Topics of limnological research in Mexico

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UNIVERSIDAD DE COLIMA

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This book is dedicated to
Dr. Singaraju Sri Subrahmanya Sarma,
in gratitude for all his teachings in the world of limnology.

Index

Environmental Problems on Water Resources: A Review at the Basin Level with Emphasis on Tuxpan River in Veracruz, Mexico

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Abstract

Environmental conflicts arise from differing perceptions of situations and impacts where stakeholders have conflicting objectives or incompatible interests regarding water resources. The Tuxpan River basin, located in the northern part of Veracruz, has experienced an increase in population density, leading to escalating environmental challenges. To address these issues, a characterization of the water resource and an analysis of their underlying causes were conducted. A bibliographic review of academic articles and official documents was undertaken to assess the current state of the basin. The Tuxpan River basin features diverse morphological and topographic characteristics. The aim of this study is to identify the challenges related to water resource usage in Mexico's river basins with a particular focus on the Tuxpan River basin. This is achieved by compiling and analyzing available regional data, emphasizing the demand and distribution of water resources. Notably, the agricultural sector requires significant amounts of water for crops and livestock. These activities, combined with the climatic variability present in the Tuxpan River basin, impact water availability. Furthermore, increased precipitation in the upper regions—often degraded or sparsely vegetated—leads to sediment transport, which adversely affects the lower basin, making it more vulnerable to flooding.

Keywords

Environmental issues, Gulf of Mexico, water management, basin, characterization.

Introduction

Conflict and environmental issues are aspects to consider managing natural resources in Mexico. Environmental conflicts occur when human actions, whether intentional or unintentional, negatively impact natural resources, compromising human well-being. (Maya, 2019; Ortegón, 2019). In contrast, the environmental issue refers to any problem or challenge resulting from human activities or natural processes that negatively impact the environment, ecosystems, or natural resources.

Environmental issues and conflicts within river basins have escalated over the past few decades. These challenges have highlighted the need for sustainable water resource management (Rua de Cabo et al., 2006; Guerra, 2018; Maya, 2019; Ortegón, 2019).

Several basins in South America are experiencing disturbances linked to economic and productive activities, which have intensified with urban expansion and population growth. According to Aguayo et al., (2009), these activities have drastically altered land cover over the past 300 years. As a result, there has been a significant decline in vegetation, loss of natural habitats, disruption of hydrological and biogeochemical cycles, decline of native species, introduction of exotic species, and shifts in climate patterns associated with global change (Velázquez et al., 2002; Ureña-Retana, 2004; Ruiz et al., 2013).

A common issue observed in most river basins is the removal of forest cover, particularly in their upper regions. This poses a threat to the hydrological cycle by reducing both the availability and quality of water, leading to additional challenges in the provision of ecosystem services within the watershed (François et al., 2024). Deforestation is further driven by the overexploitation of water resources, the discharge of wastewater into water bodies, and unsustainable agricultural practices. If the relationship between ecosystems and productive activities within watersheds is not adequately studied, the provision of these services will continue to decline and further deteriorate (Manson, 2004).

Mexico is among the Latin American countries with the highest rates of deforestation. In 2019 alone, 321,000 ha were deforested, equivalent to 83.3 million tons of CO_2 emissions (WRI, 2020). Despite having extensive mangroves and seagrass ecosystems, Mexico has lost significant portions of these habitats due to coastal development associated with urban, industrial, and tourism expansion. Restoring and conserving mangrove and seagrass habitats could strengthen climate change mitigation and adaptation strategies by preserving blue carbon ecosystems. However, the loss of mangroves and seagrasses continues, making it essential to implement actions aimed at maintaining environmental services, increasing and preserving natural carbon sinks, reducing emissions from deforestation and forest degradation, and restoring and conserving marine-coastal ecosystems (Herrera-Silveira, 2020).

Deforestation is also driven by the overexploitation of water resources, the discharge of wastewater into water bodies, and unsustainable agricultural practices. If the relationship between ecosystems and productive activities within basins is not properly analyzed, the provision of ecosystem services will continue to diminish and deteriorate.

At the basin level, Matthews et al. (2000) highlight that vegetation provides crucial ecosystem services, including maintaining balance and supporting the proper exchange of energy and matter from the upper to the lower basin, soil stabilization, flow volume regulation, flow periodicity, and water filtration. These services are increasingly impacted by deforestation, agriculture, wildfires, and urban development, all of which disrupt the water supply network and its area of influence. This leads to reduced soil water availability and flooding in lower areas (Richard, 2016).

These issues are significant for informing decision-making processes related to development, public policies, and the management and administration of basins, not only in Mexico but also in other countries such as Colombia, Costa Rica, Uruguay, Peru, and Ecuador (Correa, 2005; Vargas, 2005; Maya, 2019). In certain cases, methodologies have been employed to identify socio-environmental conflicts, enabling the characterization of these challenges (Guerra, 2018; Maya, 2019; Bustamante, 2022)

The Tuxpan River basin, located primarily in the northern part of the state of Veracruz, has experienced a rise in population density, increasing from 6.9 million in 2000 to 8 million in 2020 (INEGI, 2017). Additionally, livestock and agricultural activities, along with oil and natural gas extraction, have intensified pressure on the river basin. However, environmental problems and conflicts related to water resources in the region have not been thoroughly characterized. This study aims to address this gap by identifying issues related to water resource use in Mexico's river basins, with a particular focus on the Tuxpan River basin. The analysis is based on a comprehensive review of the available data for the region.

Materials and Methods

Bibliographic Analysis for Problem Identification

This study was conducted through the compilation and analysis of documentary information, including scientific articles, ecological territorial planning documents, watershed management plans, and Action Plans for Integrated Watershed Management (PAMIC). A national reference framework for watershed management in Mexico was established.

A detailed analysis of these documents was carried out to examine environmental problems from the perspective of various authors. Environmental problems are defined as negative impacts or alterations to the environment that disrupt the balance of ecosystems and affect humans (Maya, 2019; Ortegón, 2019). Based on this definition, the environmental problems of the Tuxpan River basin were identified using methodological tools proposed by Villareal (2015) and Ortegón (2019), which are considered highly applicable.

The methodology consisted of three steps:

1. Characterization of the Water Resource – Determining its coverage and area of influence.
2. Identification of Causal Factors – Finding direct and indirect causes that affect the water resource.
3. Environmental Problem Identification – Determining the specific environmental issues within the Tuxpan River basin.

This analysis helps reveal the current problems facing the basin and assess whether environmental issues exacerbate the impact on water resources (Fig. 1, Table 1).

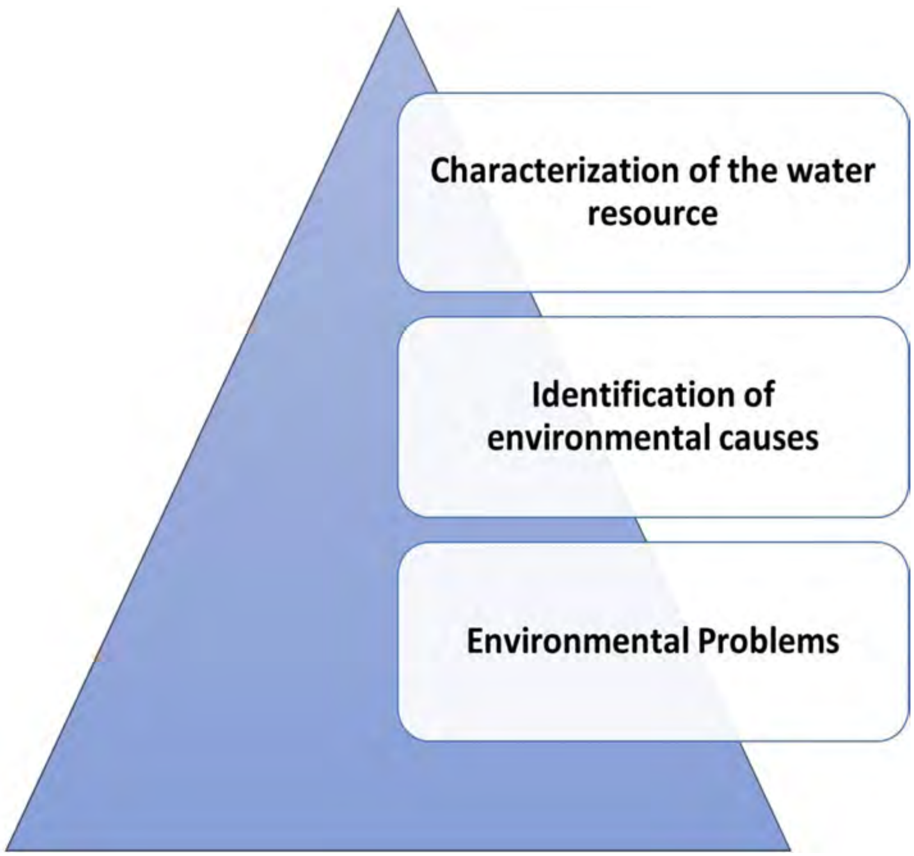

Figure 1. Description of the Process for the Identification of Environmental Issues.

Table 1. Bibliographic References Used to Identify the Different Aspects of Environmental Problems in the Tuxpan River Basin.

Aspects to Identify Environmental Problems	References
Characterization of Water Resources	INEGI-INE-Conagua (2007); INEGI (2013, 2016); Conagua (2016, 2017); INECC-FGM (2018); CONABIO (2019);
Identification of Causes	Paruelo et al., (2005); Landa & Carabias (2008); García-Orozco et al., (2011); Ellis et al., (2012); FAO and ITPS (2015); Armenta-Montero & Ellis (2016); Melchor-Marroquín & Chagoya-Fuentes (2016); INECC-FGM (2018).
Environmental Issues	Gómez-Maya (2006); Hernández-Martínez (2008); Vergara et al., (2011); Ellis et al., (2012); Armenta-Montero & Ellis (2016); Melchor–Marroquín & Chagoya-Fuentes (2016); SEMARNAT (2016); INECC-FGM (2018); Medina-Núñez (2019); Cardona (2021).

Context of Basin Management in Mexico

In Mexico, effective basin-level management is uncommon. In 2007, three governmental agencies—the National Institute of Statistics and Geography (INEGI), the National Institute of Ecology and Climate Change (INECC), and the National Water Commission (Conagua)—established standardized topographic and hydrographic criteria for basin delimitation and nomenclature. This effort resulted in the identification of 1,471 basins, classified as exorheic, endorheic, and areal basins. These basins are organized into 37 hydrological regions, 25 Basin Councils, and 13 hydraulic-administrative regions (Cotler, 2008; Cotler et al., 2010; Torres et al., 2013).

Furthermore, studies on water availability have been conducted based on the proposed basin-level classification. It has been observed that Thirty-five percent of the country's population is found in the lower zones of the basins where the storage capacity predominates and enables productive activities. However, these areas face numerous threats, including the contamination of rivers, lakes, and aquifers, as well as the impacts of climate change. Changes in precipitation and temperature patterns are expected to disrupt the water balance within the basins (Cotler et al., 2010).

In Mexico, hydrological basin problems are particularly complex due to rapid population growth in recent years, which has significantly increased water consumption. On average, a person in Mexico uses 380 liters of water per day (INECC, 2020)—200 % more than the 100 liters per day recommended by the World Health Organization (WHO) for meeting basic consumption and hygiene needs (UNESCO, 2020). This excessive demand has led to the overexploitation of 100 out of the 664 identified aquifers, while 26 of the 37 hydrological regions in the country are now in critical condition (Vargas, 2005).

Overexploitation is not the only challenge facing Mexico's hydrological basins; soil erosion is another severe issue, resulting from a combination of factors such as steep slopes, climate, improper land use, vegetation cover, and ecological disasters. Human activities, particularly agriculture, have greatly accelerated erosion rates (FAO & ITPS, 2015). Excessive cultivation and low humidity conditions deteriorate soil structure, further increasing the risk of erosion. For example, in southern Mexico, the periodic use of fire to eliminate agricultural residues is a major contributor to soil degradation. Conventional agricultural practices often involve burning stubble from previous harvests, leaving the soil exposed during the rainy season, which exacerbates erosion (Conagua, 2009).

Water pollution is another major issue affecting most of Mexico's basins, largely driven by human activities, particularly industrial, agricultural, and livestock operations. The central-western basins of Mexico are among the most severely impacted by this problem. Deforestation, often resulting from land-use changes for agricultural and livestock purposes, has significant consequences at the basin level, including the reduction of biodiversity, soil erosion, and landslides (Durán & Torres, 2003; Boehm, 2005; Conagua et al., 2009).

These environmental changes can be broadly summarized as disruptions to climatic elements, primarily caused by human activities in conjunction with deforestation, the burning of fossil fuels, and the contamination of water and soil. These factors contribute to long periods of drought and an increase in extreme weather events, such as torrential rains and high-category hurricanes (Granados-Sánchez et al., 2013).

Tuxpan River Basin

The Characterization of the Water Resource

The Tuxpan River Basin originates in the eastern part of the Sierra Madre Oriental. The upper section of the basin is marked by rugged terrain, with elevations reaching up to 3,000 meters above sea level, while the lower section consists of a vast coastal plain with elevations below 200 meters above sea level (Fig. 2) (INEGI, 2013). The basin is part of the Tuxpan-Nautla Hydrological Region (RH 27), and its primary tributaries include the Pantepec, Vinazco, Tecomate, Buenavista, and Tuxpan rivers. It spans across the states of Veracruz (75.6 %), Puebla (13.2 %), and Hidalgo (11.2 %), with Veracruz represented by 19 municipalities, Puebla by seven, and Hidalgo by five (INEGI, 2016). The Tuxpan River, the basin's main watercourse, stretches for 236 km, while the total length of the river network, including tributaries, extends to 11,283 km. Despite the vast extent of the basin's water network, the drainage system suggests that, in the event of heavy rainfall, the outflow response will be moderate. This means that the drainage outflow in response to climatic events will be slower, thus extending the concentration time for runoff. Most of the the basin's elevations are below 500 meters above sea level, as shown in the hypsometric curve, which illustrates the distribution of contour lines (Fig. 3). The region's economy is primarily driven by livestock farming and agriculture, with oil and gas extraction also taking place (INEGI, 2013; INECC-FGM, 2018).

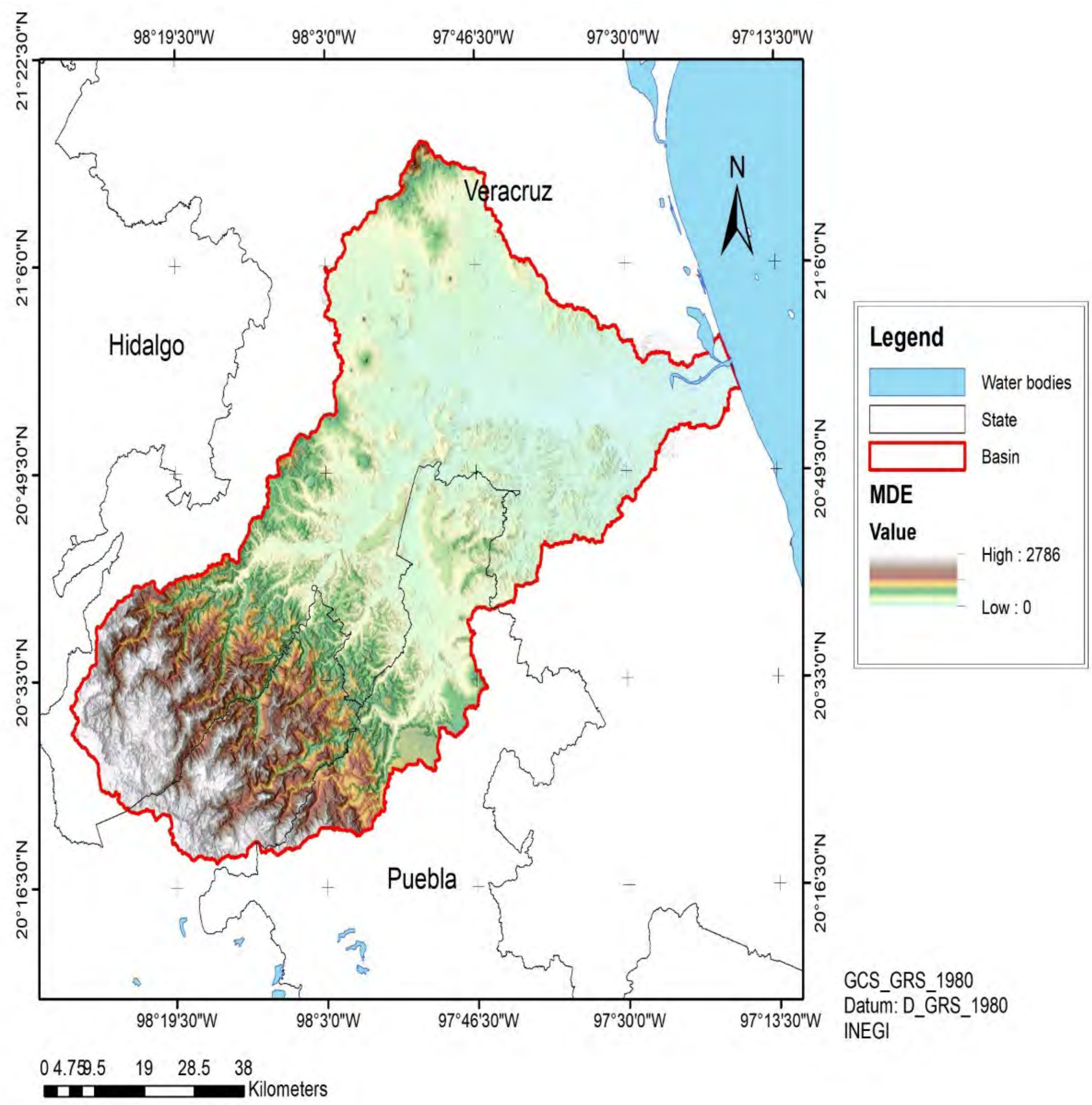

Figure 2. Location of the Tuxpan River Basin. INEGI (2016).
(DEM, Digital Elevation Model).

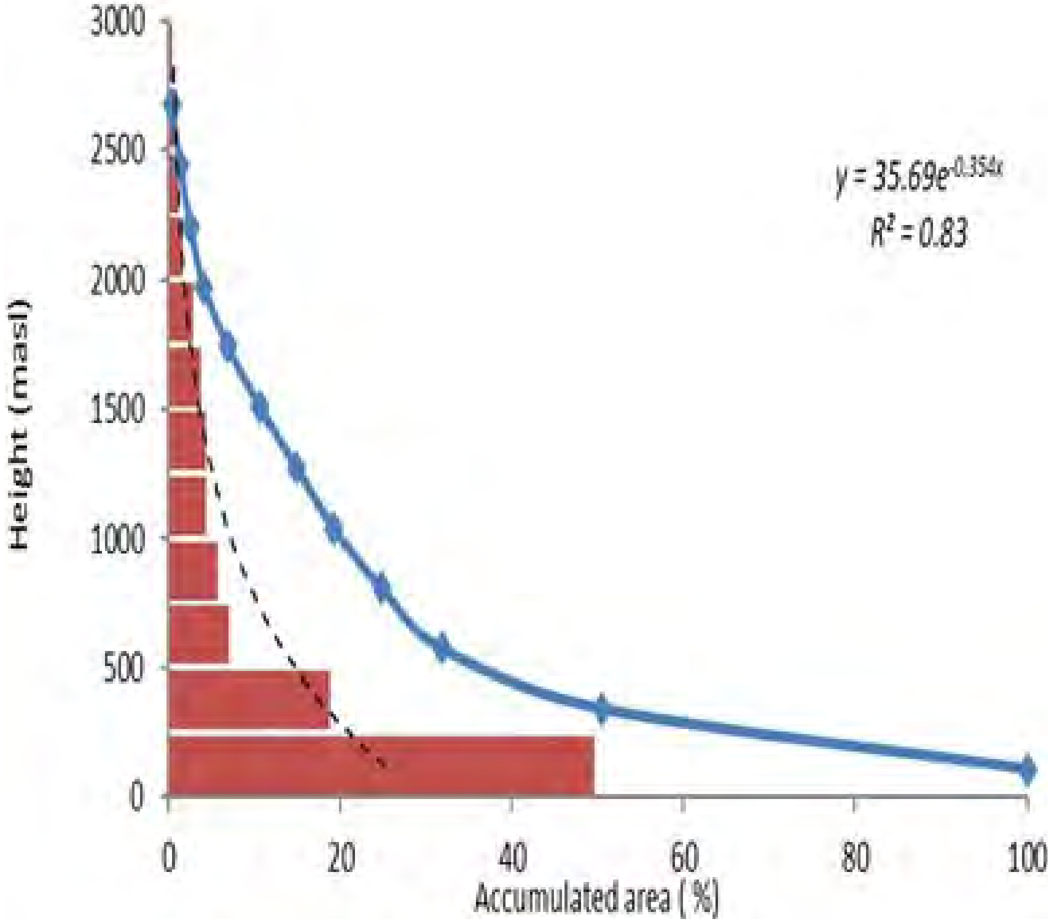

Figure 3. Hypsometric Curve and Frequency of Altitudes
(Data Obtained from INEGI).

Identification of Environmental Causes

The Tuxpan River Basin encompasses several rural areas. Although it does not have large urban centers, the existing urbanization places significant pressure on water resources, leading to political, economic, environmental, and social conflicts over water use. One of the outcomes of urbanization is the loss of vegetation, which undermines the stability of water resources, reducing their availability and coverage (Paruelo et al., 2005; Landa & Carabias, 2008; FAO & ITPS, 2015). The reduction in vegetation cover is driven by three main factors: demographic, social, and economic (García-Orozco et al., 2011). The Tuxpan River Basin, with a population density of 80 inhabitants per square kilometer, is particularly vulnerable to water erosion. The combination of population density, economic activities, topography, and precipitation contributes to widespread erosion, which affects the entire basin (Melchor-Marroquín & Chagoya-Fuentes, 2016).

In 2011, vegetation cover accounted for 27 % of the total area of the basin. The coniferous forests in the upper regions of the basin have been severely impacted, with a decline of up to 95 % (INECC-FGM, 2018). These changes in vegetation are largely a consequence of urbanization, where natural environments are increasingly being converted into agricultural and livestock areas.

These activities, compounded by the basin's climatic variability, significantly impact the availability of water resources. Furthermore, increased rainfall in the upper areas—often degraded or sparsely vegetated—results in sediment being transported downstream, which in turn exacerbates flooding in the lower basin (Ellis et al., 2012; Armenta-Montero & Ellis, 2016; Melchor-Marroquín & Chagoya-Fuentes, 2016).

According to the Public Registry of Water Rights (REPDA, 2014), the basin's water resources are allocated to seven different uses, including aquaculture, agriculture, industry, livestock, public-urban services, and domestic purposes, with surface water concessions granted for these uses. The Tuxpan River Basin's water demand is highest for agricultural, public-urban, services, and domestic purposes, with seven sub-basins categorized as having very high demand (INECC-FGM, 2018).

Environmental Causes

The analysis of the Tuxpan River Basin highlights that the primary issue facing the region is the alteration of natural vegetation, which is being converted into agricultural and urban land, particularly from the upper to the lower basin. This has led to an annual loss of 16.86 km² of vegetation, with the greatest loss occurring in the middle-lower basin, where agricultural land use predominates. This land use has increased by 9.20 %, with the municipality of Álamo being the largest contributor to this trend (Ellis et al., 2012; Armenta-Montero & Ellis, 2016; Melchor-Marroquín & Chagoya-Fuentes, 2016; INECC-FGM, 2018).

The root causes of biodiversity loss stem from human activities, primarily the rapid population growth and unsustainable consumption of natural resources. At the current rate, natural systems are no longer able to meet human needs. The destruction of vegetation directly impacts water resources, reducing their availability and coverage (Paruelo et al., 2005; FAO & GTIS, 2015). Between 1999 and 2019, vegetation cover in the municipality of Tuxpan decreased by 0.17 % (1.55 km²) (Cardona, 2021), driven by the factors previously mentioned (García-Orozco et al., 2011).

The decline in vegetation, including oak forests, high evergreen forests, and sub-evergreen forests, exacerbates vulnerability in downstream areas. According to Ortiz-Lozano (2013), deforestation increases surface runoff, which impacts areas such as Álamo and Tuxpan. These regions have experienced extreme weather events, and the removal of vegetation leads to heightened water erosion and sediment transport, increasing the likelihood of flooding. Ellis et al. (2012) reported return periods of 522 to 544 km² over periods ranging from 2 to 100 years, resulting in significant damage, economic losses, and human casualties, particularly in the agricultural and urban areas of Tuxpan and Álamo (Marroquín & Chagoya-Fuentes, 2016; Ibarra-Zabaleta et al., 2017; Rodríguez-Hernández et al., 2020).

Environmental Problems

The influx of sediments from the upper regions of the Tuxpan River Basin, combined with water contamination from the oil and citrus industries, as well as power generation activities near the rivers, has led to the disruption and even disappearance of some water wells in the basin (Medina-Núñez, 2019). Additionally, the spillage of hydrocarbons into water bodies and soil in certain municipalities in the lower basin, such as Cerro Azul, Temapache, and Tuxpan, has caused significant contamination of both water and soil resources. This pollution has had detrimental effects on native vegetation in the region (Vergara et al., 2011).

Hydrocarbon contamination in water resources renders them unsuitable for human consumption and harmful to other living organisms, which cannot survive due to the high concentrations of carbon and other toxic substances. As a result, these organisms die, further degrading the quality of the water and making it unsafe for consumption (Gómez-Maya, 2006; Hernández-Martínez, 2008; Medina-Núñez, 2019). In the Álamo and Temapache regions, citrus juice companies also play a significant role in water contamination. These industries consume large amounts of water and produce toxic waste, which is discharged directly into drainage systems that are connected to local water sources, making the water unfit for use by the surrounding communities.

Demographically, the population in the lower basin has been steadily increasing (SEFIPLAN, 2022), resulting in higher demand for housing, education, healthcare, and commercial infrastructure. This growing demand is putting pressure on local vegetation types. The combined impact of population growth, infrastructure development, and industrial and port activities is reflected in the expansion of human settlements, which increased by 3.29 % (31.80 km²) between 1999 and 2019. Economically, the municipality of Tuxpan has been growing in tourism, port activities, industry, livestock, and agriculture. The first three sectors are primarily driven by the municipality's coastal location, which serves as a key transportation route for goods, machinery, and industrial equipment (Valdez-Lazalde et al., 2011).

The distribution of water for domestic use is a significant issue throughout the basin, as there is no centralized drinking water network to supply the municipalities. Water is only available in certain areas, and due to the poor condition of the pipes, it is not distributed daily. In some instances, water is not provided for several weeks because of the deteriorating infrastructure. This uneven distribution becomes remarkable during the dry season when the water levels in the sources from which the water is collected drop.

Recommendations

Based on our review, we propose that the issues identified can be addressed through the strategies outlined in the PAMIC of the Tuxpan River Basin, along with ongoing management efforts. These proposals focus on the sustainable management of resources, ensuring their conservation and renewal. Additionally, we strongly recommend the establishment of a basin council to support the management of programs aimed at securing regular funding. To effectively tackle these challenges, it is also crucial to provide comprehensive training and guidance in environmental education.

Furthermore, we propose the implementation of mitigation mechanisms for environmental services. It is essential to seek basin-wide solutions rather than concentrating on isolated issues. As such, the state must reassess its policies and programs, adopting a strategy that acknowledges environmental problems and addresses market failures that have undermined equity, environmental sustainability, and the quality of life for the population.

Environmental concerns must be prioritized, as current environmental spending is insufficient to meet key challenges. Therefore, financial solutions are necessary, seeking both international and national support to secure resources for environmental projects.

Finally, the growing water shortage—both in terms of quality and quantity—facing the basin is increasingly recognized by the population as one of the most pressing environmental problems, both now and in the future. In many regions, this issue remains difficult to explain or substantiate, as the availability of water has decreased or deteriorated due to poor management. Consequently, this issue must be given higher priority across all sectors. Comprehensive management actions must be implemented throughout the basin, directing and regulating the use of land and natural resources in a way that enables society to meet its needs without causing environmental harm.

Authors' Contributions

BERC and JLAM conceptualized this contribution. BERC compiled the literature, prepared the figures, and wrote the original manuscript. CFRG and KCGG wrote and edited the manuscript. All authors reviewed and approved the final document.

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This book takes a significant step in showcasing the relevance of limnology to our survival. Freshwater habitats, though they cover less than 1 % of the Earth's surface, are home to a substantial portion of the world's biodiversity—at least 10 % of all known species. Freshwater habitats and the biodiversity they support are under threat. Moreover, our survival depends on access to high-quality freshwater. This book not only highlights the beauty of limnology and the scientific methods used to study it, but it also draws attention to the major causes of biodiversity loss in freshwater ecosystems. It shows all readers what it means to deal with inland waters as a scientist interested in understanding ecosystems and protecting them.

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