

Environmental flow modeling for the conservation of the endemic trout *Oncorhynchus nelsoni* (Evermann, 1908) in a basin located in the Mexican region of Mediterranean California

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Abstract

Driven by global economic and population growth, the diversion of streamflow, via pipeline networks, for agricultural, livestock, or domestic purposes, has had a significant impact on water demand. These processes have created an urgent need for sustainable water resource management. Environmental flow regimes have become a key tool in watershed-wide management plans, as they enable appropriate water allocation while maintaining the functionality of riverine ecosystems. The northwestern region of the State of Baja California, Mexico, is characterized by a mediterranean climate, an average annual precipitation lower than 400 mm, and a critical water availability situation due to the overexploitation of aquifers for agriculture and urban development. The present study proposes environmental flow modeling to support the habitat connectivity of the endemic trout *Oncorhynchus nelsoni* (Evermann, 1908) in a third-order stream in a basin forming part of the Mexican region of what is known as Mediterranean California, due to its specific climatic characteristics. The modeling was achieved *via* an adaptation of the hydrobiological Instream Flow Incremental Methodology (IFIM) that adhered to the procedures stipulated under Official Mexican Standard NOMX-AA-159-SCFI-2012. Given special protection status under Official Mexican Standard NOM-059-ECOL-2010, this endemic trout is currently threatened by various anthropogenic activities and natural factors, including climate change. The present study developed a riverine habitat model in the El Potrero Stream, a representative site in the distribution range of the trout of interest, to evaluate the environmental flow required to maintain aquatic habitat connectivity. A minimum environmental flow of $0.02 \text{ m}^3\text{s}^{-1}$ was identified as sufficient to ensure habitat connectivity, while a value of $0.01 \text{ m}^3\text{s}^{-1}$ was determined as sufficient for the formation of a discontinuous stream with isolated pools that could serve as temporary thermic refuges for the trout during prolonged multi-year drought conditions. The present study found that levels exceeding the optimal water volume did not increase access to a suitable habitat for the endemic trout and may even become detrimental to it during high-flow events. We recommend the continued implementation of hydrological monitoring programs in the El Potrero Stream, along with the inclusion of representative sites such as the San Antonio de Murillos stream (type locality), which is currently threatened by anthropogenic activities. Monitoring these streams will enable a more robust characterization of temporal streamflow variability under seasonal climatic conditions and will contribute to a better understanding of the hydraulic connectivity between stream segments throughout the annual cycle.

Key words: *Oncorhynchus nelsoni*; environmental flow; Santo Domingo; river; watershed; hydrobiological method; endemic; IFIM.

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Introduction

The impact of anthropogenic activities, such as agriculture or livestock farming, on rivers and streams is raising increasing global concern due to the degradation of aquatic ecosystems caused, on both a local and global scale (Geist and Hawkins, 2016). Such activities severely affect the biological communities associated with these ecosystems (Arthington *et al.*, 2021), particularly impacting the distribution of salmonid fish in North America (Rieman and Isaak, 2010). Therefore, it is crucial that their conservation or degradation status is assessed to establish effective mitigation and management mechanisms (Meza-Rodríguez *et al.*, 2017).

Understanding flow dynamics is essential for water resource management, flood prediction, sediment transport assessment, and drought assessment. Currently, various efforts are being undertaken in many parts of the world to conserve river systems and preserve the environmental flow regimes that ensure the maintenance of lotic ecosystems (Resh *et al.*, 1988).

The term flow regime refers to the movement of water in a river in terms of quantity, timing, and variability under natural conditions and without the influence of hydraulic structures that alter the hydrological pattern (Poff *et al.*, 2017). An altered flow regime is one in which flow depends entirely on water storage and anthropogenic use, thereby modifying the river's natural hydrological flow (Arthington and Pusey, 2003). Within this

context, the term environmental flow regime refers to the quality, quantity, and variability of water flow necessary to protect and maintain the components, functions, and processes of freshwater ecosystems, ensuring the balance of the natural elements involved in the hydrological cycle (SE, 2012).

In Mexico, various techniques are currently being implemented, in accordance with Official Mexican Standard NMX-AA-159-SCFI-2012, to determine environmental flow in hydrological basins. This standard stipulates a range of methodologies (encompassing hydrological, hydraulic, hydrobiological, and holistic approaches), which can be tailored to the specific characteristics of each study site (SE, 2012).

In the Mexican state of Baja California, the Santo Domingo River Basin provides the natural habitat for the endemic trout *Oncorhynchus nelsoni* (Evermann, 1908) (Fig. 1), which currently faces a range of threats stemming from anthropogenic activities, such as extensive livestock grazing, mining, and the construction of hydraulic infrastructure (dams, reservoirs, and irrigation canals). These activities result in the diversion of flows for agricultural irrigation, among other impacts, altering flow and temperature regimes, as well as nutrient flow patterns downstream (Ruiz-Campos, 2017; Meza-Matty, 2022; Ruiz-Campos and González-Acosta, 2024). In addition, the potential impact of global climate change -occurring *via* altered precipitation and rising temperatures- is expected to affect the altitudinal distribution of this endemic species, as temperatures $\geq 28^{\circ}\text{C}$ are considered to be lethal for this trout (Meza-Matty *et al.*, 2021). Exposure, in terms of both time and quantity, to temperatures above this thermal threshold induces physiological stress on a cellular level, triggering the synthesis of heat shock proteins and, ultimately, leading to organismal death (Lund *et al.*, 2002). These threats could lead to stream fragmentation and siltation, significantly affecting trout population density, structure, and distribution, as well as habitat quality in the short and medium term (Meza-Matty, 2022). Stalnaker *et al.* (1995) emphasize that determining the flows necessary to a river ecosystem requires careful consideration of the various flow levels and environmental conditions that fish species need throughout their life histories.

The present study developed a model to calculate the environmental flow required to maintain effective habitat connecti-

ty for the endemic trout inhabiting the Santo Domingo River Basin. This approach, based on an adaptation of the IFIM hydrobiological methodology, consisted of simulating habitat conditions under various flow scenarios to estimate the potentially usable habitat available in each case, based on the specific ecological requirements of the endemic trout of interest. Thus, determining the environmental flow for this site will be of critical importance for conserving the functionality and connectivity of aquatic and riparian ecosystems within this hydrological basin located in Mediterranean California.

Based on the approach mentioned above, the following research question was formulated: Does the adaptation of the IFIM method, in compliance with the procedure set out in the Mexican standard, enable environmental flow modeling that ensures habitat connectivity for *O. nelsoni* in the type of stream subject to the research? In this context, we hypothesized that implementing the IFIM method, adjusted to local conditions and aligned with national regulations, would enable us to model an environmental flow that ensures habitat connectivity for this species, thereby contributing to its conservation.

Study area

The field sampling was carried out in a 775 m-segment of the El Potrero Stream, (coordinates 629425 m E and 3421157 m N, Zone 11 N, WGS84, 894 m). This third-order stream is one of the main tributaries of the Santo Domingo River Basin and is identified as an area vulnerable to multiple anthropogenic pressures and natural processes (Ruiz-Campos, 2017; Meza-Matty, 2022). The study region has a predominantly mediterranean climate, with an average annual rainfall of 400 mm, reaching up to 1000 mm mainly during the winter season, and an average annual temperature of 7°C . Rainfall in the region is of orographic origin, as generated by cold fronts or tropical cyclones (Álvarez, 1985). Based on records obtained by the Mexican National Water Commission at Vicente Guerrero Hydrometric Station Number 6, the average annual discharge of the Santo Domingo River Basin was equivalent to approximately $2.2\text{ m}^3\text{s}^{-1}$ over a 27-year period (1960-1986), within a catchment area of 122,700 ha (Zúñiga-Castillo, 1995). (Fig. 2).



Fig. 1. Endemic trout, *Oncorhynchus nelsoni*, from the Sierra San Pedro Mártir. Photograph by Gorgonio Ruiz Campos.

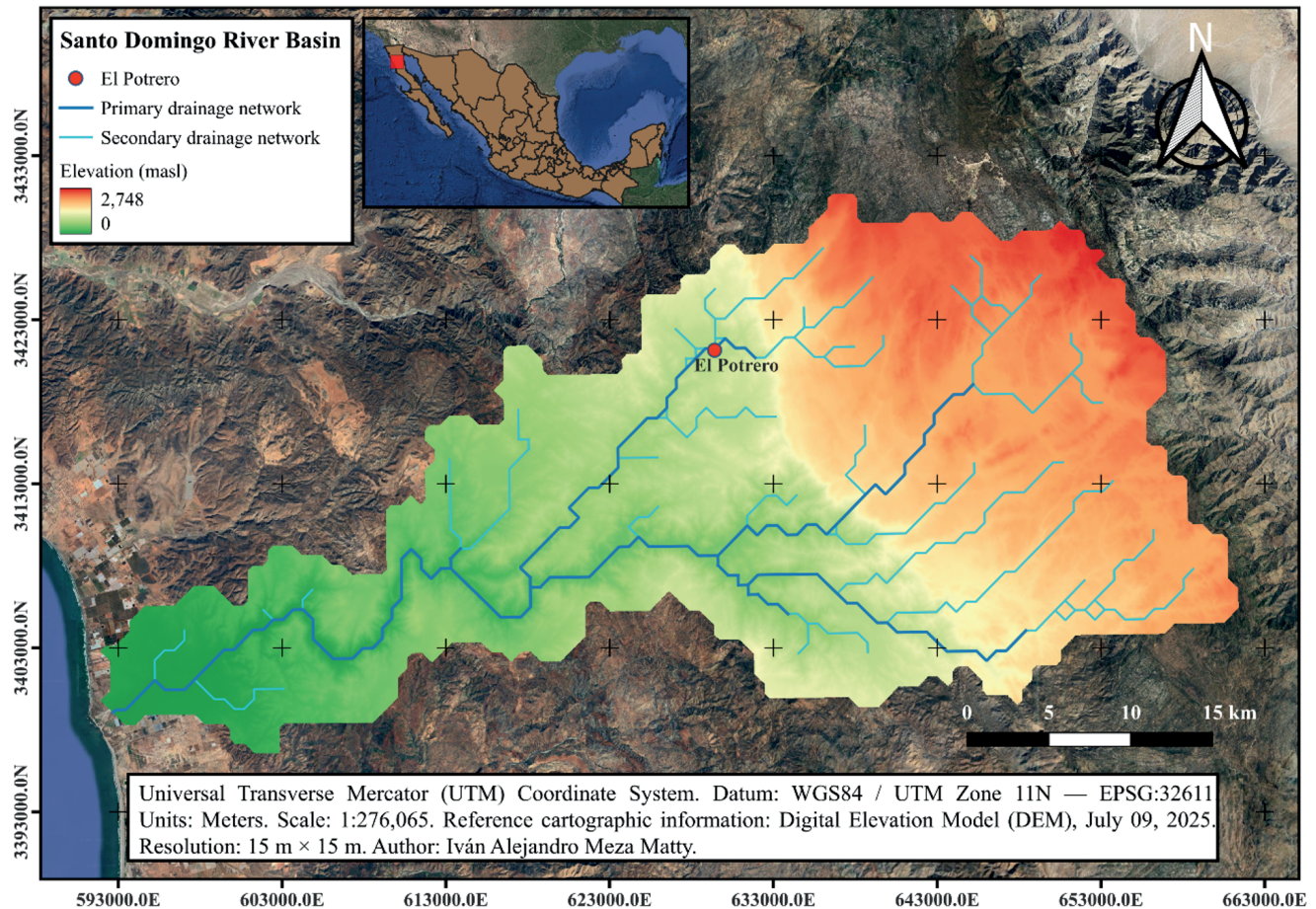


Fig. 2. Area of the Santo Domingo River Basin, Baja California, Mexico, and the main and secondary hydrographic networks. The study site (the El Potrero Stream) is depicted with a red circle.

METHODS

Hydrobiological method

To generate the environmental flow proposed, the present study used the IFIM (Instream Flow Incremental Methodology, cf. Guevara and Rodríguez, 2013) hydrobiological methodology recommended by Official Mexican Standard NMX-AA-159-SCFI-2012. The methodology was applied in six steps: i) the selection of the study site; ii) the selection of the target species representative of the site; iii) the generation of microhabitat preference curves as a key component in the construction of habitat models; iv) the fieldwork required for the construction and calibration of the habitat models; v) the evaluation of the river habitat; and vi) the formulation of the environmental flow proposals.

The IFIM methodology is grounded in the analysis of the relationships between streamflow volume and habitat availability within a defined segment of the stream of interest. In this approach, the simulation model calculates, based on the current flow in the stream, the amount of habitat that is available for a specific species.

The habitat simulation model comprised two main components. The first, the hydraulic model, predicted the depth and

velocity of the water at the cross-section taken of the stream using field data to simulate the behavior of the stream connectivity under different flow conditions. The second component, the habitat model, evaluated each cell in the cross-section, assigning values of between 0 and 1 for each of the habitat parameters considered (depth, velocity, and substrate), thus determining the impact of these parameter levels on the target species. The habitat model calculated these values for different flows, generating a usable area index known as the weighted usable area.

To obtain hydraulic simulation, the hydraulic characteristics of the stream were measured and the target species selected. These two variable sets were integrated to link the physical characteristics of the stream cross-section with the habitat needs of the target species. The specific stream reach was selected for its representativeness of both the channel and the target species, considering aspects such as the heterogeneity of habitat units (Ruiz-Campos *et al.*, 2022; 2023) and the high degree of vulnerability of the area to anthropogenic threats (Ruiz-Campos, 2017). In this section of the stream, five types of habitat units were identified, based on Ruiz-Campos *et al.* (2023).

On May 26 2024, high-resolution topographic data were acquired via an aerial LiDAR survey using a CHCNAV AlphaAir 450 sensor mounted on a DJI Matrice 300 RTK Unmanned Aerial

System. The survey was flown at an altitude of 100 meters, achieving a point density of 325 points per square meter. Five flights were conducted to cover the 200-hectare transect area, using the ITRF08-2010 reference frame, projected onto Universal Transverse Mercator (UTM) Zone 11N (WGS84 datum).

The LiDAR point cloud was processed using CoPre 3.3 software to classify and extract bare earth returns by removing vegetation and other non-ground features. The resulting ground-classified point cloud was used to generate a high-resolution digital elevation model (DEM) of the terrain, a model which provided input for hydrological simulations in the International River Interface Cooperative (IRIC) model, thus supporting the assessment of flood scenarios relevant to habitat and connectivity analyses.

To complement the elevation data obtained from the inundated sections of the stream channel, 137 additional points were collected using CHCNav i80 multifrequency GNSS-RTK receivers and i73 mobile antennas. These GNSS-derived measurements were integrated with the LiDAR point cloud to produce a seamless topobathymetric model of the study area, capturing both terrestrial and submerged topography critical for hydrodynamic modeling.

For each cross-section of the different habitat units identified, the water surface width (m) was measured *in situ* to calculate the circulating flow, with the granulometry of the dominant substrate (mm) then also taken. For each cross-section of the habitat unit, the depth (m) and current velocity (m s^{-1}) were measured at 30 cm intervals using a ruled rod (cm) and a Swoffer 2100 flow meter, respectively (Arend and Bain, 1999). The discharge rate was calculated using the Hynes equation (1972): $Q=(W \times D \times V) \times CF$, where Q =discharge rate (m^3s^{-1}), W =average stream width (m), D =average depth (m), V =average current velocity (m s^{-1}), and CF =constant friction for sandy substrate (0.9) and rocky substrate (0.8).

The measurement of the circulating flow was performed at the inlet (upstream section) and at the outlet (downstream section) of the sampled segment of the stream.

The species selected for the analysis conducted by the present study was the San Pedro Mártir trout *O. nelsoni*, a species endemic to the mountain streams on the western slope of the Sierra San Pedro Mártir, Baja California, Mexico (Ruiz-Campos and Pister, 1995; Ruiz-Campos, 2017; Ruiz-Campos and González-Acosta, 2024). This trout occurs at altitudes ranging from 553 to 2,080 meters above sea level, in stream and pool habitats where temperatures do not exceed an average of 25°C during the summer (Ruiz-Campos, 1993, 2017; Meza-Matty *et al.*, 2021; Ruiz-Campos and González-Acosta, 2024). It is considered the southernmost species of the genus *Oncorhynchus* on the Pacific coast of North America (Behnke, 2002) and possibly represents one of the most genetically-conserved populations of the rainbow trout complex in southwestern North America (Abadía-Cardoso *et al.*, 2016). Due to the low abundance observed within its distribution range, this species is classified as of special concern by the Endangered Species Committee of the American Fisheries Society (Jelks *et al.*, 2008) and under the Special Protection category by the Mexican government (NOM-059-ECOL-2010).

Once the target species and hydraulic characteristics of the stream had been defined, the iRIC v4 software FaSTMECH (flow and sediment transport with morphological evolution of chan-

nels) module was used to simulate the habitat under various scenarios. Topographic data served as the main model input data, based on which the central axis of the stream was defined and then used as a reference for generating the simulation mesh. The bathymetric information was interpolated using the TIN (triangular irregular network) technique to populate each model mesh node within the model domain. Then, the initial conditions, initial flow, and water surface elevation at the outlet were entered into the model for calibration purposes. The model was run through a calculation process that established 1200 interactions per cycle until mass conservation was achieved (Nelson *et al.*, 2016).

To validate the circulating flow, a second-order polynomial regression model was employed to characterize the relationship between the simulated and observed water surface area, as a function of the circulating flow rate, with the data obtained then compared via the use of a Mann-Whitney test, with a significance value of 0.05.

Subsequently, the habitat suitability and usable potential habitat (UPH) were obtained. Habitat suitability for the target species was calculated using an index that ranged from 0 (non-suitable) to 1 (optimum). The combined suitability index for a specific microhabitat was determined as the weighted geometric mean of the habitat values obtained for each variable considered, thus enabling the UPH to be defined as the percentage of usable potential habitat, expressed as the flooded area of the stream, which indicates the population's strongest preference (Meza-Rodríguez *et al.*, 2017).

Finally, the curve showing the relationship between flow and UPH was used to determine the minimum environmental flow required to ensure the connectivity of the habitat of the trout *O. nelsoni*. This approach enabled the identification of the minimum environmental flow proposed.

Environmental flow proposal

This proposal considers that a value below the minimum environmental flow level will lead to a significant decline in the population of the trout of interest in the study area due to decreased UPH. Additionally, the basal flow during prolonged drought periods was calculated, a flow primarily comprising the discharge of water stored in the basin (aquifers and groundwater, *etc.*) during the dry season (Yang *et al.*, 2019).

RESULTS

Hydrobiological method

To characterize the heterogeneity of aquatic habitat units at the study site, a 40-meter transect of the El Potrero Stream was surveyed on May 26, 2024, with the following five habitat units identified in the transect: Run (RUN); Backwater Pool (BWP); Lateral Run (LRUN); Lateral Scour Pool (LSP); and Mid-Channel Pool (MCP) (Fig. 3).

An average circulating flow of $0.05 \text{ m}^3\text{s}^{-1}$ was recorded in the segment of the stream sampled. The calibration of the model required that the flow velocities observed in each habitat unit within the transect shown in Fig. 3 be compared with those simulated by the iRIC software. The model was adjusted until the difference between both values was minimized, thereby ensuring greater accuracy and reliability in the analysis conducted on the simulation scenarios (Mann-Whitney test, $U=12$, $p=0.97$) (Fig. 4).

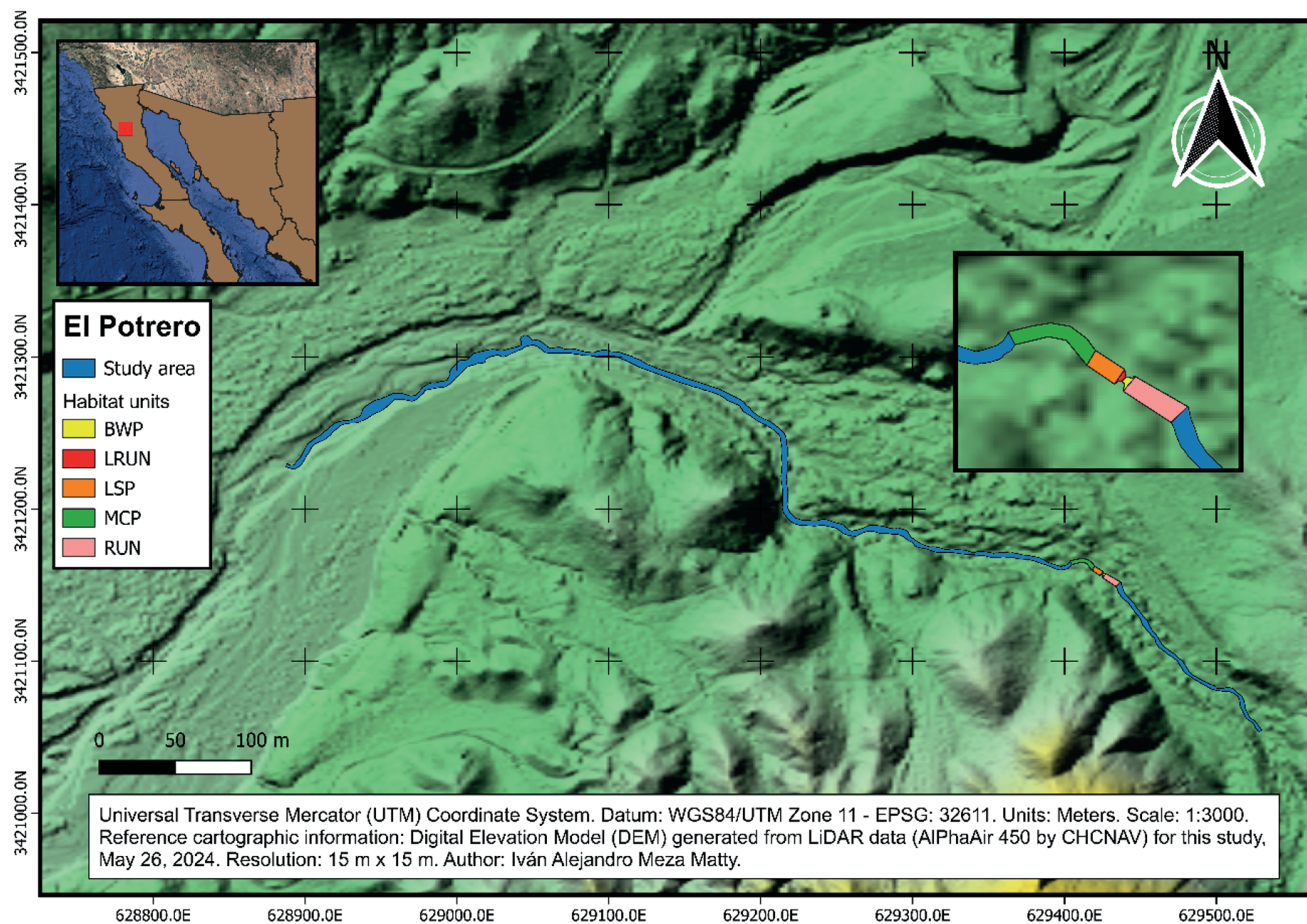


Fig. 3. Representation of habitat units in a selected segment of the sampling site at the El Potrero Stream, Santo Domingo River Basin, Baja California, Mexico, on May 26, 2024. The map was generated using the Geographic Information System Quantum GIS version 3.34.11. Run (RUN), Backwater Pool (BWP), Lateral Run (LRUN), Lateral Scour Pool (LSP), and Mid-Channel Pool (MCP).

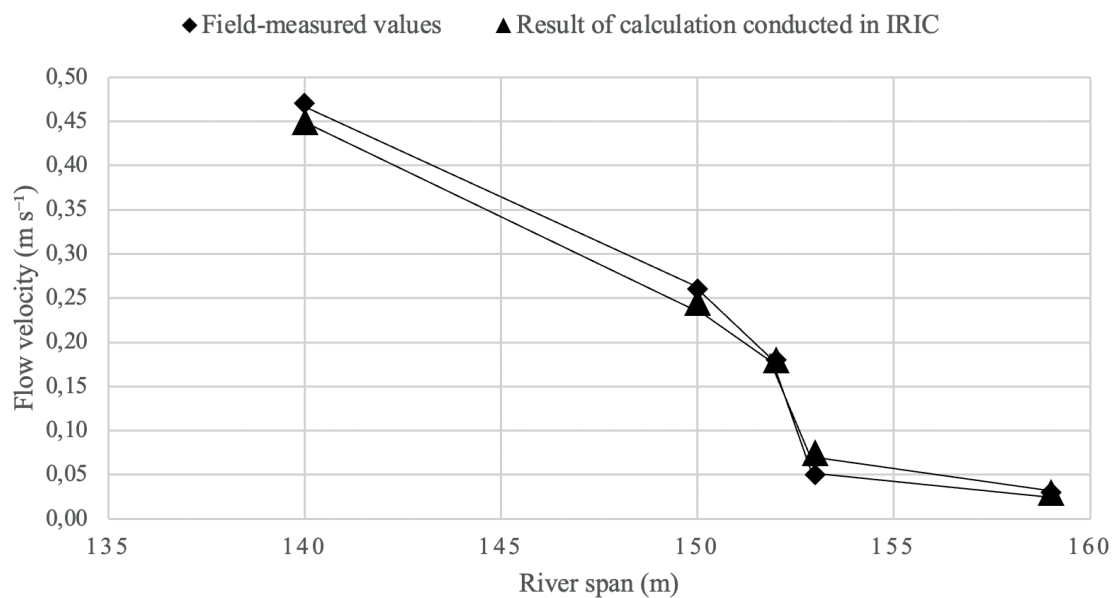


Fig. 4. Comparison of field-measured data and data calculated using the iRIC software at the El Potrero Stream site, Santo Domingo River Basin, Baja California, Mexico.

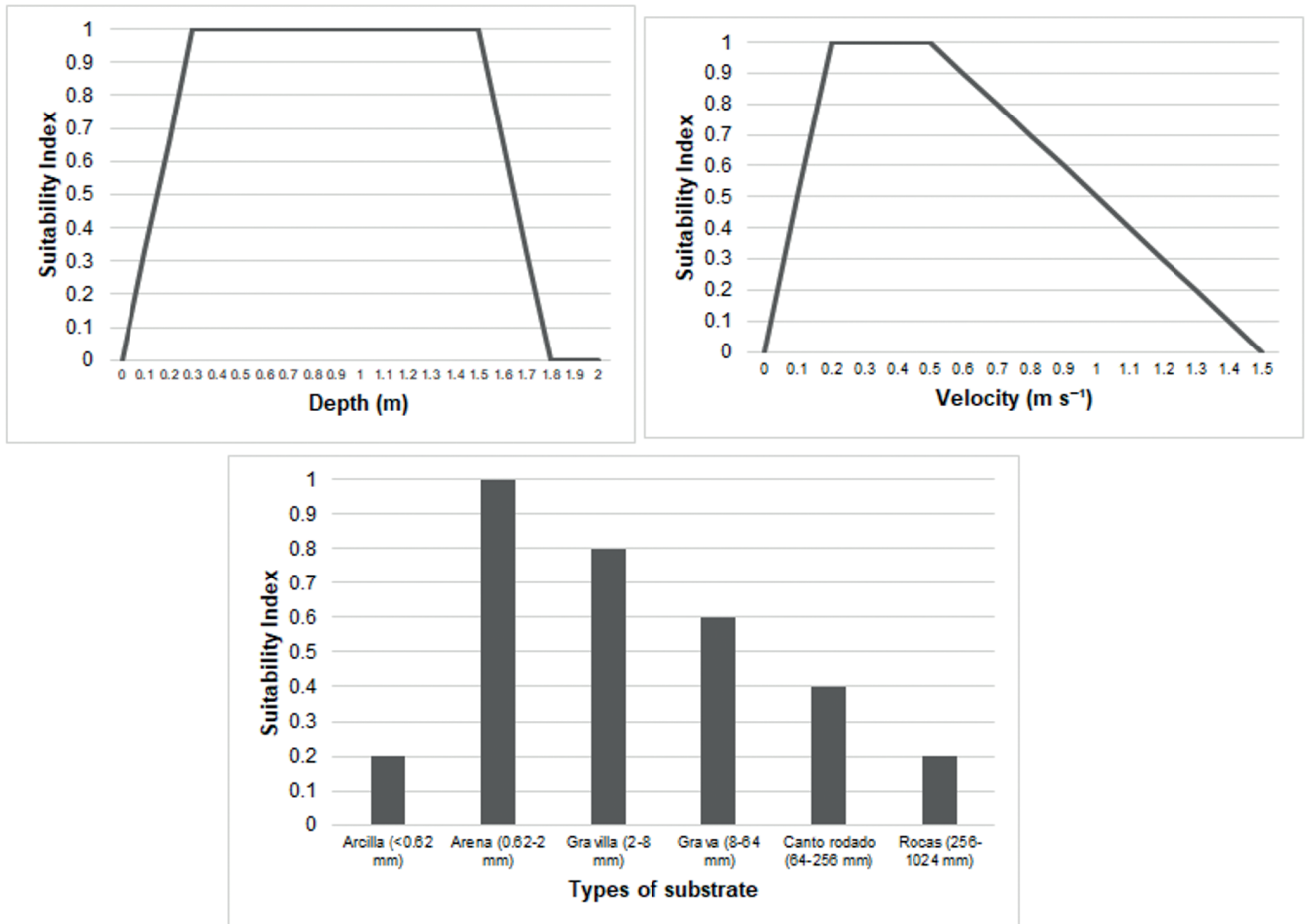


Fig. 5. Suitability curves proposed for the estimation of usable potential habitat (UPH) for *O. nelsoni*, where a value of 1 represents maximum suitability.

Upon completion of model calibration, a comprehensive literature review of previous studies conducted in the Sierra San Pedro Mártir was undertaken to develop habitat suitability curves for the target species (endemic trout) at the study site. These curves served as the basis for subsequent ecohydraulic simulations (Fig. 5).

Based on the hydrobiological modeling obtained using the iRIC software, simulations were performed at different flow rates generating different scenarios of habitat suitability and UPH for the target species (Fig. 6).

The minimum environmental flow was estimated at $0.02 \text{ m}^3\text{s}^{-1}$ for the target species, indicating that, at any flow below this value, the trout populations would be seriously affected due to the drastic decline in their UPH (Fig. 7).

Fig. 7 depicts the optimal flow of $0.1 \text{ m}^3\text{s}^{-1}$ calculated for the trout at the study site, a value which corresponds to the maximum UPH reached by the system for this fish species. The analysis conducted also revealed a low flow value ($0.01 \text{ m}^3\text{s}^{-1}$) for the stream, which represented the minimum flow required to maintain the water connectivity of the stream surface. Said low flow value occurs dur-

ing prolonged droughts in the summer season and should never fall below $0.01 \text{ m}^3\text{s}^{-1}$.

Fig. 7 shows the different flow/UPH variation intervals, wherein a drastic loss of UPH for this trout is observed at between 0.01 and $0.02 \text{ m}^3\text{s}^{-1}$. In the 0.02 to $0.05 \text{ m}^3\text{s}^{-1}$ range, the trout of interest shows an increased UPH, while the trout reaches the optimal UPH in the intervals observed from 0.05 to $0.1 \text{ m}^3\text{s}^{-1}$. At flow rates above $0.15 \text{ m}^3\text{s}^{-1}$, a constant decline in UPH would be observed.

Proposed environmental flow

Based on the analysis carried out by the present study, a minimum environmental flow regime of $0.02 \text{ m}^3\text{s}^{-1}$ is proposed to support the ecological flow necessary for the conservation of the trout population of interest in the study area. However, in years with prolonged droughts, the low flow value should be defined at $0.01 \text{ m}^3\text{s}^{-1}$, corresponding to the minimum environmental flow required to maintain streamflow connectivity along the studied transect.

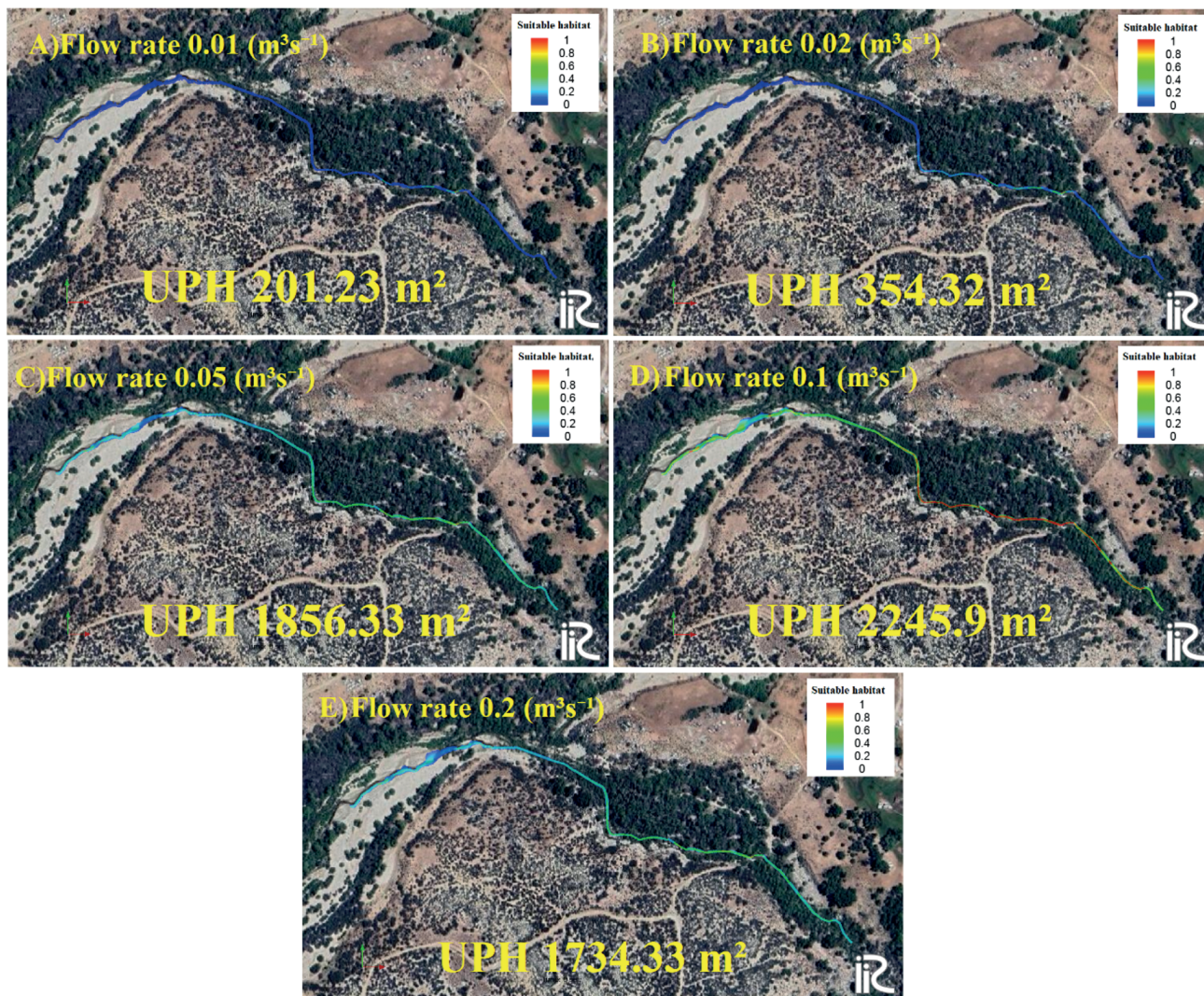


Fig. 6. Hydraulic simulation at different flow rates and estimation of UPH at the El Potrero Stream site. A) $0.01 \text{ m}^3\text{s}^{-1}$; B) $0.02 \text{ m}^3\text{s}^{-1}$; C) $0.05 \text{ m}^3\text{s}^{-1}$; D) $0.1 \text{ m}^3\text{s}^{-1}$; E) $0.2 \text{ m}^3\text{s}^{-1}$. Red areas indicate maximum suitable habitat (value=1), gradually shifting to blue (value=0), representing unsuitable habitat for trout.

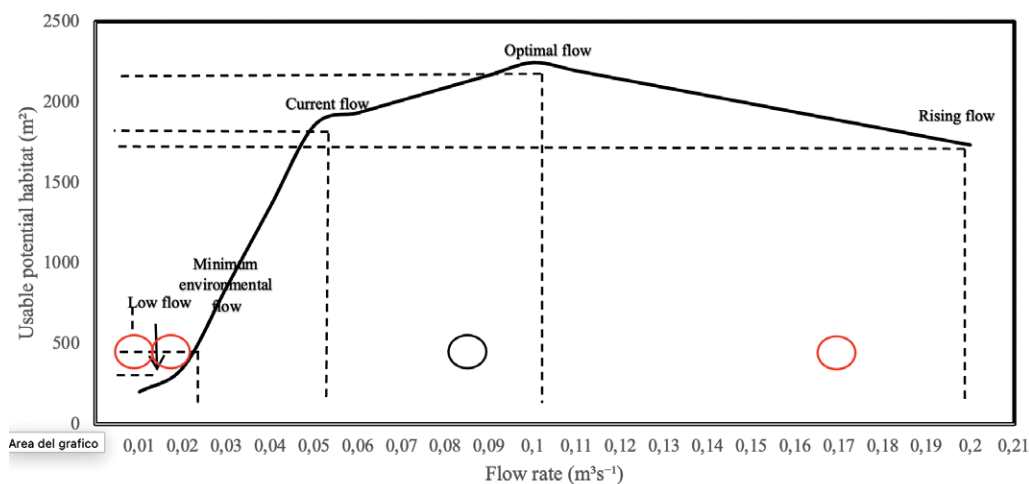


Fig. 7. Relationship between UPH and flow rates for *O. nelsoni*, including the identification of the minimum environmental flow, optimal flow, rising flow, and low flow in a segment of the El Potrero Stream, Santo Domingo River Basin, Baja California, Mexico.

DISCUSSION

The present study is the first research of its kind on the ecological flow requirements of a mountain stream in northwestern Mexico inhabited by native trout species. Specifically, it focuses on the selection of a target species, the endemic trout (*O. nelsoni*), whose potential usable habitat was determined through the development of habitat suitability curves and hydraulic modeling (Pastor *et al.*, 2014). Once this was determined via the hydrobiological method, the flow level necessary for the survival of the indicator species and the persistence of its habitat was estimated, thus contributing to the conservation of the connectivity of riverine and riparian ecosystems facing anthropogenic pressures and climate change (Poff *et al.*, 2017).

In Mexico, the estimation of environmental flows has largely relied on hydrological approaches, often conducted without the integration of biological or hydraulic data (Pastor *et al.*, 2014; De la Lanza-Espino *et al.*, 2018). However, the effective implementation of ecological flows demands an understanding of not only the hydrological and geomorphological context, but also the fluvial hydraulics and the biological characteristics of the target species (Tharme, 2003).

One of the main limitations of hydrological methods lies in the lack of continuous and accurate hydrometric flow records, which are essential for determining an environmental flow regime. This data gap represents a major challenge in both Mexico and many other regions worldwide (Poff *et al.*, 2017; Tickner *et al.*, 2020). In this context, hydrological models are often used to reconstruct natural flow regimes. However, the lack of site-specific data hampers model validation, increasing uncertainty and the occurrence of potential estimation errors.

In the El Potrero Stream, stable flows have been documented over the past 30 years (1989-2019) (Ruiz-Campos, 2017; Meza-Matty, 2022). Reported discharges range from 0.05 to 0.14 m³s⁻¹ (Ruiz-Campos, 2017), consistent with the 0.08 m³s⁻¹ measured in 2019 (Meza-Matty, 2022) and the 0.05 m³s⁻¹ recorded in May 2024 in this study. In contrast, the San Rafael River Basin has experienced a severe decline in average discharge, dropping from 1.23 m³s⁻¹ (1988-1989) to 0.20 m³s⁻¹ (2014-2015) (Ruiz-Campos, 2017), likely due to hydraulic infrastructure that disrupts natural flow and temperature regimes (Tickner *et al.*, 2020), degrading ecological integrity and affecting aquatic biota (Amadio *et al.*, 2022). Additional impacts include increased sediment loads associated with road development, which further alters key habitat conditions for *O. nelsoni* (Ruiz-Campos, 2017). Within this context, the environmental flow modeling conducted here supports the conservation of *O. nelsoni* by ensuring longitudinal hydraulic connectivity. A minimum flow of 0.02 m³s⁻¹ provides suitable winter reproductive habitat, while a threshold of 0.01 m³s⁻¹ during summer droughts maintains isolated pools functioning as thermal refuges. Flows above 0.1 m³s⁻¹ do not enhance habitat availability and may generate unfavorable hydraulic conditions.

To examine aquatic habitat heterogeneity, five habitat units were identified in the stream segment of interest, based on the salmonid habitat classification system (USDA-USFS, 1990). According to various studies (Ruiz-Campos, 1993, 2017; Ruiz-Campos *et al.*, 2022, 2023), trouts in lotic ecosystems show a preference for habitats characterized by high discharge and current velocity, facilitating the dispersal of spawning adults and optimizing the selection of suitable spawning sites. However, the formation of these habitat units is dynamic and can undergo abrupt mod-

ifications due to extreme flooding events, which significantly alter the channel morphology and cause changes in habitat structure (Evermann, 1908; Needham, 1938; Ruiz-Campos, 1993, 2017; Meza-Matty, 2022).

The construction of suitability curves for the endemic trout *O. nelsoni* was undertaken based on an extensive literature review. Ruiz-Campos (2017) determined that the occupied depth range in pools for *O. nelsoni* is 30 to 150 cm. During spawning season (January to March), this trout prefers flow velocities ranging from 0.34 to 0.99 m s⁻¹ (Ruiz-Campos, 2017; Ruiz-Campos *et al.*, 2022). Katzman *et al.* (2010) reported that adult salmonids in their reproductive stage show a preference for current velocities ranging from 0.2 to 0.5 m s⁻¹. Finally, Ruiz-Campos *et al.* (2022) documented that *O. nelsoni* showed a marked affinity for sandy substrates, defined by particle diameters ranging from 0.0625 to 2 mm. We acknowledge the limitations of habitat suitability curves based on expert judgment or literature, but they remain a valid alternative in remote or hard to access sites, where continuous sampling is unfeasible.

CONCLUSIONS

The environmental flow modeling developed in this study ensures longitudinal hydraulic connectivity in the stream and supports the conservation of *O. nelsoni*. A minimum flow of 0.02 m³s⁻¹ maintains suitable habitat for reproduction during winter, while a lower threshold of 0.01 m³s⁻¹ during summer droughts preserves isolated pools that act as thermal refuges. Additionally, flows greater than 0.1 m³s⁻¹ do not increase usable habitat and may even produce unfavorable hydraulic conditions.

The methodological approach presented in this study is applicable to other Mediterranean climate regions, such as United States of America (California), Chile, South Africa, and southern Europe, which face similar challenges related to drought, strong seasonality, and increasing pressure on water resources. Integrating hydrobiological criteria into environmental flow modeling provides a transferable tool to enhance habitat connectivity and support adaptive management under climate change scenarios. Thus, the findings contribute not only to the conservation of *O. nelsoni* but also to global efforts to protect freshwater biodiversity in vulnerable Mediterranean ecosystems.

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