow-ecology based water reserves, the process for their establishment and progress achieved

The volumes that were recommended to CONAGUA for environmental allocation which were assessed using the holistic methodology showed that they would provide the most comprehensive flow-ecology relationships and were grounded on on-site knowledge about current ecological conditions. The recommended volumes seem feasible in most cases and received feedback and approval from panels of experts. However, it should be recognized that e-flow assessments are merely a first step towards a much longer and complex administrative and legal process in establishing water reserves (Figure 2.5).

In addition to each EWR assessment, an economic evaluation (cost-benefit analysis) should be performed to demonstrate that securing a healthy flow regime and the related environmental services outweigh the associated costs; the most relevant of these would be the need for changes in the water tariffs due to the decrease in the relative water availability. According to the present legislation, these costs' increases would be charged to the productive users of water. This implication is a misconception of the social benefit of the water reserves, and its unpopularity has become an important challenge to the process and progress of allocating environmental water. The alignment of the EWR and the water tariff mechanisms are currently under discussion between the Deputy Director General's Office for Technical Affairs and the Coordination of Fiscal Revision and Payments of CONAGUA in order to make the legislation coherent with current environmental water science and to prevent social rejection.

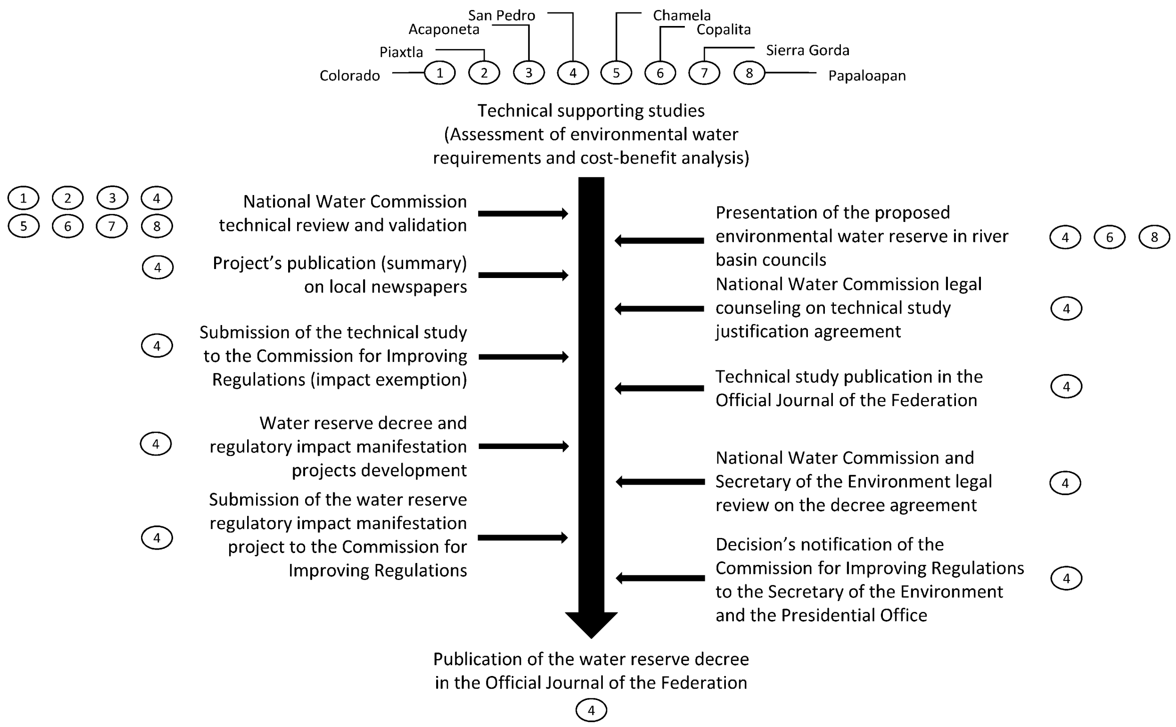


Figure 2.5. General process and progress for establishing environmental water reserves.

Among the technical studies supporting the EWR that have passed the approval stage are San Pedro (1:16 cost-benefit ratio in a 20-year horizon at a 12% discount rate), Papaloapan (1:31) and Copalita (benefits only) [Instituto Mexicano de Investigaciones en Derecho Ambiental A.C. (IMIDA), 2013; Agroder S.C., 2014]. By 2014, only EWR for the San Pedro zone has been adopted as a precautionary measure. The process for the corresponding decree has been completed, declaring for this basin an environmental use of 2,297 Mm^3/year for a 50-year term [Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), 2014], higher than the volume originally recommended. This EWR is currently being integrated to the Marismas Nacionales management plan, based on flow-ecology relationships for on-site monitoring (Blanco et al., 2011; Téllez Duarte et al., 2014; González-Díaz, Soria-Barreto, Martínez-Cardenas & Blanco y Correa, 2015; Wickel, Salinas Rodríguez, Martínez Pacheco, Colditz & Ressl, 2016).

2.5 Lessons learned and recommendations

2.5.1 General strategy in environmental flows norm implementation

Despite differences, a general consistency is apparent between the baseline environmental objectives and the outcomes of the on-site comprehensive approach, as well as among the hydrological and holistic methods for assessing e-flows. The increased detail in the assessment of the ecological importance factor, which integrated site-level information and an expert panel evaluation, confirmed or supported a change in the environmental objectives for more accurate and balanced water use and conservation. Additionally, this factor was assessed largely with high or very high levels of confidence. This result is consistent with the high biological richness and conservation values criteria used for the identification of potential water reserves (CONAGUA, 2011).

The e-flow regimes and reserves were determined and volume differences occurred due to the aforementioned changes in environmental objectives and because of the metrics of the flow regime components used in each method. The final similarity between volumes and the use of indices of regime variability (CV, BFI, and CVB) to understand the scope of the flow components metrics suggest the potential for developing a desktop reserve model for Mexican streams, along the lines of the South African method developed by Hughes & Hannart (2003) and Hughes et al. (2014). This would require further in-depth analysis in more river basins characteristic of the wider climatic and geographic conditions throughout the country, in order to represent the full range of short and long-term seasonal flows variability, their ecological functioning and the flow-habitat requirements. For 94% of the sites, EWR annual volumes are within current water availability for potential environmental allocation, although e-flow assessments advise the need for further detailed analysis of the MAR recognized in official agreements. Despite the fact that the hydrological approach has a higher temporary resolution, applying the holistic methodology to assess the volume of an EWR provides a greater understanding of a basin's current conditions, integrates higher levels of ecological knowledge and builds on expert review and validation. It is important to recognize that the methodologies described do not exclude, but rather complement each other.

2.5.2 National Water Reserves for the Environment Program contributions and limitations

The allocation of environmental flows assessed under National Water Reserves Program would preemptively secure water, limit the flow alteration, and sustain the ecological integrity of a river basin. Biologically, e-flows in the 25 reference sites were assessed to meet the water needs and habitat requirements of 93 freshwater-dependent species (40 under protection). This information provides a baseline for conducting further in-depth research and an opportunity for the inclusion of environmental water requirements in protected area management plans, as is currently piloted in the Marismas Nacionales' management plan.

With regard to the social dimension, EWR would secure the provision of water for small rural communities settled along the rivers with low net consumption and high vulnerability in terms of access to water. For instance, in the context of the overall water balance of the considered basins, that would mean water provision for 1,833,136 inhabitants (35% of total basins' population) from 21,888 communities below 2,500 inhabitants.

It is very important to recognize that the outcomes of this program, thus far, are mainly based on systems with low water resource demands and little development of water management infrastructure. E-flow assessments are also required across basins with greater impacts in biotic aspects, ecological integrity, and flow regime components, in order to evaluate the consistency and performance of the outcomes of both methods in terms of wider objectives (e.g. restoration). Furthermore, more research in the systematic analysis of concrete and quantitative flow-ecology and social relationships could enrich the variety of cases and provide feedback for improving the norm and setting strategic monitoring indicators for the implementation of the EWRs.

One last limitation of the current methods that should be recognized is that the hydrological analysis is based exclusively on historical flow records and associated flow-ecology relationships, regardless of if the methods are applied in basins with or without relative pressure. An important aspect for future research would be to consider climate change impacts on flow variability and adaptive capacities of people and nature to provide climate-smart EWR.

2.6 Conclusion

Mexico's National Water Reserves for the Environment Program is focused on establishing environmental flow allocations in basins that currently experience low water pressure and which are of high conservation value, through conducting e-flow assessments that are based on and further enrich the Mexican Environmental Flows Norm.

As the norm has been applied in eight pilot zones, strategic capacities for its implementation have been built and have provided the opportunity for setting ecologically and socially sustainable limits of current and future water extraction, preventing ecosystems degradation and sustaining ecological processes and services. While the process of establishing an EWR may take years, there are significant advantages for the Mexican environmental water science and allocation practice. On one hand, water planning and management are strengthened by enhancing water security through preempting over-allocation and therefore overexploitation risks. On the other hand, natural resources and biological conservation efforts benefit from the more comprehensive implementation of integrated water resources management and the specific definition of environmental water requirements.

The most important contribution of this approach consists in the production of functional proposals for water allocation that are mostly grounded in international state-of-the-art e-flow practices. In the meanwhile, a system of EWR is being built and enriched, based on the standardization and systematization of experiences, creating a growing institutional and expert network and community of practice, which directly inserts flow-ecology knowledge and feedback mechanisms into the integrated management of water resources in Mexico. This strategy provides the foundations for a subsequent stage in the allocation of water for the environment, across basins where higher pressure on water resources exists.

3

Hydrology-based approach for preventive environmental water allocation

Moving toward preventive water allocation to anticipate over-abstraction and limiting flow alterations is a strategic decision for maintaining biodiversity and ecological integrity. Hydrology-based desktop methodologies are the most time and cost-effective approaches to produce functional proposals from a water management and nature conservation perspective. In this chapter a hydrological methodology for environmental water allocation is presented, its origins, ecohydrological foundations and application results in protect flows. The flow regime analysis includes (1) the natural intra-annual (seasonal pattern) and inter-annual ranges of variability. (2) Environmental flows are determined based on (a) four hydrological low flow conditions and (b) a flood regime of three peak flow events. The main methodological contribution is that the flow regime components are adjusted to (3) a four-tiered environmental objective class system, based on (4) a novel frequency of occurrence approach for delivering (5) environmental water volumes for preventive allocation. The method is applied in seven rivers that drain into a coastal wetland of international importance under the Ramsar Convention. The outcomes revealed an overall consistency with regard to the variability characteristics of the river flow in two sets of records, one period as a reference for validation and another for the assessment ($R^2 \geq$ 0.9 in 78% of the cases for the performance validation).

This chapter is based on:

Salinas-Rodríguez S.A., Sánchez-Navarro R. and Barrios-Ordóñez J.E. Frequency of occurrence of flow regime components: A hydrology-based approach for environmental flow assessments and management in Mexico. *Frontiers in Environmental Science*. (In review).

3.1 Introduction

Environmental water science has contributed meaningfully to the global understanding and recognition of the key role that the natural flow regime plays in providing and sustaining healthy and resilient ecological functions and their related environmental services in aquatic ecosystems. However, these ecosystems continue to degrade at alarming rates, mainly due to habitat loss, degradation and direct overexploitation (Dudgeon et al., 2006; WWF, 2018). Furthermore, and based on current water usage conditions, the global demand is expected to increase by 55% between 2000 and 2050, and today up to two-thirds of the global population live under severe water scarcity [Organisation for Economic Co-operation and Development (OECD), 2012; Mekonnen & Hoekstra, 2016]. The continued pressure over freshwater ecosystem resources drives the urgency of setting sustainable limits on water extraction.

According to a recent report about water resources allocation, in 92% from 37 surveyed systems, there is a clear definition of the limit of consumptive uses [Organisation for Economic Co-operation and Development (OECD), 2015]. The same report indicates that in 81% the most frequently cited driver of reforms on water allocation systems was for environmental improvement or protection (81%), however, environmental flows are not secured in at least 25% of the surveyed cases. Based on the current state of ecohydrological knowledge, hydrological approaches for determining environmental flows have improved significantly, and offer low time-consuming solutions at few costs that have been used historically in water management (King et al., 2000; Tharme, 2003; Poff & Matthews, 2013; Poff et al., 2017). In general, hydrological methodologies are accepted by the scientific community for preventive environmental water allocation to protect the regime ecological main components and attributes within early sustainable limits before water infrastructure development takes place (Richter, 2010; Richter et al., 2012; Acreman et al., 2014ab; Opperman et al., 2018).

In the Mexican context, the initiative of the NWRP aims to secure environmental flows and enact preventive water allocations as a public policy measure to protect flow-dependent aquatic ecosystems (Moir, Thieme & Opperman, 2016; Harwood et al., 2017; Horne et al., 2017; Salinas-Rodríguez, Barrios-Ordóñez, Sánchez-Navarro & Wickel, 2018). By 2018, allocating water for the environment became the primary goal of Mexico's Programmatic Plans of Environment, Water, and Climate Change regarding water and the environment (Secretaría de Gobernación, 2013 and 2014ab; Barrios-Ordóñez et al., 2015).

The goal of this chapter is to present a detailed hydrological method for determining environmental flows and the ecohydrological foundations for preventive and functional environmental water allocation that accompany the holistic assessments. The procedure includes a novel approach based on the frequency of occurrence of two major components of the full variability range of flows: the low flows of different hydrological conditions and a flood regime according to characteristic peak flow events of different magnitudes. The contextual background is provided including the method's origin, ecohydrological foundations, and early applications. The definitions of the method components, metrics, and contextual appropriateness and performance validation procedures are described prior to their application on a set of rivers in western Mexico as a case study.

The outcomes are analyzed in terms of their consistency with the natural flow characteristics, while water volumes for environmental water allocation are provided according to a four-tiered system of environmental objectives. Furthermore, the first case of strategic implementation of e-flows in public policy is described for the San Pedro Mezquital water reserve. In this case, the utility and contribution of the method outcomes are exemplified in the development of flow-ecology relationships for monitoring, assessing (on-site validation) and providing feedback on the performance of the water reserve. An overall discussion of the method is examined including advantages, limitations, and recommendations before reaching the conclusion.

3.2 A new hydrological approach for protecting flows in preventive environmental water allocations: Ecohydrological foundations, adoption, and early applications

For over the last decades, hydrological methodologies for determining environmental flows have been widely implemented aiming the maintenance of rivers ecological functionality. This method category focuses on the statistics of the flow regime to deliver recommendations of water volumes at different time scales. The Montana method (Tennant, 1976) and others such as the analysis derived from flow duration curves (e.g. Q95, Q90, and 7Q10) are amongst the first examples (Tharme, 2003; Poff et al., 2017). By applying these methodologies, the environmental flows recommendations generally are percentages of the mean annual, seasonal, or monthly flow volumes (Tharme, 2003; Poff et al., 2017).

In recent times, other methodologies substantially improved the hydrological approach by integrating higher resolution of ecologically relevant flow characteristics. Streamflow attributes of magnitude, frequency, duration, timing, and rate of change in the context of the regime components of low flows and flood events were incorporated. Examples of these methods are the *Range Variability Approach* (Richter et al., 1997), the *Desktop Model* (Hughes & Hannart, 2003; Hughes et al., 2014), the *Environmental Flow Components* (Mathews & Richter, 2007), and the *Presumptive Standard for Environmental Flow Protection* (Richter et al., 2012).

The first Mexican hydrology-based environmental flow determinations were conducted through the Montana method, adapted to the country's flow variability conditions (e.g. García et al., 1999; Alonso-Eguía Lis et al., 2007; Santacruz de León & Aguilar-Robledo, 2009). However, they lacked the inclusion of the flow regime attributes and components according to the environmental water science knowledge available at that time. The hydrological method presented in this chapter was originally developed in western Mexico's San Pedro Mezquital River as an attempt to fill in that gap [Alianza World Wildlife Fund-Fundación Gonzalo Río Arronte I.A.P. (WWF-FGRA), 2010; Sánchez Navarro & Barrios Ordóñez, 2011].

The method emerged as a hydrology-based desktop approach along the lines of the ecohydrological theory applicable in rivers with variable flow regimes. It is based on the natural flow regime paradigm, with its whole range of variability and disturbances, cornerstone for understanding and building practical flow-ecology relationships in environmental flow assessments (Poff et al., 1997; Richter et al., 1997; Postel & Richter, 2003; Richter, Warner, Meyer & Lutz, 2006; Mathews & Richter, 2007; Stone & Menendez, 2011; Poff & Zimmerman, 2010; Poff et al., 2017).

This approach of environmental flows determination and further implementation was developed grounded on the opportunity, from a water management public policy context, of limiting the flow alteration and unsustainable water abstraction through preventive water allocation in low-impacted systems. This scope has been an emerging trend in the last decade and aims to ensure a sustainable balance between the water use and the conservation of aquatic ecosystems in river basins with unregulated or impaired flow (Postel & Richter, 2003; Le Quesne et al., 2010; Acreman et al., 2014a; Arthington et al., 2018a).

The aim of this hydrologic method is to deliver "quick", science-based water volume requirements for ecosystems maintenance and sustainability. It acknowledges that there is not a single and static flow regime necessity, but rather many guidelines related to the multiple conditions of flow variability over time associated to non-stationary challenges (Arthington, Kennen, Stein & Webb, 2018b; Poff, 2018), for which the aquatic ecosystem has naturally evolved. Furthermore, the method outcomes fulfill two management requirements for feasible implementation under the Mexican system for allocating water.

First, the hydrology-based e-flow regimes need to be grounded on the before mentioned applicable ecohydrological theory. Additionally, they need to be flexible enough to allow for implementation under different climatic conditions. Such conditions are present in nature (e.g. wet, average, dry and very dry hydrological years) and to which all users in a water allocation system must adjust. Second, the environmental flow regimes should be adjusted and provided according to a desired conservation or restoration ecohydrological status for the flow regime. In practical implementations, those desirable statuses are built upon the flow alteration-ecological response relationships theory bound to environmental objectives or management classes (Richter, Baumgartner, Powell & Braun, 1996, Bunn & Arthington, 2002; Lloyd et al., 2003; Davies & Jackson, 2006; Acreman et al., 2014ab).

Unlike previous detailed hydrological methodologies (Richter et al., 1997; Hughes & Hannart, 2003; Mathews & Richter, 2007; Hughes et al., 2014), the main and innovative contribution of this method strives in a frequency-of-occurrence approach as an evaluating and integrating factor of the two management requirements for environmental water allocation. Two flow regime components are assessed: (i) the inter-annual and the seasonal (intra-annual) variability of low flows hydrological conditions; and (ii) a flood regime derived from a set of peak flow events. E-flows regimes and annual volumes reserves are integrated according to a four-level system of environmental objectives classes.

Since 2012, the method was adopted as a detailed hydrology-based approach in the Mexican standard and it has been complementary to holistic e-flows assessments (Barrios-Ordóñez, Salinas-Rodríguez, Martínez-Pacheco, López-Pérez, Villón-Bracamonte & Rosales-Ángeles, 2015; Salinas-Rodríguez et al., 2018). Afterward, it started to be tested in other streams and to date, there are some examples of implementations.

The early outcomes in the San Pedro Mezquital (Alianza WWF-FGRA, 2010; Sánchez Navarro & Barrios Ordóñez, 2011) led to the first environment-strategic reserve for preventive ecological protection (SEMARNAT, 2014; Salinas-Rodríguez et al., 2018). The establishment of this reserve has triggered a process of public consultation between stakeholders with the purpose of integrating detailed e-flows requirements to management programs (National Commission of Natural Protected Areas, personal communication).

Flow-ecology relationships have been analyzed to understand the importance of conserving the flow regime components integrity for setting up a hydrogeomorphological, biological and chemical monitoring program to assess the performance of the reserve, and for ultimately providing feedback in its implementation. Other applications of the method have been conducted in the Acaponeta, Piaxtla, Verde, and Ayuquila-Armería rivers (De la Lanza et al., 2012 and 2015; Gomez Balandra et al., 2014; Meza-Rodríguez et al., 2017).

3.3 Methodology

3.3.1 Intra (seasonal) and inter-annual variability for low flow conditions

The full range of inter-annual and seasonal variability of flows is encompassed in the concept of low flows. In this methodology, it is defined as the natural, regularly present surface flows in dry and wet seasons at monthly scale. This flow regime component supports several ecological functions such as the maintenance of seasonal habitats' diversity and connectivity, the water chemistry and other hydrodynamic conditions, in addition to purging invasive and introduced species from the aquatic and riparian communities, among others (for a larger list refer to Postel & Richter, 2003 or Richter et al., 2006).

As Richter's et al. (1997) *Range Variability Approach* and Mathews & Richter's (2007) *Environmental Flow Components*, in this method is proposed the analysis in a wide range of inter-annual and seasonal variability of low flows. Based on a frequency of occurrence approach, it considers four hydrological conditions: wet, average, dry and very dry low flows. They are computed in cubic meters per second (m^3/s), according to the flows characteristic of percentiles 75th, 25th, 10th and 0th of the full set of natural or unregulated inter-annual mean monthly observed records (Figure 3.1).

These percentiles set the threshold of each hydrological condition, and thus the flows' variability by their frequency of occurrence. The characteristic flows of wet conditions are those that exceed only 25% of the time from the full set of records. Similarly, the threshold of flows for the average condition is ± 25% of percentile 50th (median). The flows characteristic of percentile 25th set the lower limit of this condition while the ones of percentile 75th set the upper limit. The flows characteristic of dry and very dry conditions are below the average threshold. For these conditions, the 10th and 0th percentiles set the limits, respectively. With this characterization, flows are expected to happen within the thresholds with the following natural frequency of occurrence: wet 25%, average 50%, dry 15%, and very dry 10% of the time.

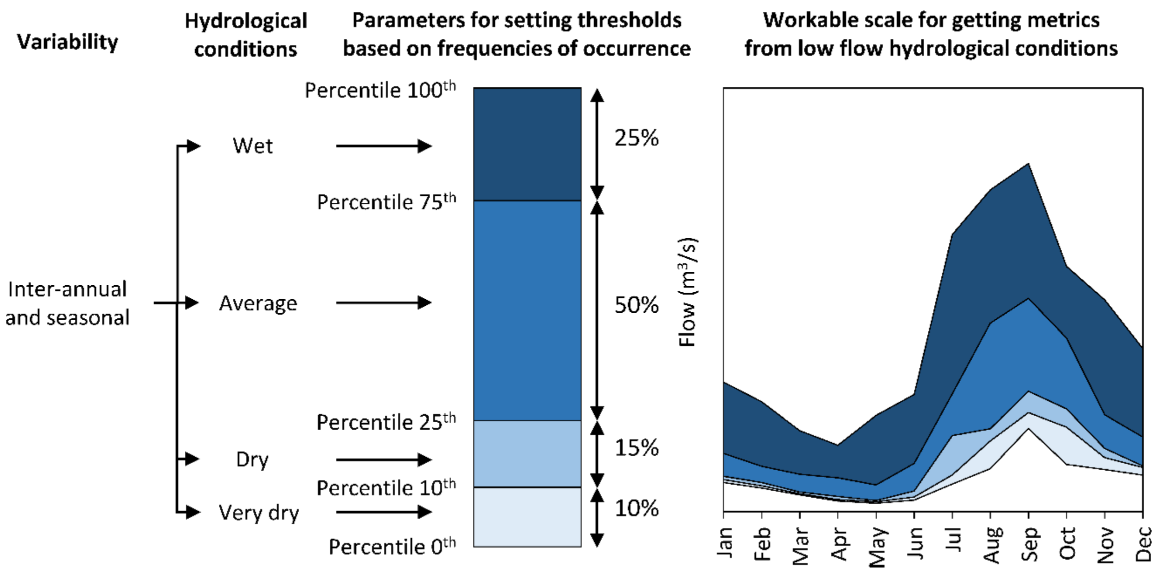


Figure 3.1. Conceptual procedure for setting the inter-annual and seasonal variability limits of the hydrological conditions of low flows based on frequencies of occurrence.

3.3.2 High flow pulses and flood regime

The flood regime in this method is defined as a set of peak flow episodic events. They are identified based on the maximum daily natural or unregulated flows (m^3/s) per year of the full set of records, with their corresponding attributes of magnitude, frequency, duration, time of occurrence (timing) and rate of change (rise and fall). The set of flow events are typified for at least three categories of peaks (I, II and III) according to their historical and modeled frequencies of occurrence at 1, 1.5 and 5 years return period. The recurrence intervals of these events represent the magnitudes of the natural range of (I) intra-annual or high flow pulses, (II) the inter-annual characteristic of bankfulls, and (III) moderate inter-annual peak events. Altogether, these events play an important role in connecting the river laterally with its floodplain and sustaining the related ecological and biological processes, among other functions.

Although peak flow events of greater magnitude (e.g. 10 or 20-year return period) are also beneficial for the river system's geomorphological dynamics, they are difficult to implement on-site in flow-regulated cases. Generally, these rivers also face pressure on their riparian corridors and floodplains. Larger events in this method are advisable only where there is no water infrastructure along the river stream (e.g. levees, water diversions, and dams), nor human settlements on the river floodplain (e.g. houses, towns, and cities). Additionally, existing specialized studies on flooding risks must be taken into account, and the peak events characteristic of this flood regime should be supported by legal mechanisms or regulations to delimitate the rivers' public domain or space.

The magnitude of the three categories of peak flow events is obtained by, first, identifying the maximum daily flow per year of the full set of observed daily records considered natural or unregulated. Log-Normal, Gumbel, and Log-Pearson Type III logarithmic regression models are also recommended in some cases, where they are considered more appropriate based on site-specific knowledge (e.g. peak flow data symmetry/asymmetry distribution from a particular river; Chow, Maidment & Mays, 1994). Second, the characteristic magnitude of the peak flows is selected based on the magnitude's average associated to 1, 1.5 and 5-year return period derived from the four models, and the average value rounded up on a multiple-of-five basis for easy handling. This step of the procedure is implemented for the method's proof-of-concept and proposed as a standard practice. Third, the events from characteristic magnitudes are identified in the full set of observed daily records and filtered from the component the low flows.

Consistent with the overall approach, the attributes of duration, timing and rate of change of the peak flow events are set upon frequency-based probability criteria, hydrologically appropriate for high variable regimes. The duration of each episodic event, in number of consecutive days that typically last, is determined according to the cumulative relative frequency in which said events have occurred historically in the complete natural or unregulated series of flow data. A value between 75 – 85% is adequate. Likewise, the timing is determined based on the months of the natural occurrence of these same events. In the case of Mexican rivers, a relative frequency of approximately 80 – 90% is a functional indicator because it captures the typical peak flow's seasonality. With regard to the rate of change, this is set based on a percentile approach over the events' rise and fall daily flow changes that have occurred historically. Percentiles 90th and 10th are suitable because these parameters depict the quickest rates more closely.

3.3.3 Setting-up environmental flow regimes and reserves for preventive water allocation

The criteria for setting and adjusting the environmental flow regimes according to this method is based on a top-down approach which puts higher weight in the ecohydrological conservation merits of the flow regime over a modified condition, coherent with the preventive water allocation scope. The approach assumes that a river basin has different levels of water use pressure and ecological importance with legal environmental flow protection bindings.

The criteria and process for the application of this method are described in the following sections. However, it is important to mention that the desired state or condition of an ecosystem and the future development of a river basin are the product of a societal discussion and collective agreement (Acreman et al., 2014ab; Poff et al., 2017). Furthermore, although this method, as other desktop-based approaches, could be used to diagnose the hydrological functioning of the river systems, it is not appropriate for cases of over-allocated and exploited rivers in which the flow components need to be totally rebuilt. Examples of such cases can be seen across entire basins with a highly intense consumptive usage of water that dries up the river streams for several months, and where other bottom-up, detailed approaches like habitat simulation models or holistic methodologies are more suitable.

Environmental objectives and desired status

As similarly reported by the e-flow science and practice literature (Hughes and Hannart; 2003; Kendy et al., 2012; Acreman et al., 2014b; Hughes et al., 2014), a four-tiered environmental objective class system (A – D) is used in this method. The flow regime components (inter-annual and seasonal variability of low flows conditions and the flood regime set of peak flow events) and attributes (magnitude, frequency, duration, timing, and rate of change) are adjusted to a desired ecohydrological status. Class A means a very good state, where the flow regime keeps or is very close to, its hydrological integrity and therefore its ecological-related functioning, such as wild, free-flowing or highly conserved rivers without relevant anthropogenic infrastructure running through or discharging within protected areas.

Classes B and C represent the good and moderate desired states respectively. Minor or sensible changes in the flow regimes of the rivers in these classes would be expected. Mostly because of the presence of infrastructure of low or small to moderate sizes, such as roads, levees, water diversions or dams, that in the same proportion have impacted the flow-related ecological integrity of the rivers. In class D, rivers present high abundance from moderate to big-size infrastructure for water use (i.e. hydropower or irrigation dams); thus, the flow regime in these is completely regulated.

The frequency factors of occurrence: Criteria for setting and adjusting environmental flows for water allocation

The frequency of occurrence from the hydrological conditions of low flows and the peak flow events, presented in Tables 3.1 and 3.2, is used as an integrating criterion of e-flows regimes (components and attributes) into water reserves for environmental allocation adjusted to the desired ecohydrological status. These reference values of occurrence frequencies have the following reasoning.

Table 3.1. Frequency factors of occurrence for the integration of low flows regimes into annual volumes for environmental water allocation, according to a desired ecohydrological state and environmental objective class.

Desired ecohydrological status	Environmental objective	Frequency of occurrence for low flow regimes			
		Wet	Average	Dry	Very dry
Very good	A	0.1	0.4	0.3	0.2
Good	B	0.0	0.2	0.4	0.4
Moderate	C	0.0	0.0	0.4	0.6
Deficient	D	0.0	0.0	0.0	1.0

Table 3.2. Frequency factors of occurrence for the integration of the peak flow events (categories I, II and III) into annual volumes for environmental water allocation, according to a desired ecohydrological state and environmental objective class.

Desired ecohydrological status	Environmental objective	Frequency of occurrence of peak flow events		
		Category I	Category II	Category III
Very good	A	10	6	2
Good	B	5	3	2
Moderate	C	3	2	1
Deficient	D	2	1	1

A very good desired status of the low flows (environmental objective class A) and ultimately the proposed amount of water for environmental allocation of this flow component should secure in the mid and long-term the magnitude and occurrence (frequency) of all the hydrological conditions of intra and inter-annual variability (duration and timing). At the same time, the e-flows requirements and protection should also allow a low water usage. In this context, for example in a 10-year hypothetical time horizon, the wet, average, dry and very dry hydrological conditions (characteristic magnitudes and regimes) would occur with a frequency of one, four, three and two years, respectively, instead of 25%, 50%, 15% and 10% occurrence as the natural frequency was characterized.

In the case of a good desired status, the proportions of the wet, average, dry and very dry conditions decrease to zero, two, four and four, accordingly, as rivers within this environmental objective class (B) generally have some water consumption rates associated for productive usage. Likewise, as long as there is more water committed to supplying productive uses, the flow regime desired status decrease and, therefore, their associated environmental objectives.

The frequencies of occurrence for the moderate and deficient classes of desired status (environmental objectives C and D) are proposed to follow at least the flow's natural pattern in four and six years for dry and very dry conditions in the former case, and permanently in a very dry condition for the latter.

The algorithm to integrate the low flows to the proposal of environmental reserve volume for water allocation is presented in Equation 3.1. Q_{lf} is the annual discharge volume of low flows in million cubic meters (Mm^3), *F* the frequency of occurrence for the hydrological condition *i* (reference values of Table 3.1), *Q* the discharge volume for the low flow *i*, and *i* the hydrological condition for a low flow (w = wet, a = average, d = dry or vd = very dry).

$$Q_{lf} = (F_w \times Q_w) + (F_a \times Q_a) + (F_d \times Q_d) + (F_{vd} \times Q_{vd}) \qquad \text{Eq. (3.1)}$$

For integrating the peak flow events, and considering the same hypothetical 10-year time horizon, the set of the three peak flow events (categories) would be expected to occur with their corresponding characteristic magnitudes and duration, although in different frequencies. In rivers with a very good desired ecological status and class A environmental objective, the frequencies' reference values are the same as the historical (natural or unregulated) ones. That is to say, the events of the category I (high flow pulses) should occur at least 10 times (once per year). The category II of peak flow events (inter-annual characteristic of bankfulls) would happen six times in 10 years, while the category III twice (moderate inter-annual). For a good desired ecological status (class B environmental objective) the management frequency decreases to 5/10, 3/10 and 2/10 in categories I, II and III, respectively. Similarly, for a moderate class of the desired status (environmental objective C) the frequency of occurrence decreases to 3/10, 2/10 and 1/10 and 2/10, 1/10 and 1/10 in a deficient class (environmental objective D).

Similar to the low flows, the algorithm for integrating the peak flow events to the environmental reserve volume for water allocation proposal is given in Equation 3.2. Q_{fr} is the annual discharge volume of the flood regime (Mm^3), *F* the frequency of occurrence of the flood event *i* (reference values of Table 3.2), *D* the duration of the peak flow event *i*. *Q* is the discharge volume (Mm^3) per day of the peak flow event *i*, and *i* the category of the peak flow event (I = 1, II = 1.5 or III = 5-year return period).

$$Q_{fr} = \frac{(F_{fI} \times D_{fI} \times Q_{fI}) + (F_{fII} \times D_{fII} \times Q_{fII}) + (F_{fIII} \times D_{fIII} \times Q_{fIII})}{10} \quad \text{Eq. (3.2)}$$

A schematic procedure of the methodology is presented in Figure 3.2. Finally, the total volume of environmental reserve for water allocation is the sum of the corresponding annual discharge (Mm^3) from both the low flows and the peak flow events (flood regime).

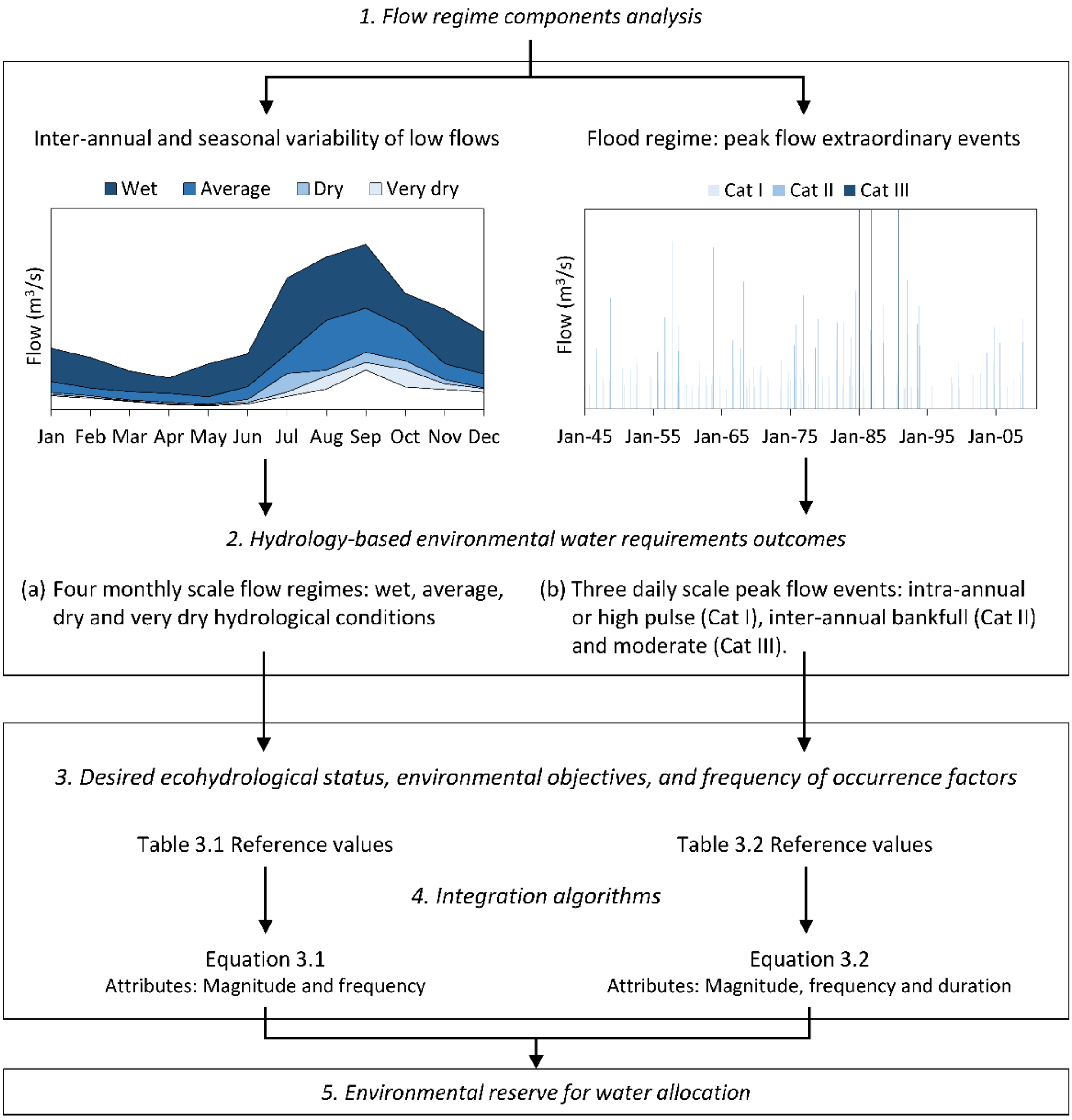


Figure 3.2. Overall schematic procedure for determining environmental volumes for water allocation based on the hydrology-based frequency of occurrence approach.

3.3.4 Method's application and performance validation: A case study in rivers discharging into the Marismas Nacionales (National Marshlands) wetland

Marismas Nacionales is a coastal wetland of international importance located in western Mexico between coordinates 105-106° W and 21-23° N (Figure 3.3). According to a recent functional diagnosis study, it comprises around 487,000 hectares of hydrogeomorphological processes and linkages (Blanco et al, 2011). There are up to 200,000 hectares protected under the Ramsar Convention (site 732), to which the Mexican government declared 133,854 hectares as a biosphere reserve. The full range of flows variability of discharging rivers is recognized by the protected area management plan for sustaining the ecological integrity and ecosystemic dynamics of the wetland [Secretaría de Medio Ambiente y Recursos Naturales and Comisión Nacional de Áreas Naturales Protegidas (SEMARNAT-CONANP), 2013]. For the purpose of this case study, the method was implemented in seven rivers discharging into this wetland: Santiago, San Pedro Mezquital, Baluarte, Acaponeta, Bejuco, Cañas, and Rosamorada.

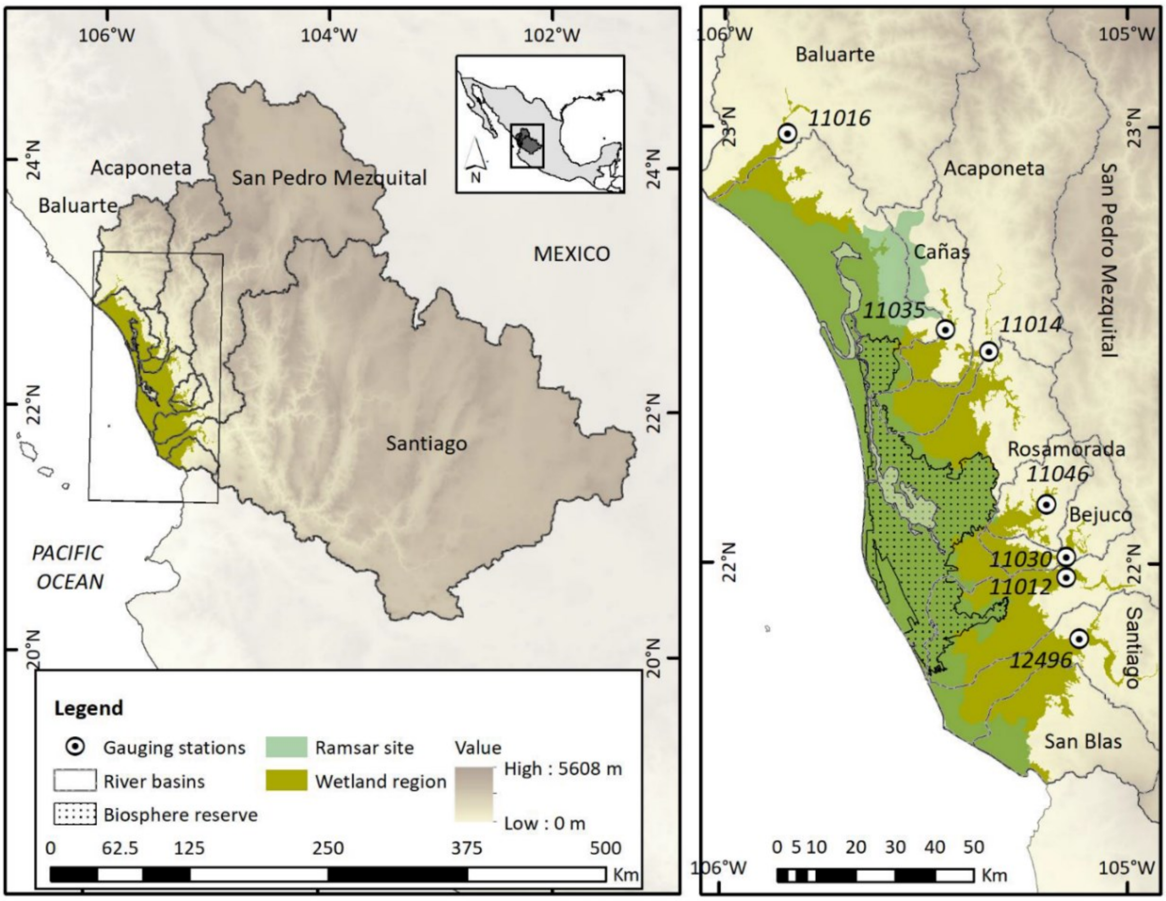


Figure 3.3. Geographic location of the Marismas Nacionales protected wetland and the river basins that discharge in it.

The implementation followed an assessment procedure in two-time sections of the total observed period of flow records, appropriate for this type of approach

(Richter et al., 1997, Mathews & Richter, 2007, Biondi, Freni, Iacobellis, Mascaro & Montanari, 2012). Daily flow records of all the rivers were obtained from the national gauging stations repository operated by the Mexican Water Commission (ftp://ftp.conagua.gob.mx/Bandas/).

Each flow data set was inspected for selecting the sections with the best available consecutive time length (Table 3.3). This supervised inspection secures enough representativeness from mid to long-term of unregulated streamflow variability on the sections selected. The first period of records is considered as a reference for validation, and the second for testing the approach (onwards referred as assessment period).

Regulated flow periods were avoided in the Santiago River due to significative infrastructure development for hydropower generation (e.g. Aguamilpa dam, the closest to the river mouth with 5,540 Mm^3 of storage capacity). On the contrary, the San Pedro Mezquital River flows (gauging station code 11012) were restituted with flows derived ~5 km upstream for relatively small-scale irrigation (station code 11039, 0.7 m^3/s of median annual flow, the maximum peak of 1.4 m^3/s in March, period 1960 – 2001). This restitution was considered necessary in order to assess in equal conditions the assessment period against the reference, especially for the very dry low flow condition.

Table 3.3. Flow variability indices for both the reference (earlier) and the assessment (latter) periods of the rivers discharging into Marismas Nacionales wetland. MAR = Mean annual runoff, CV = Coefficient of variation, MABF = Mean annual baseflow, BFI = Baseflow index and CVB = Overall index of flows variability (CV/BFI).

River basin	Gauging station (code)	Period of records	MAR (m^3/s)	CV (%)	MABF (m^3/s)	BFI (%)	CVB
Santiago	12496	1955 – 1970	265.60	125.99	38.42	14.46	8.71
		1971 – 1986	242.75	107.53	40.04	16.49	6.52
San Pedro Mezquital	11012 and 11039	1944 – 1973	86.74	195.72	3.05	3.51	55.73
		1974 – 2003	86.85	275.27	1.94	2.24	123.16
Baluarte	11016	1948 – 1969	49.83	176.36	0.75	1.50	117.51
		1970 – 1992	60.32	185.44	0.76	1.27	146.54
Acaponeta	11014	1945 – 1976	41.62	115.84	1.61	3.88	29.89
		1977 – 2008	40.63	197.37	1.53	3.77	52.38
Bejuco	11030	1958 – 1971	6.27	206.11	0.08	1.23	168.14
		1972 – 1985	4.69	239.36	0.00	0.00	–
Cañas	11035	1961 – 1972	4.58	170.51	0.00	0.10	1,745.21
		1973 – 1985	4.03	138.92	0.01	0.15	912.69
Rosamorada	11046	1971 – 1978	2.93	201.06	0.00	0.00	–
		1979 – 1985	2.60	241.75	0.00	0.00	–

About the rivers' flow characteristics, all the streams exhibit high seasonal variability with coefficients of variation (CV) greater than 100% (based on the indices developed by Hughes & Hannart, 2003 and Hughes et al., 2014). The San Pedro Mezquital and Acaponeta rivers have increased meaningfully this variability (41 Δ% and 70 Δ%, respectively).

The Santiago, San Pedro Mezquital, Acaponeta, and Baluarte rivers could be considered as perennial streams with a mean annual baseflow (MABF) from nearly 1 m^3/s or greater. Baluarte, Bejuco and Cañas streams showed the lowest baseflow buffer capacity (BFI ≤ 1.5%), and the greatest overall index of variability in both periods with values above 100 (the proportion between the CV and the BFI).

The performance validation indicators were chosen based on the factors of the flow regime components that influence the outcome of Equations 3.1 and 3.2. For each hydrological condition regime, the volumes between the reference and the assessment period of the low flows discharge per calendar month (Mm^3) were subtracted (residuals) and correlated.

Equation 3.1 was applied at a monthly scale for the four environmental objectives based on the frequency factors of occurrence as Table 1 provides them; the volumes residuals and scatter plots were graphically displayed. The coefficients of determination (R^2) were calculated according to the linear regressions of the volumes per hydrological condition, as well as for the low-flows component for the environmental reserves integrated by such conditions and their corresponding frequencies of occurrence.

As for the flood regime component, the R^2 for 16 characteristic peak flow events (1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 10, 15 and 20-year return period) were calculated and adjusted based on (1) linear regressions of the discharge magnitudes between both sets of records; and (2) their independent logarithmic distribution models (return period *vs*. magnitude). The magnitude (m^3/s), duration and occurrence (number of consecutive days and cumulative frequency) of each peak flow event type considered for the application of Equation 3.2 were displayed in supporting graphs for both the reference and the assessment periods. The corresponding flow regime components volumes of the low flows, the flood regime, and together for the environmental water reserve were examined in the context of the overall performance assessment.

3.4 Results

3.4.1 Environmental flows: Regime characteristics and volumes for water allocation

Consistent with the rivers' flow variability characteristics, the low-flows of all the hydrological conditions experienced high variability between dry and wet seasons, and in the reference and assessment periods (Figure 3.4 A – N). The rivers that discharged water permanently in all the conditions of the reference period were Santiago, San Pedro Mezquital and Acaponeta.

The Baluarte River discharged only during the wet years while the Bejuco, Cañas, and Rosamorada in wet seasons of all the yearly conditions. This magnitude pattern of low flows practically is maintained in all the conditions of the assessment period. The exception was the San Pedro Mezquital River that in the recent decades has experienced a change and discharged water permanently only in wet conditions.

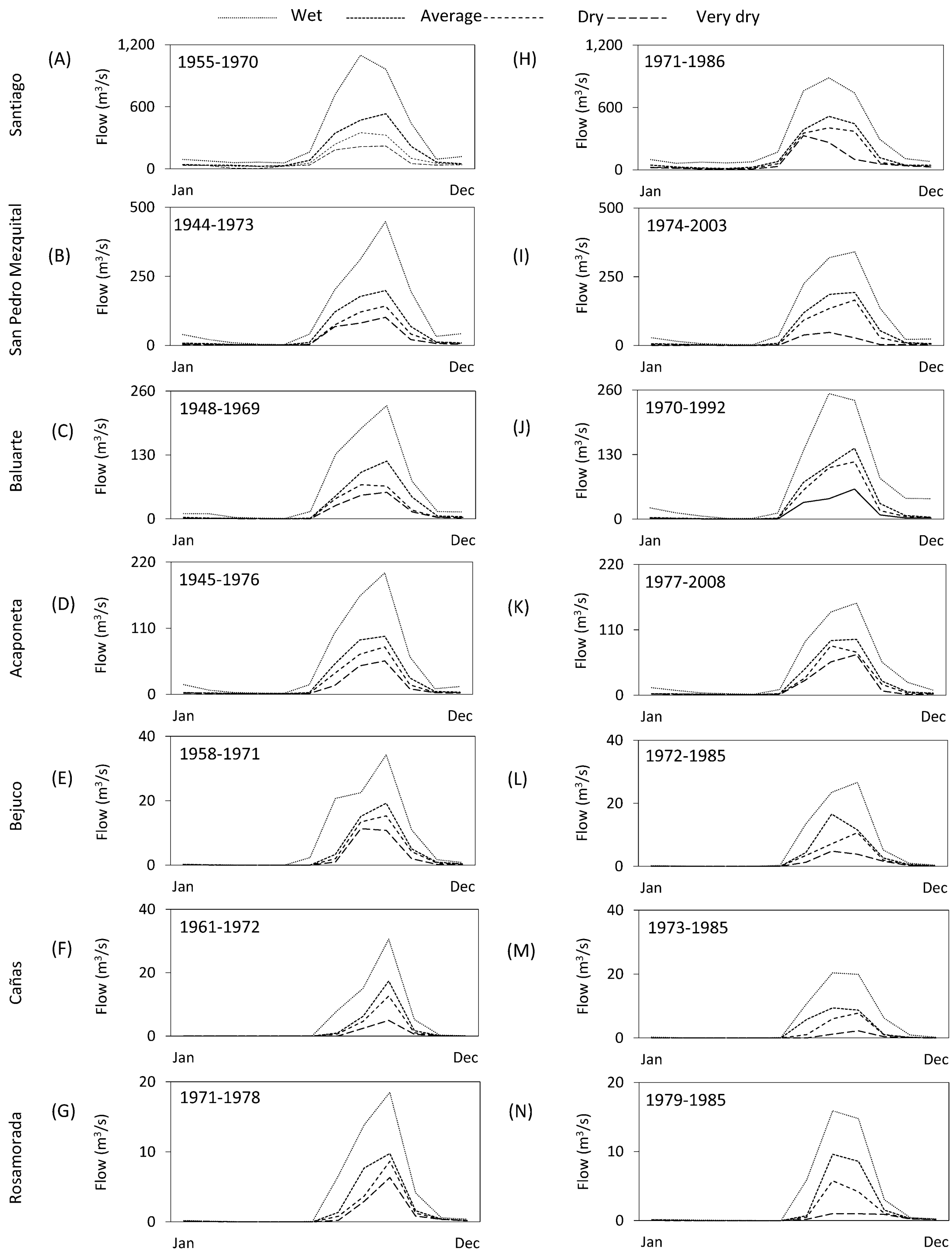


Figure 3.4. Reference (A – G) and assessment (H – N) low flows for wet, average, dry and very dry conditions (monthly scale) of the rivers discharging into Marismas Nacionales wetland.

River streams also showed high variability in the magnitude of their peak flow events in the two set record periods (Table 3.4). The comparison between the reference and the assessment periods revealed some cases of major changes in the magnitude of the peak flow events. For the high flow pulse (Cat I) the rivers with significant changes were observed for Bejuco from 70 to 35 m^3/s (-50 Δ%), San Pedro Mezquital from 350 to 245 m^3/s (-30 Δ%), and Baluarte from 305 to 380 m^3/s (25 Δ%).

In the case of the characteristic of bankfulls (Cat II), Bejuco and Cañas streams discharge decreased in magnitude from 120 to 90 m^3/s (-25 Δ%) and from 170 to 130 m^3/s (-24 Δ%), respectively. A third river with also a considerable change was Baluarte from 800 to 995 m^3/s (24 Δ%). For the moderate inter-annual peak flow events, Cañas (435 – 280 m^3/s, -36 Δ%), Santiago (3,075 – 4,005 m^3/s, 30 Δ%) and San Pedro Mezquital (1,780 – 2,180, 23 Δ%) presented the most relevant changes.

The peak events in all the rivers' flood categories showed a decreasing trend in number of days (Cat I ≥ II ≥ III) and regularly lasted between one to three days in both periods of analysis. The exceptions were found in Santiago from 2 – 11 days to 1 – 7 days, San Pedro Mezquital from 2 – 7 days to 1 – 11 days, and Rosamorada from 1 – 5 to 1 – 4 between the reference and assessment periods.

The most common timing for the peak events in all the rivers was from July to September, although in Acaponeta, Baluarte and San Pedro Mezquital the peak events lasted until October. The first two with also significative peaks in January according to the latter period of analysis, while in San Pedro Mezquital the high flow pulse timing included June in the assessment period.

About the rate of change, the rivers with consistency between the periods of analysis were Santiago (46% and around -30%), San Pedro Mezquital (72% ±4 and -39%), Baluarte (~180% and ~62% ±6). Sensitive changes in this flow attribute were presented only for rise events in Acaponeta (from 101% to 156%) and Rosamorada (from 145% to 226%), whereas Bejuco and Cañas manifested dramatic changes in both rise and fall. The rise rate increased from 34% to 138% and from 69% to 205%, accordingly. The fall rate in the Bejuco River decreased from -37% to -70%, and increased from -249% to -76% in the Cañas River.

Table 3.4. Set of peak flow events according to both the reference and the assessment periods of the rivers discharging into Marimas Nacionales wetland.

River basin	Period of records	Reference			Assessment		
	Peak event category	I	II	III	I	II	III
	Return period (# years)	1	1.5	5	1	1.5	5
Santiago	Magnitude (m^3/s)	860	1,745	3,075	865	1,525	4,005
	Duration (# days)	11	5	2	7	5	1
	Timing (months)		Jul – Sep			Jul – Sep	
	Rate of change		45.5			45.7	
	(% rise and fall)		-32.7			-30.2	
San Pedro Mezquital	Magnitude (m^3/s)	350	785	1,780	245	845	2,180
	Duration (# days)	7	3	2	11	3	1
	Timing (months)		Jul – Oct			Jun – Oct	
	Rate of change		68.2			75.9	
	(% rise and fall)		-39.1			-38.4	
Baluarte	Magnitude (m^3/s)	305	800	2,920	380	995	2,695
	Duration (# days)	3	2	1	3	2	1
	Timing (months)		Jul – Oct			Jan, Jul – Oct	
	Rate of change		180.9			178.9	
	(% rise and fall)		-68.2			-54.9	
Acaponeta	Magnitude (m^3/s)	215	505	1,705	210	520	1,500
	Duration (# days)	3	2	2	3	3	2
	Timing (months)		Jul – Oct			Jan, Jul – Oct	
	Rate of change		101.1			155.7	
	(% rise and fall)		-61.6			-60.2	
Bejuco	Magnitude (m^3/s)	70	120	165	35	90	180
	Duration (# days)	2	1	1	2	1	1
	Timing (months)		Jul – Sep			Jul – Sep	
	Rate of change		34.0			137.5	
	(% rise and fall)		-37.4			-69.6	
Cañas	Magnitude (m^3/s)	50	170	435	55	130	280
	Duration (# days)	2	1	1	1	1	1
	Timing (months)		Jul – Sep			Jul – Sep	
	Rate of change		69.3			205.3	
	(% rise and fall)		-249.1			-75.8	
Rosamorada	Magnitude (m^3/s)	15	50	100	15	50	110
	Duration (# days)	5	2	1	4	1	1
	Timing (months)		Jul – Sep			Jul – Sep	
	Rate of change		144.8			226.0	
	(% rise and fall)		-64.2			-65.2	

3.4.2 Hydrological performance assessment and validation

In general, the greatest residuals of discharge volumes between the reference and the assessment periods were found during the wet season from June to October for all the hydrological conditions regimes (Figure 3.5 A – G). Some noticeable outcomes from this indicator in the Santiago River (Figure 3.5 A) were the month of July where the residuals of all the conditions were between -111 Mm^3 and -391 Mm^3. In August also remained also higher for the average, dry and very dry conditions (residuals around -132 Mm^3), and for September the dry condition (close to -120 Mm^3). This change indicates that during the latter period (1971 – 1986) the discharge volumes increased in comparison to the earlier period (1955 – 1970).

So too the San Pedro Mezquital (Figure 3.5 B) between periods of analysis (1944 – 1973 *vs*. 1974 – 2003). For the months of July and August residuals in wet condition were about -63 Mm^3 and -25 Mm^3, in August average condition -23 Mm^3, and July, August, and September -48 Mm^3, -37 Mm^3 and -57 Mm^3 in dry condition. The Baluarte River (Figure 3.5 C) showed a more regular discharge increase throughout the wet season between periods (1948 – 1969 *vs*. 1970 – 1992). In this case, the mean seasonal residuals from June to October were -47 Mm^3, -29 Mm^3 and -53 Mm^3 in the wet, average, and dry conditions, respectively. Opposable to the Baluarte is the Bejuco River (Figure 3.5 E), where the mean seasonal residuals were 11 Mm^3 in wet, 4 Mm^3 in average, 6 Mm^3 in dry, and 7 Mm^3 in very dry conditions (1958 – 1971 *vs*. 1972 – 1985).

The Acaponeta River presented an intermediate changing condition (Figure 3.5 D, 1945 – 1976 *vs*. 1977 – 2008); here the most relevant mean seasonal residuals were found in wet and very dry conditions (50 Mm^3 and -16 Mm^3). The Cañas (1961 – 1972 *vs*. 1973 – 1985) and Rosamorada rivers (1971 – 1978 *vs*. 1979 – 1985) presented more focalized changes (Figures 3.5 FG). In the first, noticeable residuals were in July, August and September for the wet and average conditions (-7, -14 and 28 Mm^3; -13, -8 and 23 Mm^3), and in September for the dry (13 Mm^3) and very dry (7 Mm^3). In the second, August with all the residuals between -5 and 5 Mm^3, and September 3 – 14 Mm^3.

The variability of the rivers discharge residuals for all the hydrological conditions was also reflected in the scatter plots between the regimes outcomes of such conditions from the reference and assessment periods (Figure 3.5 H – N). Graphically, Baluarte and Acaponeta rivers (Figure 3.5 JK) showed the best overall fit in all the conditions followed by Santiago, San Pedro and Bejuco in a second level (Figure 3.5 HIL), and the Cañas and Rosamorada rivers in a third (Figure 3.5 MN). In the same way, scatter plots of the low flows component for the environmental water reserves showed consistency, within and between the four environmental objectives (Figure 3.5 O – U).

About the characteristic peak flow events (Figure 3.6), all the rivers displayed a high level of fitness in both comparisons, the discharge magnitudes (A – G) and the logarithmic distribution based on the return periods (H – N).

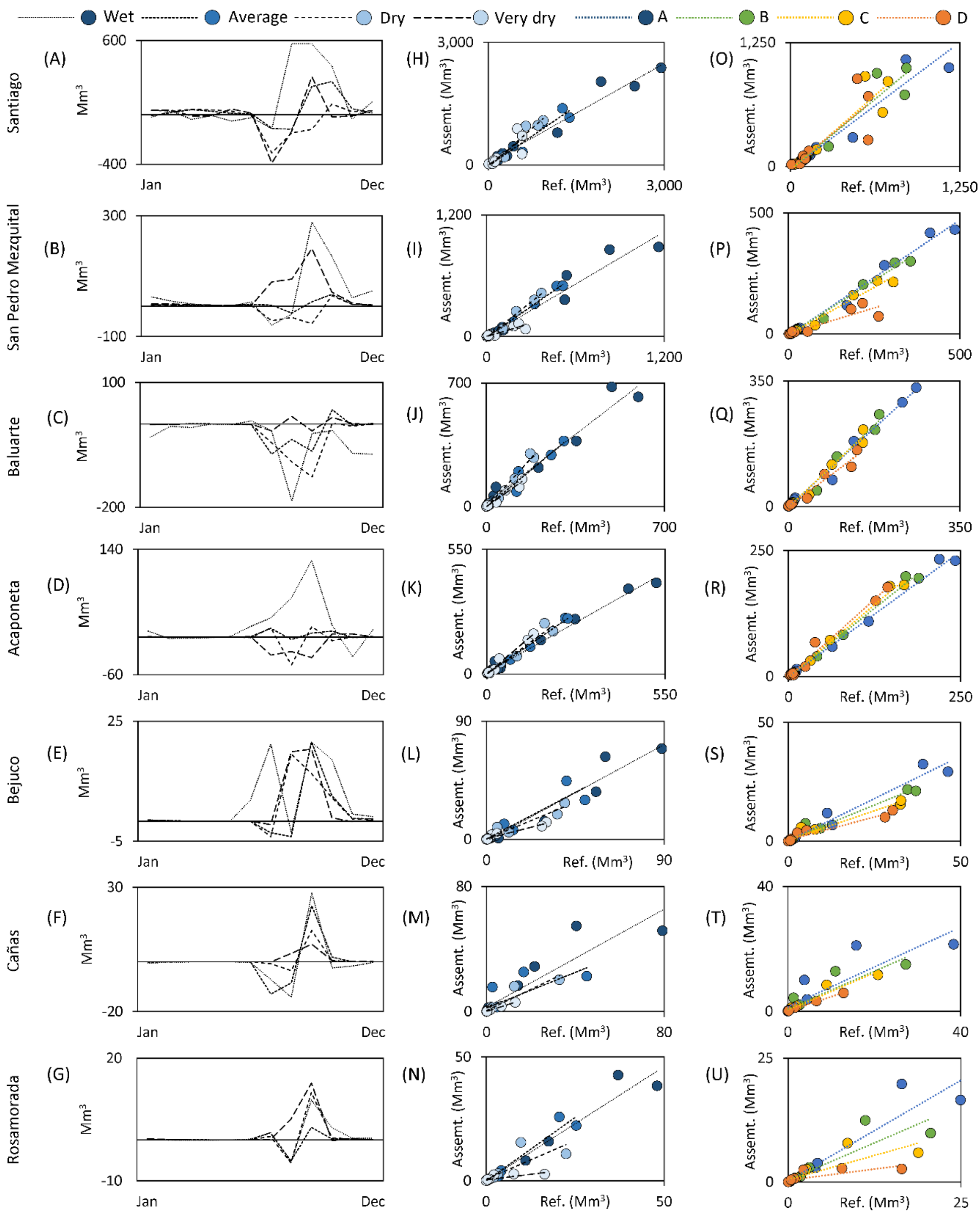


Figure 3.5. Performance validation indicators of the low flows component analysis (monthly scale) of the rivers discharging into Marismas Nacionales wetland. Reference and assessment discharge residuals (A – G), scatter plots of the hydrological conditions (H – N) and scatter plots of the integrated low flows based on the frequency factors of occurrence according to each environmental objective class (O – U).

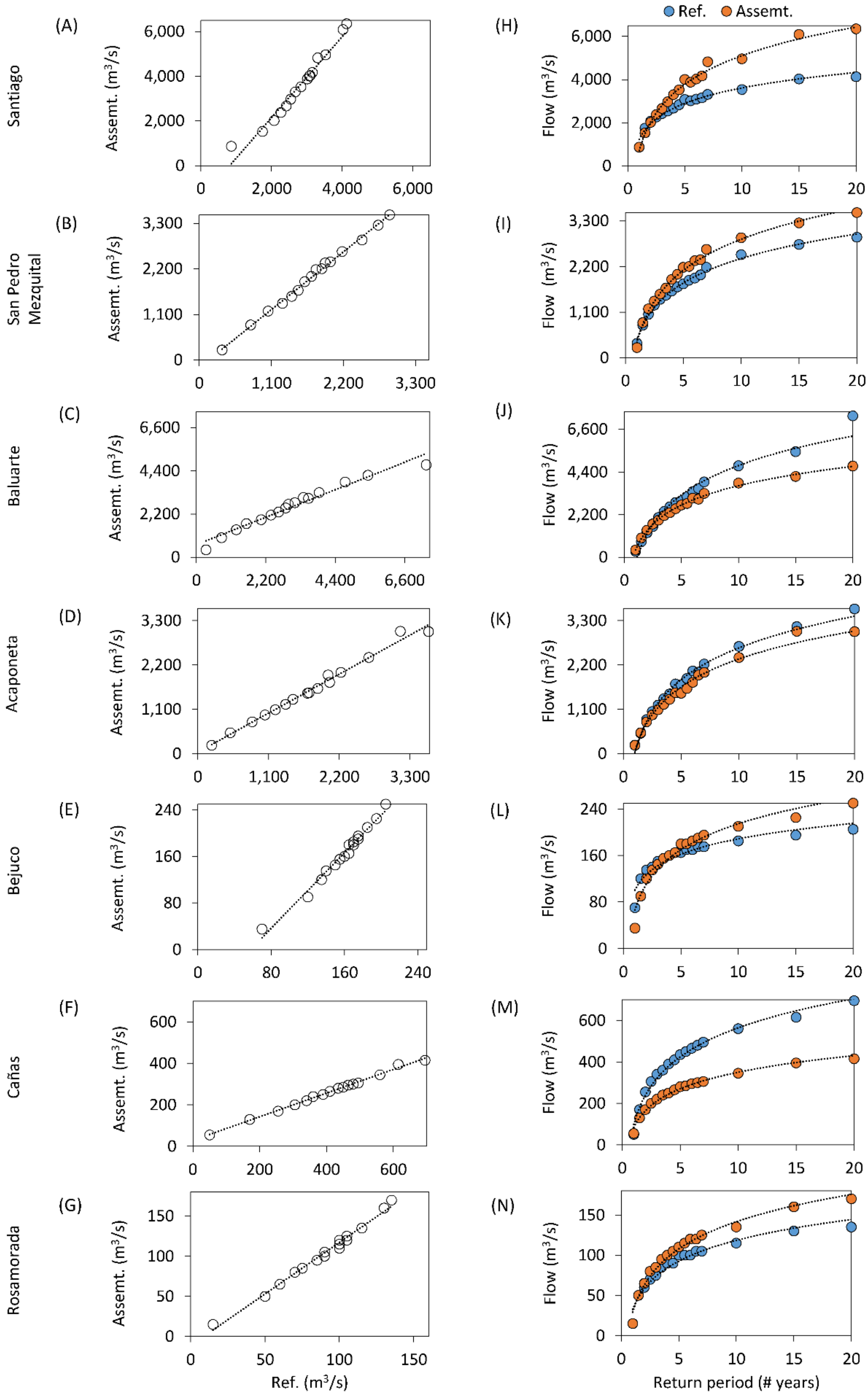


Figure 3.6. Performance validation indicators of the peak flow events analysis (flood regime component) of the rivers discharging into Marismas Nacionales wetland. Reference and assessment scatter plots of 16 characteristic peak flow magnitudes (1 – 20-year return period) (A – G), and their logarithmic distribution models (return period *vs*. magnitude) (H – N).

The R^2 values supported these fitness levels (Table 3.5). In the first level, the R^2 values for the hydrological conditions regimes were above 0.96. In the second, Santiago and San Pedro Mezquital presented lower values in the very dry condition, 0.71 and 0.84, and Bejuco in the average (0.88). In the third, Cañas showed R^2 values of 0.84, 0.61 and 0.88 in the wet, average and dry conditions, and Rosamorada 0.67 and 0.64 in the dry and very dry.

Similarly, the best overall fitness level of the low flows component of the environmental reserves exhibited R^2 values above 0.95 in all the environmental objectives. In addition to the Baluarte and Acaponeta Rivers, Bejuco also reached the best fit. In the case of the San Pedro Mezquital, the lowest fit was presented for the environmental objective class D (R^2 = 0.83), in the Santiago in C and D (0.88, 0.71), the in Cañas in A and B (0.78, 0.85), and in the Rosamorada in all the classes (from 0.89 to 0.64).

As for the performance validation metric for the 16 characteristic peak flow events, the R^2 values of the magnitudes comparison were ≥ 0.96 in all the rivers with the exception of Bejuco in the reference period logarithmic distribution model (> 0.91).

Table 3.5. Coefficients of determination (R^2) between the periods of reference and assessment for the performance validation indicators of the rivers discharging into Marimas Nacionales wetland. R^2 values were calculated for (1) the corresponding regime volumes of low flows per the hydrological condition, (2) the low flows regime component for the environmental reserves based on the frequency factors of occurrence for each environmental objective class. (3) The magnitudes of 16 characteristic peak flow events (from 1 to 20-year return period), and (4) their logarithmic distribution models (return period *vs*. magnitude).

Performance validation indicator	River basin						
	Santiago	San Pedro Mezquital	Baluarte	Acaponeta	Bejuco	Cañas	Rosamorada
Low flows per hydrological condition							
Wet	0.96	0.95	0.96	0.98	0.94	0.84	0.96
Average	0.95	0.99	0.97	0.99	0.88	0.61	0.96
Dry	0.97	0.99	0.98	0.96	0.93	0.88	0.67
Very dry	0.71	0.84	0.96	0.98	0.94	0.99	0.64
Low flows per environmental objective							
A	0.95	0.99	0.99	0.99	0.96	0.78	0.89
B	0.93	0.99	0.98	0.99	0.97	0.85	0.80
C	0.88	0.98	0.98	0.99	0.96	0.94	0.71
D	0.71	0.83	0.96	0.99	0.95	0.99	0.64
Peak flow events							
Magnitudes	0.97	1.00	0.96	0.99	0.98	1.00	0.99
Reference period distribution	0.98	0.99	0.96	0.99	0.91	0.99	0.96
Assessment period distribution	0.99	0.99	1.00	0.98	0.96	0.99	0.98

The peak flow magnitudes that typified the high pulse intra-annual events (Cat I), the bankfulls' characteristic (Cat II) and the moderate inter-annual one (Cat III), as it was described in detailed previously (showed in Table 3.4), presented differences between the analysis periods. However, the graphs in Figure 3.7 (A – G) revealed that in both periods there have been cases with increase or decrease of maximum daily flows per year in the historical set of records.

In the Santiago, San Pedro Mezquital and Baluarte cases (Figure 3.7 A – C), the main changes were in the Cat III magnitude which increased in the first two, and in the Cat I and II in the last river. Additionally, the San Pedro Mezquital also showed a significant decrease in the Cat I due to the annual peaks from 1997 and 1998 were missing in the wet season section of the flow records. In the other hand, the main changes in Bejuco and Cañas rivers were focused in a reduction of their peak flow magnitudes; in Cat I and II for the first, and in Cat II and III for the second (Figure 3.7 EF). The Acaponeta and Rosamorada rivers were the ones that showed the most similar magnitude values in all the peak flows throughout their sets of records (Figure 3.7 DG).

In terms of differences in the duration, these were related to the magnitude of the characteristic peak flows, the number of events and the own set of records analyzed between periods. In this context, during the reference period in the Santiago River occurred a total of 71 out 83 events of Cat I (86% of cumulative frequency), 21/24 of Cat II (88%) and 3/5 of Cat III (60%) (Figure 3.8 A). In the assessment period, there were 68/79 events for Cat I (86%), 25/29 (86%) for Cat II and 3/4 (75%) for Cat III (Figure 3.8 B). In the San Pedro Mezquital, the differences in duration between periods were in Cat I with 147/172 (86%) *vs*. 163/190 (86%), and Cat III with 5/8 (63%) *vs*. 4/6 (67%) (Figure 3.8 CD). The difference in Acaponeta was found in Cat II with 36/40 (90%) *vs*. 23/26 (89%) (Figure 3.8 GH); while in the Cañas and Rosamorada they were at Cat I with 52/56 (93%) *vs*. 47/55 (86%) (Figure 3.8 KL), and 57/64 (89%) *vs*. 38/44 (86%) (Figure 3.8 MN). For the Baluarte and Bejuco rivers, peak flows duration remained the same (Figure 3.8 EFIJ).

The overall performance of the method was generally consistent between both the assessed sets periods of flow records and the environmental objectives classes (Table 3.6). The flood regime volumes for the environmental water reserves showed less than 5% MAR difference according to each basin and the own set of records per period. The low flows volumes for water allocation regularly presented differences below 10% MAR. That was the case in the Santiago, Baluarte, Acaponeta, and Cañas rivers. However, this was not the case for environmental objectives C and D in the San Pedro Mezquital, Bejuco and Rosamorada rivers. The low flows component and the total environmental water reserves differed between periods by 17% MAR in the San Pedro Mezquital environmental objective D (785 *vs*. 332 Mm^3/year; 878 *vs*. 419 Mm^3/year). In the Bejuco by 10% in class C (79 *vs*. 44 Mm^3/year, 86 *vs*. 49 Mm^3/year) and by 13% in D (68 *vs*. 32 Mm^3/year, 73 *vs*. 35 Mm^3/year). In the Rosamorada by 13 – 14% in C class (33 *vs*. 18 Mm^3/year, 38 *vs*. 22 Mm^3/year) and by 20% in D (29 *vs*. 9 Mm^3/year, 32 *vs*. 12 Mm^3/year).

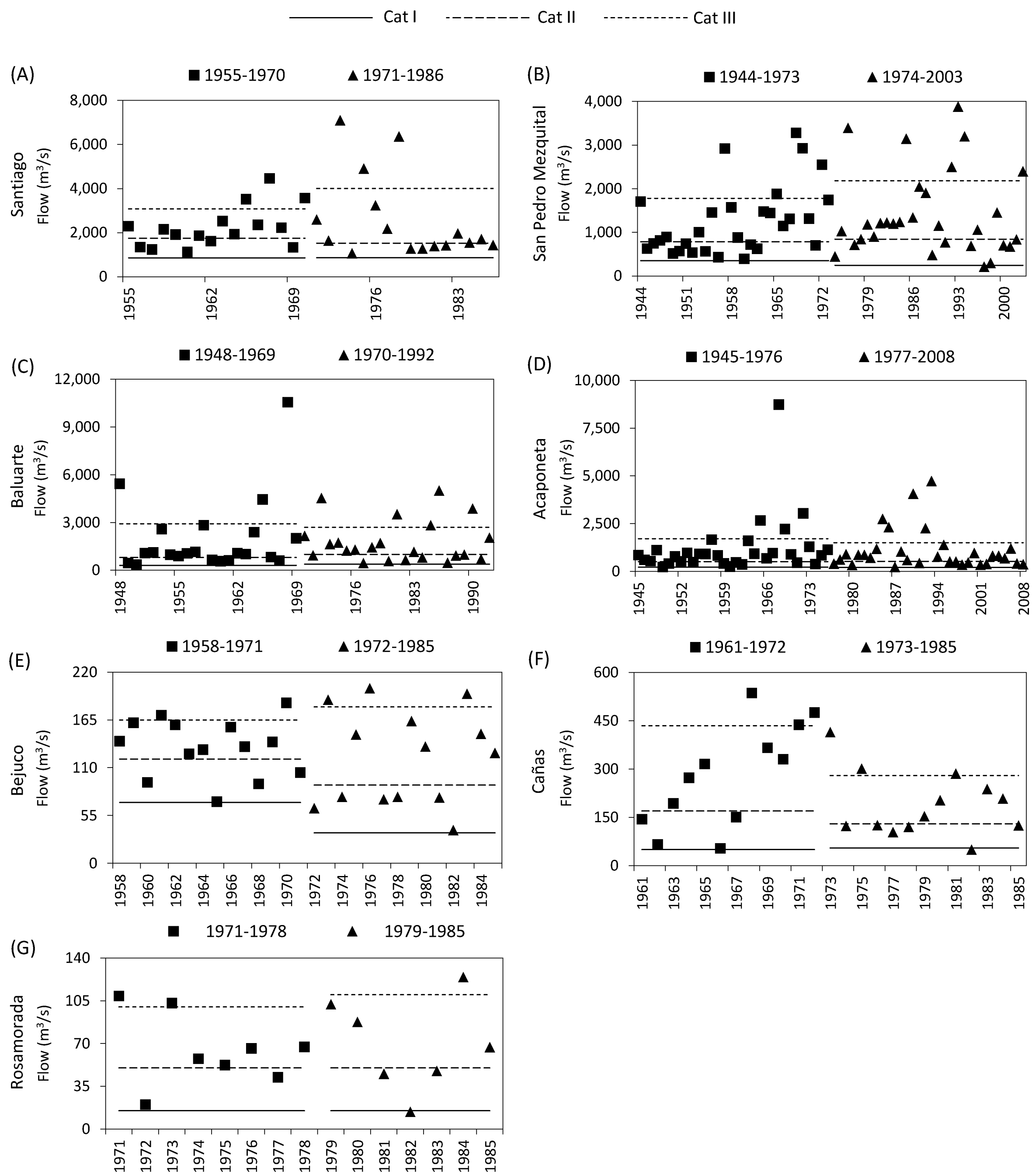


Figure 3.7. Magnitudes (A – G) of the peak flow events of the rivers discharging into Marismas Nacionales wetland. The events' magnitudes correspond to 1, 1.5 and 5-year return period (Cat I, II and III, respectively). Flow series were divided into two periods for the performance validation analysis, reference (left) and assessment (right) in each graph.

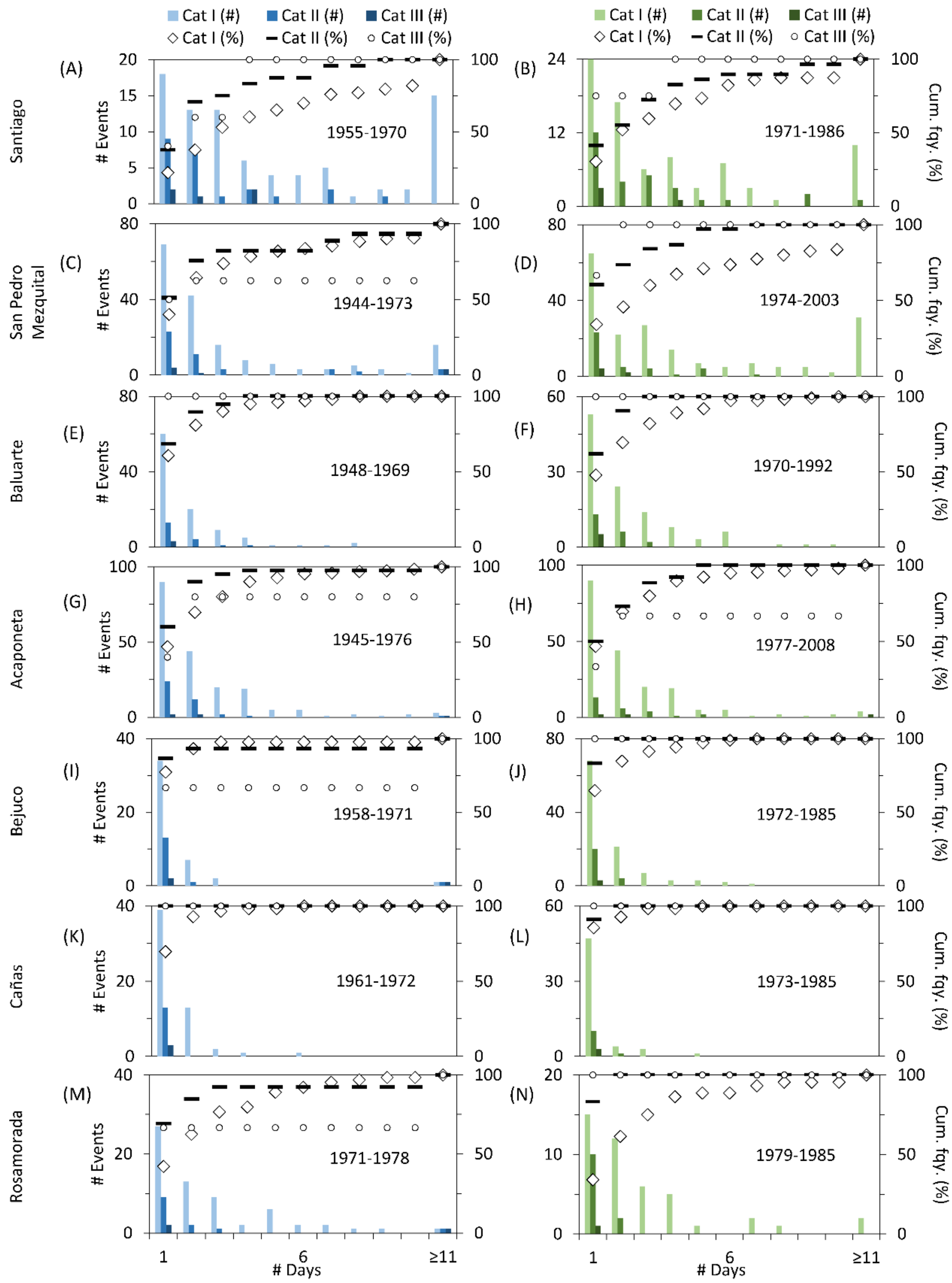


Figure 3.8. Number, duration (days) and cumulative frequency (percentage) of the peak flow events of the rivers discharging into Marismas Nacionales wetland. The event's magnitudes correspond to 1, 1.5 and 5-year return period (Cat I, II and III, respectively). Flow series were divided into two periods for the performance validation analysis (A, C, E, G, I, K, M reference period, and B, D, F, H, J, L, N assessment period).

Table 3.6. Environmental reserve volumes (Mm^3/year) for water allocation of the rivers discharging into Marismas Nacionales wetland according to (i) both the reference and the assessment periods, and (ii) different environmental objectives.

River basin	Environmental objective class	Low flows		Flood regime		Environmental water reserve	
		Ref.	Assemt.	Ref.	Assemt.	Ref.	Assemt.
Santiago	A	4,591	4,383	1,376	988	5,967	5,371
	B	3,344	3,404	741	528	4,085	3,933
	C	2,793	2,958	449	323	3,243	3,282
	D	2,334	2,434	292	205	2,626	2,639
San Pedro Mezquital	A	1,498	1,348	396	402	1,894	1,750
	B	1,080	913	229	220	1,309	1,133
	C	910	668	135	133	1,045	800
	D	785	332	94	87	878	419
Baluarte	A	768	949	213	248	981	1,197
	B	549	687	131	147	681	834
	C	460	568	77	87	536	655
	D	402	403	55	60	456	463
Acaponeta	A	701	687	167	187	868	875
	B	522	554	113	120	635	673
	C	446	497	64	69	509	566
	D	369	442	49	50	418	492
Bejuco	A	114	82	21	14	135	96
	B	89	57	12	9	101	66
	C	79	44	7	5	86	49
	D	68	32	5	4	73	35
Cañas	A	63	57	25	16	88	74
	B	43	35	16	11	59	45
	C	33	23	9	6	43	30
	D	22	11	7	5	29	15
Rosamorada	A	52	44	13	10	65	54
	B	38	28	8	6	46	33
	C	33	18	5	3	38	22
	D	29	9	3	2	32	12

3.4.3 The San Pedro Mezquital River water reserve in depth: Utility of the regime components for building flow-ecology relationships reference guidelines toward a strategic program for ecological validation

The hydrological outcomes of this method provide quantitative flow guidelines based on their historical recurrence of variability. Along with the current knowledge in the environmental flow science, on-site, in-depth studies and literature review, some flow-ecology relationships were analyzed and these are proposed for future on-site monitoring and ecological validation (Figure 3.9).

On the one hand, the low flows component of the water reserve should secure the flows provisioning for at least (i) the lower limits of each hydrological condition of the full range of the seasonal variability, at a monthly scale. On the other hand, (ii) the flood regime component should secure the flows for the intra-annual high pulses, the bankfulls' characteristic ones and the moderate inter-annual floods at daily scale.

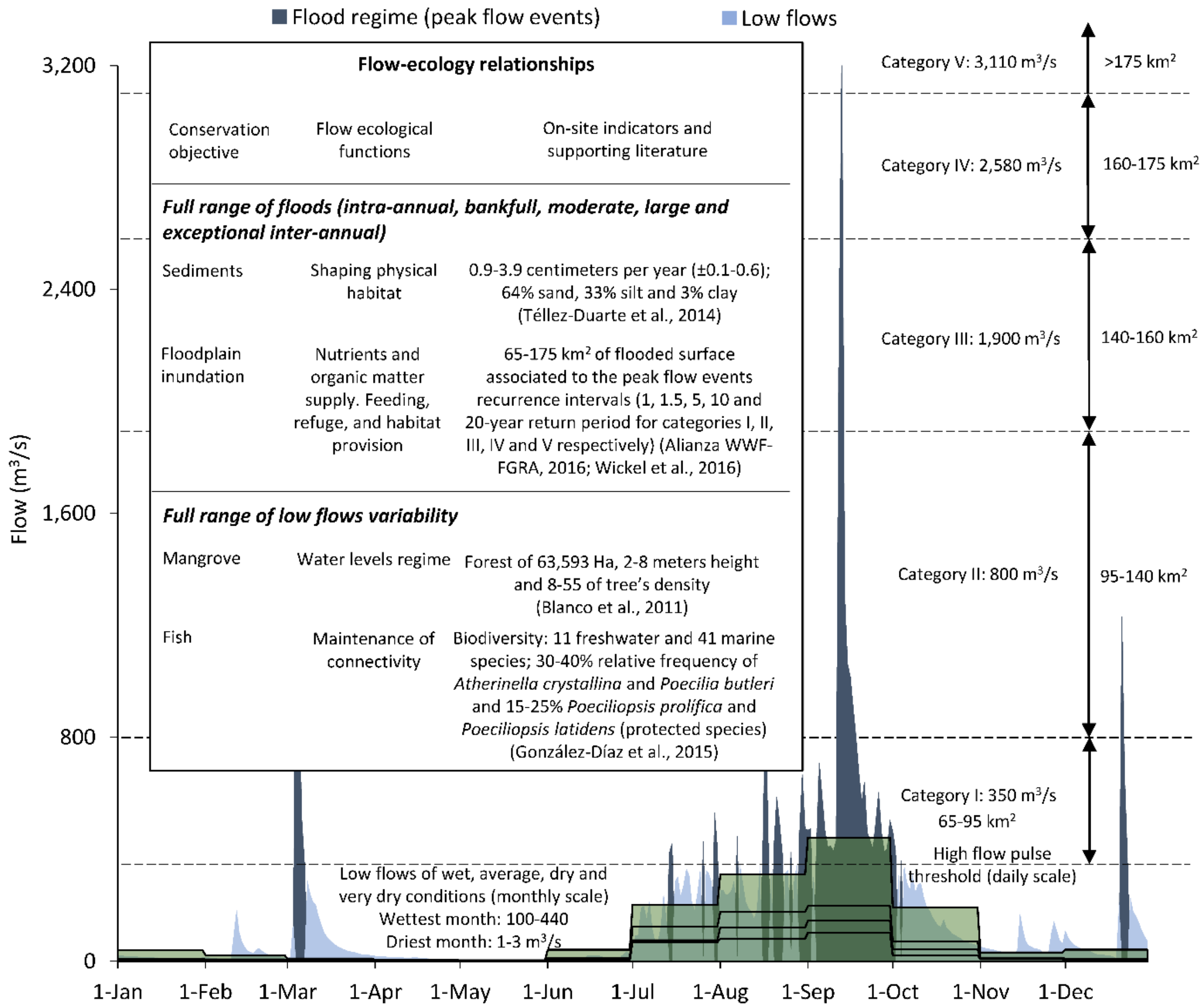


Figure 3.9. Flow-ecology relationships of the San Pedro River in Marismas Nacionales. The conceptual hydrograph is shown at two-time scales: (i) daily, for differentiating the flood regime's peak flow events in dark blue (categories in dashed lines) and mean low flows in light blue; and (ii) monthly, for the low flows regimes thresholds in light green and solid lines.

Based on the method's foundations, these flow variability conditions, as they occur, would also secure different longitudinal connectivity conditions. In the mid and long-term, for example, such conditions of variability should benefit and maintain the fish community diversity. From the estuary to the river in mid-basin, the variability of the flow should allow and provide the specific requirements of movement, habitat, refuge, feeding, and other seasonal needs.

These requirements should be quantitatively identified and related to the hydrological conditions, and differentiated for the life cycle stages of the species (Richter et al., 1997; Postel & Richter, 2003).

According to González-Díaz et al. (2015) in the lower San Pedro Mezquital, there are 11 freshwater and 41 marine species. From those, there are four currently under protection: the Blackfin Silverside (*Atherinella crystallina*), the Pacific Molly (*Poecilia butleri*), the Blackstripe Livebearer (*Poeciliopsis prolifica*) and the Lowland Livebearer (*Poeciliopsis latidens*). All of them with a relative frequency between 15% and 40%. Flow-related key aspects for further in-depth monitoring and ecological validation of these method hydrological outcomes would be to assessing the species requirements at river reach scale (Richter et al., 2006; Mathews & Richter, 2007; Acreman et al., 2014ab).

Water-level depth and velocity along the river bankfull and between this and in its floodplain are hydraulic parameters widely used to relate the flows magnitude and habitat characteristics with the fish species preferences and requirements for their life stages development (King et al., 2000; Poff et al., 2017). A basic working hypothesis would be that the full range of low flows seasonal variability sustains in the mid to long-term the fish community integrity, diversity and the relative frequency baseline of protected species. Based on these method outcomes and for mentioning one example, 1 – 3 m^3/s and 100 – 440 m^3/s would be the flow threshold recommendations at the river's discharge to Marismas Nacionales wetland. These recommendations consider the full range of hydrological conditions for the driest and wettest months (May and September).

Other more detailed and challenging working hypotheses would be that in the mid to long-term the hydrological conditions of low flows recommendations for the driest month will reach around 3 ±0.1 m^3/s (wet), 1.1 ±0.7 m^3/s (average), 0.8 ±0.7 m^3/s (dry) and 0.5 ±0.5 m^3/s (very dry). Likewise, 385 ±55 m^3/s (wet), 190 ±3 m^3/s (average), 140 ±10 m^3/s (dry) and 75 ±37 m^3/s (very dry) in the wettest month. In both cases, having considered the differences between the reference and the assessment periods here presented.

Similarly, the freshwater discharge would maintain its exchange with the marine water, as well as the salinity gradient based on the low flows regimes conditions (King et al., 2000; Marchand, 2003). Over time, these regimes have contributed to this brackish environment favorable to the establishment of the mangrove forest, with a reported extension within the San Pedro's influence of nearly 63,600 hectares, from 2 to 8 meters height and 8 – 55 tree's density (Blanco et al., 2011). In this case, a flow-related aspect for monitoring would be the salinity gradient along the river and in the estuary, its relation with the freshwater discharge, the forest structure, and the mangrove species composition. The working hypothesis for the ecological validation would be that the full range of low flows derived from this approach sustains the mangrove structure and species composition, with the salinity gradient and the freshwater discharge as quantitative indicators.

The flood regime and its full set of peak flow events component of the water reserve should guarantee the San Pedro River's lateral connectivity (Mathews & Richter, 2007; Acreman et al., 2014a). The interaction between the river and its floodplain provides ecological functions such as triggering migration spawning cues for fish and new life phases in aquatic invertebrates, and providing new habitats, flush organic matter and woody debris, among others (Postel & Richter, 2003; Richter et al., 2006). Recent in-depth studies in the lower San Pedro have identified flows-related quantitative indicators for keeping the hydrogeomorphological processes and linkages between the river discharge and its delta.

Téllez-Duarte et al. (2014) studied the influence of the San Pedro on the sediments deposition and particles' texture at the river delta. They found that over the last 40 years the river has deposited a cumulative rate of sediments at an average range of 0.9-3.9 (±0.1 – 0.6) centimeters per year with 64%, 33% and 3% of sand, silt and clay proportions, respectively. The river's peak flow events longitudinally transport these sediments load. However, large and exceptional floods (Cat IV = 10 and Cat V = 20-year return period) play a greater role to disperse them over the floodplain for the additional exchange of water, nutrients and organic matter.

Furthermore, and based on a remote sensing recent analysis on the San Pedro's River coastal floodplain wetlands, the flooded surface extension influenced by the full set of peak flow events ranges from 65 km^2 to more than 175 km^2 (Wickel et al., 2016). This area of periodic lateral connectivity represents feeding, refuge, and habitat provision opportunities for fish in the wet season and for resident and winter-season migratory waterfowl [Alianza World Wildlife Fund-Fundación Gonzalo Río Arronte I.A.P. (WWF-FGRA), 2016].

In this case, the working hypothesis would be that the peak flow events, particularly the bankfulls' characteristic and the moderate inter-annual or even larger, carry the sediments volumes and proportions for sustaining the cumulative deposition rates and particles' texture as it was reported in this geomorphologic dynamic. Based on the two set of period of records, the recommended flow magnitudes would be around 350 m^3/s (Cat I), 800 m^3/s (Cat II), 1,900 m^3/s (Cat III), 2,580 m^3/s (Cat IV), and 3,110 m^3/s (Cat V). Another opportunity for deeply understand the ecological relevance on-site of this flow regime component would be to track the flooding surface extent via periodic remote sensing analysis (e.g. every 3 – 5 years), as well as validating the beneficial aspects through fish and bird's needs.

3.5 Discussion

The outcomes of the implementation of this hydrology-based method in several rivers basins with a variety of time-length sets of daily flow records (from 15 to 64 years) showed an overall consistency between the reference and assessment periods.

The low flows regimes for the hydrological conditions experienced high variability between dry and wet seasons (CV > 100% in all the rivers). So too among the sets of peak flow events with their corresponding flow attributes. The frequency factors of occurrence delivered relatively similar volumes of environmental reserves; 86% of the cases with differences ≤ 10% MAR (four environmental objectives in seven river basins). The highest differences were found in environmental objectives classes C and D due to the low flows component corresponding volumes. The validation indicators for this component exhibited well ($R^2 \geq 0.9$) and acceptable (≥ 0.8) performance in the seven rivers for the wet condition, in six rivers for the average and dry conditions and five for very dry. As for the peak flow events component, the three indicators performed well (characteristic magnitudes and modeled logarithmic distribution for each period). Based on the total R^2 values (77), 78% and 87% of the cases exhibited well and acceptable performance, respectively.

A second but still related results' consistency factor to consider in further applications is the quality of the flow records that are intrinsically tied to hydrological models. Gaps in the flow records could influence inconsistent outcomes in these type methodologies. This was the case in the San Pedro Mezquital where the gaps in 1997 and 1998 induced a lower magnitude for the intra-annual peak flow event (Cat I) in the second period of assessment (245 m^3/s). Without those couple wet season unrepresentative maximum daily annual flows, the intra-annual event would be 415 m^3/s. This value is consistent with the increasing trend depicted in the other peak flows magnitudes in this river (Cat II and III). Based on the method outcomes and other similar hydrological approaches from the literature, it could be argued that the length and quality of the flow records is a sensitive variable for obtaining consistency of results. Long-term daily streamflow dataset (> 20 years) are regularly recommended (Richter et al., 1996 and 1997; King et al., 2000).

Examples of this could be found by comparing the results here presented with other applications of the method. First, Sánchez Navarro & Barrios Ordóñez (2011) reported for the San Pedro Mezquital 63% MAR of water reserve for an environmental objective class A. In the case study here presented, that was 64 – 69% MAR. De la Lanza et al. (2012) reported 72% MAR for the Acaponeta River *vs*. 67% MAR in this case study (class A). Similarly, De la Lanza et al. (2015) for the Piaxtla River and Gómez Balandra et al. (2014) in the Verde River reported 58 – 64% MAR *vs*. 61 – 71% MAR in these case studies (class A); and Meza-Rodríguez et al. (2017) for the Ayuquila-Armería River 48% MAR *vs*. 12 – 38% MAR for a class D.

The third factor of results' consistency that could lead to under or overestimations, or simply differences in the environmental flows and water reserves –in the same line than the previously described– is the uncertainty of our model (equations 1 and 2). If the length and quality of the flow records are in optimal conditions, e.g. > 20 years and < 5% gaps, and there is full confidence that the flow regime is not significantly altered or regulated, then it could be explained by the selection of the data set. Far earlier time flow datasets could describe well the natural regime, but the closest to recent times reflect the present conditions of variability. Both are important and when possible the set of records to assess should be as long as possible to represent the full range of variability history (Richter et. al., 1996 and 1997, King et al., 2000; Mathews & Richter, 2007). Uncertainties of our model are likely to lie at these factors, the flow records (discharge or water levels), the appropriateness of the period selected, and the natural variability caused by inherent chaotic natural system behavior (Warmink, Janssen, Booij & Krol, 2010; Acreman et al., 2014b).

3.5.1 Advantages

The main contribution of the method lies in analyzing and using the occurrence frequencies as a novel integration criterion of several low flows hydrological conditions and a flood regime to deliver environmental reserves at an annual scale. The approach allows a theoretical science-based adjustment for delivering practical and functional environmental flow proposals, coherent to different climatic conditions and levels of the desired ecohydrological states of the flow regime. This is a step forward to cope with flow regime's non-stationary challenges (Arthington et al., 2018b; Poff, 2018). These have been critical methodological characteristics for its adoption in the Mexican Norm of Environmental Flows and to secure the feasibility of its implementation in the country's water allocation system and other public policies.

Another but still related advantage consists, as a hydrology-desktop methodology, in its useful application for quickly science-based determining environmental reserves from a top-down water management approach. This methodology falls in the first category from the *holistic (eco)hydrologic desktop* hierarchical methods, described by Opperman et al. (2018) in their contribution *three-level framework for assessing and implementing environmental flows*. The San Pedro's reserve, for example, was established for up 2,297 Mm^3 per year for preventive environmental protection and rules the full basin water usage (SEMARNAT, 2014). This level of preventive water allocation (environmental flow protection) in the context of this method implies the possibility of mimicking the hydrological conditions even closer to the parameters of natural frequency of occurrence as well as integrating two more peak flow events for large and exceptional magnitude floods (e.g. Cat IV =10 and Cat V = 20-year return period).

To reflect such conditions and events in the San Pedro's environmental water reserve, adjustments in the frequency factors of occurrence need to be made prior to the implementation of Equations 3.1 and 3.2. These would consist in factoring 0.25 wet, 0.50 average, 0.15 dry, and 0.10 very dry instead of those provided for a class A in Table 3.1. Likewise, large and exceptional magnitude floods with their corresponding duration (1 day) and frequency (Cat IV = 1 and Cat V = 0.5 every 10 years) should be added in Equation 3.2. With these adjustments the total volume of environmental reserve would go from 2,156 to 2,388 Mm^3 (79 – 87% MAR).

These natural frequencies factors of occurrence could be considered for an environmental objective class A^+, more appropriate for a river that discharges into a wetland of international importance with environmental flow public policies bindings (SEMARNAT-CONANP, 2013; SEMARNAT, 2014). In this sense, the method's outcomes provide an initial four-to-five-level strategic management reserve baseline, useful in the absence of detail ecological information for triggering discussions on desirable ecohydrological states and flow-ecology relationships. In addition, the quantitative outcomes of the flow regime components could be used for on-site monitoring of the water reserve, ecologically validate them, and for providing feedback about its performance.

From a bottom-up approach perspective, in line with Opperman's et al. (2018) *holistic expert panel* (framework's second level), our method outcomes have depicted a high level of consistency in comparison to on-site in-depth environmental flow assessments (holistic methodology). According to the reported by Salinas-Rodríguez et al. (2018), 18 out of 25 studied river basins exhibited results of reserves' volumes variation below 11%. Greater differences were mainly attributed to each method´s hydrologic scope (temporary resolution), the basins geographical location and the climatic influence on them, where this hydrological model encompassed better the natural flow seasonal variability and dry episodes. Moreover, this consistency of results was possible due to a strategic top-down and bottom-up approach simultaneously implemented. In this sense, on the ground assessments allowed a first evaluation of the frequency-of-occurrence approach here presented, probed its effectiveness, and provided confidence toward its suitability among scientists and water managers.

3.5.2 Limitations and recommendations

The method was developed based on flow-ecology theoretical relationships. Gathering precise biological and ecological on-site information prior to or along with environmental flow assessments remains to be challenging in comparison to the hydrological one available in many places. However, as Richter (2010), Richter et al. (2012), Acreman et al. (2014ab) and others stated, decisions on water allocations for the environment still need to be made and it is better to embrace this challenge under a precautionary approach.

In this context, it is difficult to predict with quantitative accuracy and certainty the flow alteration-ecological consequences. The model was developed based on a top-down approach whose outcomes have more confidence levels as long as the desirable status of flows conservation remains higher rather than lower (environmental objectives classes). It is aligned to situations with low risk or controversy in limiting unsustainable water abstraction through its preventive environmental allocation and flow protection (Opperman et al., 2018; Salinas-Rodríguez et al., 2018). Without legal binding public policy mechanisms for the protection of environmental water, particularly in over-allocated and exploited basins, it is highly recommended to conduct site-specific, in-depth studies of flow alteration-ecological response (e.g. habitat simulation models or holistic methodologies).

Another different and important aspect is that more research is needed on the occurrence frequencies factors. Although this approach offers an advance in environmental water implementation, the integration criteria were formulated based on a decreasing water availability model originally focused on highly variable flow regimes, yet for perennial rivers. Under this reasoning and based on existing literature (e.g. Costigan et al., 2017), it could be expected that intermittent and ephemeral streams exhibit higher vulnerability than perennial rivers to such a model.

It is important to assess in detail the relative importance of wetter and drier hydrological conditions contributions on different river types, and the climatic and geographic influence on them. The assessment of significant differences of hydrological contributions and trends (decreasing or increasing) in site-specific stream types, the related socioeconomic, ecological and biological consequences, would provide new insights to adjust the occurrence frequencies factors within the conceptual framework of the method. This knowledge would enrich the model and improve the method’s future implementation experiences as a nature-based solution in the face of a changing and dynamic climate (Arthington et al., 2018ab; Poff, 2018). It would also provide alternatives for better adaptive management future on water availability shifts over a wider set of river types for the benefit of people and ecosystems (Capon et al., 2018).

3.6 Conclusion

The effort developed in Mexico for protecting flows through environmental water allocations is a commitment stated in public policies at their highest level. It is based on the strategic opportunity to proactively protect flows in river basins with water availability, low demand from consumptive uses, high biological richness and conservation values. The hydrological method presented in this chapter was developed and grounded in the available environmental water science and practice. It is distinguished from existing methodologies of the same kind by the use of a frequency of occurrence model to assess environmental flows and for integrating the outcomes in water allocations systems. On-site assessments play a substantial role in understanding and increasing the knowledge of ecohydrological relationships. Such knowledge is needed for monitoring, improving or validating the model performance on the ground.

The continued implementation of the method along to in-depth studies and deeper methodologies informs strategic decision-making for water and conservation public policies. During this process, outcomes of the method will be enriched by subsequent in-depth environmental flow assessments at the on-site level. This interaction will strengthen and provide the indicators for validating or adjusting the system's legal limits for water abstraction to the sustainable level urgently needed to stop the flow alteration-related degradation of aquatic ecosystems.

4

A Mexican rivers classification based on inter-annual and seasonal variability

The previous chapter presented an environmental flow hydrology-based methodology and a novel frequency of occurrence approach for integrating environmental reserves volumes for preventive water allocation. Despite it was developed for highly variable flow regimes, the method has been implemented with the same frequency of occurrence criteria regardless of the magnitude of the hydrological contributions of wet, average, dry and very dry conditions. The goal of this chapter is to perform a nationwide assessment on the inter-annual and seasonal flow variability contributions of Mexican rivers for supporting the need of recommending a science-based adjustment to the frequency of occurrence criteria. Forty rivers are assessed based on their climate, geographic and hydrological representativeness throughout the country. Three river classifications are tested: by flow type (11 ephemeral, 12 intermittent, 17 perennial), according to their location with regard to the Tropic of Cancer (13 northern, 27 southern), and their drainage direction [exorreic (13 Atlantic, 21 Pacific) or endorreic (6)]. Multivariate assessments are conducted for the grouping of river types (principal components analysis) and on the differences between the hydrological contributions (one-way PERMANOVA). Results revealed that the most comprehensive classification is by flow type (wet condition dependency: ephemeral > intermittent > perennial), exhibiting significant differences in the flow variability contributions for all hydrological conditions (p-values < 0.05).

This chapter is based on:

Salinas-Rodríguez S.A. (2018, April). *Inter-annual and seasonal variability of flows: A Mexican rivers classification towards climate-smart environmental flows*. Presented at the EGU General Assembly 2018 and Geophysical Research Abstracts. Vol. 20, EGU2018-1556. Vienna, Austria. https://meetingorganizer.copernicus.org/EGU2018/EGU2018-1556.pdf.

4.1 Introduction

The flow regime characteristics linked to the inter-annual and seasonal variability play a major role in hydrology-based environmental flow assessments (EFA) and further water allocations (Poff et al., 1997; Richter et al., 1997; Hughes & Hannart, 2003; Richter et al., 2006; Mathews & Richter, 2007; Richter et al., 2010; Richter et al., 2012; Hughes et al., 2014). These type of methods focus on conserving or restoring the inter-annual and seasonal flow regime variability components and attributes based on the analyses of historical records as a reference (Tharme, 2003; Acreman et. al., 2014a; Poff et al., 2017; Opperman et al., 2018).

Hydrology-based methodologies assume that ecological and biological processes and environmental services would be maintained or recovered as long as ecologically relevant streamflow metrics be considered as the foundation of freshwater-dependent ecosystems integrity. As it was seen in previous chapters, this is grounded on flow-ecology theoretical relationships (Bunn & Arthington, 2002; Postel & Richter, 2003; Davies & Jackson, 2006; Richter et al., 2006; Poff & Zimmerman, 2010; Acreman et al., 2014b; Arthington et al., 2018b; Poff, 2018).

In this context, the frequency of occurrence approach here developed is the novel contribution to the environmental water science and management. However, to date, it hasn't been systematically investigated the magnitude of the hydrological contributions of the wet, average, dry and very dry conditions from the inter-annual and seasonal variability. Furthermore, if such contributions are differentiated on rivers and streams by climatic-influence or geographic location. These aspects have been identified as potentially sensitive model's parameters that could be improved, particularly important for ephemeral and intermittent streams which have depicted the highest flow variability indices. The primary goal of this chapter is to fill these gaps.

To test the differences of climatic influence and geographic location on the flow regimes, three basins classifications were assessed and compared in order to find the suitable typification for evaluating in-depth the hydrological contributions of the wet, average, dry and very dry conditions from the inter-annual, dry and wet season variability in a selected sample of river basins throughout the country.

The specific objectives were to identify (1) which of the river basins typologies reflects the heterogeneity of the flow regimes contributions per condition in both inter-annual and seasonal variabilities, and (2) which class of rivers exhibits the highest dependency on wet years or season condition. It is hypothesized that there are significant differences in the hydrological conditions and variabilities between the rivers types.

4.2 Methodology

4.2.1 Study area, research design, and data requirements

Mexico's geography and climate range in altitude from sea level to more than 5,600 meters, and annual rainfall from below 400 to 3,400 millimeters (mm), where two-thirds of the territory is considered arid or semi-arid (Instituto Nacional de Estadística y Geografía, 2008; Cotler Ávalos, 2010; CONAGUA, 2016a). Hydrographically, 87% of the country surface runoff discharges in 51 rivers, there are 393 basin systems grouped mainly based on their surface, drainage direction, and regional physiographic province and water management criteria (Cotler Ávalos, 2010; CONAGUA, 2016a).

Mexican local empirical knowledge has shown that EWR volumes depend in different ways on flow regime variability (Salinas-Rodríguez et al., 2018). In order to assess the hydrological contribution influenced by regional climates as well as the geographic and orographic effects, 40 rivers were selected based on three major criteria: the variability of flows, the climate, and geographic representativeness (Figure 4.1).

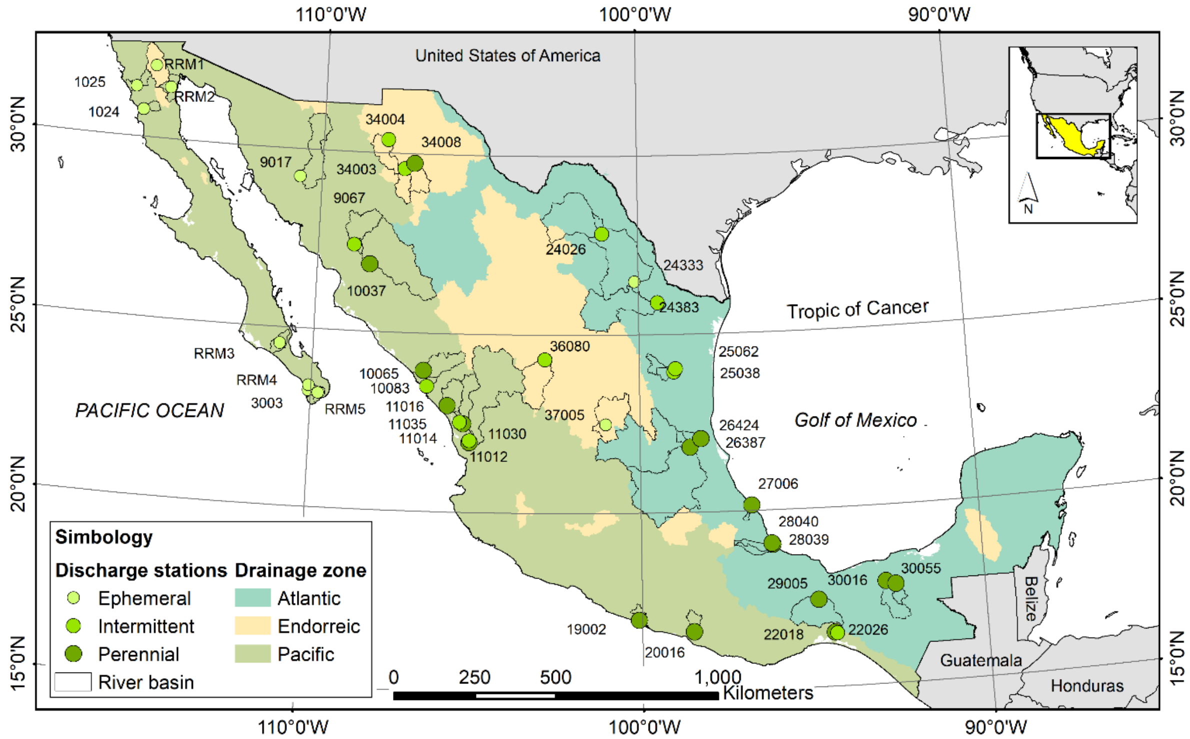


Figure 4.1. Location of the 40 study basins. Numbers in labels: Codes of gauging stations or centroids of basins where rainfall-runoff models (RRM) were developed.

First, as a proxy of the flow's variability, the basins were identified based on the mainstream's flow type. According to previous chapters, ephemeral and intermittent streams have exhibited higher variability than perennial rivers. Theoretically, this is a direct response of the basins to their dominant climates (e.g. arid, humid, temperate, etc.), geography and orographic effects (e.g. surface, altitudinal gradient, drainage system) (Hughes & Hannart, 2003; Hughes et al., 2014; Costigan et al., 2017). This relationship leads to the hypothesis that ephemeral and intermittent streams experience more seasonal and yearly wet conditions. Flow duration curves at a daily scale from each river were used to classify them by flow type [percentage of time that discharge volume (Q) in cubic meters per second (m^3/s) is exceeded] (Figure 4.2). The criteria used was by following Equation 4.1.

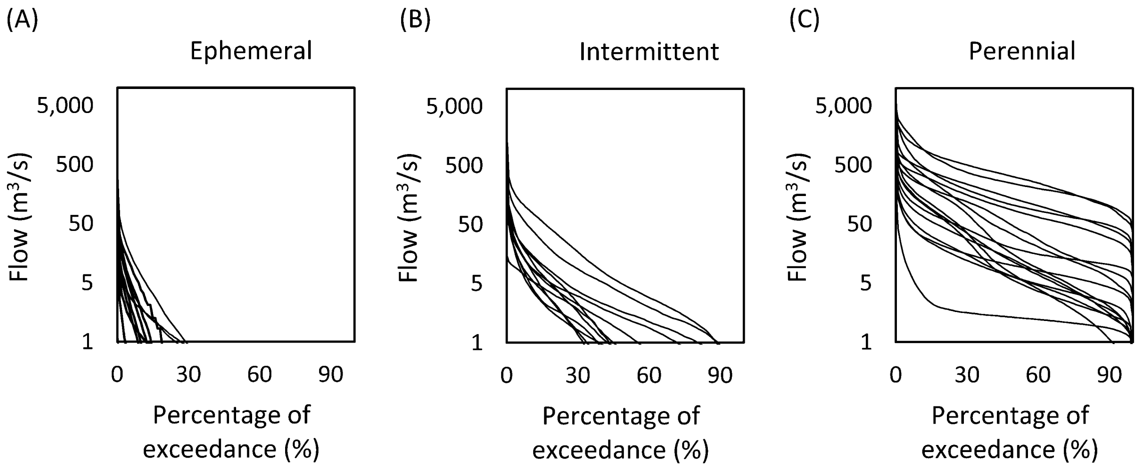


Figure 4.2. Flow duration curves of the 40 study basins per flow type: (A) ephemeral, (B) intermittent, and (C) perennials.

$$Flow\ type = \begin{cases} ephemeral,\ if\ Q > 0.5 \leq 30\% \\ intermittent,\ if\ Q > 0.5 > 30\% < 90\% \\ perennial,\ if\ Q > 0.5 \geq 90\% \end{cases} \qquad \text{Eq. (4.1)}$$

Second, the location of the rivers with regard to the Tropic of Cancer was considered in order to sample basins with greater frequency of both droughts and floods in dry and wet seasons. Generally, droughts are known to occur in northern Mexico, while floods in the south due to a higher incidence of tropical storms and hurricanes (Méndez González, Návar Cháidez & González Ontiveros, 2008; CONAGUA, 2016a). Third, the drainage system direction according to a general zonation was considered (Ortíz Pérez, 2010). 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 Pacific Ocean and the Gulf of Mexico– and the Neovolcanic Axis or Transversal Volcanic System in the center (Méndez González et al., 2008). The basins were classified as exoreic and drain to the Gulf of Mexico in the Atlantic or to the Pacific Ocean, or if they are endorreic.

The information requirements were observed streamflow records at daily scale for at least 20 consecutive years (< 10% of gaps) without significant intervening water infrastructure. Given the scope of this assessment, the unregulated time periods were selected based on a visual inspection of the hydrographs at annual and monthly scale.

The observed streamflow records were obtained from the National Data Bank of Surface Water repository (ftp://ftp.conagua.gob.mx/Bandas/) and from five rainfall-runoff existing models developed in previous EFA [SIM, 2015; Sonoran Institute Mexico A.C. (SIM), 2016; Table 4.1)].

Table 4.1. Overview of rivers selected for conducting the inter-annual and seasonal flow variability contributions assessment. RRM = rainfall-runoff model.

Station code	River	Flow type	Tropic of Cancer	Drainage zone	Period of records used	No. years
1024	Santo Domingo	Ephemeral	Northern	Pacific	1950 – 1977	28
1025	San Vicente	Ephemeral	Northern	Pacific	1960 – 2004	45
3003	Plutarco E. Calles	Ephemeral	Southern	Pacific	1961 – 1980	20
9017	Sonora	Ephemeral	Northern	Pacific	1942 – 1990	49
9067	Mayo	Intermittent	Northern	Pacific	1961 – 2012	52
10037	Fuerte	Perennial	Northern	Pacific	1942 – 1992	51
10065	Piaxtla	Perennial	Southern	Pacific	1953 – 1987	35
10083	Quelite	Intermittent	Southern	Pacific	1961 – 1985	25
11012	San Pedro Mezquital	Perennial	Southern	Pacific	1944 – 1974	31
11014	Acaponeta	Perennial	Southern	Pacific	1946 – 2007	62
11016	Baluarte	Perennial	Southern	Pacific	1948 – 1992	45
11030	Bejuco	Intermittent	Southern	Pacific	1958 – 1985	28
11035	Cañas	Intermittent	Southern	Pacific	1961 – 1985	25
19002	Coyuca	Perennial	Southern	Pacific	1962 – 2011	50
20016	Quetzala	Perennial	Southern	Pacific	1959 – 1995	37
22018	Ostuta	Perennial	Southern	Pacific	1975 – 2011	37
22026	Zanatepec	Intermittent	Southern	Pacific	1954 – 1985	32
24026	Sabinas	Intermittent	Northern	Atlantic	1938 – 1967	29
24333	Salado	Ephemeral	Northern	Atlantic	1964 – 2005	42
24383	Pesquería	Intermittent	Northern	Atlantic	1968 – 1989	22
25038	Corona	Intermittent	Southern	Atlantic	1968 – 1997	30
25062	Purificación	Intermittent	Southern	Atlantic	1972 – 2011	40
26387	Moctezuma	Perennial	Southern	Atlantic	1968 – 2013	46
26424	Pánuco	Perennial	Southern	Atlantic	1991 – 2011	21
27006	Misantla	Perennial	Southern	Atlantic	1961 – 2000	40
28039	Cotaxtla	Perennial	Southern	Atlantic	1952 – 1980	28
28040	Jamapa	Perennial	Southern	Atlantic	1952 – 2011	60
29005	Coatzacoalcos	Perennial	Southern	Atlantic	1988 – 2011	24
30016	De la Sierra	Perennial	Southern	Atlantic	1948 – 2006	59
30055	Macuspana	Perennial	Southern	Atlantic	1956 – 1986	31
34003	Santa María	Intermittent	Northern	Endorreic	1950 – 1985	36
34004	Casas Grandes	Intermittent	Northern	Endorreic	1943 – 1987	45
34008	Del Carmen	Perennial	Northern	Endorreic	1952 – 1986	35
36080	San Francisco	Intermittent	Southern	Endorreic	1977 – 2002	26
37005	San José-Los Pilares	Ephemeral	Southern	Endorreic	1963 – 1982	20
RRM1	Cerrada Laguna Salada	Ephemeral	Northern	Endorreic	1982 – 2011	30
RRM2	El Borrego	Ephemeral	Northern	Pacific	1982 – 2011	30
RRM3	Las Pocitas-San Hilario	Ephemeral	Southern	Pacific	1994 – 2014	21
RRM4	Pescaderos	Ephemeral	Southern	Pacific	1994 – 2014	21
RRM5	San José del Cabo	Ephemeral	Southern	Pacific	1994 – 2014	21

As a reference of hydrological variability, for each river flow set period of records were obtained the coefficient of variation (CV) and the baseflow indices (BFI) based on Hughes & Hannart (2003) and Hughes et al., 2014 approach. The full set of sampled rivers exhibited wide flow variability ranging from 64% to 594% CV, and from zero to 33% BFI (Figure 4.3). The CV and BFI values from the sample size of the population of selected rivers were equally proportionated based on a quartile approach. The central values (median ±1 quartile) ranged from 134 to 340% CV (218% median) and 1 – 10% BFI (4% median).

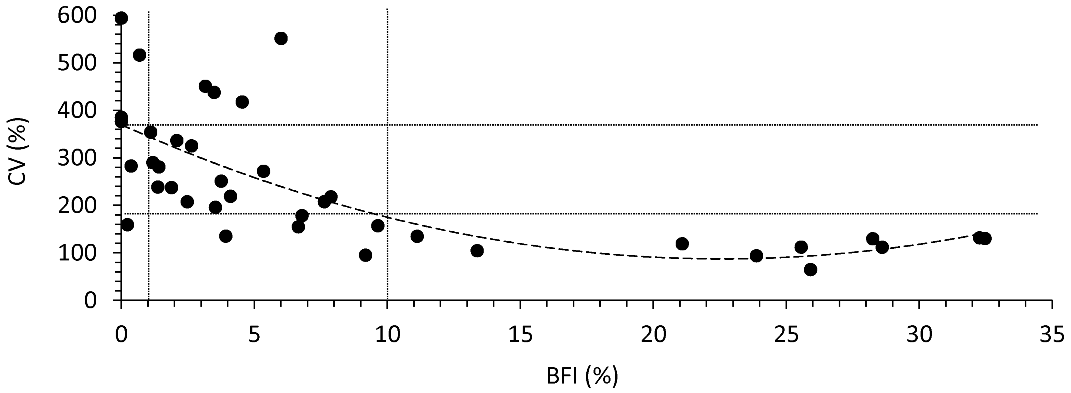


Figure 4.3. Coefficient of variation (CV) and baseflow (BFI) indices of the 40 study basins based on Hughes and Hannart (2003) and Hughes et al., 2014. Dotted lines are the lower and upper limits of the central range (median ±1 quartile). The relationship between the indices is presented in the polynomic dashed curve (R^2 = 0.48).

4.2.2 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 based on the e-flows hydrological method parameters. This procedure consisted of the computation of the characteristic mean inter-annual flows at monthly scale for the four hydrological conditions (*i* = wet, average, dry and very dry) according to the 75th, 25th, 10th and 0th percentiles of the selected period of records. The corresponding months of dry and wet seasons were identified based on Equation 4.2, where Q_{mmr} is the mean discharge of a given month (n = 12) and Q_{mar} the mean inter-annual flows (runoff).

$$Season\ (S) = \begin{cases} for\ S_{dry},\ if\ Q_{mmr} < Q_{mar} \\ for\ S_{wet},\ if\ Q_{mmr} > Q_{mar} \end{cases} \qquad \text{Eq. (4.2)}$$

Afterward, the hydrological contribution of wet, average, dry and very dry conditions from each type of variability was obtained. The procedure followed was, first, by calculating the relative discharge volume contribution of the variability *j* (RQ_j) with regard to the historical maximum (Q_{max} = 100th percentile corresponding discharge), where *n* is the total discharge volume of the months from the condition *i* of the variability *j* (Equation 4.3):

$$RQ_j = 100 \times \frac{\sum_{i=1}^{n} Q_i}{Q_{max}}$$ Eq. (4.3)

Second, each volume of relative discharge contribution for the condition *i* (RQ_i) of the variability *j* was standardized from one to 100 (SQ_j), where *n* is the total relative discharge volume contribution from all conditions *i* (Equation 4.4):

$$SQ_j = 100 \times \frac{RQ_i}{\sum_{i=1}^{n} RQ_i}$$ Eq. (4.4)

The SQ from the inter-annual, dry and wet seasons' variability and conditions are the response variables of the streams types to climate and geography influence. This index was explored, analyzed and assessed based on descriptive and inference statistics. Among the descriptive statistics are the central (median ±1 quartile) and full range distributions from the complete set (N = 40), and the medians of the subsets of streams types (n = ephemeral 11, intermittent 12 or perennial 17), the number of basins with regard to the Tropic of Cancer (n = northern 13 or southern 27) or their drainage direction (n = Atlantic 13, Pacific 21 or endorreic 6).

Inference statistics were performed with non-parametric tests due to the fact that the response variables showed significantly non-normal distributions (skewness of chi-squared for small-sample correction and omnibus *p*-normal < 0.05). A principal components analysis (PCA) was carried out for grouping. The experimental design consisted of 40 observations (N) each with 12 response variables (three types of variabilities and four hydrological conditions), and three factors or sources (independent) categorical variables with different group subsets (n).

The PCA eigenvalues and the variance for the 12 principal components (PC), and the eigenvectors of the 40 observations were analyzed and assessed in the context of the basins' hydrological, climatic, and geographic characteristics. The analysis of consistency was limited to the two PCs that included 98% of the cumulative variance (PC1 = 88% and PC2 = 10%). The decision of the most comprehensive river classification was made based on the following aspects:

- The interpretation of the PC based on the matrix of correlations, the biplot of eigenvectors, and the number of basins according to the PC and their relation with the response variables (Jackson, 1993; Peres-Neto, Jackson & Somers, 2003).
- The correlation of PC1 (significant variance *p*-value < 0.05) with independent indices of hydrological variability (CV and BFI) (Hughes & Hannart, 2003; Hughes et al., 2014), their characteristic medians, central (±1 quartile) and full ranges. Coefficients of determination (R^2) were calculated according to polynomic regressions of the PC1 by CV and BFI for the whole population.

- The percentage of dominant climates upstream from gauged locations [Instituto Nacional de Estadística y Geografía (INEGI), 2008; Martínez-Pacheco & Salinas-Rodríguez, 2018, based on CONAGUA 2016b].

A one-way PERMANOVA test of significant differences was conducted for assessing the effects of response variables between the subsets of the most comprehensive river basins classification in light of the PCA outcomes. This assessment was run pairwise between the contributions of the same condition among variabilities and the river stream classes. Together with the PCA test, it was hypothesized that (a) a certain river class(es) exhibit a higher dependency on wet conditions than other(s). Moreover, (b) there are significant differences at 95% confidence level in the response variables, (c) this is reflected in the full spectrum of river types. The normal distribution, PCA and one-way PERMANOVA tests were performed by using Past 3.19 software.

4.3 Results

4.3.1 Descriptive statistics of the inter-annual and seasonal variability

The distributions of the SQ per hydrological condition exhibited the same pattern between the types of variability and strong correlations (R ≥ 0.92; Figure 4.4 A). The median of the wet conditions among variabilities was around 61%, while the average 19%, dry 13%, and very dry 7% (Figure 4.4 B). Similarly, the central range was about 50%, 14%, 7% and 2% in the lower quartile, and 77%, 23%, 17% and 11% in the upper for the wet, average, dry and very dry conditions, respectively.

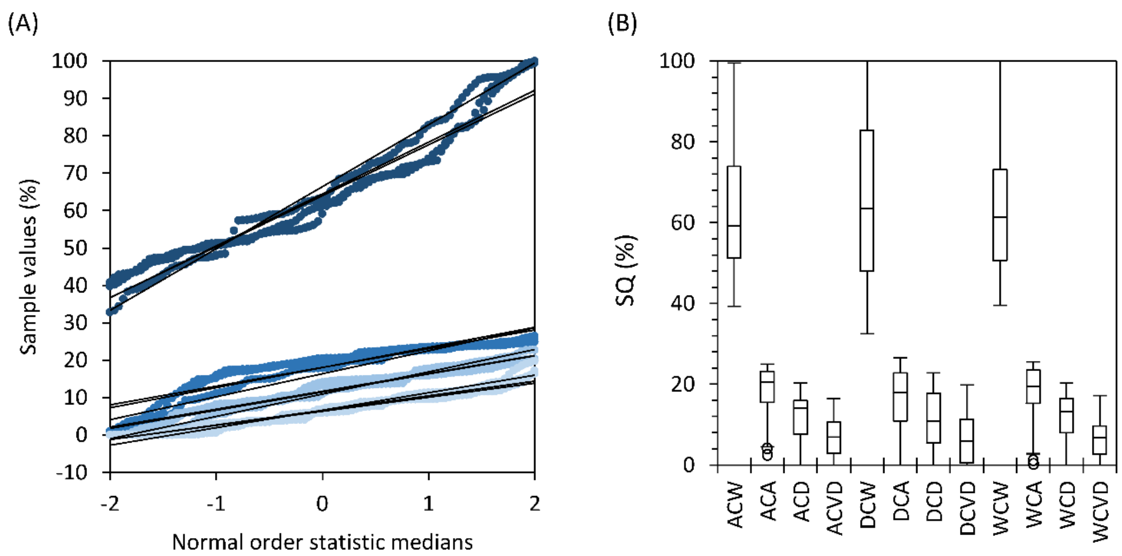


Figure 4.4. Exploratory data of the standardized discharge (SQ) volume contribution for the conditions of each type of hydrological variability. (A) Normal distribution probability plot (R ≥ 0.92). (B) Full range of the data population's distribution plot of wet conditions for inter-annual (ACW), dry (DCW) and wet (WCW) seasons variability, average (ACA, DCA and WCA), dry (ACD, DCD and WCD) and very dry (ACVD, DCVD and WCVD).

However, the dry season variability presented the greatest amplitude by a condition within the central ranges (wet 48 – 83%, average 11 – 23%, dry 5 – 18% and very dry 1 – 11%). With regard to the data outside of the central range, the highest values were depicted by the wet conditions for the inter-annual and seasonal variabilities reaching out > 95%. In contrast, the rest of the hydrological conditions and variabilities displayed the opposite situation, commonly below 5%, two of which with outliers (average condition of inter-annual variability and in wet season). The median of the stream types' subsets analysis revealed also similar patterns (Figure 4.5).

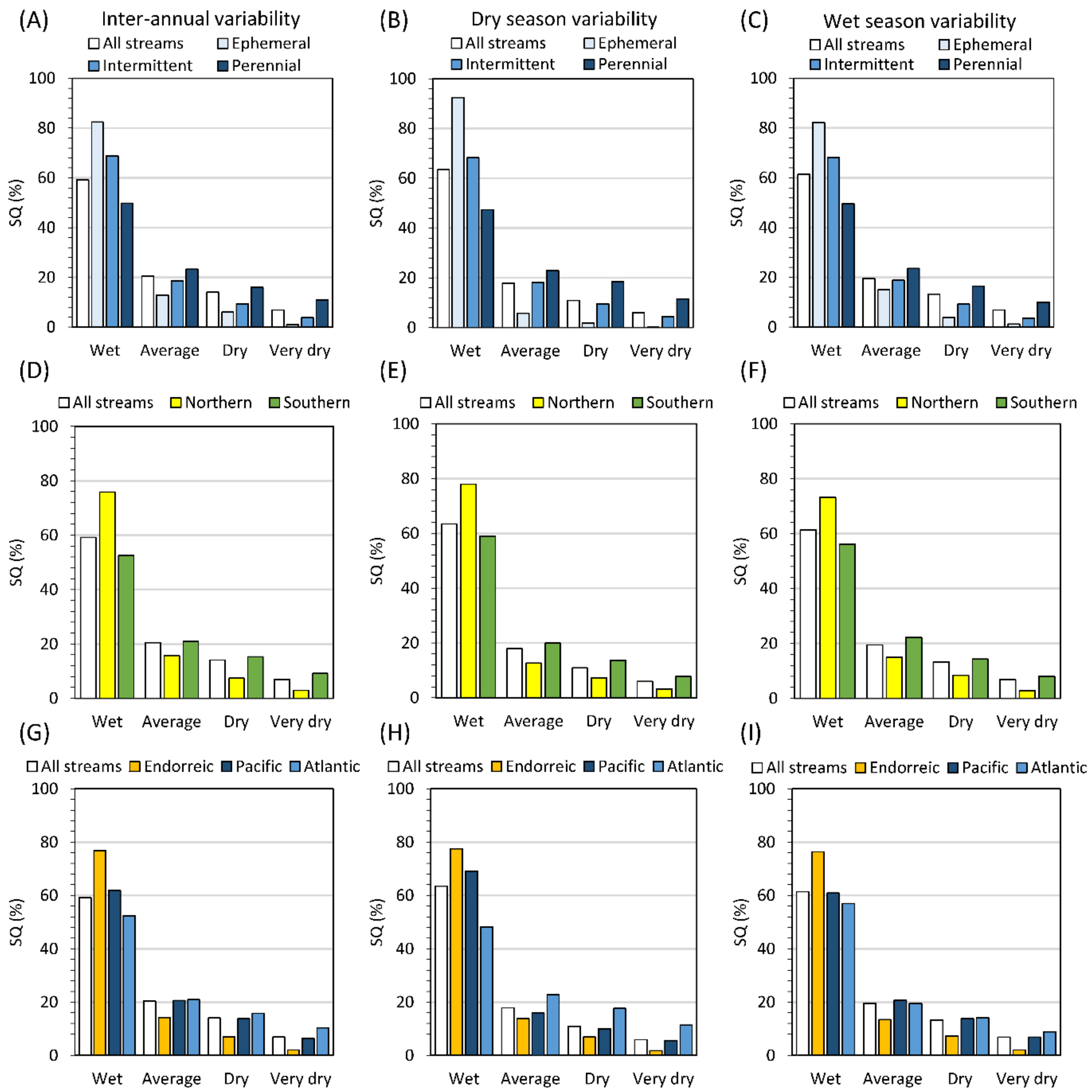


Figure 4.5. Data central population tendency detailed analysis on the standardized discharge (SQ) volume contribution per river classification. On the vertical axis, the inter-annual variability (left), dry season (center), and wet season (right). On the horizontal axis the rivers classifications: on top the flow type (A), (B) and (C), in the middle the Tropic of Cancer (D), (E) and (F), and at the bottom the drainage zone (G), (H) and (I). The standardized discharge volume contribution of all the data is also plotted per graph as a reference (white bars).

By stream type, the inter-annual, dry and wet season variability showed that there was a greater SQ volume contribution under wet conditions for ephemeral (82 – 92%) than in intermittent streams (68 – 69%) and perennial rivers (47 – 50%). Nevertheless, the magnitude of these contributions and their proportions tend to be larger for perennial rivers (average 23 – 24%, dry 16 – 18% and very dry 10 – 12%) than for intermittent (average 18 – 19%, dry 9 – 10% and very dry ≤ 4%) and for ephemeral streams (average 6 – 15%, dry 2 – 6% and very dry ≤ 1%). (Figure 4.5 A – C).

The rivers and streams located with regard to the Tropic of Cancer and to the drainage zones showed the same pattern of contributions. Under the wet condition, for northern rivers and streams was greater (73 – 78%) than for southern (53 – 59%), but in the rest of the conditions this relation was inverted (southern = average 20 – 22%, dry 14 – 15% and very dry 8 – 9%; northern = average 13 – 16%, dry 7 – 8% and very dry 3%) (Figure 4.5 D – F). Likewise, for endorreic rivers and streams there was a greater contribution under wet conditions (76 – 78%) than those that drain to the Pacific (61 – 69%) or Atlantic oceans (48 – 57%), but also reversed in average, dry and very dry conditions (Pacific 16 – 21%, 10 – 14% and 6 – 7%; Atlantic 19 – 23%, 14 – 18% and 9 – 11%; endorreic 13 – 14%, 7% and 2%) (Figure 4.5 G – I).

4.3.2 Relationships, groups' ordination and effects on response variables

According to the PCA, the SQ had a strong and positive correlation with the PC1 under wet conditions (R ≥ 0.92), and a strong and negative with the rest (R ≤ -0.87), regardless of the type of variability (Table 4.2).

In the PC2, this relationship had less strength but contributed to the remaining variance at the seasonal level. In dry season conditions, this component had a similar effect on the response variables, that is a positive correlation under wet condition (R = 0.38), and negative in average, dry, and very dry conditions (R ≤ -0.34). In contrast, this relationship was inverted in the wet season with a negative correlation with the wet condition (R = -0.33), and positive with the rest (R ≥ 0.14).

Table 4.2. Matrix of correlations between the first two principal components (PC) and the response variables. Codes: Wet conditions for inter-annual (ACW), dry (DCW) and wet (WCW) seasons variability, average (ACA, DCA and WCA), dry (ACD, DCD and WCD) and very dry (ACVD, DCVD and WCVD).

	Variables											
	ACW	ACA	ACD	ACVD	DCW	DCA	DCD	DCVD	WCW	WCA	WCD	WCVD
PC1	0.98	-0.93	-0.98	-0.94	0.92	-0.90	-0.91	-0.88	0.94	-0.87	-0.93	-0.92
PC2	-0.16	0.28	0.16	0.00	0.38	-0.34	-0.39	-0.37	-0.33	0.43	0.34	0.14

Consistent with the descriptive analysis, the interactions between the components and the response variables suggested a differentiated, gradient-like, climatic dependency of the rivers classes' along the year, reflected in the biplot for ordering and the reference hydrological long and short-term variability indices (Figure 4.6).

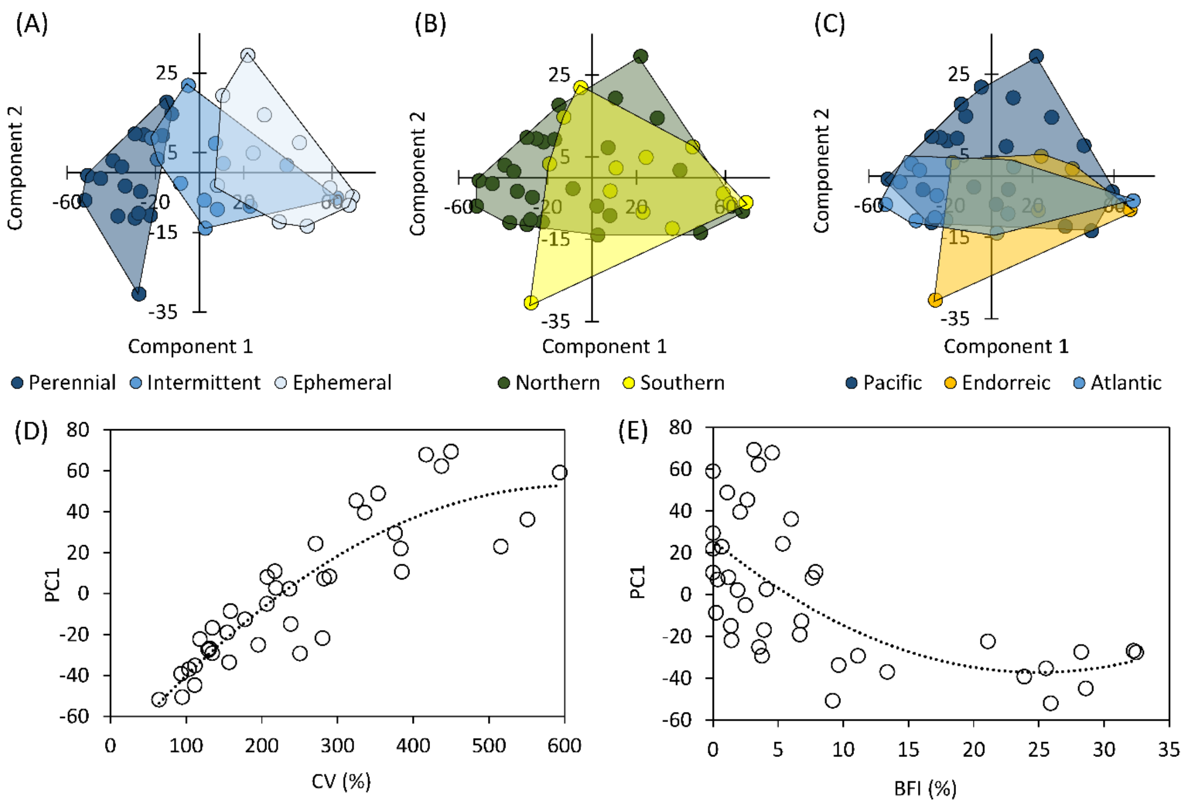


Figure 4.6. Principal components biplots per river classification (A – C), and their relationship with the reference hydrological indices. (D) Coefficient of variation (R^2 = 0. 80) and (E) baseflow index (R^2 = 0.40).

In the case of the stream types, PC1 and PC2 eigenvectors located the intermittent stream class in a transition zone between the ephemeral and perennial ones. In contrast, practically all the northern and southern rivers and streams, and those draining into closed basins and to the Atlantic and Pacific oceans overlapped without a distinctive separation. This is further explained by the presence of each river class according to the PC combination, the independent flow variability indices (CV and BFI), and the dominant climatic units upstream from gauged locations (Table 4.3).

From the total of observations, all the ephemeral (11) and eight out of 12 of the intermittent streams (67%) fell in the components eigenvectors combination +PC1/+PC2, and +PC1/-PC2, and none of the perennial rivers. This set of streams had the greatest dependency on wet conditions regardless of the type of variability. On the contrary, in -PC1/+PC2, and -PC1/-PC2 there were no ephemeral streams, 33% of the intermittent, and all perennial rivers (17).

Table 4.3. Number of basins according to the combination of the principal components indices (PC), the characteristic ranges of streamflow coefficient of variation (CV), baseflow (BFI) indices, and their dominant climatic units upstream from gauging sites (INEGI, 2008).

River types and classes	+PC1/+PC2	+PC1/-PC2	-PC1/+PC2	-PC1/-PC2	CV (%)	BFI (%)
Flow type						
Ephemeral	5	6	–	–	271.2 – 593.9	< 6.0
Intermittent	3	5	3	1	154.4 – 515.9	< 7.9
Perennial	–	–	7	10	64.4 – 250.6	1.4 – 32.5
Tropic of Cancer						
Northern	3	6	3	1	129.1 – 593.9	< 28.3
Southern	5	5	7	10	64.4 – 417.3	< 32.5
Drainage zone						
Atlantic	1	4	2	6	64.4 – 450.2	3.2 – 32.5
Endorreic	2	2	1	1	129.1 – 515.9	0.7 – 28.3
Pacific	5	5	7	4	94.9 – 593.9	< 11.1

Table 4.3. *Continue.*

Dominant climatic units
Dry temperate (25%), dry warm (20%), very dry semiwarm (12%), semidry temperate (11%), and dry temperate (10%)
Semidry temperate (24%), temperate subhumid (18%), dry semiwarm (15%), very dry semiwarm (12%), and semidry semiwarm (10%)
Temperate subhumid (33%), semidry temperate (16%), warm subhumid (14%), semiwarm humid (8%) and warm humid (8%)
Temperate subhumid (19%), dry semiwarm (16%), semidry temperate (13%), very dry semiwarm (11%) and dry warm (10%)
Temperate subhumid (26%), semidry temperate (20%), warm subhumid (15%), semiwarm humid (8%) and warm humid (8%)
Temperate subhumid (17%), dry semiwarm (14%), semidry temperate (12%), semidry semiwarm (10%) and semiwarm humid (9%)
Semidry temperate (40%), dry temperate (16%), dry semiwarm (12%), semicold subhumid (9%) and very dry semiwarm (7%)
Temperate subhumid (39%), semidry temperate (14%), warm subhumid (12%), semicold subhumid (11%) and semidry semiwarm (4%)

Furthermore, the full range of the reference indices of hydrological variability was also shown as a gradient. Ephemeral streams had the greatest range of CV (271 – 594%), followed by the intermittent class as an intermediate (154 – 516%), while perennial rivers had the shortest (64 – 251%). In contrast, perennial rivers had BFI that ranged from 1 – 33%, while in ephemeral and intermittent streams it was constrained to less than 6 – 8%, respectively, where 11 out of 23 streams (44%) exhibited values below or equal to 1%. The overlapping of these variability indices suggested that there was not a clear quantitative definition between classes, but rather a characteristic transition zone among them, which was consistent with the PCA outcome.

Similarly, there was a clear dominance of semidry, dry and very dry weather over ephemeral and intermittent rivers (78 – 79%), while in perennial the prevalent climatic conditions were temperate subhumid, semidry temperate, warm subhumid, semiwarm humid, and warm humid in perennial (79%) (Figure 4.7). These differences between classes were not evident in the other two typologies based on the rivers' location with regard to the Tropic of Cancer and their drainage direction (e.g. high values of CV and BFI, and mixed dominant climates) due to the fact of a generalized overlapping as the PCA biplot revealed.

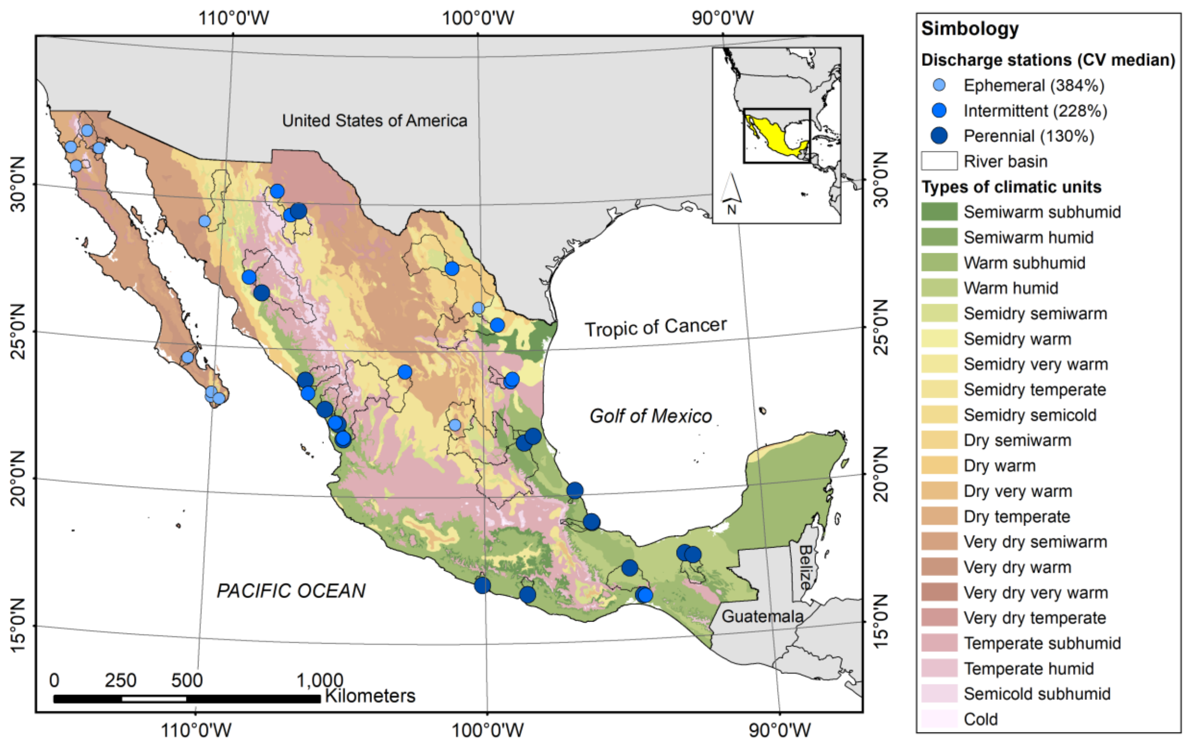


Figure 4.7. Study basins location, flow type at the gauged point, the median of the coefficient of variation index (CV), and types of climate based on the Köppen climatic classification system (INEGI, 2008).

About the multivariate assessment of differences, the response variables revealed a significant level both between the groups of the hydrological conditions (wet ≠ average ≠ dry ≠ very dry; *p*-values = 0.0001), by type of variability (inter-annual, dry and wet seasons) and among the river classes (ephemeral ≠ intermittent ≠ perennial; *p*-values ≤ 0.0354) (Tables 4.4 and 4.5).

Table 4.4. Effects of the response variables between the groups of types of variability (inter-annual, dry and wet season). *P*-value calculated based on the Euclidean similarity index (permutation 9,999 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	6,151	2,870	21.15	0.0001
Dry	4,815	1,760	32.12	0.0001
Very dry	3,051	846	48.19	0.0001

Table 4.5. Pairwise test of the response variables between the groups per stream type. *P*-value calculated based on Bonferroni correction and Euclidean similarity index (permutation 9,999 times).

Stream 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	–

4.4 Discussion and conclusion

The gradient-like hydrological dependency of the basins was based on the contribution of wet, average, dry and very dry conditions on different stream types, characteristic from the flows' inter-annual and seasonal variability, explained by their climatic influence and geographic location. This part of the research supported the need for providing new criteria of frequency of occurrence for determining e-flows regimes sharpen by the mainstream's flow type.

The differentiating gradient ordered by the PCA was related to the stream type's characteristic ranges of flows variability between dry and wet seasons, within a year and along successive cycles in the long-term, as it was described by Hughes & Hannart

(2003) and Hughes et al. (2014), similarly reported by Salinas-Rodríguez et al. (2018). The CV index resulted to be an overall, accurate predictor of the streams wet condition dependency level: the higher this 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 -52 to -13; CV = 271 – 594% *vs*. 64 – 251%, respectively). Such boundary was barely distinguishable between intermittent and perennial rivers; however, it was not presented between ephemeral and intermittent streams. Instead, it was identified a long transitional zone with overlapping indices values, a shared characteristic consistent with the dominant dry climate (INEGI, 2008; Martínez-Pacheco & Salinas-Rodríguez, 2018, based on CONAGUA, 2016b).

This was due to the fact that the classification used was not an end but a mean to evaluate their wet conditions dependency at an inter-annual and seasonal time resolution to guide, inform and improve the environmental water science and management knowledge in Mexico (Olden, Kennard & Pusey, 2012; Poff et al., 2017; Opperman et al., 2018). There were significant differences (95% confidence level) in the response of hydrological conditions and variabilities between the three stream classes.

4.4.1 Limitations and recommendations

The number of ephemeral and intermittent streams sampled basins limited the scope of this research. This was influenced greatly by the available flow sets of records within the research design requirements. Although significant differences were found in the hydrological dependency between the stream types, it was not possible to associate them with the location of the basins with regards to the Tropic of Cancer or the drainage zone. According to the three major criteria considered for the basins selection, the mainstream's flow type, their location with regard to the Tropic of Cancer and the drainage system direction, 18 possible combinations of classes may result. A more representative number of sample basins would be 80 ±10, ideally with 4 – 5 per class (20 ±2% of the country's total number; Cotler Ávalos, 2010; CONAGUA, 2016a), that is around twice this effort. In this sense, to identify suitable ephemerals and intermittent streams is the greatest challenge and further research is required on them. One possibility would be to expand their search in basin headwaters, which also would increase the chance of having greater representativeness of different climates (Costigan et al., 2017).

Another limiting factor was that flow duration curves did not captured the characteristics of flow cessation, which are extremely important in the development of biological and ecological processes in ephemeral and intermittent streams (e.g.

species dispersal and hydrological connectivity; Bunn & Arthington, 2002; Postel & Richter, 2003; Richter et al., 2006; Costigan et al., 2017).

Clearer quantitative boundaries among the stream types could be improved by increasing the time resolution of the hydrological metrics and investigating particular flow-ecology relationships on which the streams classes and healthy 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 (Mathews & Richter, 2007; Datry et al., 2017). So too the low flows for different hydrological conditions at monthly scale together with the basins' topography, geology, land cover and climate characteristics (Hughes & Hannart, 2003; Mathews & Richter, 2007; Hughes et al., 2014; Costigan et al., 2017; Poff et al., 2017; Opperman et al., 2018).

5

Assessment of Mexican rivers towards climate-smart environmental flows

Based on the previous findings, in this chapter, the historical trends in discharge and rainfall are assessed (Mann-Kendall test) in the set of 40 study basins. An adjustment to the reference values of frequency of occurrence to integrate environmental volumes for water allocation is proposed based on the sensitivity of each river type to the hydrological contribution conditions. Environmental volumes reference values are obtained per stream type according to the method baseline and the adjustment, and a performance assessment is carried out focused on the impact of the reserves in the rivers water availability balances. Results showed that the new criteria of frequency of occurrence deliver more robust non-stationary environmental flows and smarter water reserves that strengthen the water balance by buffering future climatic uncertainties.

This chapter is based on:

Salinas-Rodríguez S.A. and van de Giesen N.C. Inter-annual and seasonal variability of flows: Assessment of Mexican rivers towards climate-smart environmental flows. *Environmental Earth Sciences*. (In review).

5.1 Introduction

Environmental water science and management have rapidly increased the available knowledge and improved practice all around the globe. The study of flow-ecology and flow alteration-ecological response relationships have been key in EFAs to protect and restore freshwater ecosystems (Acreman et al., 2014ab; Poff et al., 2017), before and after the recently updated *Brisbane Declaration and Global Action Agenda on Environmental Flows* (Arthington et al., 2018a). Furthermore, those relationships have been strategic inputs for a number of national, regional or basin scale programs to assess e-flows requirements and to allocate water volumes mainly as a response of recognizing the environment as a legitimate user (OECD, 2015; Poff et al., 2017; Kennen, Stein & Webb, 2018).

Hydrologically, the more advanced methodologies in EFAs focus primarily on the attributes of the natural flow regime and its inter-annual and seasonal variability components built upon theoretical flow-ecology relationships (e.g. Poff et al., 1997; Richter et al., 1997; Hughes & Hannart, 2003; Mathews & Richter, 2007; Hughes et al., 2014; Poff et al., 2017). In such methodologies, normally the natural, or close to unimpaired, historic flow regime is seen as a reference desirable state to conserve or restore freshwater ecosystems. However, climate change imposes an emerging core challenge to this hydrologic-reference conceptualization: the uncertainty of non-stationarity water availability and regimes regardless of environmental water allocations (Poff & Matthews, 2013; Poff et al., 2017; Arthington et al., 2018b; Capon et al., 2018; Poff, 2018).

In Mexico, EFAs are normed according to a standard that sets the ruling principles and technical procedures, applicable through a triple hierarchical approach from desktop hydrology-based to holistic methodologies (Secretaría de Economía, 2012; Opperman et al., 2018; Salinas-Rodríguez et. al., 2018). 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 (Poff et al., 2017; Salinas-Rodríguez, Sánchez-Navarro & Barrios-Ordóñez, in review).

The most detailed hydrological method was developed to cope with the non-stationarity of water availability based on a novel frequency of occurrence approach to integrate the e-flow requirements into EWRs. Nevertheless, the method was developed for perennial rivers. What has not yet been investigated is climate change, the historical trends in river discharge and basin rainfall. Neither has been revised the appropriateness of the current criteria of frequency of occurrence between different river types. The overall goal of this chapter is focused on those gaps.

The specific objectives are to demonstrate that (1) any river type and basin could exhibit significant trends in discharge and/or rainfall. Evidence in that direction would endow to the Mexican environmental water science and management with a new knowledge perspective towards climate-smart EFAs. It will provide supporting information to (2) improve the method's current criteria with new reference values of frequencies of occurrence adjusted according to a differentiated climatic influence on the river types, and (3) deliver likely EWRs volumes for water allocation.

5.2 Methodology

5.2.1 Research design and data requirements

The set of forty basins from the previous chapter was used to conduct the present assessment. In addition to the rivers' streamflow discharge, observed rainfall at basin scale was incorporated into the analysis. Rainfall records from a total of 209 climatic stations were obtained from the Climatological Database web platform [Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), 2018] administrated by the National Meteorological Service (Figure 5.1).

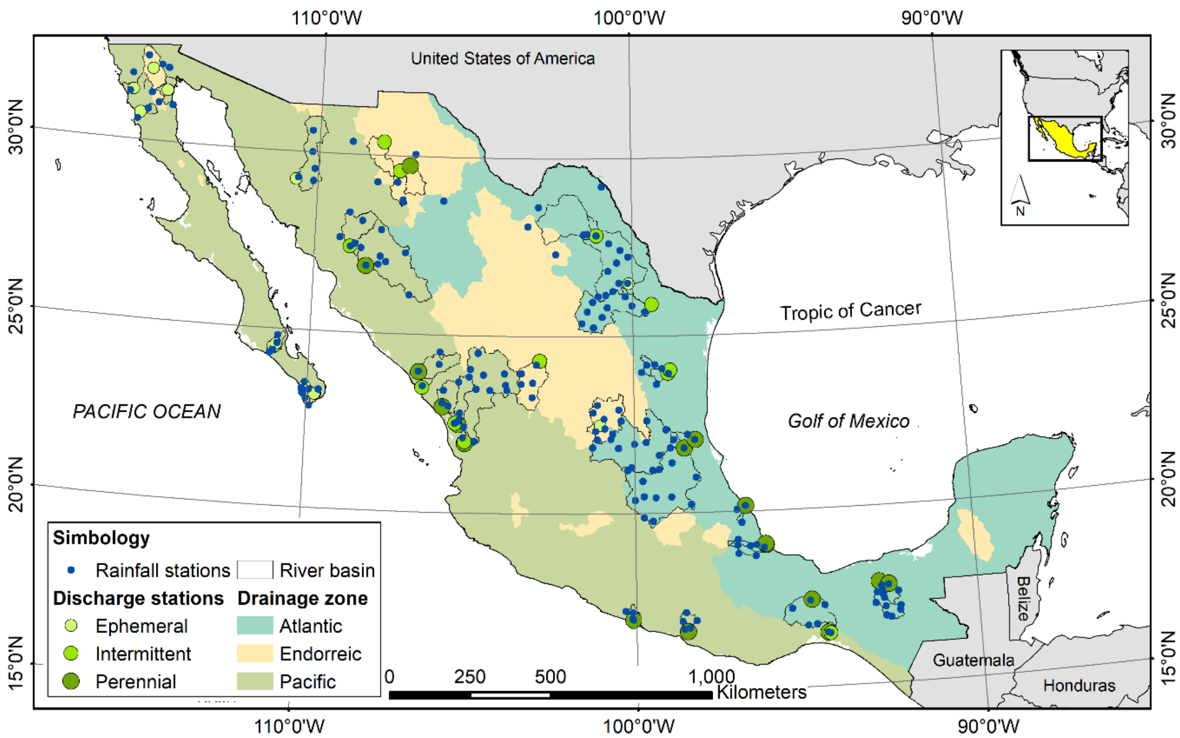


Figure 5.1. Location of rainfall and discharge gauging stations of the study basins per drainage zone.

Unlike the flow records datasets with highly heterogeneous time spans, total monthly rainfall (mm) was calculated for ≥ 25 consecutive years from recent decades with more homogeneous sample (Figure 5.2). This procedure was performed by selecting climatic stations with similar time-periods, within or close to the basin border (upstream from discharge gauging point) according to the official delimitation (Martínez-Pacheco & Salinas-Rodríguez, 2018, based on CONAGUA, 2016b). Thiessen polygons and surface area were obtained with ArcGIS 10.4 software. The basin's total rainfall was calculated by summing the proportional rainfall from all the stations.

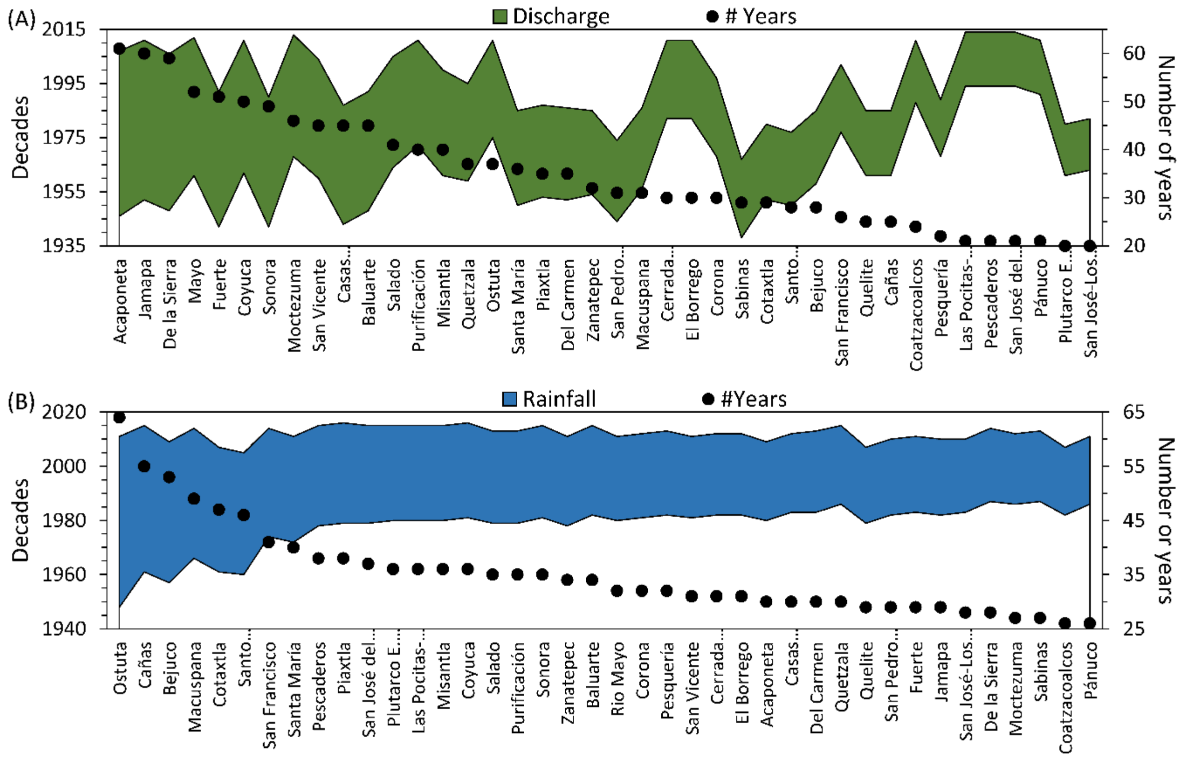


Figure 5.2. Periods of analysis for (A) discharge and (B) rainfall of the study basins. Decades comprised in the left vertical axis (colored area), and number of consecutive years in the right vertical axis (dots).

5.2.2 Inference statistics on discharge and rainfall

Trends on the mean inter-annual discharge and rainfall in all the study rivers were calculated based on the Mann-Kendall (MK) non-parametric test (Mann, 1945; Kendall, 1975). Regardless of the dataset distribution over time, missing values, their seasonality or the type of trend, this approach has been widely used in environmental, climate and hydrological observed data to identify trends with confidence levels, including Mexico (e.g. Hirsch, Slack & Smith, 1982; Yue, Pilon & Cavadias, 2002; Méndez González et al., 2008; Martínez-Austria, Patiño-Gómez & Tamayo-Escobar, 2014; Nourani, Mehr & Azad, 2018).

Even though not all the discharge sets of records were present for recent times, their trends were calculated to compare them with corresponding ones from rainfall, which is a direct indication of water availability and potential climate change impacts in the river basins. Since all periods of record comprise ≥ 20 years, MK's Z statistics follow a normal distribution and the positive or negative signs indicate increasing or decreasing trends over time (Mann, 1945; Kendall, 1975; Yue et al., 2002). Z test and p-values were calculated by using Minitab 18.1 software.

In MK's test, it was assumed that similar directions of discharge and rainfall trends (increasing or decreasing) from recent times indicate that the basin has remained stable in long-term runoff generation processes. It was hypothesized that significant increasing and decreasing trends (*p*-values < 0.05 and 0.10) occur in both discharge and rainfall from ephemeral, intermittent and perennial streams types.

5.2.3 Climate-smart environmental flows and water reserves reference values

E-flows regimes and EWRs volumes were calculated based on the hydrology-based methodology described in Chapter 3. In light of the PCA and multivariate for significant differences outcomes from Chapter 4, new reference values of frequency factors of occurrence for ephemeral and intermittent streams were proposed for the implementation of Eq. 3.1 and 3.2 (Table 5.1). The reference values for perennial rivers remained the same due to the general consistency previously reported between this method's results and holistic on-site assessment outcomes (Chapter 2). The application of these reference values differentiates the stream types' wet hydrological conditions dependency and it considers that all of them could exhibit significant increasing or decreasing trends in water availability.

Table 5.1. Frequency factors of occurrence for the integration of the flow regime components into annual volumes for environmental water allocation for ephemeral, intermittent and perennial stream types, according to environmental objectives classes.

Environmental objective	Ordinary or low flows hydrological condition				Flood regime		
	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

EWRs volumes were calculated for all the environmental objective classes (EOC) of the stream types and they were expressed as a percentage of the MAR. Full and central ranges (medians ±1 quartile) from each river class were examined separately (Adj_EWR + codes A, B, C or D; n = ephemeral 11, intermittent 12 or perennial 17). R^2 values based on linear regressions of PC1 eigenvectors from characteristic EWR per

EOC were calculated for each stream type class. Furthermore, the procedure for determining EWRs was also conducted according to the method baseline criteria (NMX_EWR; N = 40) to compare these results with the ones provided by the new reference values outcomes. EWRs from each river basin according to their actual EOC (norm's Appendix A) were identified for conducting a performance assessment.

5.2.4 Performance assessment of the reserves for environmental water allocation

The performance assessment of the EWRs outcomes from the new frequency of occurrence was conducted by focusing on their impact on the water availability in comparison to the EWRs results from the method baseline criteria. Volumes were taken from the basins latest official water balances by following a modified version of the current administrative procedure (CONAGUA, 2016b).

First (Eq. 5.1), the downstream MAR (DMAR) was calculated based on the subtraction of the volumes from consumptive uses (Cu), evaporations (Ev), exportations (Ex) and storage variation in water bodies (Sv), from the volumes of natural MAR (NMAR), the amount of water coming from upstream (UMAR), returns (R) and importations (Im). Afterward (Eq. 5.2), water availability (Wav) was obtained by subtracting the downstream committed volumes (DCu) from the DMAR.

$$DMAR = NMAR + UMAR + R + Im - (Cu + Ev + Ex + Sv) \quad \text{(Eq. 5.1)}$$

$$Wav = DMAR - (DCu + EWR_i) \quad \text{(Eq. 5.2)}$$

The modification of the official equation consisted in summing the EWR to the DCu in order to track easily the basins susceptible to impacts[1], where *i* is one of the following percentages of MAR based on each basin corresponding EOC:

- The method baseline criteria (NMX_EWR).
- Scenario 1: The adjustment (new) on the frequency of occurrence (Adj.Fqy.Oc).
- Scenario 2: A reference value based on each stream type median minus one quartile (Ref.Val.Med-1Q).
- Scenario 3: A reference value based on each stream type median (Ref.Val.Med).
- Scenario 4: A reference value based on each stream type median plus one quartile (Ref.Val.Med+1Q).

The comparison indicator was obtained by calculating the degree of change in water availability after the hypothetical environmental water allocation (Eq. 5.3) where *i* is the available volume after one of the scenarios resulted from Eq. 5.2. In this sense,

[1] In recent Mexican environmental water allocations the EWR are either covered by the existing DCu or the higher between both is set as DCu due to in practice they do not compite each other (e.g. ~300 EWR declared on June 6th 2018, http://www.diariooficial.gob.mx).

zero means no impact on water availability in comparison to the method baseline (Wav_NMX_EWR), a positive value implies a lower impact (overall positive balance after water allocation), while a negative one a greater (less availability).

$$Degree\ of\ change\ (\Delta) = \frac{Wav\_Scenario_i - Wav\_NMX\_EWR}{Wav\_NMX\_EWR} \qquad \text{(Eq. 5.3)}$$

5.3 Results

5.3.1 Discharge and rainfall trends

From the total of basins assessed, 19 cases had a recent period of records reaching beyond the 2000s in both rainfall and discharge (Figure 5.3). Eight of those have kept the same trend direction: Cerrada Laguna Salada, El Borrego and Las Pocitas-San Hilario ephemeral streams, intermittent San Francisco, and Acaponeta, Pánuco, Coatzacoalcos and De la Sierra perennial rivers.

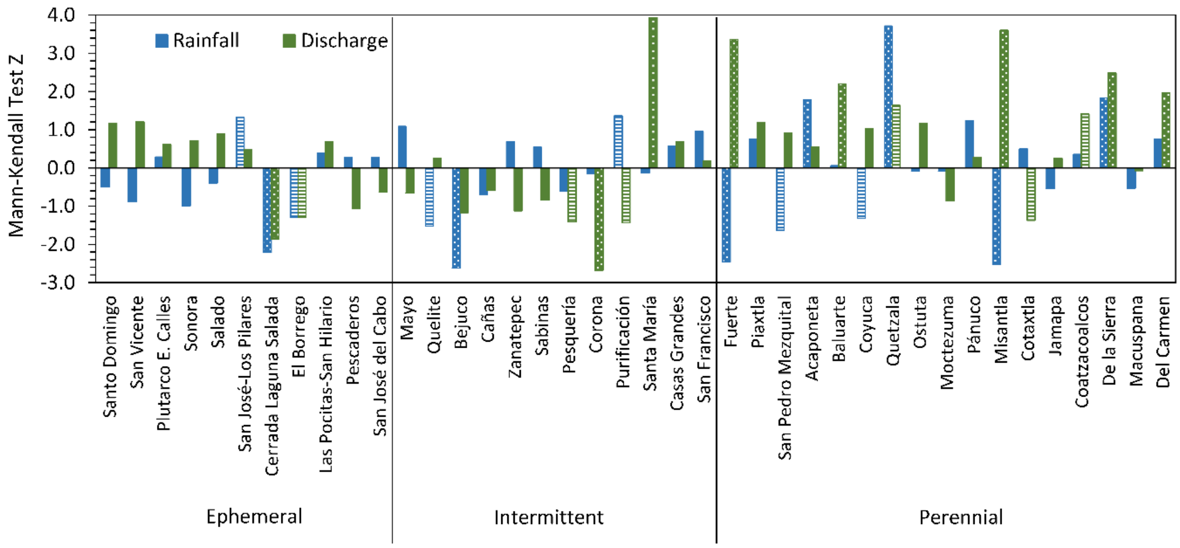


Figure 5.3. Basins discharge and rainfall Mann-Kendall trend test. Significant confidence levels are displayed in dotted (95%) and stripped (90%) bars.

About discharge, 15 exhibited increasing and 25 decreasing trends, while in rainfall the proportion was equal. In both cases, around one-third of the basins had trends at least at 90% significance level and approximately one-fifth at 95%. For all the river types significant trends were detected at 95% or 90% confidence levels. In rainfall specifically, ephemeral streams that exhibited significant trends were San José-Los Pilares (increasing), Cerrada Laguna Salada and El Borrego (decreasing). Purificación (increasing), Quelite and Cañas (decreasing) were intermittent streams. The perennial rivers with increasing trends were Acaponeta, Quetzala, and De la Sierra, whereas decreasing trends were found in Fuerte, San Pedro Mezquital, Coyuca and Misantla basins.

5.3.2 Frequency of occurrence and environmental water reserves reference values

The full and central ranges of the EWRs outcomes depicted distinctive thresholds among the method baseline criteria and the adjustment based on the new frequencies of occurrence (Figure 5.4). The full range in the baseline varied from 19 to 76%, 6 – 63%, 3 – 57% and 2 – 52% of the MAR from EOC A to D, respectively (Figure 5.4 A). Regardless of the EOC, the interquartile range was around 20 – 22% MAR with the following relative magnitudes: 41 – 62% for a class A, 23 – 44% for B, 14 – 36% for C and 9 – 29% for D.

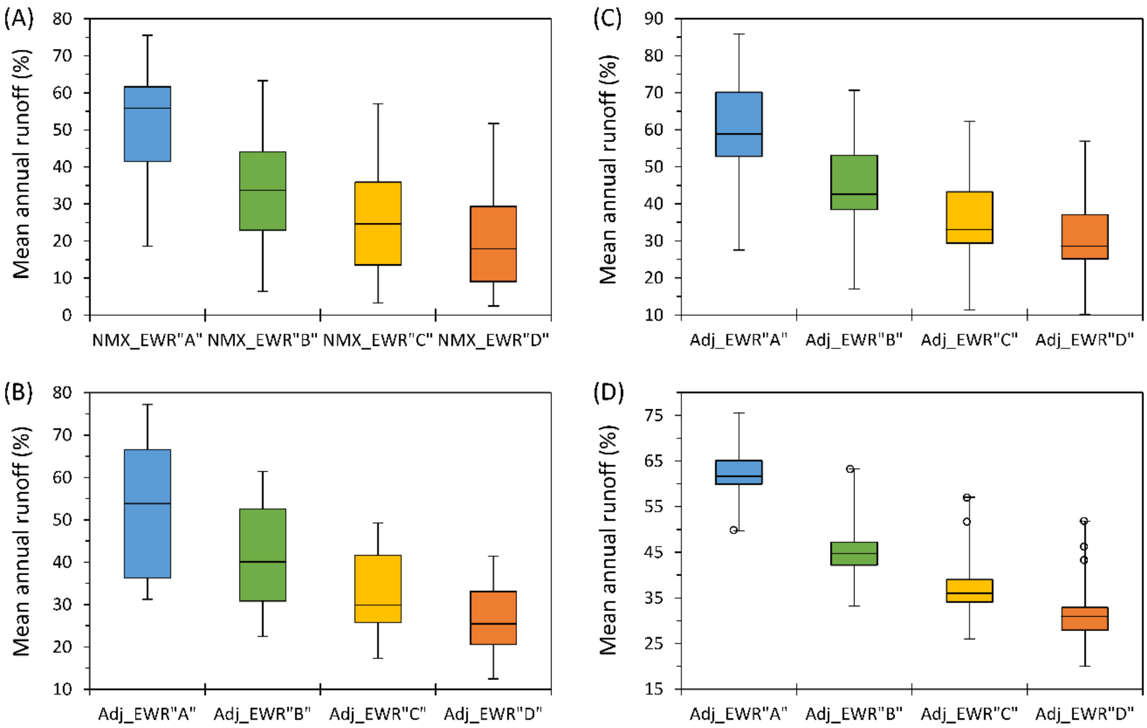


Figure 5.4. Central and full range of environmental water reserves volumes per environmental objective class. (A) The method baseline criteria applied in the 40 basins, and the adjustments based on the new criteria of frequency of occurrence reference values for (B) ephemeral (n = 11), (C) intermittent (n = 12) and (D) perennial rivers (n = 17; outliers displayed in circles).

The outcomes in ephemeral streams with the adjustment ranged from 31 to 77% of the MAR (A), 23 – 61% (B), 17 – 49% (C) and 12 – 41% (D) according to the minimum and maximum per EOC (Figure 5.4 B). The relative magnitudes of the central thresholds were 36 – 67% MAR (A), 31 – 53% (B), 26 – 42% (C) and 21 – 33% (D) with interquartile range between 13 – 30%. In comparison, intermittent streams presented wider full ranges running from 28 – 86% MAR (A), 17 – 71% (B), 11 – 62% (C) and 10 – 57% (D); while the central ones varied from 53 – 70% (A), 38 – 53% (B), 29 – 43% (C) and 25 – 37% (D) with narrower interquartile range between 12 – 17% (Figure 5.4 C). Similarly, perennial rivers exhibited the shortest full and central ranges from all (Figure 5.4 D): 50 – 76% MAR (A), 33 – 63% (B), 26 – 57% (C) and 20 – 52% (D); 60 – 65%, 42 – 47%, 34 – 39% and 28 – 33%, accordingly (interquartile range 5%; all classes depict outliers).

Another important distinction between the baseline and the adjustment results were the proportions of the ordinary or low flows and the flood regime from the EWRs volumes (Figure 5.5). In the baseline, the average of the low flows component was around 75% of the EWRs in A and B classes and 80% in C and D. With the adjustment, this increased in perennial rivers about 87% (A – B) and 92% (C – D), while in the intermittent class remained similar (73 – 76%), and it was reduced substantially in ephemeral streams (67% A, 62% B, 58% C and 52% D). These changes reflected the relative importance of each EWR component between the river types. The correlation of PC1 with the characteristic EWRs volumes per stream type was negative and strong (Figure 5.6). For class A, R^2 values were equal to 0.67 in ephemeral, 0.85 intermittent and 0.77 perennial. In class B, the R^2 values were 0.70, 0.85 and 0.77, respectively. Likewise, for class C the values were 0.70, 0.85, and 0.87; and 0.70, 0.84 and 0.88 for class D, accordingly.

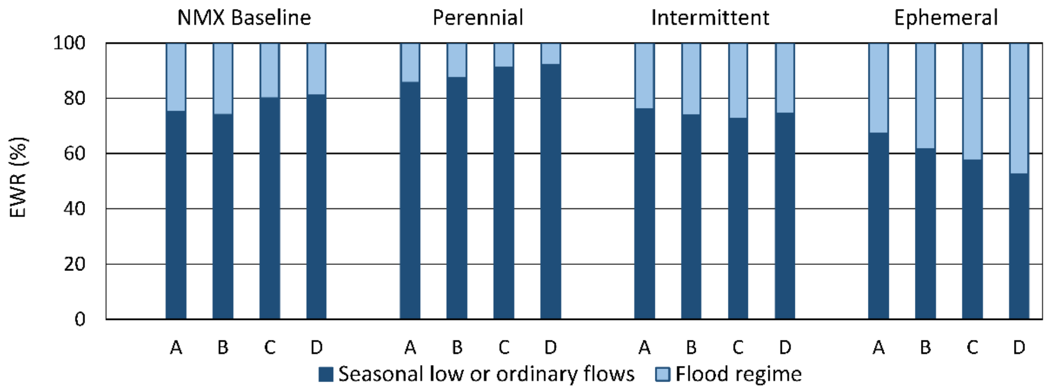


Figure 5.5. Average proportions of the environmental water reserves (EWR) components per environmental objective class according to the baseline and per stream type.

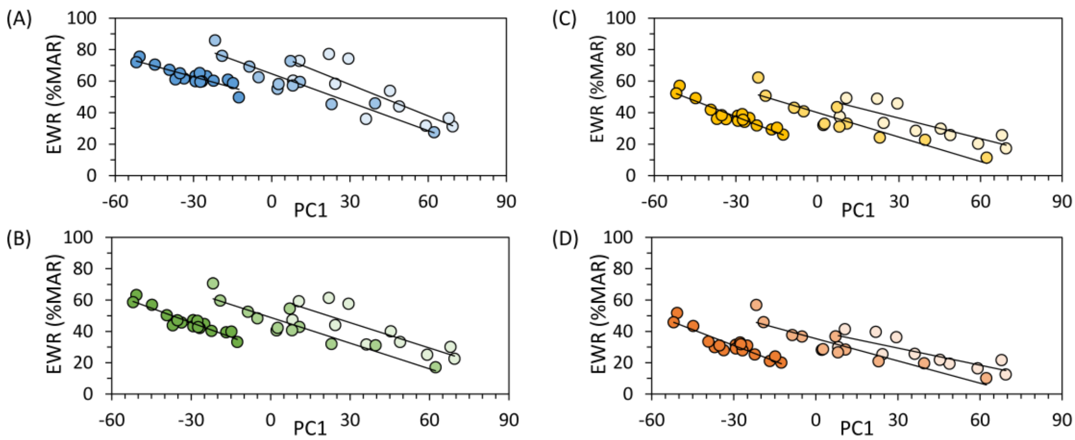


Figure 5.6. Linear regressions between the principal component 1 eigenvectors (PC1) and the environmental water reserves volumes [expressed as a percentage of the mean annual runoff –EWR (%MAR)] from the adjusted criteria of frequency of occurrence per stream type (colors gradient: lighter ephemeral, intermediate intermittent and darker perennial). The scatter plots (A, B, C, and D) are displayed according to the environmental objectives A, B, C and D in blue, green, yellow and red tones, respectively.

5.3.3 Reference values performance in the basins water balance

Regardless of the method variations for determining the EWR (baseline or any of the 4 scenarios), in 75% of the basins would remain water availability for productive uses (Figure 5.7).

In comparison to the method baseline, the performance indicator on the adjustment of the frequency of occurrence, the median, and the minus one-quartile reference values (scenarios 1, 2 and 3) remained in zero ±0.25 in 48-50% of the basins, and 38% in the median plus one-quartile (scenario 4). If only positive and low index results were considered (greater than -0.50), then the number would increase in all scenarios to 60-73% and the higher impacts would concentrate in the ephemeral and intermittent streams (2-15%).

From the 25% of the basins that would run out of water, Sonora and Salado ephemeral streams, and intermittent Sabinas, Pesquería, Corona and Purificación already have been over-allocated beyond sustainable limits. San José-Los Pilares, Mayo (both ephemerals), Santa María and Fuerte basins (intermittent and perennial, respectively) would enter in deficit due to the fact that their current downstream committed volumes were very close to the available water sustainable limit.

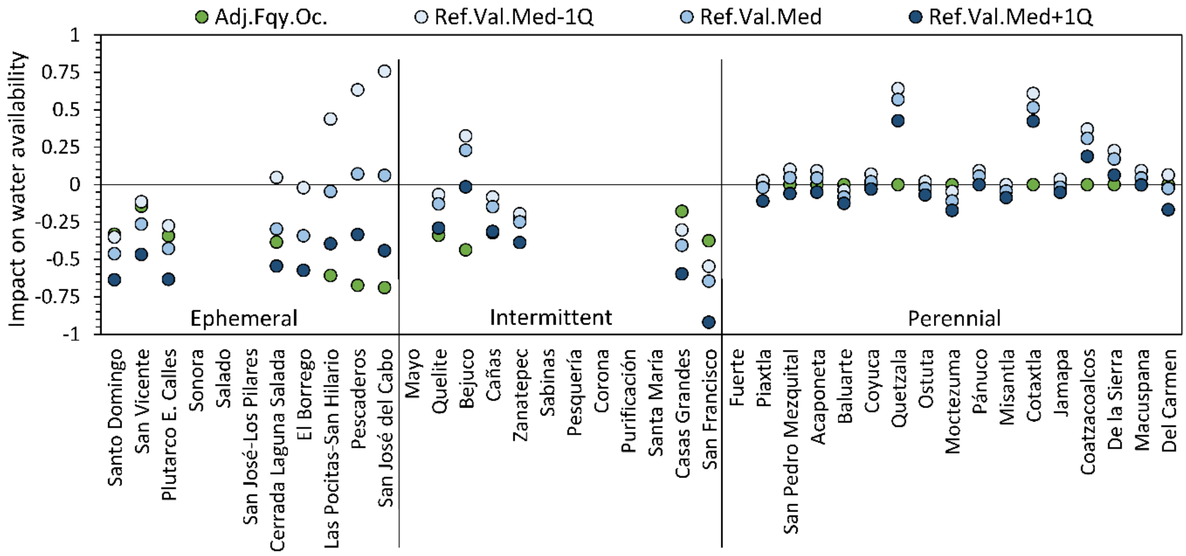


Figure 5.7. Performance assessment of the environmental water reserves reference values (scenarios) on the basins' water availability balance. The impact on water availability of each scenario is displayed in comparison to the method's current baseline.

5.4 Discussion and conclusion

Regardless of the stream type and basin location, there were significant trends whether increasing or decreasing in both discharge and rainfall sets of records (90% and 95% confidence levels). However, different direction of trends between both sets indicates that most likely there have been man-induced changes in the basin (Mathews

& Richter, 2007; Costigan et al., 2017). These could be either by altering the flow regime due to water infrastructure for productive use or flood protection (e.g. dams, levees or weirs) or over the basin landscape (e.g. urbanization, deforestation, and erosion rates, among others) (Mathews & Richter, 2007; Costigan et al., 2017).

For rainfall specifically, according to Méndez González et al. (2008), Mexico has exhibited significant trends in an overall gradient from the arid and semi-arid northwest (increasing) to the humid-rainy coasts of the Gulf of Mexico southeast (decreasing). In this context, 46% of the basins depicted an opposite trend direction. This difference could be due to the number of sampled basins, the spatial resolution between the studies (basin *vs*. region), the number of stations considered (209 *vs*. 789) and the length of the records periods (26 – 64 *vs*. 30 – 85 years; average 40 *vs*. 50) (Yue et al., 2002). Moreover, there were basins that partially comprised two or three regions from the ones analyzed by Méndez González et al. (2008), e.g. San Pedro Mezquital, Moctezuma and Pánuco with the influence of different dominant climates.

With regard to the characteristic EWRs, the higher relative median volumes varied from perennial rivers to ephemeral streams (EOC A – D = 62 – 31% and 54 – 25%) with increasing central thresholds (interquartile range from 5% in perennial to 13 – 30% in ephemeral). This was because of the weighing in the new frequency of occurrence from the EWR components. EWR volumes reflected the differentiated dependency of wet conditions between the streams types, consistent with the PC1 eigenvectors (R^2 = 0.67 – 0.88), the related characteristics of each class, and the significant differences among them. There are several implications of these findings.

5.4.1 Implications and contributions

First, in comparison with the current NMX baseline, the new criteria of frequency of occurrence improve the EFA. Under or overestimations of EWR could be avoided particularly in ephemeral and intermittent streams due to the fact that the method was originally developed for perennial rivers (Costigan et al., 2017). It is clear that, by stratifying the streams types, common patterns with significant differences arise at a hydrological level (Costigan et al., 2017; likewise reported by Salinas-Rodríguez et al., 2018). This also contributes to the development of working hypotheses on hydro-ecological functions by focusing them per stream type, in a desktop approach or an on-site level, and their particular ecological processes and environmental services (Costigan et al., 2017; Poff et al., 2017).

A second implication is that the e-flows regimes capture significant trends in rainfall, which occur throughout the country regardless of the stream type. Such trends influence 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 (Cotler Ávalos, 2010; Costigan et al., 2017; Capon et al., 2018). As long as the discharge series compiles ≥ 20 years at daily scale (≤ 10% of gaps) from recent decades, and there is evidence that the flow regime and the basin overall structure are close to natural state or relatively low impacted, the changes over time in rainfall patterns and water availability should be reflected in the flow regime and ultimately in water availability (Mathews & Richter, 2007).

E-flows regimes for wet, average, dry and very dry conditions are assessed as well as a set of peak flow events to conform the EWR. These two components of the EWR are integrated based on their historical and trending recurrence and provide a climate-smart solution in environmental water allocations. There is a recognized high uncertainty on how climate change impacts the flow regime at the basin or regional scales (Arthington et al., 2018b; Poff 2018). However, the inclusion of a wide array of hydrological ordinary and extraordinary conditions in EWRs overcomes the challenge of the e-flows implementation under different climate scenarios. This is an important advantage towards the maintenance of the ecosystems health and their resilience capacity (Poff & Matthews, 2013; Costigan et al., 2017; Arthington et al., 2018a; Capon et al., 2018).

The most important implication is that the strength of the reference values depends on the provision of a range of relative volumes based on a sample of basins with and without significantly increasing and decreasing trends from different climates and geographies, as a reflection of a non-stationary, dynamic climate. By explicitly including EWRs likely scenarios for water allocation, the impacts of climate change on the water balance and the environment could be either anticipated, buffered, tracked over time or facilitate transitional changes from one ecological state to another. This is particularly important under the unavoidable future intensification of competition for the resources (Poff & Matthews, 2013; Mekonnen & Hoekstra, 2016; Poff et al., 2017; Arthington et al., 2018ab; Capon et al., 2018; Poff, 2018).

5.4.2 Limitations and recommendations

The sets of streamflow records limited the trends analysis to 19 basins (7 ephemeral, 3 intermittent and 9 perennial) encompassing recent decades to compare them with rainfall as a direct indication of climate change. By increasing the number of basins as it was concluded in the previous chapter, a greater sampled basins from different mainstream's flow type and geographies could be studied, associations or correlations made with more robust inference statistics, and stronger conclusions achieved.

6
Conclusions, implications and outlook

This thesis aimed to determine Mexican climate-adaptive environmental flows reference values for people and nature. The research was based on state-of-the-art environmental water science and practice, and on the current national standard for conducting desktop and on-site assessments.

The frequency-of-occurrence criteria for integrating environmental flow regimes into volumes for water allocation were adjusted for ephemeral, intermittent and perennial rivers. This was based on the magnitude of the contribution of hydrological wet, average, dry and very dry low flow conditions (inter-annual and seasonal variability), as well as a flood regime per stream type. River discharge, basin rainfall trends, and environmental flow regimes were examined in a set of 40 study cases selected according to climate, geography and hydrology representativeness. Hydrology-based likely environmental reserve volumes for preventive water allocation, expressed as a percentage of the mean annual runoff, were obtained based on a central range distribution approach.

The performance assessment of these reference values demonstrated that the impact on water availability for allocating such volumes is no different from the current method (baseline) though significantly improved for avoiding under and over-estimations.

6.1 Conclusions

The Mexican environmental flows norm foundations, the implementation experience, and early results were introduced in chapter 2. The outcomes from one hydrology-based methodology and from on-site assessments were examined. The findings revealed a good performance at the water allocation level. This was due to the fact that both methodologies used similar metrics for the ordinary seasonal low flow component. Another reason was that these two methodologies were simultaneously implemented in basins strategically selected across the country with environmental objectives in general consistent between the baseline and the on-site assessments.

It is important to note that both methodologies do not exclude but complement each other. The increased detail delivered by an expert panel based on on-site assessments contributed to understanding the scope of each methodology. This standard implementation of methodologies has contributed to building an institutional and expert network to discuss and agree upon flow-ecology knowledge, and supported and feedbacked strategic water resources management. The experience grounded the foundations for setting preventive environmental water allocations before facing the challenge of assessing environmental flows in basins with higher pressures.

The hydrology-based methodology was presented and discussed in chapter 3. What makes this desktop method different from the currently available one is the novel criterion of frequency-of-occurrence to integrate environmental flow regimes into water reserves. The criteria derived from a strong empirical background, scientific knowledge, and ecologically relevant hydrological statistics to evaluate two major flow components: low flow ordinary conditions and a flood regime of peak flow extraordinary events. The environmental flows and reserves cope with the non-stationarity challenge of water availability in the environment by explicitly handling four hydrological conditions of inter-annual and seasonal variability: wet, average, dry and very dry. Environmental water requirements are integrated based on the natural probabilistic occurrence of the flow regime components and adjusted according to a four-to-five level system of environmental management objectives.

The outcomes from this *(eco)hydrologic desktop* approach were thought to support top-down preventive environmental flows and water allocation assessments at a planning and management level. From a bottom-up perspective, the method brings new insights for building flow-ecology relationships in the context of intermediate and detailed assessments, more appropriate for protected areas or in cases of water infrastructure projects at an on-site level.

Empirical knowledge about the relative importance of inter-annual and seasonal variability of flows in Mexican basins was scientifically tested in chapter 4. River basin classification based on mainstream flow type turned out to be the most comprehensive one and depicted a gradient-like wet condition dependency. Descriptive and inference statistics demonstrated that ephemeral and intermittent streams have a greater dependency on annual and seasonal wet conditions than perennial rivers, consistent with independent indices of hydrological variability and the basins dominant climates. Furthermore, inter-annual and seasonal variability of wet, average, dry and very dry conditions in ephemeral, intermittent and perennial rivers exhibited significant differences (95% confidence level; p-values < 0.05). The flows' coefficient of variation between dry and wet seasons resulted to be a good predictor of the rivers wet condition dependency (R^2 = 0.80). These findings supported the need for revising the appropriateness of frequency of occurrence criteria by flow type.

In chapter 5, the impact of climate change on the water resources was evaluated based on river discharge and basin rainfall observed trends. Regardless of the flow types, dominant climate and basins geographic location, increasing and decreasing significant trends were found in at least the last 25 consecutive years of records (90% and 95% confidence levels; p-values < 0.10 and 0.05). It was not possible to associate with inference statistics the significant trends with the stream types, climates and geographic locations due to the fact of the limited sample of study cases.

Although there is regional climate change impact evidence in rainfall patterns (i.e. increasing trends in arid and semi-arid and decreasing in humid-rainy regions), this thesis findings highlight the importance of conducting basin scale water resources trend tests. Changes on water availability is a key component of environmental flow assessments towards climate-smart long-term implementation. The reference values of frequency of occurrence were adjusted per flow type for future detailed environmental flow hydrology-based assessments, and subsequent management. Likewise, environmental water volumes reference values are provided for water planning.

6.2 Implications and outlook

The two-way strategic approach for conducting environmental flow assessments, top-down and bottom-up, informs the national standard implementation performance, environmental water science and practice. On the one hand, the findings of this research support empirical knowledge on strategic frameworks for setting sustainable limits of water abstraction (Le Quesne et al., 2010; Acreman et al., 2014ab; Opperman et al., 2018). Hydrology-based outcomes in the appropriate contexts (i.e. low pressure from water users and high ecological importance values) deliver “quick” science-based environmental water requirements for preventive climate-smart allocations with significant levels of benefits.

Based on the early results of the National Water Reserves for the Environment Program, an initial approximation of the number of people potentially benefiting from the flow-related environmental services is around 1.8 million inhabitants from nearly 22,000 rural communities. Furthermore, the economic evaluation of such benefits in the firsts technical studies revealed a cost-benefit ratio ≥ 1:16 in a 20-year horizon (12% discount rate; IMIDA, 2013; Agroder S.C., 2014).

On the other hand, at an on-site bottom-up level and from a biological point of view, 93 freshwater-dependent species (40 protected in national and international lists) in at least 25 reference sites have now a baseline of water needs and habitat requirements for further in-depth studies. This information provides an advance for selecting key species, ecological processes, and habitat requirements for discussing site-specific flow-ecology relationships (eco-hydrological working hypotheses). Academic agreement upon such relationships would ground the basis for incorporating them into 20 protected areas management plans [16 wetlands of international importance (Ramsar sites)]. In addition, based on these relationships a performance assessment system could be developed for monitoring the environmental flows ongoing implementation towards adaptive management. Likewise, it contributes to the environmental water knowledge and practice to strengthen the Mexican standard, and turning it in an obligatory public policy instrument in the short to mid-term (< 5 years).

At a policy level, this two-way strategic approach has supported the biggest decision-making in the Mexican environmental water practice in recent times. Based on desktop analyses and on-site assessments (Barrios et al., 2015; Harwood et al., 2017; Opperman et al., 2018), in June 6th 2018 the government declared 10 environmental water reserves for up to 50 years in 295 river basins (http://www.diariooficial.gob.mx). These reserves represent around the 40% of the basins and 55% of the total national surface flow for ensuring water provisioning to 45 million people, and to ecosystems in 82 protected areas (~175,000 km^2), 64 wetlands of international importance (~47,000 km^2) [Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), 2018].

To date, how many freshwater-dependent species directly benefit from these reserves is unclear although they could be potentially hundreds due to the fact that Mexico is considered a megadiverse country. These reserves imply a significant step forward to stop the country's current negative trends of freshwater biodiversity loss (Contreras-Balderas et al., 2003; Baena et al., 2008; Valderrama-Landeros et al., 2017), and a contribution at global level given the projected future of water demand (Dudgeon et al., 2006; Vörösmarty et al., 2010; OECD, 2012; Mekonnen & Hoekstra, 2016; WWF, 2018).

In the context of environmental flows, the new reference values of frequency of occurrence brought smarter climate-adaptive environmental water reserves for people and nature. Theoretically, they improve environmental water allocations at water planning and management level in the long-term. However, they also bring new challenges to research-driven on-site intermediate and detailed assessments.

For example, what would be the expected relationship between the different low flow conditions (wet, average, dry and very dry years) and the biotic community integrity (e.g. species population rates and their life strategies)? What are the trends in frequency (number) and duration of zero flow events, ordinary low flows and peak flow extraordinary events? Are such trends significant? Do the new frequencies accurately reflect water availability shifts at a daily-scale level for ensuring species' climate resilience in the long-term? If not, which ecological and biological processes would be affected and how could their vulnerability be reduced? On-site long-term monitoring is required for answering these and other related questions (Costigan et al., 2017; Poff et al., 2017; Arthington et al., 2018ab; Capon et al., 2018; Poff, 2018).

6.3 Closing remarks

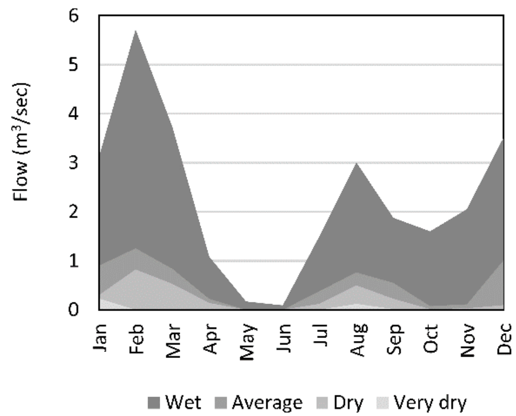
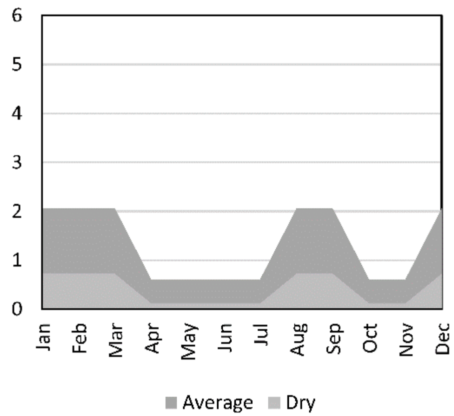
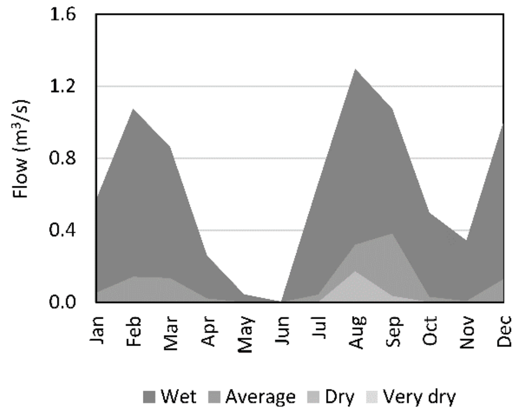
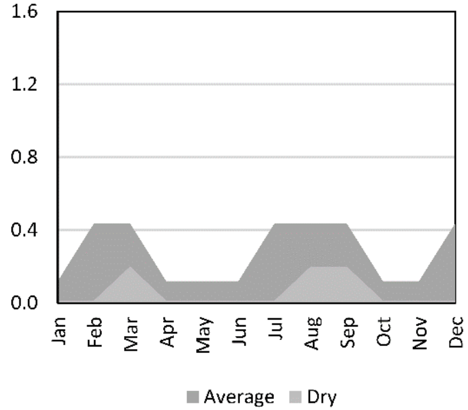
The findings of this research present a successful innovative experience, from its roots to an implementation phase, based on the opportunity of limiting flow alterations to maintain diversity and ecological integrity of freshwater ecosystems compatible with sustainable use of water. Strategic frameworks for conducting site context-specific environmental flow assessments are useful not only in early implementations, but they also bring knowledge and capacities to overcome obstacles along the decision-making process. Decisions on setting ecosystem water requirements and environmental allocations are still urgent and need to be made.

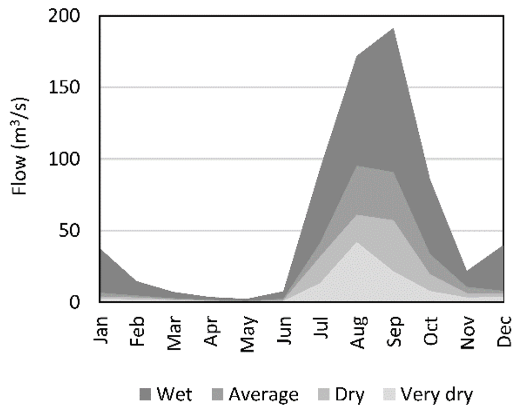
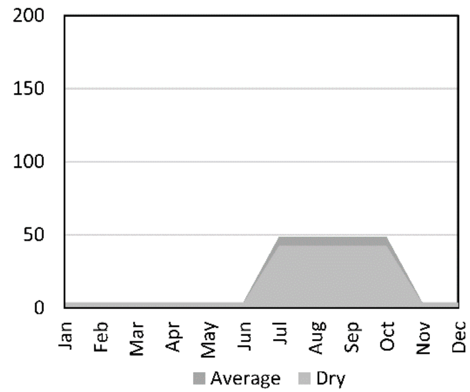
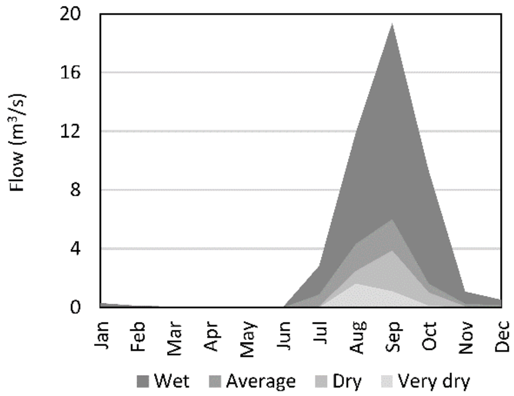
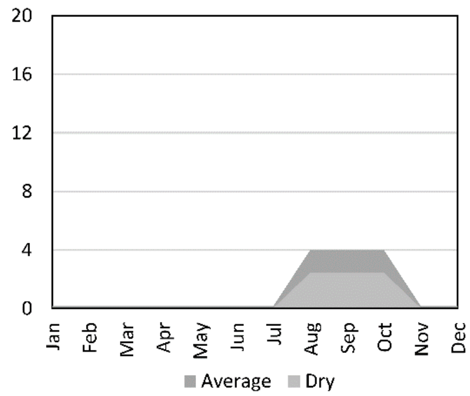
Due to the current and projected demand for water supply to food and energy production, over-extraction and flow modification have been key drivers of freshwater biodiversity loss, among others. Hydrology-based assessments grounded on the environmental water science are amongst the most cost-efficient methodologies for setting ecosystem water requirements. They fit effectively in strategic hierarchical frameworks at planning, management, and intermediate assessment levels.

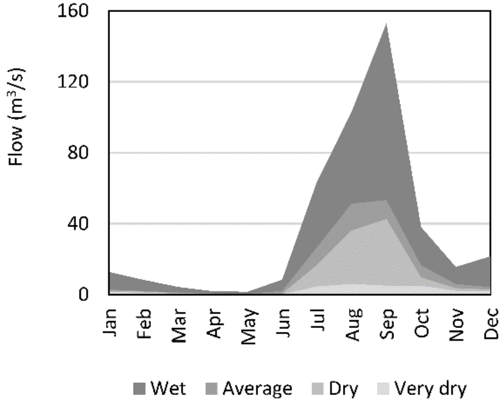
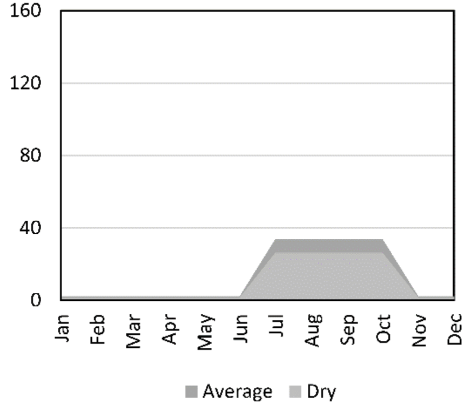
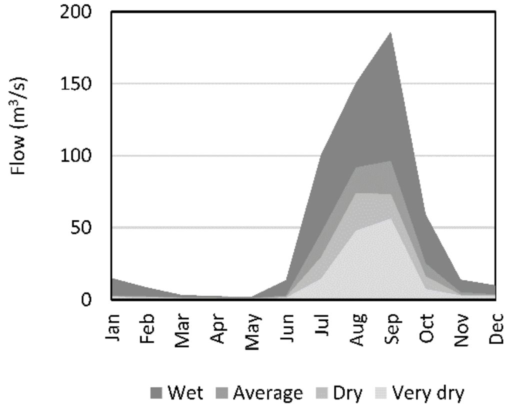
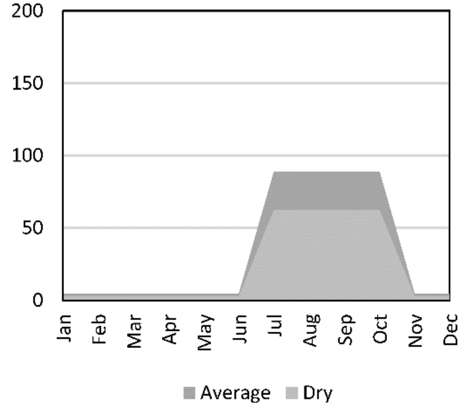
By the explicit integration of the non-stationary challenge of the flow regime in such methodologies, these thesis findings demonstrate how the potential climate change impacts on water availability could be overcome. The implementation of the climate-adaptive reference values here provided for preventive water allocations contribute to anticipate and stop the undeniable trends of freshwater biodiversity loss in a smarter way.

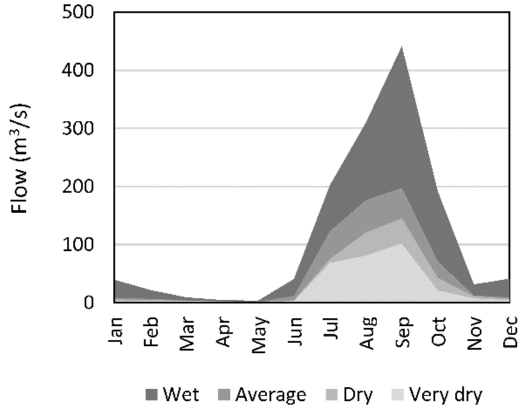
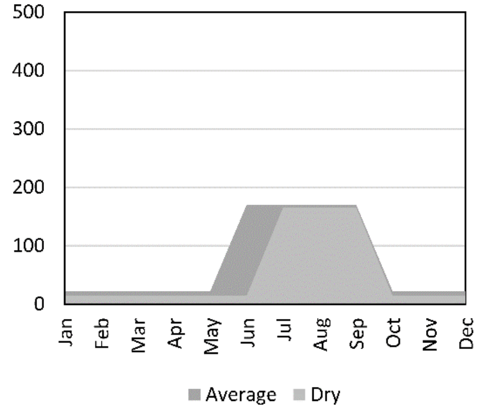
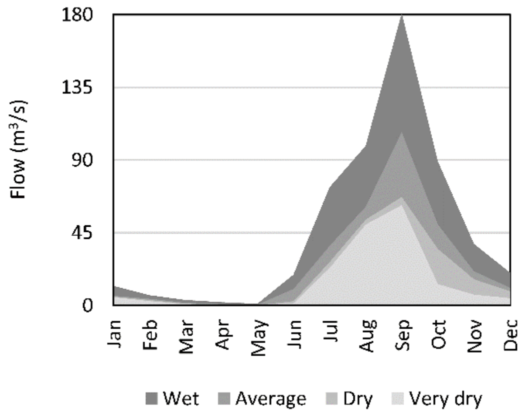
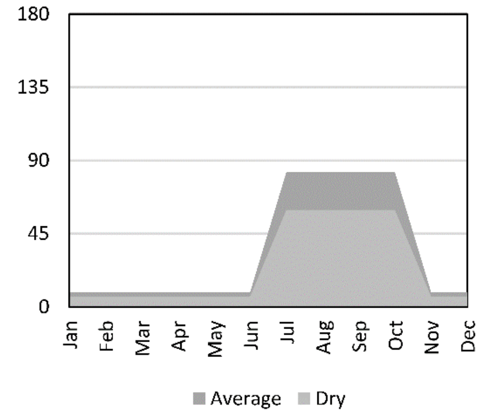
7
Appendix

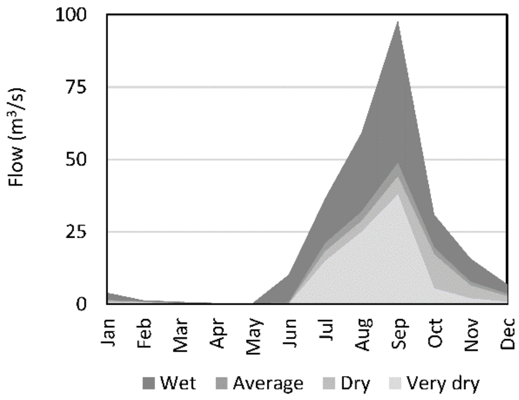
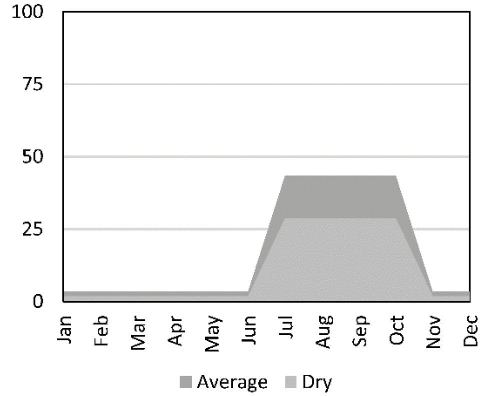
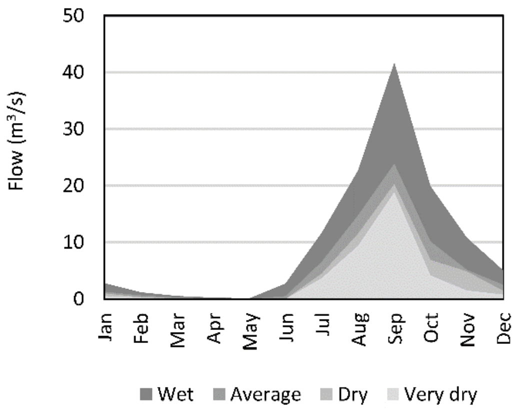
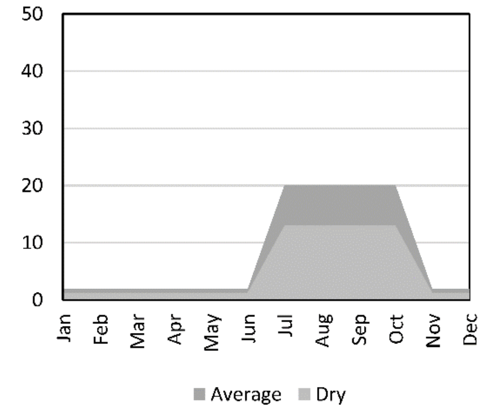
A1. Hydrological and holistic environmental flow regimes in pilot river reference sites

River basin	Environmental flows regimes (intra and inter-annual variability) Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
			Flow attribute	Cat I	Cat II	Cat III
Cerrada Laguna Salada			Magnitude (m^3/s)	23	48	90
			Frequency Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	1	1	1
			Timing (Months)		May-Jul	
			Rate of change (%)		114.2 -57.7	
El Borrego			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	9	20	46
			Frequency Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	1	1	1
			Timing (Months)		May-Jul	
			Rate of change (%)		221.1 -71.9	

<table>
<tr><th rowspan="2">River basin</th><th colspan="6">Environmental flows regimes (intra and inter-annual variability)</th></tr>
<tr><th>Hydrological approach</th><th>Holistic method</th><th colspan="4">Flood regime per category (Cat) of peak flow event</th></tr>
<tr><td rowspan="8">Piaxtla 2</td><td rowspan="8"></td><td rowspan="8"></td><td>Flow attribute</td><td>Cat I</td><td>Cat II</td><td>Cat III</td></tr>
<tr><td>Magnitude (m^3/s)</td><td>180</td><td>515</td><td>1,330</td></tr>
<tr><td>Frequency</td><td></td><td></td><td></td></tr>
<tr><td>Recurrence interval (Years)</td><td>1.0</td><td>1.5</td><td>5.0</td></tr>
<tr><td>Events in 10 years</td><td>10</td><td>6</td><td>2</td></tr>
<tr><td>Duration (Days)</td><td>7</td><td>2</td><td>1</td></tr>
<tr><td>Timing (Months)</td><td colspan="3">Jul-Oct</td></tr>
<tr><td>Rate of change (%)</td><td colspan="3">81.7
-42.6</td></tr>
<tr><td rowspan="8">Quelite 2</td><td rowspan="8"></td><td rowspan="8"></td><td>Flow attribute</td><td>Cat I</td><td>Cat II</td><td>Cat III</td></tr>
<tr><td>Magnitude (m^3/s)</td><td>20</td><td>95</td><td>325</td></tr>
<tr><td>Frequency</td><td></td><td></td><td></td></tr>
<tr><td>Recurrence interval (Years)</td><td>1.0</td><td>1.5</td><td>5.0</td></tr>
<tr><td>Events in 10 years</td><td>10</td><td>6</td><td>2</td></tr>
<tr><td>Duration (Days)</td><td>7</td><td>2</td><td>1</td></tr>
<tr><td>Timing (Months)</td><td colspan="3">Jul-Oct</td></tr>
<tr><td>Rate of change (%)</td><td colspan="3">309.7
-67.7</td></tr>
</table>

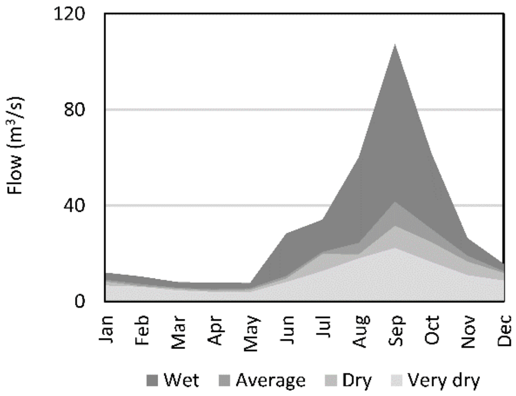
River basin	Environmental flows regimes (intra and inter-annual variability) Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
Presidio 2			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	105	330	1,150
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	5	3	2
			Duration (Days)	7	4	1
			Timing (Months)		Jul-Oct	
			Rate of change (%)		86.3 -46.3	
Acaponeta 1			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	215	595	1,760
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	3	2	2
			Timing (Months)		Jun-Oct	
			Rate of change (%)		113.7 -57.7	

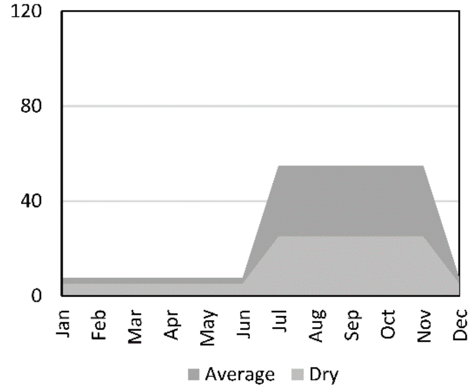
<table>
<tr><th rowspan="2">River basin</th><th colspan="3">Environmental flows regimes (intra and inter-annual variability)</th></tr>
<tr><th>Hydrological approach</th><th>Holistic method</th><th>Flood regime per category (Cat) of peak flow event</th></tr>
<tr><td>San Pedro Desem.</td><td>
</td><td>
</td><td><table>
<tr><td>Flow attribute</td><td>Cat I</td><td>Cat II</td><td>Cat III</td></tr>
<tr><td>Magnitude (m³/s)</td><td>350</td><td>800</td><td>1,900</td></tr>
<tr><td>Frequency</td><td></td><td></td><td></td></tr>
<tr><td>Recurrence interval (Years)</td><td>1.0</td><td>1.5</td><td>5.0</td></tr>
<tr><td>Events in 10 years</td><td>10</td><td>6</td><td>2</td></tr>
<tr><td>Duration (Days)</td><td>3</td><td>2</td><td>1</td></tr>
<tr><td>Timing (Months)</td><td colspan="3">Jul-Oct</td></tr>
<tr><td>Rate of change (%)</td><td colspan="3">74.5
-39.5</td></tr>
</table></td></tr>
<tr><td>San Nicolás A</td><td>
</td><td>
</td><td><table>
<tr><td>Flow attribute</td><td>Cat I</td><td>Cat II</td><td>Cat III</td></tr>
<tr><td>Magnitude (m³/s)</td><td>205</td><td>295</td><td>605</td></tr>
<tr><td>Frequency</td><td></td><td></td><td></td></tr>
<tr><td>Recurrence interval (Years)</td><td>1.0</td><td>1.5</td><td>5.0</td></tr>
<tr><td>Events in 10 years</td><td>10</td><td>6</td><td>2</td></tr>
<tr><td>Duration (Days)</td><td>2</td><td>2</td><td>1</td></tr>
<tr><td>Timing (Months)</td><td colspan="3">Jun-Oct</td></tr>
<tr><td>Rate of change (%)</td><td colspan="3">61.9
-36.1</td></tr>
</table></td></tr>
</table>

River basin	Environmental flows regimes (intra and inter-annual variability) Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
			Flow attribute	Cat I	Cat II	Cat III
Purificación			Magnitude (m^3/s)	110	200	435
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	2	1	1
			Timing (Months)		Jun-Oct	
			Rate of change (%)		56.7 -53.4	
			Flow attribute	Cat I	Cat II	Cat III
Cuitzmala			Magnitude (m^3/s)	40	85	385
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	2	2	2
			Timing (Months)		Jun-Oct	
			Rate of change (%)		137.4 -55.9	

River basin	Environmental flows regimes (intra and inter-annual variability)		
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event

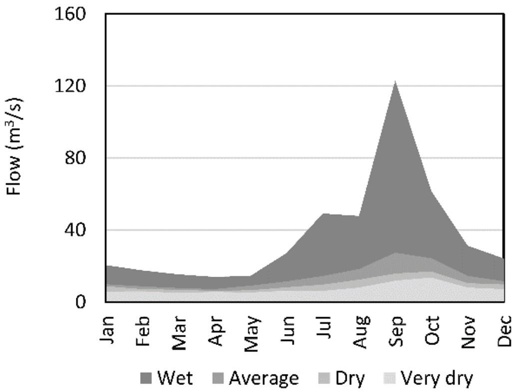
Copalita 1

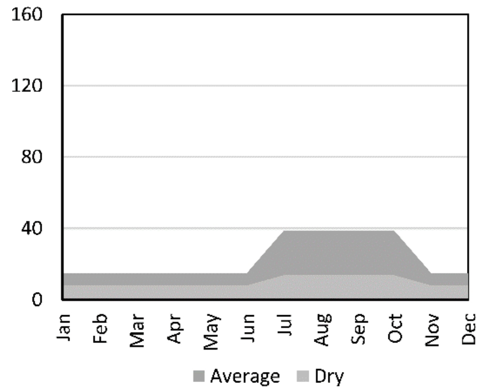




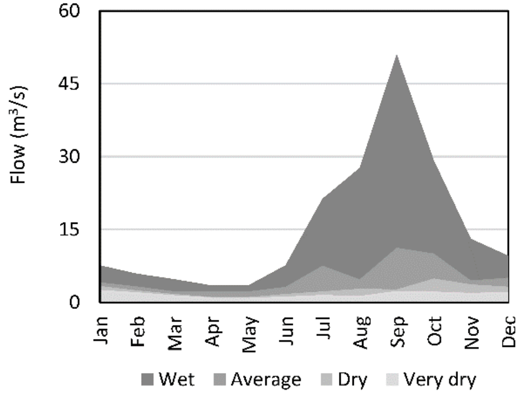
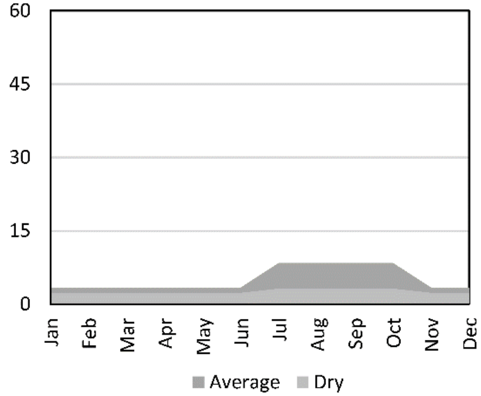
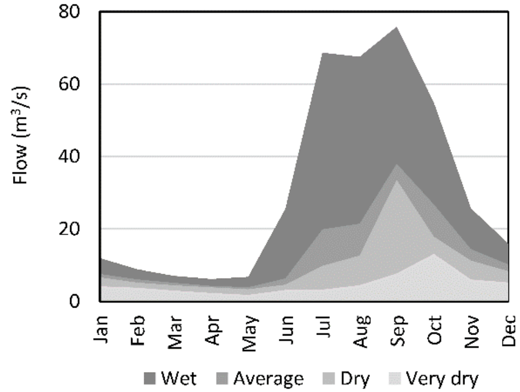
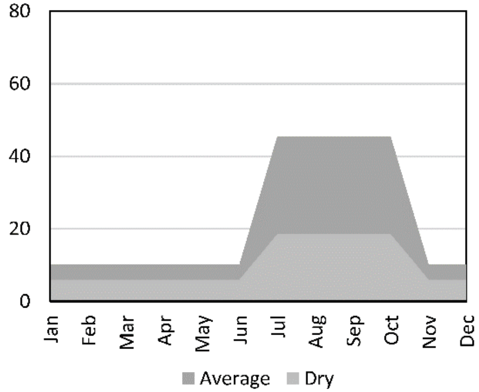
Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	30	90	560
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	4	5	6
Timing (Months)		Jul-Oct	
Rate of change (%)		55.1 -21.4	

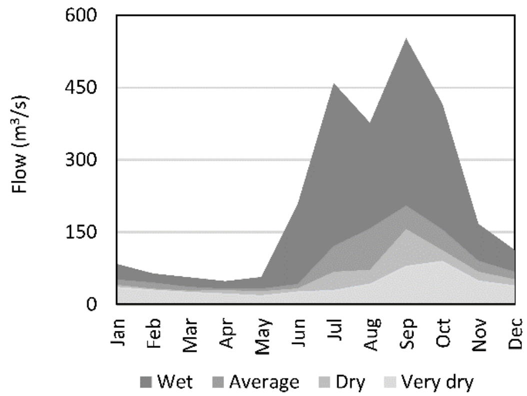
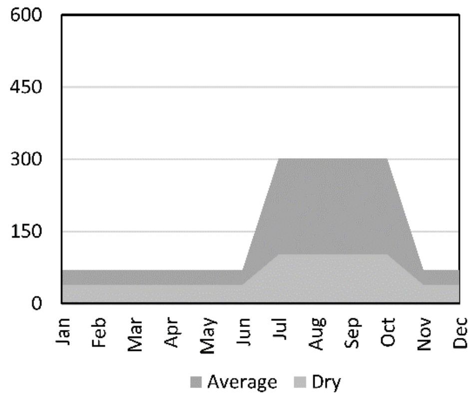
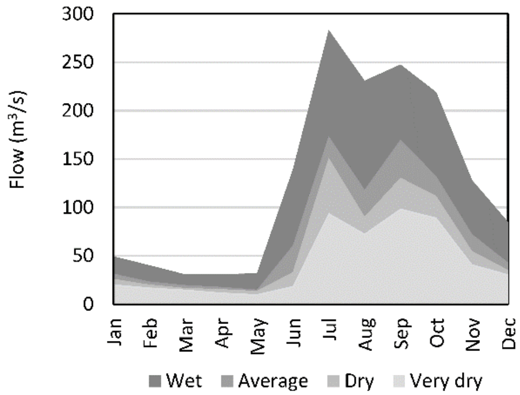
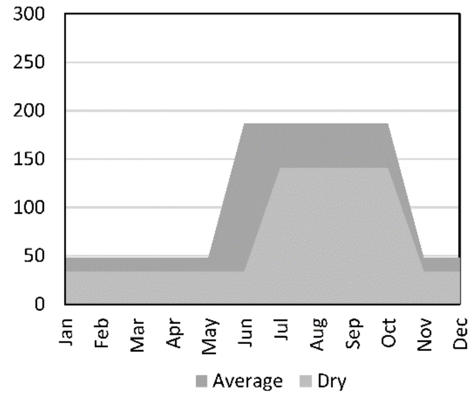
Santa María 3

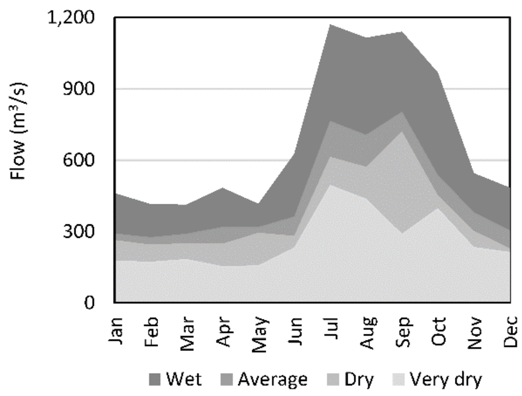
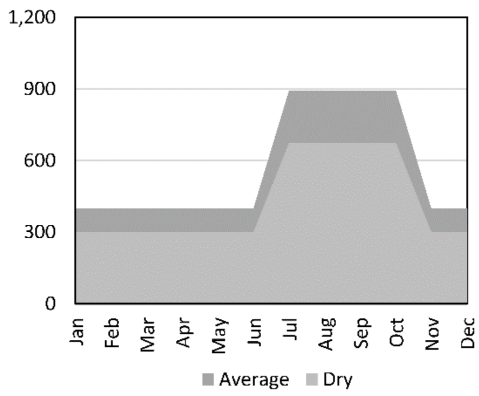
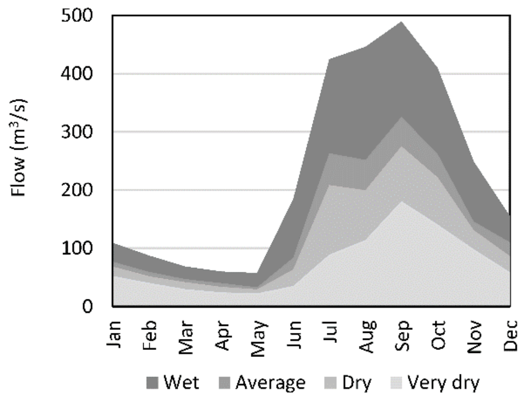
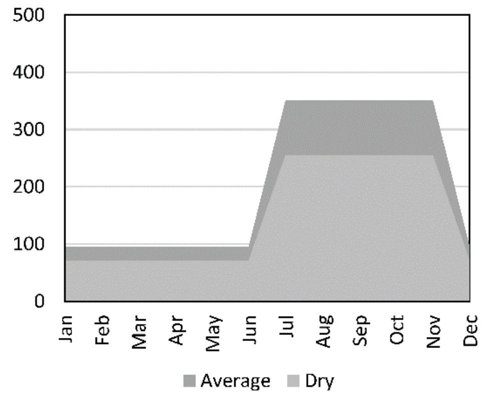




Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	95	220	775
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	4	2	3
Timing (Months)		Jun-Oct	
Rate of change (%)		128.6 -34.9	

River basin	Environmental flows regimes (intra and inter-annual variability) Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event: Flow attribute	Cat I	Cat II	Cat III
Verde 3			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	40	95	315
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	5	3	2
			Duration (Days)	4	3	3
			Timing (Months)		Jun-Oct	
			Rate of change (%)		165.1 -34.9	
El Salto			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	75	185	345
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	4	3	3
			Timing (Months)		Jun-Oct	
			Rate of change (%)		67.5 -26.2	

River basin	Environmental flows regimes (intra and inter-annual variability)					
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
Tampaón 1			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	530	1,180	2,625
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	4	3	3
			Timing (Months)		Jun-Oct	
			Rate of change (%)		75.4 -26.6	
Valle Nacional			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	525	890	1,400
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	2	2	1
			Timing (Months)		Jul-Oct	
			Rate of change (%)		78.5 -48.5	

River basin	Environmental flows regimes (intra and inter-annual variability)		
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event
Papaloapan			see below
Playa Vicente			see below

Papaloapan — Flood regime per category (Cat) of peak flow event

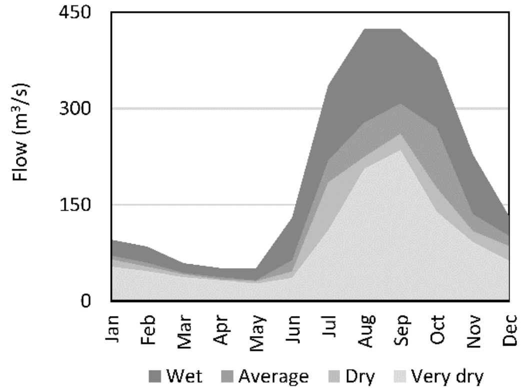
Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	1,620	3,250	5,195
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	5	3	2
Duration (Days)	4	3	3
Timing (Months)		Jun-Sep	
Rate of change (%)		36.33 -21.3	

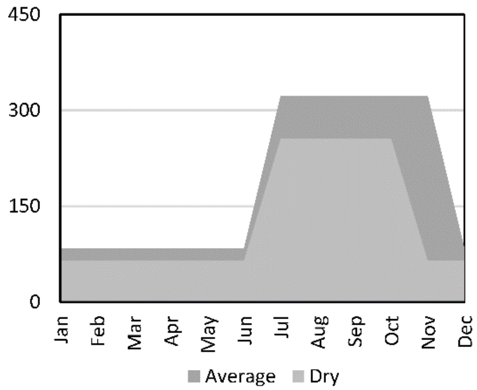
Playa Vicente — Flood regime per category (Cat) of peak flow event

Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	560	870	1,275
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	3	2	2
Timing (Months)		Jul-Oct	
Rate of change (%)		34.8 -23.9	

River basin	Environmental flows regimes (intra and inter-annual variability)		
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event

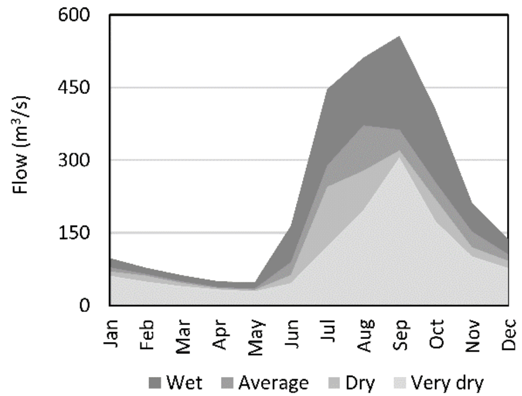
Tesechoacán

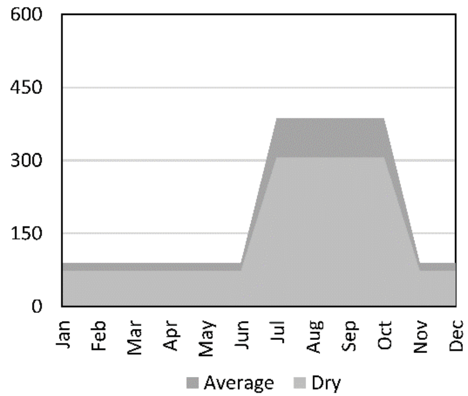




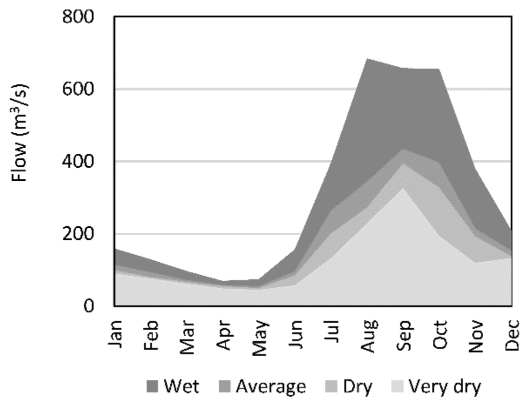
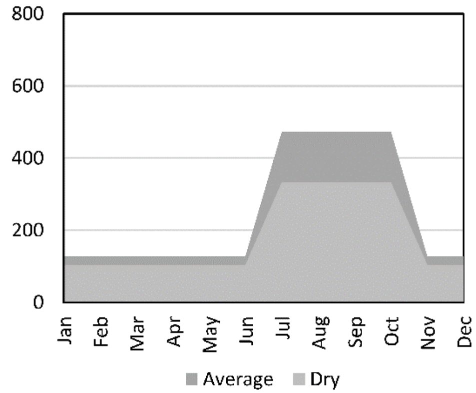
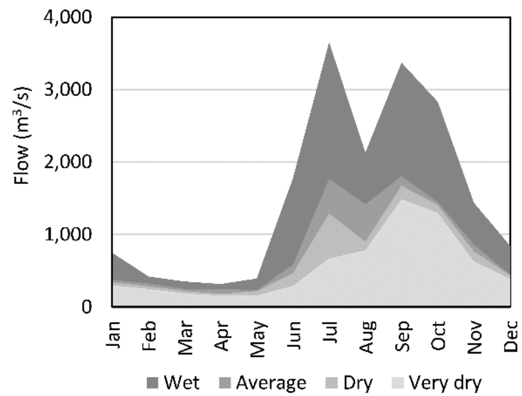
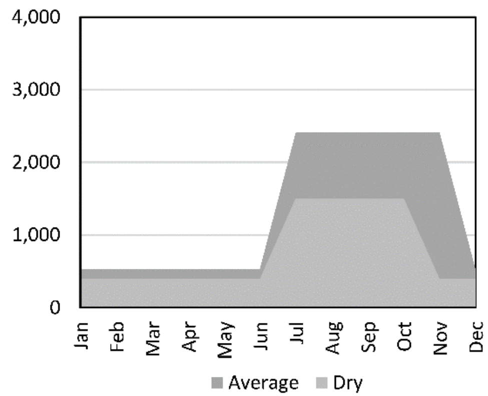
Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	440	585	790
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	12	8	8
Timing (Months)		Jul-Oct	
Rate of change (%)		42.9 -24.2	

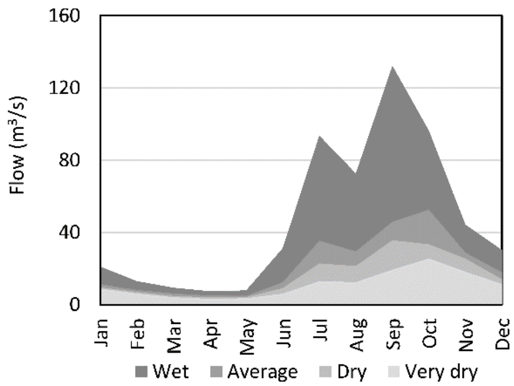
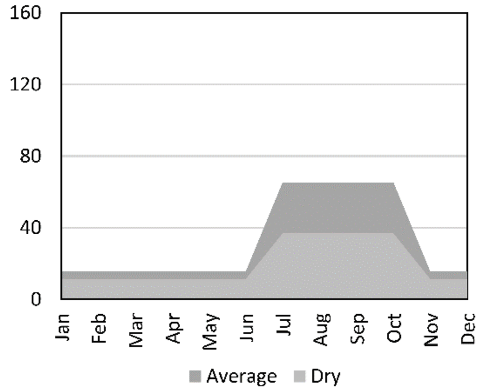
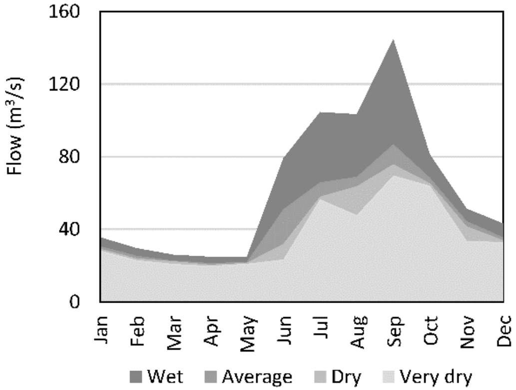
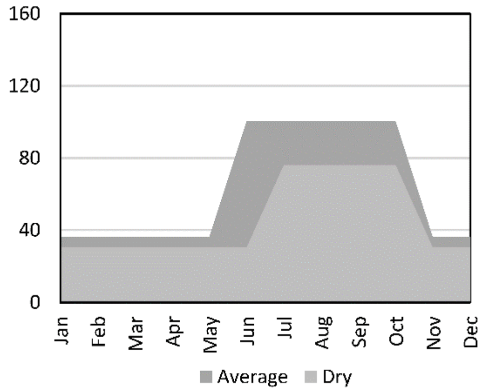
Trinidad





Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	735	1,065	1,480
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	5	3	3
Timing (Months)		Jul-Oct	
Rate of change (%)		30.5 -20.4	

River basin	Environmental flows regimes (intra and inter-annual variability)					
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
San Juan			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	585	970	1,520
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	15	9	7
			Timing (Months)		Ago-Oct	
			Rate of change (%)		18.6 -12.7	
Llanuras de Papaloapan			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	3,295	5,450	7,620
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	10	6	2
			Duration (Days)	7	5	3
			Timing (Months)		Jul-Oct	
			Rate of change (%)		29.7 -17.3	

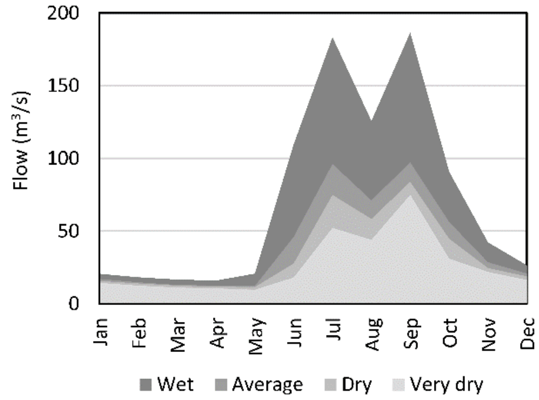
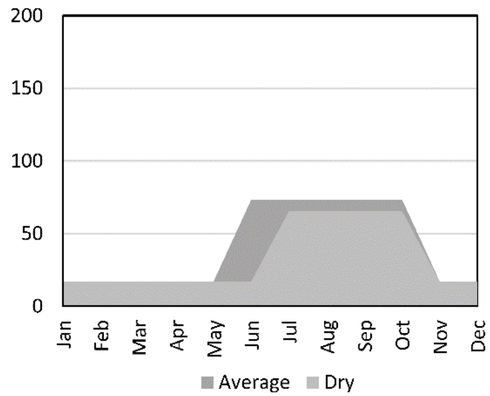
River basin	Environmental flows regimes (intra and inter-annual variability)		
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event
Grande			see below
Blanco			see below

Grande – Flood regime per category (Cat) of peak flow event

Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	85	245	590
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	8	3	2
Timing (Months)		Jul-Oct	
Rate of change (%)		83.6 -26.5	

Blanco – Flood regime per category (Cat) of peak flow event

Flow attribute	Cat I	Cat II	Cat III
Magnitude (m^3/s)	145	270	475
Frequency			
Recurrence interval (Years)	1.0	1.5	5.0
Events in 10 years	10	6	2
Duration (Days)	2	3	4
Timing (Months)		Jul-Sep	
Rate of change (%)		59.4 -36.4	

River basin	Environmental flows regimes (intra and inter-annual variability)					
	Hydrological approach	Holistic method	Flood regime per category (Cat) of peak flow event			
Jamapa-Cotaxtla			Flow attribute	Cat I	Cat II	Cat III
			Magnitude (m^3/s)	175	500	945
			Frequency			
			Recurrence interval (Years)	1.0	1.5	5.0
			Events in 10 years	5	3	2
			Duration (Days)	4	3	3
			Timing (Months)		Jul-Sep	
			Rate of change (%)		94.6 -39.0	

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