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Comprehensive Methodology and Analysis to Determine the Environmental Flow Regime in the Temporary Stream "La Yerbabuena" in Aguascalientes, Mexico

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Abstract: In this study, a comprehensive methodology was adapted to determine the environmental flow regime of "La Yerbabuena", a temporary stream located in the Aguascalientes Valley, Mexico. The analysis was divided into four stages: the geomorphological watershed analysis, a hydrologic analysis, hydraulic modeling, and environmental analysis. The main geomorphological features of the study area were defined from maps in the spatial block, and with them, a synthetic series of daily and monthly discharge was determined and further used in the next stages. In the hydrological stage, the IHA (Indicators of Hydrologic Alteration) methodology and the procedures from the Mexican regulation, named NMX-159, were applied to the stream, and their results were comparatively analyzed. A similar interannual flow variation from both methodologies was found for wet and dry seasons, ranging from 0.010 to 0.108 m^3/s. In the hydraulic modeling stage, a micro-basin part of the stream was modeled in the software HEC RAS, observing that the IHA methodology results had water levels that matched the baseflow of the stream, which allows understanding the hydraulic behavior of the water flow through the generation of different profiles in function of the rainy season. Finally, for the environmental stage, the hydrological health of the stream was evaluated using the software Flow Health, additionally observing that the IHA methodology was closer to the desired water level of the reference. This study demonstrates that the proposed methodology achieves the objectives defined by the NMX-159, which establishes a streamflow regime considering a natural interval of hydrologic variability in both ordinary and after-disturbance conditions. This application of the methodology for temporary streams provides an understanding of the hydrological behavior of the environmental flow throughout the year, and regarding the existing regulations, it presents a correlation with the obtained results, as well as greater precision in the dry season.

Keywords: baseflow; temporary streams; environmental flow; hydraulic modeling; hydraulic depth

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Citation: Reyes-Cedeño, I.G.; Hernández-Marín, M.; Pacheco-Guerrero, A.I.; Gannon, J.P. Comprehensive Methodology and Analysis to Determine the Environmental Flow Regime in the Temporary Stream "La Yerbabuena" in Aguascalientes, Mexico. *Water* **2023**, *15*, 879. https://doi.org/10.3390/w15050879

Academic Editor: Aizhong Ye

Received: 7 January 2023
Revised: 10 February 2023
Accepted: 15 February 2023
Published: 24 February 2023

1. Introduction

Currently, there is a need to define healthy flow conditions in temporary streams, such as the minimum annual baseflow, in order to prevent and manage risks that could affect the surrounding ecosystem [1]. A temporary stream is described in the literature as a stream that does not have year-round surface flow [2].

One way to quantify healthy flow conditions is to define their natural variability regime, better known as environmental flow. This is defined as the duration and quantity of streamflow needed to preserve the recovery capacity of natural ecosystems and safeguard their characteristic species [3–5]. Worldwide, there exist numerous methodologies to assess the environmental flow, however, these methods often yield different results. For this reason, there is a global effort to establish environmental flow regulation through a rigorous implementation of a consistent method [6,7].

Since there are a wide variety of methodologies to evaluate environmental flow (Figure 1), it is important to understand the role that each component of the Natural Hydrological Regime (NHR) plays in terms of structure and functionality [8]. One approach to evaluate environmental flow is to use hydrologic methods, which (except the methodology of the IHA-RVA (Indicators of Hydrology Alteration-Regime of Variable Alteration)) use a simple statistical analysis, determining flow by occurrence probabilities of low flows. However, these methods may underestimate the complex character of natural systems [9].

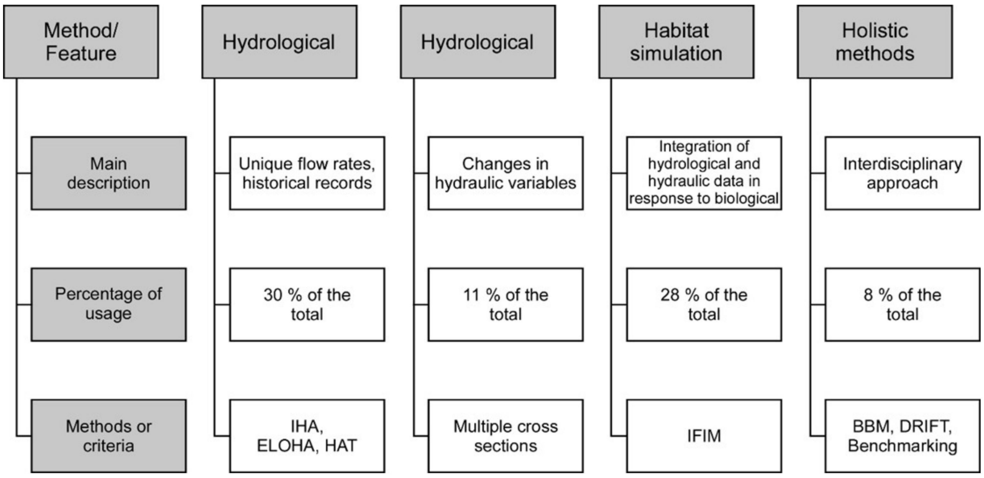

Figure 1. Classification of methodologies to determine environmental flow. From the methods or criteria: IHA = Indicators of Hydrological Alteration, ELOHA = Ecological Limits of Hydrological Alteration, HAT = Hydrological Assessment Tool, IFIM = Instream Flow Incremental Methodology, BBM = Building Block Methodology, DRIFT = Downstream Response to Imposed Flow Transformations.

Recent work towards establishing methods to determine environmental flows has increasingly focused on ecohydrological methods, which integrate hydrological, hydraulic, and biological response data in order to identify key flow events for a range of ecosystem components [10,11]. In Mexico, the NMX-AA-159-SCFI-2012 normative establishes diverse methodologies to determine the environmental flow of a river; nevertheless, the appendix of its regulation only focuses on perennial streams, which have continuous streamflow throughout the year. However, some northern and central watersheds of Mexico, such as those of the Aguascalientes state, have dry climatic conditions and deep water tables, resulting in the occurrence of temporary streams [12]. These types of streams are also very common worldwide and are receiving particular attention because they are becoming more common [13]. In fact, a conservative estimation is that temporary streams represent more than 30% of the global stream length, resulting from several anthropogenic factors such as direct extraction of water from the rivers, groundwater extraction, and damming [14]. This has caused the conversion of some streams from perennial to temporary, including some branches of great rivers such as the Nile, Indo, Yellow, Amu, Syr Darya, Rio Grande, and Colorado. It is expected that the number of temporary rivers will grow in regions with drying climates and/or increased water appropriation [15].

Regarding surface water contamination, the authors of [16] evaluated the spatiotemporal variation of the concentrations of organic matter, nutrients, organic toxins, and coliform organisms and heavy metals in the San Pedro River, Aguascalientes, Mexico, which together with the research in [17] used two toxicity tests (*Daphnia magna* and *Lecane quadridentata*) in the main treatment plants in the state of Aguascalientes, during the dry and rainy seasons. It was observed that the COD (chemical oxygen demand) and BOD5 (biochemical oxygen demand), dissolved oxygen, conductivity, and pH values complied with the maximum permitted levels. However, the levels of Al, Fe, Zn, Mn, Pb, and As were above the permitted levels, concluding that this type of study would be the subsequent step once the hydraulic behavior of the type of temporary currents was analyzed. In another case [18], coupled hydrological and hydraulic models in a 2D numerical model were used to estimate hydraulic transmission losses due to infiltration in a river, placing control points along sections of the San Pedro River basin in Sonora, Mexico and Arizona, USA. For this, two hydraulic models were installed, where the first only considers the net runoff from the canal and the second was developed to take into account several hydrographs with transmission losses as limitation conditions, considering the losses due to infiltration. At the same time, the authors of [19] worked on the isotopic characterization of rainwater and groundwater in order to obtain potential recharge sites in the Calera basin, Zacatecas, taking the fault zone as the main variable and cracks in conjunction with the area's hydrographic network, as well as stable isotope water sampling.

The flow regimes in temporary flow in streams are understudied, despite their wide distribution and importance for the management and conservation of water resources. For instance, during rainy seasons, these streams transport more solids and cause retention zones generated by the topography of the area. Delso et al. [20] state that to understand and characterize flow patterns of temporary streams, descriptors of dry periods, such as frequency and duration, must be known. To conclude, coupling a methodology based on indicators of hydrological alteration with an eco-hydraulic simulation could offer better results to determine the environmental flow of temporary streams.

The main objectives of this study are as follows:

1. Define the regime of environmental flow for La Yerbabuena stream, adapting the existent methodologies for temporary streams.
2. Compare the results of environmental flow obtained with the proposed methodology for temporary streams against the methodologies of existing standards.
3. Apply hydraulic modeling to understand the behavior of La Yerbabuena as a temporary stream under scenarios of dry and rainy seasons.

The importance of the research is that it involves a proposed methodology to determine the environmental flow of a temporary river, which is based on the IHA-RVA procedure to determine a variability threshold. On the other hand, by comparing the proposed methodology with the application of the NMX-159 normative in Mexico, it permitted us to obtain a comparative framework of the results, because in terms of temporary rivers, the existing information is scarce. This is the main contribution and importance of this analysis: it is an exploratory study that provides information on the hydrological behavior of a temporary river. In addition, the comparison of methods established criteria of similarity, tendency, advantages, and disadvantages about the analysis of environmental flow in temporary rivers. Therefore, if a method offers a different result, this indicates, in the case of the IHA methodology, that it provides additional data, such as an analysis of periods of drought and environmental flow thresholds considering daily series, with respect to existing methodologies that have a more general analysis.

Application of the IHA Methodology for the Determination of Environmental Flows in Temporary Rivers

The IHA-RVA methodology has been applied in various cases around the world and has different approaches, especially for recommendations of ecological flows. This methodology is supported by the IHA 7.1 software, including hydrological parameters to establish ranges of environmental variables [21,22]. There are recent investigations of ecological flow using this methodology that favored the development of the experimental campaign that is presented in Appendix A.

For example, there was a recent investigation on the Yuna River in the Dominican Republic, where environmental flows were estimated using this method of analysis at three points in the basin, and the series of daily flows were obtained by means of the generic combination of mostly monthly flows. This study concluded that the application of the

IHA methodology is a recommended option to carry out calculations of ecological flows whose results can be used to develop a reservoir operation program [23]. Another investigation was recently carried out in Mexico for the Mezcalapa river. For this investigation, hydrological and hydraulic methodologies were complemented using a series of data of 19 and 35 years for the natural and altered regime, respectively, identifying physical features and their relationship with the environmental processes, obtaining hydrological values through hydraulic modeling that are related to the development of the ecosystem [24]. In another case applied to the operation of reservoirs [25], the IHA methodology was used to determine, through the environmental flow threshold, an experimental operation of the Jinghong reservoir in the upstream part of the Mekong basin, comparing five scenarios with different objective functions and constraints. These are some examples of the application of both methodologies, however they were all concerning sections in perennial rivers (Appendix B). Therefore, an area of opportunity is to apply this methodology in temporary rivers, comparing with current regulations in the case of the study area.

2. Materials and Methods

The purpose of this study was to find a method for determining environmental flows in temporary streams, based on the regime of hydrologic alteration of the stream under study. To do this, the methodology was divided into four stages: geo-spatial, hydrologic, hydraulic, and environmental. Furthermore, the IHA (Indicators of Hydrologic Alteration) methodology described by Richter et al. [26] was applied. This methodology is based on 33 intra-annual attributes of ecological relevance, composed by 67 statistical parameters, but divided into 2 groups: the IHA parameters and the parameters of the Environmental Flow Components, as stated in The Nature Conservancy Manual [21]. Figure 2 displays a generalized scheme of the four stages that define the methodology.

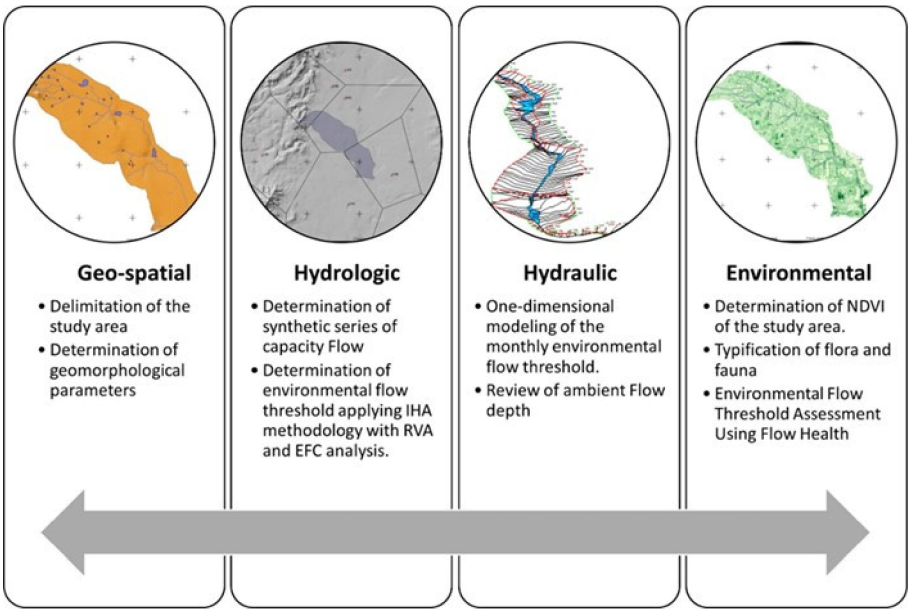

Figure 2. Descriptive scheme of the global methodology, describing the activities performed in each of the four stages that define the core methodology.

2.1. Study Area

This study was conducted west of Aguascalientes, Mexico, in the watershed containing La Yerbabuena stream. The La Yerbabuena watershed is 17.05 km^2, with a perimeter of 23.07 km and a stream length of 11.65 km. The average watershed slope is 2%, with a land use of 40% for agricultural areas, 38% for urbanized areas, 17% for rural settlements, and the rest is mountainous areas. The mean annual precipitation is on the order of 520 mm, while the potential evapotranspiration is of 2200 mm [27]. At the regional scale, La

Yerbabuena stream represents the main tributary of the San Pedro River Basin, which is inside the Hydrologic Region Lerma-Santiago (Figure 3). This hydrologic region is classified as environmental objective type-D, according to the NMX-159, which implies a deficient conservation state.

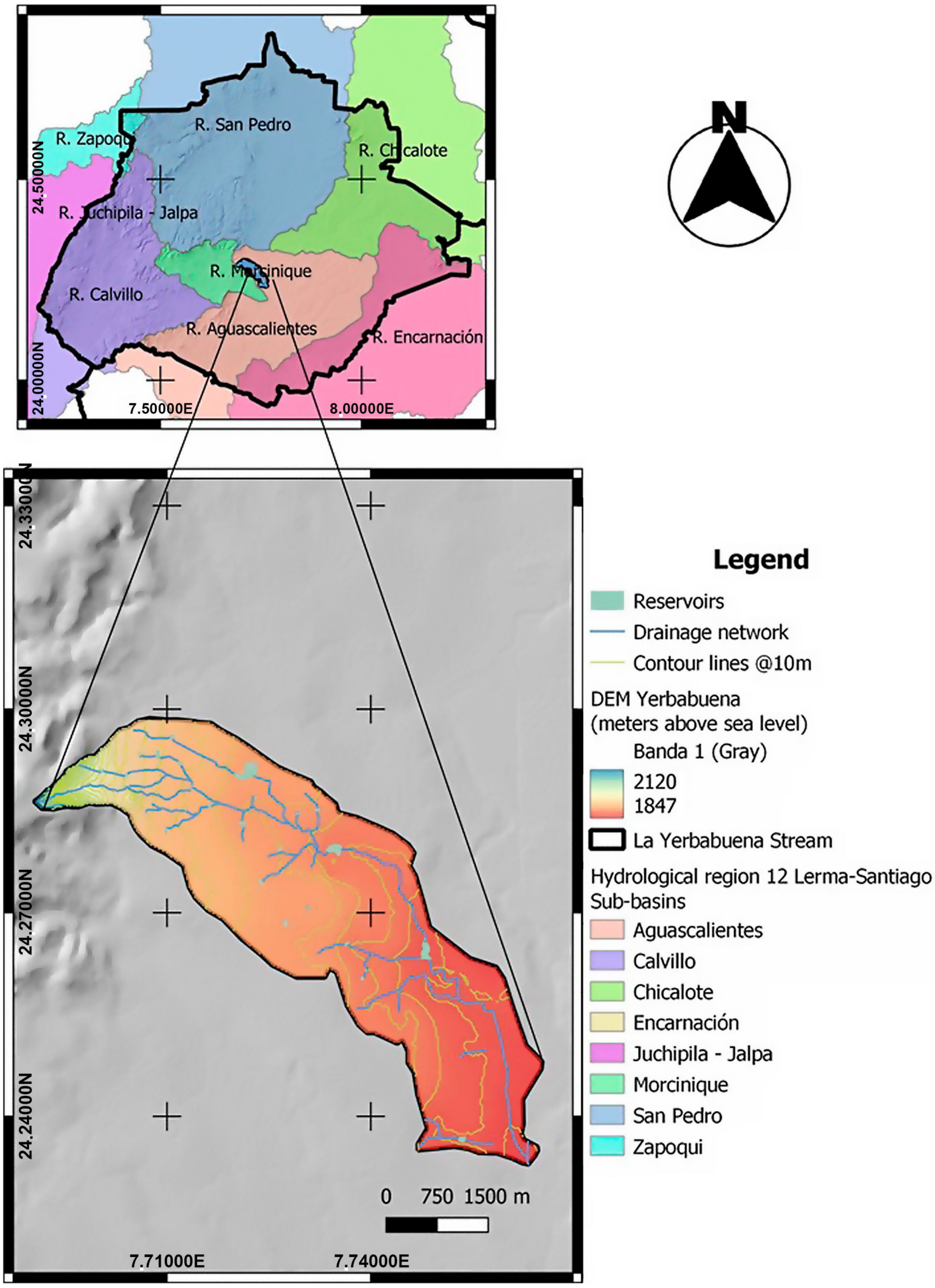

Figure 3. Description and main characteristics of the study area, that includes the reservoirs, drainage network, and contour lines from the sub-basin "La Yerbabuena".

Particularly, La Yerbabuena stream was selected because it is typical of a temporary stream, with common wet (June–August) and dry seasons. Additionally, the watershed experienced a notable change in its topography and land cover after an increase in urbanization starting in 1992.

2.2. Geo-Spatial Stage

The main geomorphological parameters were obtained during the geo-spatial analysis. The software programs Qgis and Google Earth were used to obtain the geomorphological maps, such as land use, drainage network, slope, and elevation of the study area. A topographical field survey was complemented with digital elevation models of the stream reach.

2.3. Hydrologic Stage

The watershed involved in the study is currently not gauged, and therefore, a synthetic time series of monthly and daily discharges was estimated to obtain the regime of environmental flow. To calculate synthetic discharge, the IHA methodology was applied. Initially, the synthetic flows were determined using both the weighted precipitation from daily maximum records and the number of the runoff curve number (N). The first was computed with the precipitation records of hydro-climatic gauges around the study zone, along with the Thiessen Polygons Method, while N was obtained using maps of vegetal and land use cover. To complete the required parameters, the streamflow in normal conditions was determined using the drained area of the study basin, along with the runoff coefficient and the drainage time. Once the synthetic series of daily flows was created, the software IHA 7.1 (Appendix A) was used to determine the regime of environmental flow through a parametric analysis of two periods, the first before disturbance by human activities (1950–1992) and the second after that event (1992–2013). Furthermore, with the series of monthly flows, the Appendices C (Tennant modified) and D (WWF), from the 10NMX-159 normative, were estimated, in order to compare the modified flow regime.

IHA allows assigning a classification for each daily flow record, obtaining that the component with the highest frequency in the analyzed micro-basin is the extremely low flow that works as base flow in retention zones, whose topography was affected by the presence of infrastructure. In addition to offering a monthly analysis with the series of daily records, it allows to establish a monthly variability threshold for environmental flow strategies.

The methodology applied to determine the synthetic series of flows was to take the precipitation in excess of the different climatological stations within the basin of the study area, and then to later carry out a weighting of the precipitation according to the area of influence of each meteorological measurement point.

The equation used for the synthetic series of expenses was:

$$\mathrm{Ve} = \mathrm{C} \times \mathrm{Pe} \times \mathrm{A} \quad (1)$$

Ve = Volume of runoff (m^3)
C = Runoff coefficient (adimensional)
Pe = Excess precipitation (mm)
A = Basin area (m^2)

To determine Pe, a hydrological criterion was applied using the following formula:

$$Pe = \frac{\left(P - \frac{5080}{N} + 50.8\right)^2}{P + \frac{20320}{N} - 203.2} \quad (2)$$

P = Precipitation record (mm)
N = Runoff curve number for the average moisture condition of the basin (adimensional)

2.4. Hydraulic Modeling Stage

A one-dimensional model was used with the discharge data obtained by the IHA methodology and the NMX159 normative in order to determine the maximum hydraulic depth of the water in the stream for the environmental flow. The software HEC RAS was used for permanent and varied flow. Furthermore, the simulations of three types of ecological years requested in the NMX-159 normative were modeled. These three years include dry, medium, and humid years, in order to evaluate the health conditions of the main stream.

2.5. Environmental Stage

The open-source software Flow Health was used to evaluate the methodology of the IHA and compare it with the NMX-159. In addition, a field survey of the species of flora and fauna was conducted in the study area for their classification. Finally, based on LANDSAT-8 satellite images, the NDVI (normalized difference vegetation index) of the study area was determined to evaluate the quality and development of the flora. Once the information was integrated and evaluated, different scenarios were modeled to define the regime of flow variability for the prevalence of the local and neighboring ecosystems to natural temporary streams.

3. Results

According to the Appendix A of the NMX-159, which presents a list of environmental objectives for hydrological basins of Mexico, "La Yerbabuena" stream was classified as an environmental objective D, with high use pressure, low ecological importance, poor-quality conservation status, 40% of areas destined for cultivation and livestock, and approximately 60% for human settlements.

The following sections provide the results of the characterization based on analyses of the four parts of the study: geo-spatial, hydrologic, hydraulic modeling, and environmental analyses.

3.1. Geo-Spatial Characterization

Maps of vegetation, land use, and the river network location and profile were obtained from the spatial and hydrologic analysis. The river was calculated to be 11.65 km long, with an average slope of 2% (Figure 4). The computed geomorphic parameters are shown in Table 1 and were obtained through analysis of the hydrologic network and digital elevation model in the software Qgis and Grass [28].

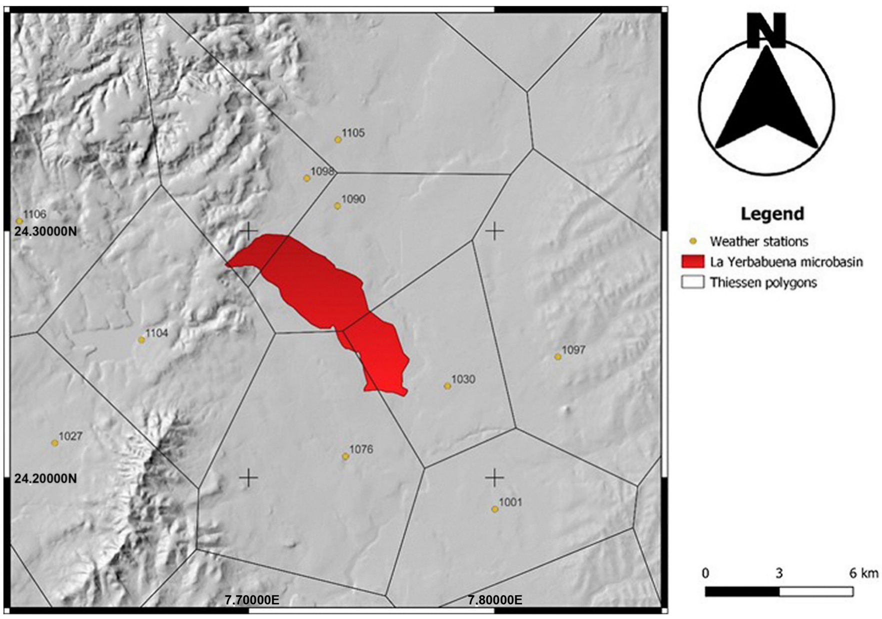

Figure 4. Trace of the Thiessen polygons to estimate the average rain, which includes the location of weather stations.

Table 1. "La Yerbabuena" micro-basin hydrogeological parameters.

SCS curve number	70.00
Drained area (km^2)	16.12
Medium slope of the basin (m/m)	0.02
Runoff coefficient, C	0.34

To obtain the curve number, a spatial analysis was completed considering five land cover areas in the micro-basin, which were: highlands, agricultural and livestock, country, rural, and human settlements, and each of them was assigned with a number (N) based on data of tables from [29], as shown in Table 1. This analysis resulted in an average runoff coefficient of 0.34 and a runoff curve number of 70 (Table 1).

3.2. Hydrologic Characterization

The annual average precipitation was estimated using the Thiessen polygons method (Figure 4), and the monthly records of precipitation were from the hydro-climatic gauges adjacent to the study zone, which have been operating since 1979. However, to complete the missing yearly data, the rational deductive method was used [29,30]. From the Thiessen polygons, the station named "Jesús María" (1090) resulted with the greatest area of influence; therefore, the daily maximum precipitation records were used together with the geomorphic parameters from Section 3.1 to calculate the synthetic series of monthly and daily discharges, as shown in Table 2.

Table 2. Synthetic series of monthly flows (m^3/s).

Year\Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	0.091	0.005	0.225	0.278	0.000	0.000	0.104	0.966	0.089	0.147	0.147	0.135
1980	0.000	0.158	0.278	0.170	0.007	0.043	0.018	0.026	1.211	0.096	0.127	0.125
1981	0.011	0.248	0.294	0.001	0.259	0.001	0.000	0.181	2.648	0.036	0.127	0.067
1982	0.000	0.000	0.294	0.051	0.009	0.046	0.000	0.278	0.010	0.003	0.000	0.000
1983	0.099	0.000	0.000	0.000	0.000	0.874	0.323	0.002	0.000	0.072	0.194	0.000
1984	0.099	0.242	0.000	0.000	0.002	0.002	0.493	0.001	0.002	0.189	0.278	0.248
1985	0.263	0.311	0.000	0.099	0.087	0.002	0.046	0.220	0.038	0.001	0.317	0.002
1986	0.000	0.117	0.000	0.000	0.147	0.085	0.645	0.009	0.013	0.037	0.091	0.000
1988	0.000	0.000	0.137	0.147	0.000	1.504	0.662	0.005	0.248	0.000	0.000	0.000
1989	0.000	0.000	0.000	0.000	0.010	0.134	0.006	0.015	0.225	0.005	0.028	0.002
1990	0.091	0.091	0.000	0.137	0.117	0.055	0.807	0.141	0.005	0.012	0.000	0.000
1991	0.000	0.147	0.000	0.000	0.000	0.056	1.040	0.001	0.000	0.003	0.000	0.033
1992	0.000	0.170	0.123	0.091	0.006	0.280	0.000	0.259	0.061	0.111	0.181	0.186
1993	0.001	0.000	0.000	0.207	0.220	0.014	0.049	0.037	0.009	0.091	0.170	0.000
1994	0.001	0.000	0.000	0.020	0.127	0.046	0.037	0.091	0.015	0.000	0.000	0.127
1995	0.248	0.170	0.000	0.000	0.091	0.546	0.183	0.201	0.037	0.000	0.009	0.000
1996	0.000	0.294	0.000	0.263	0.038	0.014	0.099	0.005	0.334	0.000	0.328	0.000
1997	0.248	0.000	0.207	0.014	0.075	0.055	0.061	0.004	0.038	0.020	0.127	0.000
1998	0.000	0.000	0.000	0.000	0.000	0.068	0.051	0.007	0.003	0.043	0.000	0.000
1999	0.000	0.000	0.294	0.000	0.311	0.024	0.000	0.081	0.397	0.207	0.000	0.000
2000	0.000	0.000	0.000	0.000	0.001	0.000	0.037	0.005	0.001	0.220	0.000	0.049
2001	0.000	0.194	0.003	0.083	0.248	0.001	0.006	0.014	0.021	0.049	0.294	0.335
2002	0.061	0.061	0.000	0.000	0.014	0.546	0.056	0.546	0.021	0.091	0.037	0.000
2003	0.248	0.311	0.000	0.000	0.028	0.442	1.668	0.003	0.009	0.091	0.000	0.000
2004	0.000	0.000	0.091	0.000	0.002	0.417	0.323	0.718	0.021	0.234	0.294	0.000
2005	0.000	0.003	0.127	0.000	0.091	0.779	0.119	0.417	0.020	0.220	0.000	0.248
2006	0.248	0.000	0.000	0.000	0.091	0.006	0.442	0.005	0.020	0.323	0.000	0.005
2007	0.061	0.061	0.000	0.028	0.002	0.261	0.183	0.033	0.000	0.108	0.311	0.311
2008	0.000	0.000	0.000	0.068	0.311	0.004	0.085	0.166	0.021	0.000	0.000	0.000
2009	0.000	0.000	0.000	0.000	0.248	0.055	0.041	0.078	0.003	0.004	0.038	0.117
2010	0.017	0.442	0.000	0.263	0.278	0.009	0.001	0.006	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.311	0.000	0.005	0.127	0.099	0.005	0.075	0.000	0.000
2012	0.075	0.009	0.000	0.000	0.000	0.067	0.032	0.072	0.104	0.127	0.294	0.006
2013	0.147	0.000	0.000	0.000	0.000	0.091	0.826	0.002	0.012	0.028	0.002	0.000

Based on the historical monthly flows previously estimated from climatological data (Section 2.3) and as stated in the normative, the dry, average, and wet years were calculated. Likewise, using historical precipitation data, a synthetic series of monthly flows were generated using the minimum flow values for a dry year, the average values for the average year, and the maximum values for a wet year. In Table 3, the flow values (m^3/s) are shown, and they were used in the determination of the environmental flow regime.

Table 3. Values of flow rate (m^3/s) to estimate the hydrologic year. Y/M is the abbreviation of year/month.

Y/M	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000
Humid	0.263	0.442	0.294	0.311	0.311	1.504	1.668	0.966	2.648	0.323	0.328	0.335
Average	0.059	0.089	0.061	0.066	0.083	0.192	0.252	0.138	0.166	0.078	0.100	0.059

With the IHA methodology, the series of daily flow was processed in the IHA 7.1 software for a parametric analysis of two periods, using the average and standard deviation of the environmental flow. This analysis to calculate the daily flow from the IHA methodology was chosen for frequency analyses of flooding or average monthly flow, in accordance with recommendations of The Nature Conservancy Manual [21]. A two-period option was used due to the noticeable changes in the land cover of the study zone after 1992 due to anthropogenic activities, the first from 1950 to 1992, and the second to 2013 (Figure 5).

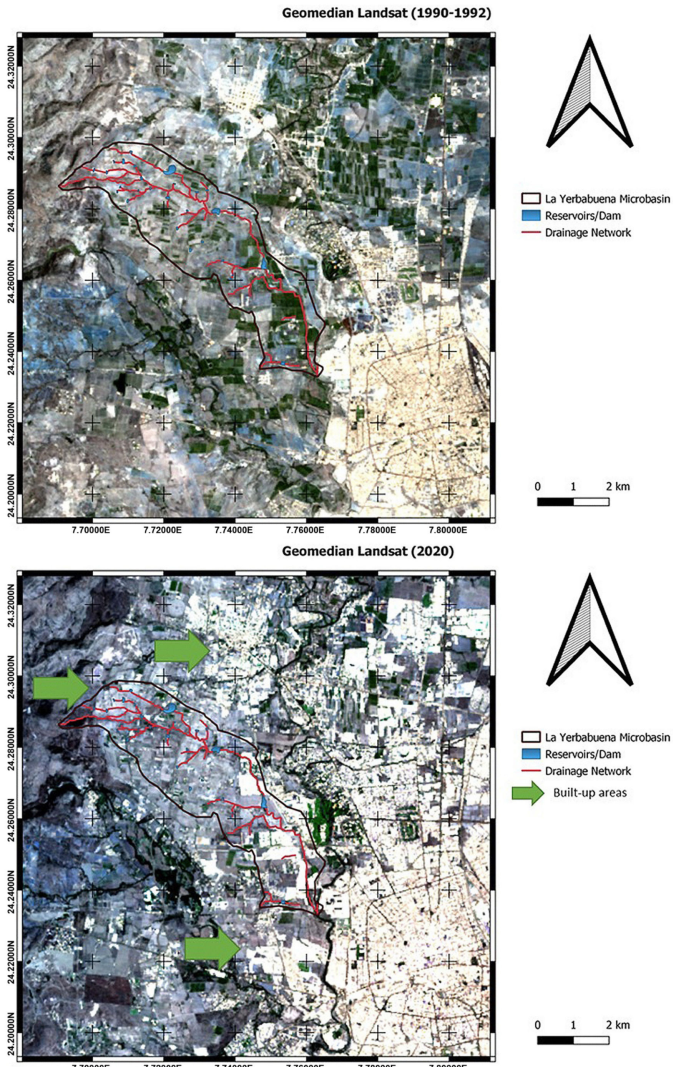

Figure 5. Geo-median Landsat image: it includes the development of urbanization in the study area, from the first image (1990–1992) to the one in the lower part, which is the most recent condition (2020).

In order to determine the regime of natural variability and the environmental flow, the parameters from the IHA methodology were used because they define the regimes of variability that streams display in either average conditions or with long drought periods. These flows can be assumed as the historic behavior of the stream. This historic behavior was used to analyze the variations of wet and dry seasons. To do this, we calculated the average monthly discharge, with the wet period defined as June to September.

The minimum environmental flow was calculated to be 0.010 m^3/s and 0.108 m^3/s for the dry and rainy seasons, respectively, using the year of 1992, which is the year when the human settlements began to develop in the zone (Figure 6). From this graph, the longest drought period was obtained, which resulted as 320 days in the pre-impact period (1980–1992), and 330 days for the post-impact period (1992–2013). Additionally, the rainy season for the pre-impact years was 6 months, and for the altered period the dry season decreased to 9 months.

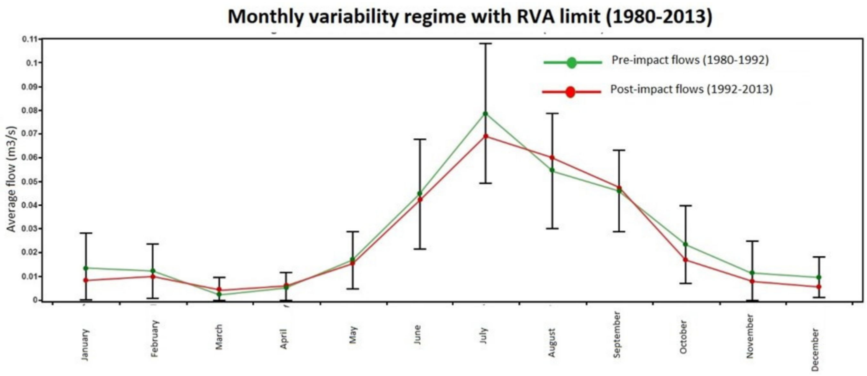

Figure 6. Regime of annual variability, which allows to observe the periods of rain and drought throughout the year.

To more accurately determine the monthly value of environmental flow, the hydrograph of the monthly variability of flow was developed, as shown in Figure 7 for July.

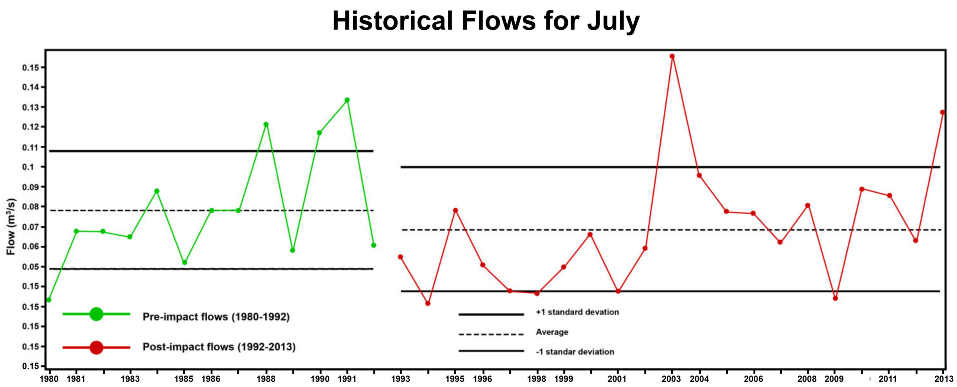

Figure 7. Regime of monthly flow variability for July: the two scenarios of pre- and post-impact for disturbances after urbanization. Limits of +1 and −1 of standard deviation are included.

3.3. Hydraulic Characterization

As an evaluation instrument in the hydraulic stage, the software program HEC RAS was used to develop one-dimensional models and evaluate the hydraulic depth that the water in the stream would reach for the environmental flow, and the result was compared with that from the NMX-159. To define the modeling zone, the local topography of the chosen suburban section of the "La Yerbabuena" stream was processed. The chosen section was from the locality "Tres Arroyos" because it is the area most affected by the urbanization around the stream, to its confluence point at the San Pedro River (Figure 8). With this information, the natural regimes for the dry, average, and wet years were modeled, resulting in flood maps for the wet year, with water levels more than a meter above the dry and average years. Moreover, the modeled discharge obtained by the IHA methodology was compared with that of the NMX-159. The IHA methodology resulted in maximum water levels in the modeled cross-sections of 0.10 to 0.20 m, with velocities up to 0.86 m/s.

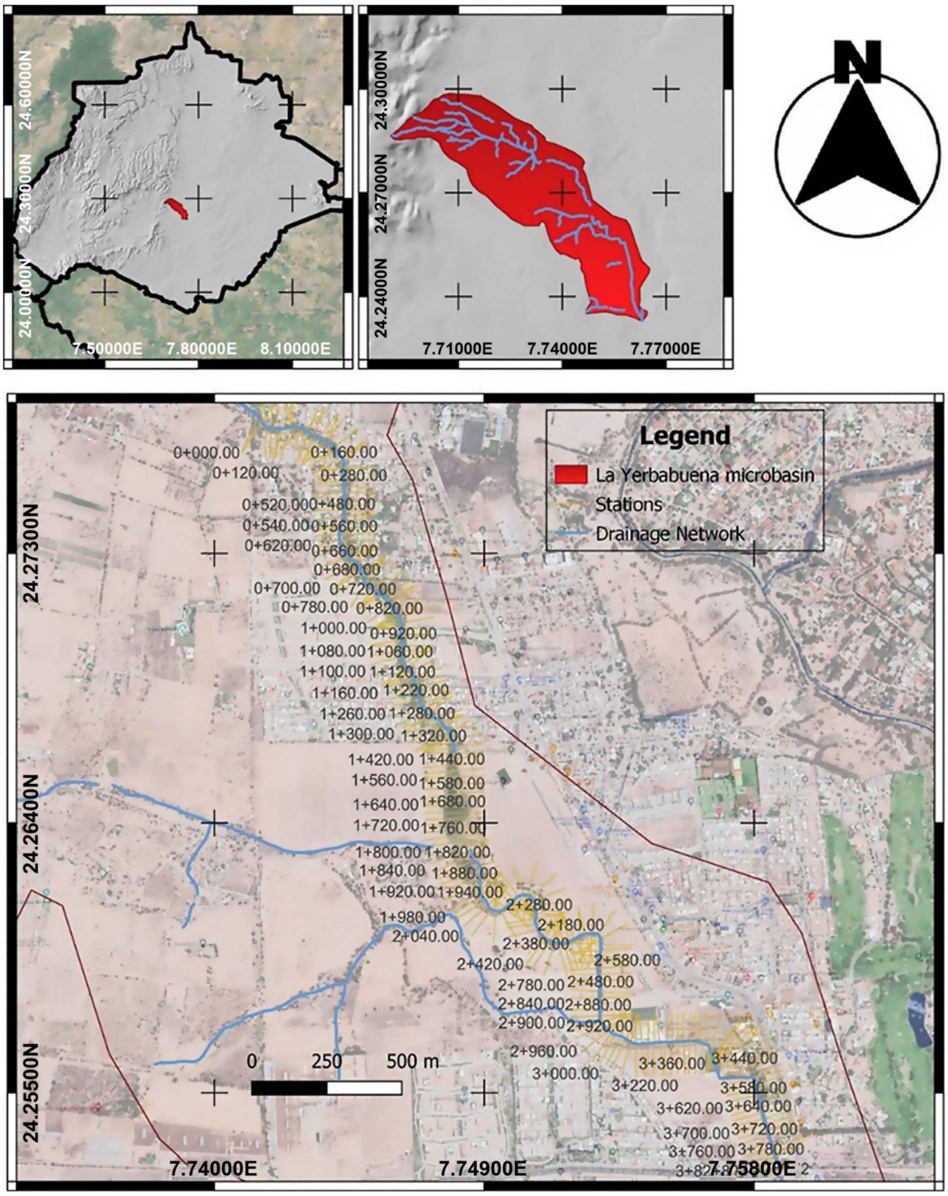

Figure 8. Suburban section selected (largest map) from the main stream. Stations in the figure refer to cross-sections.

3.4. Environmental Characterization

For the environmental characterization, the census of flora and fauna found mostly riparian species, as shown in Tables 4 and 5. Furthermore, using the images from the LANDSAT-8 satellites, the NDVI vegetation was obtained as a map, as shown in Figure 9.

Table 4. Typification of flora in the study zone.

Genera—Species	Local Name
Acacia farnesiana	Huizache
Yucca filifera Chabaud	Palma (palm)
Prosopis glandulosa	Mezquite
Ferocactus wislizenii	Biznaga (barrel cactus)
Gomphrena serrata L.	Betónica, Bolas de hilo, Borreguilla, Betónica, Cabeza de indio, Escobetilla
Dysphania graveolens_(Wild.) Mosyakin & Clements	Epazote de zorrillo (skunk epazote)
Gnaphalium spp.	Gordolobo (mullein)
Zinnia Angustifolia kunth	Hierba de la pastora, Pastora (shepherd grass)
Bidens odorata Cav.	Aceitilla, Aceitilla blanca (White aceitilla)
Grindelia oxylepis Greene	Árnica amarilla (yellow arnica)
Heterotheca inuloides Cass. var. rosei Wagenkn.	Árnica amarilla (yellow arnica)
Aster gymnocephalus (DC.)	Árnica morada (purple arnica)
Tagetes lunulata Ort.	Cinco llagas, Flor de cinco llagas (five-blisters flower)
Zinnia peruviana (L.) L.	Mal de ojo (evil eye)
Sanvitalia procumbens Lam.	Ojo de gato (cat eye)
Tithonia Desf. ex Juss.	Titonia
Cardenche Opuntia imbricata (Haw.) DC.	Cardenche
Opuntia streptacantha Lemaire	Nopal cardón
Opuntia jaliscana Bravo	Nopal chamacuero
Opuntia leucotricha De Candolle	Xoconostle amarillo, Duraznillo (Yellow xoconostle)
Ipmoea murucoides	palo bobo (silly stick)
Ipomoea purpurea (L.) Roth	Hiedra de flores chiquitas (tiny-flowers ivy)
Lepidium virginicum L.	Chile de pájaro (bird chilli)
Cucurbita foetidissima Kunth	Calabacilla loca (crazy zucchini)
Ricinus comunis	Higuerilla
Mimosa monancistra	Gatuño
Yucca filifera	Izotal

Table 5. Typification of fauna in the study zone.

Genera—Species	Local name
Zenaida asiática	Paloma aliblanca (white-winged dove)
Anas platyrhynchos	Pato mexicano (Mexican duck)
Charadrius vociferus	Tildio
Hirundo rustica	Golondrina (swallow)
Anolis nebolosus	Culebra de agua (water snake)
Spea multiplicatus	Sapo (toad)
Rana montezumae	Rana común (common frog)
Kinosternum integrum	Tortuga terrestre (land turtle)

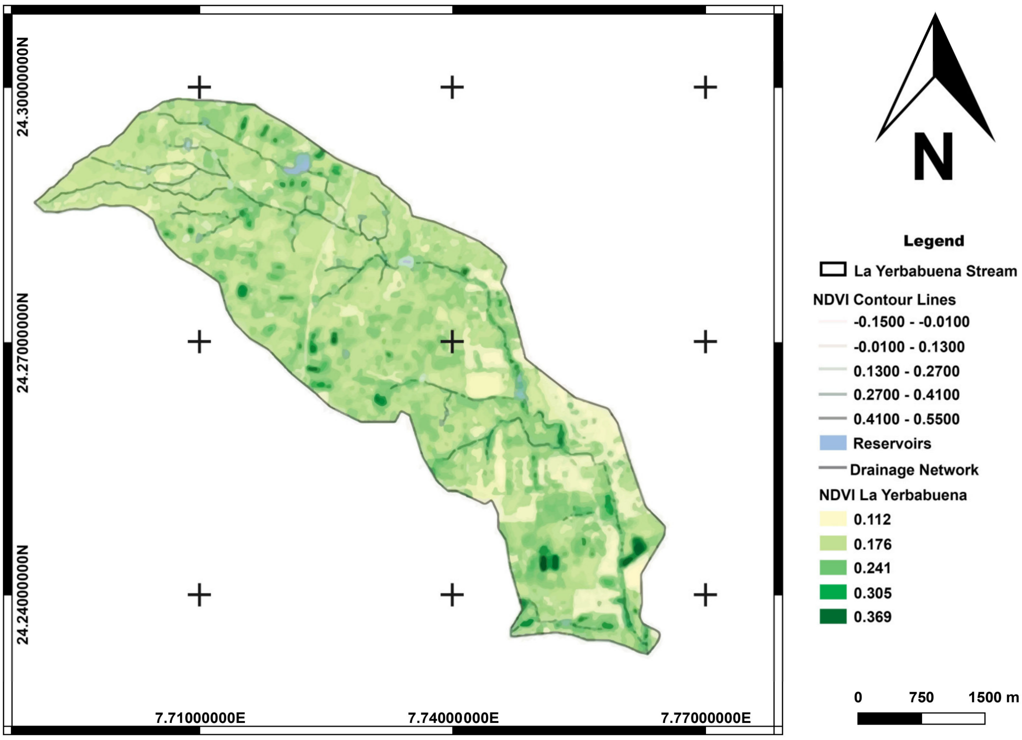

Figure 9. Index of the NDVI vegetation map.

The importance of carrying out a typification of flora and fauna in the vicinity of a temporary river is to identify endemic species, which, if there were any, would require to carry out more in-depth experimental campaigns for analysis of an environmental flow.

In this case, no species in danger of extinction were found, in which the respect or adherence to these flows would have a greater impact, since affecting these levels would be detrimental to their subsistence.

The vegetation index generates values that range between -1.0 and 1, a negative value corresponds mainly to clouds, water, and snow, and values close to zero are associated with rocky or urban areas. Very low NDVI values below 0.1 correspond to areas of sand or snow. Moderate values of 0.2 to 0.3 represent shrubland and grasslands, while high values of 0.6 to 0.8 indicate temperate and tropical zone forests [31]. For this study, using the NDVI tool, it was found that the distance occupied by riparian vegetation from the stream was close to 50 m (considering the extents of the flooding as a reference). The results of the vegetation survey indicated that the best approximation for consumptive water use was the value for Yuca. On the other hand, the effective precipitation, estimated with the Prescott and Anderson method (NRCS, 2004), resulted in 0.00277 m^3/s. This value implies that the annual effective precipitation value is sufficient to supply the environmental flow of the IHA methodology proposal and the NMX-159 processes.

Additionally, the software Flow Health [32] was used to determine the hydrologic health of the river, using a daily synthetic discharge series from the hydrologic analysis in Section 3.2. This resulted in metric scores of flows with values of 0.6 up to 1 of standard deviation, as shown in Figures 10 and 11. From these values, a score of 1 indicates close to the reference condition and a score of 0 is far from such condition.

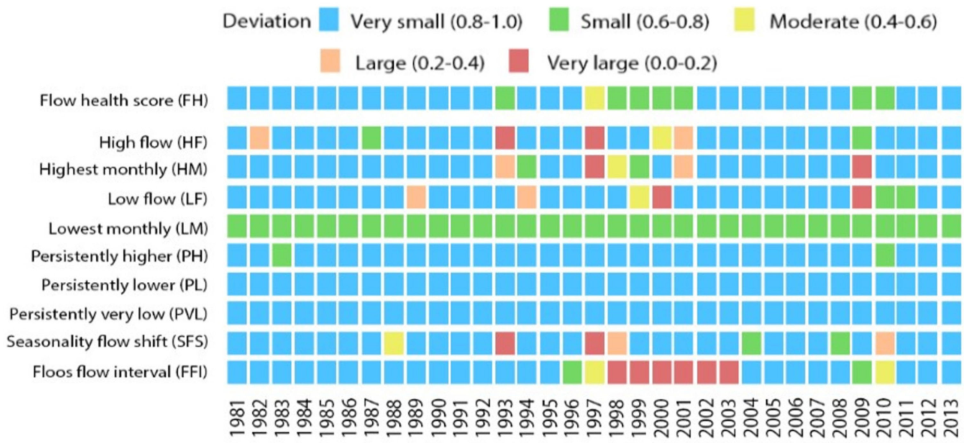

Figure 10. Graph of the mosaic to evaluate the health of "La Yerbabuena" stream.

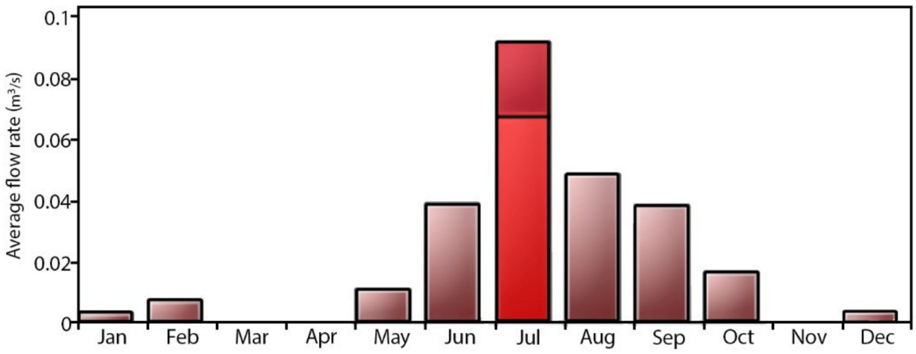

Figure 11. Regime of flow rate of minimal monthly reference for "La Yerbabuena" stream. Red color in July indicates the highest value.

The software Flow Health automatically produces the monthly minimal flow with a score of 1 (reference flow), which is the value for optimal flow under unaltered natural conditions. This produced a hydrologic annual regime for optimal conditions (Figure 12) that was taken as a reference and compared with that of the normative. In other words, the monthly flows obtained from the IHA of this proposal could be compared with the methodologies of the NMX-159 to be implemented for temporary streams (Figure 12).

According to the results of the hydrologic analysis, the regime of environmental flow with the highest score in hydrologic health resulted from the application of the IHA methodology. Moreover, with this methodology, it was found that the environmental flows in dry seasons were only present in areas with topographic depressions (ponds), and in general where the topography has been seriously affected by the urbanization process, as previously commented, as observed in the modeling with HEC RAS.

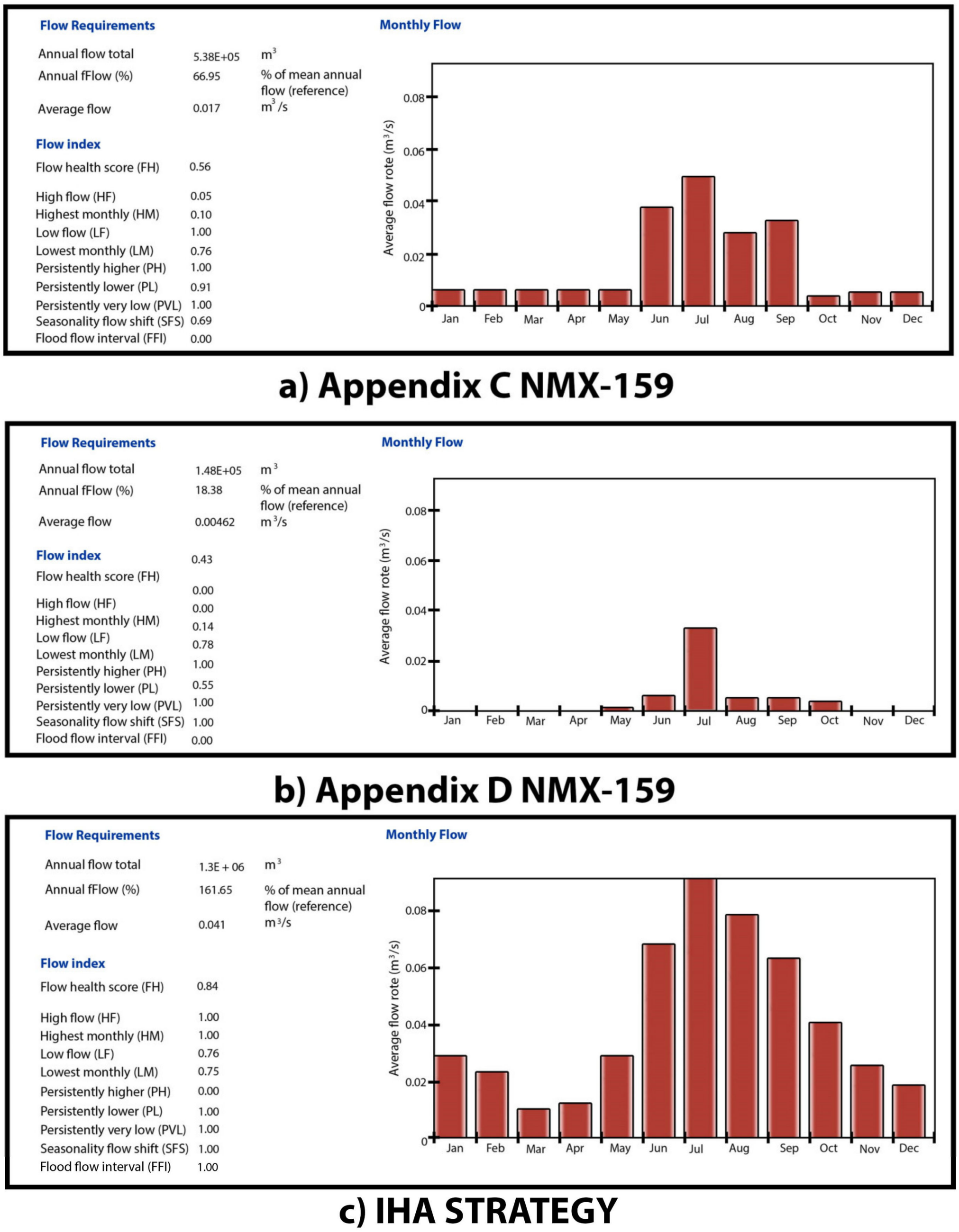

Figure 12. Assessment strategy of environmental flow.

4. Discussion

From the comparison of the natural hydrological regimes with the unidimensional modeling for the permanent flow with HEC RAS, it was observed that August was the only month of the dry year regime that was possible to model (as shown in Figure 6) since it resulted in a flow greater than zero (0.01 m^3/s). Furthermore, the stream did not show depths greater than 0.07 m for the dry hydrologic year. For the average hydrologic year, the resulting flow reached maximum depths of 0.15 m, and of approximately 0.60 m deep for dry and rainy seasons, respectively. Finally, for the humid hydrological year, the average monthly flow resulted in flooding in the rainy seasons, with levels that in certain sections reached up to 1.5 m in depth. Therefore, these results allowed us to describe the hydraulic behavior of the three types of regimes for the study area (Table 6).

Table 6. Comparative table of environmental flows (m^3/s). Qaa = Average annual flow; Qe = Environmental flow.

Month	Average Year Qaa	Appendix C Qe (NMX-159)	Appendix D Qe (NMX-159)	IHAQe
Jan	0.059	0.006	0.000	0.028
Feb	0.089	0.006	0.000	0.024
Mar	0.061	0.006	0.000	0.010
Apr	0.066	0.006	0.000	0.012
May	0.083	0.006	0.001	0.029
Jun	0.192	0.038	0.006	0.068
Jul	0.252	0.050	0.032	0.108
Aug	0.138	0.028	0.005	0.079
Sep	0.166	0.033	0.005	0.063
Oct	0.078	0.006	0.003	0.040
Nov	0.100	0.006	0.000	0.025
Dec	0.059	0.006	0.000	0.018

The proposal of the IHA methodology for temporary flows displayed results very similar to those obtained in the described proceeding of the NMX-159 appendices C and D, with a monthly variation similar to that of the unidimensional modeling with HEC RAS. Table 7 describes the main points obtained in each stage of the methodology.

Table 7. Comparative results from hydrologic methodologies for each block of study.

Parameter	Hydrologic Methodologies		
	IHA	Appendix C (NMX-159)	Appendix D (NMX-159)
Hydrologic Stage			
Hydro/average environmental flow, m^3/s	0.042	0.016	0.004
Minimum value in dry seasons, m^3/s	0.01	0.006	0.000
Maximum value in rain seasons, m^3/s	0.108	0.050	0.032
Pre-impact dry period, days	320		
Post-impact dry period, days	330		
Other features	Environmental flow components of low flow and extremely low flow.		
Hydraulic Stage			
Maximum levels of water, m	0.1 to 0.2	0.06 to 0.13	0.14 only in rain season
Environmental Stage			
Flow Health score	0.84	0.56	0.43
Remaining flow for neighboring fauna, m^3/s	0.037	0.013	0.001

The final discharge resulting from an annual effective rainfall of 0.03 m^3/s was sufficient for the total environmental flow, which was estimated by the IHA methodology and the methodologies mentioned in the normative. As shown in Table 7, the IHA methodology better adjusted to the optimal regime of the environmental flow proposed by the Flow Health software, and resulted in a variability regime of greater magnitude and greater levels throughout the stream of study.

However, the advantage of displaying environmental flow components (EFC), based on ecologic observations, allowed us to relate hydrographs of temporary streams with a set of ecologically relevant hydrographic models, for example:

(a) The extremely low flow with a frequency of 85.66%, during dry seasons, could produce the necessary conditions to form natural ponds and produce a local ecologic environment, and it could also dry low areas of flooding plains.
(b) Several floods were modeled, with low frequencies between 0.64% and 0.10%.

5. Conclusions

We have presented an adapted methodology that permitted us to determine the hydraulic behavior of a temporary stream. Unidimensional modeling with the HEC RAS and Flow Health program software confirmed that the hydrologic base of this work, referenced to the IHA methodology, generated reasonable results, with a variation similar to the methodologies established in the NMX-AA-159-SCFI-2012 normative. An environmental flow threshold was determined using the hydrological basis of the IHA methodology, obtaining an average environmental flow of 0.042 m^3/s, a minimum value in the dry season of 0.010 m^3/s, and a maximum value for the rainy season of 0.108 m^3/s. In addition, the levels reached in the hydraulic modeling with the IHA were higher and presented retention zones at some points of the river.

Based on the analysis presented, the IHA methodology obtained better results due to the statistical analysis, which involved the processing of daily flow series to then later carry out intervals or monthly thresholds, contrary to the NMX-159 methods, which are applied to rivers that require monthly data on gauged streams, and which could not be applied to intermittent or temporary streams.

On the other hand, in the water health evaluation of the flow strategies with the software Flow Health, it was observed that the hydrological analysis to determine the environmental flow regime that has the highest water health score was the IHA methodology, with a score of 0.83, which is very close to the reference level of the minimum monthly flow proposed by the software.

The objective of this research was to provide general knowledge of the hydrological behavior of temporary streams, which, due to anthropic activities, some perennial streams are converting to this type.

Author Contributions: I.G.R.-C., writing—original draft; M.H.-M., formal analysis and editing; A.I.P.-G., conceptualization and methodology; J.P.G., review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request from the authors.

Acknowledgments: The first author thanks CONACYT for the economic support received during his graduate studies.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

The Indicators of Hydrological Alteration are made up of 67 statistical parameters, divided into 2 groups: the IHA parameters and the parameters of the Ecological Flow Components (EFC), as indicated in The Nature Conservancy Manual (2011). These are classified into 5 categories, based on hydrological condition and the environmental significance for each parameter, as shown in Tables A1 and A2. Each group of IHA parameters will be described below.

Table A1. Summary of IHA parameters.

IHA Parameter Group	Hydrologic Parameters
1. Magnitude of monthly water conditions	Mean or median value for each calendar month (subtotal 12 parameters)
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean annual minima, 3-day mean annual minima, 7-day mean annual minima, 30-day mean annual minima, 90-day mean annual maxima, 1-day mean annual maxima, 3-day mean annual maxima, 7-day mean annual maxima, 30-day mean annual maxima, 90-day mean number of zero-flow days, base flow index: 7-day minimum flow/mean flow for year (subtotal 12 parameters)
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum (subtotal 2 parameters)
4. Frequency and duration of high and low pulses	Number of low pulses within each water year. Mean or median duration of low pulses (days). Number of high pulses within each water year. Mean or median duration of high pulses (days) (subtotal 4 parameters)
5. Rate and frequency of water condition changes	Rise rates: mean or median of all positive differences between consecutive daily values Fall rates: mean or median of all negative differences between consecutive daily values Number of hydrologic reversals. (subtotal 3 parameters)
	Grand total: 33 parameters

Table A2. Summary of Environmental Flow Component (EFC).

EFC Type	Hydrologic Parameters
1. Monthly low flows	Mean or median values of low flows during each calendar month (subtotal 12 parameters)
2. Extreme low flows	Frequency of extreme low flows during each water year or season. Mean or median values of extreme low flow event: Duration (days), peak flow (minimum flow during event), timing (Julian date of peak flow) (subtotal 4 parameters)
3. High flow pulses	Frequency of high flow pulses during each water year or season. Mean or median values of high flow pulse event: Duration (days), peak flow (maximum flow during event), timing (Julian date of peak flow). Rise and fall rates (subtotal 6 parameters)
4. Small floods	Number of low pulses within each water year. Mean or median duration of low pulses (days). Number of high pulses within each water year. Mean or median duration of high pulses (days) (subtotal 4 parameters)
5. Rate and frequency of water condition changes	Frequency of small floods during each water year or season. Mean or median values of small flood events: Duration (days), peak flow (maximum flow during event), timing (Julian date of peak flow). Rise and fall rates (subtotal 6 parameters)
5. Large floods	Frequency of large floods during each water year or season. Mean or median values of large flood event: Duration (days), peak flow (maximum flow during event), timing (Julian date of peak flow). Rise and fall rates (subtotal 6 parameters)
	Grand total: 34 parameters

Appendix B

The Tennant method, or the Montana method, divides the year into two periods: wet and dry, of which each one is assigned an appropriate percentage of the average interannual flow [12]. For each of the dry and wet periods, or better known in NMX-159 Appendix C as dry and flood seasons, respectively, the modified Montana method was applied, where its development and calculation, adapted to Mexico by IMTA for the evaluation of environmental impact due to hydraulic works, has generated favorable results [33]. According to the NMX-159, all the values of average monthly flows (Cmi) that are above the value of the average annual runoff (EMA) are considered flood periods.

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