Hydrological and Land Use Changes in the Bajo Balsas River Basin: Impacts on Water Storage at El Infiernillo Dam

M.Eng. **Eduardo JUAN-DIEGO[1],** Dr. **Maritza Liliana ARGANIS-JUÁREZ[1,2,*],**
M.Eng. **Margarita PRECIADO-JIMÉNEZ[3,*],** Dr. **Alejandro MENDOZA-RESÉNDIZ[1],**
Dr. **Rodrigo ROBLERO-HIDALGO[3]**

[1] Universidad Nacional Autónoma de México, Instituto de Ingeniería

[2] Universidad Nacional Autónoma de México, Facultad de Ingeniería

[3] Instituto Mexicano de Tecnología del Agua

* MArganisJ@iingen.unam.mx, preciado@tlaloc.imta.mx

Abstract: *This paper analyzes trends in water storage at El Infiernillo Dam in Michoacán, Mexico, and its relationship with climate and land use factors. Using historical data from 1994 to 2024, the research identifies a significant decline in the dam's storage volume, particularly after 2002, attributed to increased evaporation and water withdrawals for agricultural and urban use. Land use changes in the Bajo Balsas River basin, including a 17.25% increase in irrigated agriculture and a 9,323% human settlements expansion, have altered hydrological dynamics, it reducing infiltration and increasing surface runoff; natural vegetation loss such as oak and pine forests, further exacerbates water scarcity. Findings highlight urgent need for sustainable water management strategies, including soil conservation, improved water use efficiency, and climate change adaptation measures, to address the growing water crisis at this region.*

Keywords: *Water storage, land use change, climate change, hydrological dynamics, water scarcity*

1. Introduction

Reservoirs' problem in water availability terms is an issue of great relevance worldwide. Dams are critical infrastructures for water storage and management, but they face significant challenges due to factors such as climate change, population growth, and water resources overexploitation [1-2]. In Mexico, this situation is particularly worrying, as many dams operate below their optimal capacity due to prolonged droughts and inadequate water resource management [3-4].
Globally, new dams' construction and existing expansion ones also pose environmental and social challenges. Zarfl et al. (2015) [5] highlight that the boom in the construction of hydroelectric dams can have significant impacts on aquatic ecosystems and local communities. In addition; Grill et al. (2019) [6] point out that rivers fragmentation due to dams can affect the biodiversity and river ecosystems connectivity.
Sustainable dam management is essential to balance human development needs with environmental conservation. Winemiller et al. (2016) [7] suggest that it is possible to find a balance between hydropower generation and biodiversity protection in regions such as the Amazon, Congo, and Mekong. Poff et al. (2016) [8] propose the use of ecological engineering approaches to manage water sustainably under conditions of future uncertainty.
The availability of accurate and up-to-date data on dams and their impacts is crucial for effective management. Lehner et al. (2011) [9] and the International Commission on Large Dams (ICOLD) database [10] provide detailed information on the characteristics of dams and reservoirs globally, which is critical for planning and informed decision-making.
In this study, the behavior of the average daily inflow volumes of the El Infiernillo dam, Mich., was analyzed, with a parallel review of the main variables involved in the operation of the reservoir as well as taking into account the changes in the type of soil that have been reported to have been experienced by analyzed basin; for this purpose, methods were used to analyze independence, homogeneity and variables trend, in addition to quantifying change rates in land use in order to have a basis for making results interpretations.

2. Study site

The Bajo Balsas River Hydrological Basin extends from hydrometric stations La Caimanera, La Pastoría, Los Pinzanes and Los Panches to its mouth into Pacific Ocean, located at Lázaro Cárdenas, Michoacán, situated at coordinates 100° 31' 12" west longitude and 18° 16' 48" north latitude. This basin has a 13,949.96 Km area ² and is delimited by various regions and hydrological basins:

- To north: Cupatitzio and Tacámbaro river basins.
- To south: Hydrological Region 19, Costa Grande de Guerrero.
- To west: Tepalcatepec River Basin.
- To east: Middle Balsas River Basin.

Within this basin is Adolfo López Mateos dam, better known as El Infiernillo (Figure 1). This artificial reservoir is located in the municipalities of Arteaga, La Huacana and Churumuco in Michoacán, as well as in Coahuayutla, Guerrero. It was built by the Hydraulic Resources Ministry between August 1962 and December 1963, entering into operation on June 15, 1964. Its main purpose is electricity generation, in addition to use for irrigation and flooding control.
This dam has a rockfill curtain with a waterproof heart, with a height of 149 m and a length of 350 m at crown. Its powerhouse, located in an underground enclosure, is 21 m wide, 128 m long and 40 m high. On the left bank is the intake work, consisting of three pressure pipes of 8.90 m in diameter, with a capacity to conduct 194 m³/s per pipe. In addition, surplus work has three 13 m diameter spillways, capable of discharging 13,800 m³/s. This hydroelectric plant is located in one of the greatest seismic areas risks in the country, so its structures are continuously evaluated to monitor its dynamic behavior. Reservoir curtain is located 102 Km southeast of Apatzingán de la Constitución and 127.5 Km Uruapan southeast, in Michoacán state [11-14].

Fig. 1. Infiernillo Dam, Mich. Mexico, Location on Bajo Balsas River Basin

El Infiernillo Dam operation faces several challenges. One of the most important problems is water levels management during rainy seasons. In September 2024, controlled extraction from dam increased due to substantial rainfall, leading to a significant level increase for Balsas River (National Water Commission, 2024). These maneuvers are necessary to ensure dam safety and prevent flooding into surrounding areas [11], [15].
In recent years, Mexico has faced a significant water crisis. Average annual water per capita availability has decreased from 10,000 cubic meters from 1960 to 4,000 in 2012, and is estimated to fall below 3,000 cubic meters by 2030 [3]. In February 2024, the country's main dams were at 50% capacity, reflecting a decrease compared to previous years (Mexican Institute for

Competitiveness, 2024). This situation is due to prolonged droughts and combination water resources overexploitation [4].

3. Methodology

Main concepts and procedures that were considered in this analysis are described below.

Reservoir operation
Fundamental simulation equation for dam operation basin is based on continuity principle, which states that volume stored change in the basin during a time interval is equal to the difference between inputs volume and outputs volume during that same interval. This equation is expressed as follows:

$$\Delta V = I - O \quad (1)$$

Where:
- ΔV is the change in the volume stored at reservoir (hm³).
- I is inputs volume to reservoir (hm³).
- O it is outlets volume from reservoir (hm³) [16].

Variables involved in this equation are following:
Inflow Volume into reservoir (I): Inflows by own basin: surface runoff Volumes generated in the uncontrolled basin that discharges directly to dam. Transfer inflows from other basins: volumes from discharges from dams located upstream or in other basins. Inflows due to direct rain on the basin: volume of rain that falls directly on the free surface of the basin [17].
Outflow Volume (O): volume infiltrated into the reservoir, that is water that infiltrates the soil from the reservoir, spilled volume: water that overflows from the reservoir, volume extracted to meet demand: water used for human consumption, irrigation, power generation, etc.; volume evaporated directly from the reservoir: water that evaporates from the surface of the reservoir [14].
Continuity equation is essential for the design and dams' operation, as it allows modelling and predicting to behavior of water storage based on inputs and outputs, ensuring efficient and sustainable management of water resources [16].

Linear regression to identify trends
Linear regression is a fundamental statistical technique used to model the relationship between a dependent variable and one or more independent variables. In the context of data series analysis, linear regression is used to identify and quantify trends over time. The general equation of simple linear regression is expressed as:

$$y = bo + b1x + e \quad (2)$$

Where:
y is dependent variable (for example, the flow of a river at a given time). X is independent variable (e.g., time), $b0$ is regression intercept, which represents the value of Y when X=0, $b1$ is regression slope of the, which indicates the change in Y per unit change in X.
e is error term, which represents variability in Y not explained by X (Montgomery, Peck, & Vining, 2012) [18].
Linear regression is used to identify trends in data series as follows:
1. Data collection: historical data on interest variable (e.g., water levels, flows, precipitation) are collected over time.
2. Data exploration: data is analyzed to understand its characteristics and relationships, and visualized using scatter plots.
3. Regression model fit: A linear regression model is fitted to data using least squares methods, which minimize squares sum differences between the observed values and predicted values by the model [19].
4. Model evaluation: fit goodness from model is evaluated using determination coefficient (R2R2) and statistical significance tests for the regression coefficients.

5. Results Interpretation: the regression slope ($b1$) is interpreted to determine trend direction and magnitude. Positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend [20].

Linear regression is a powerful tool for trend analysis in data series, allowing engineers and scientists to quantify changes over time and make informed predictions about the future interest variables behavior [18].

Homogeneity and trend tests

Helmert Test

Helmert test is a nonparametric test that is based on sequences and changes from the mean. It is used to detect changes in the homogeneity of a series of data, evaluating the number of sequences and changes in the data [21-22].

Student's t-test

Student's t-test is a parametric test used to compare the means of two samples and determine if they are significantly different from each other. It is useful for assessing the homogeneity of two periods in a series of data [23].

Cramer's test

Cramer test is a nonparametric test that compares the mean of a subperiod with that of the complete record. It is used to detect changes in the mean of a data series, which may indicate a lack of homogeneity [24] [22].

Pettitt Test

Pettitt test is a nonparametric test that detects changes in the median of a data series. It is especially useful for identifying points of change in time series, which may indicate a trend or a change in homogeneity [25].

Standard Normal Test (SNHT)

Standard Normal Homogeneity Test (SNHT) is a parametric test that assesses the homogeneity of a series of data by comparing the means and variances of subperiods. It is widely used in climatological and meteorological studies [26].

Buishand test

Buishand test is a parametric test that uses the graph of cumulative deviations from the mean (residual mass curve) to detect changes in the mean of a data series. It is useful for identifying changes in homogeneity [26].

Von Neumann test

Von Neumann test is a parametric test that detects loss of randomness in a series of data due to unspecified deterministic components. Assesses the independence of data by analyzing variance [24] [26].

Fisher Test

Fisher test is a parametric test that assesses the homogeneity of variances between different groups of data. It is useful for detecting inconsistencies in the dispersion of data [27].

Spearman's Test

Spearman test is a nonparametric test that assesses the correlation of ranges between two variables. It is useful for identifying trends in data series when the relationship is not necessarily linear [28].

Mann-Kendall test

Mann-Kendall test is a nonparametric test that assesses trend in a series of data. It is widely used in hydrological and climatological studies to detect monotonic trends [29-30].

Anderson Independence Test (Correlograme)

Anderson's test, also known as a correlogram, assesses persistence in a data series by analyzing the serial order 1correlation coefficient. It is useful for identifying temporal dependence data patterns [31].

Land Use Layers

In this paper, different Series comparison for two land use and vegetation maps from Bajo River basin Balsas was carried out; these are Serie I and Serie VII. Serie I consist of material digitized by INEGI, 2024, [32] based on printed land use and vegetation maps prepared by INEGI between

1980-1991 years, based on the photointerpretation of aerial photographs taken between 1968-1986 years. Land Use and Vegetation Map Serie VII was obtained from photointerpretation application techniques with geomean images from Landsat satellite constellation selected with base year 2018 [33]; processed in Geographic Data Cube. This interpretation is supported by fieldwork. They are datasets that contain location, distribution, and extent of different plant communities and agricultural uses with their respective variants in vegetation types, crops, and relevant ecological information. Such digital geographic information contains data structured in vector form coded according to the Dictionary of Vector Data on Land Use and Vegetation Series IV for Scale 1:250 000 applicable to different ecological units (plant communities and anthropic uses) contained in the dataset.
Calculation sequence

1. Annual historical average was obtained from daily data on inputs storage volume by own basin, inputs by total basin, evaporation and total outputs by intakes and spillway, as well as from the elevation and area curve.
2. Trend lines were obtained from previously obtained series
3. Methods were applied to identify independence, homogeneity and series trends.
4. Existing land uses were analyzed and land use percentages were obtained to identify their changes.

4. Results

This section highlights main analysis results.

Adjustment to trend lines of the analyzed series
Average annual daily storage volume behavior as well as variables related to its estimation, can be seen at following figures. These figures present trend lines corresponding to entire series and also added trend lines of time periods in which abrupt changes in data were observed behavior. Figure 2 shows an annual average daily storage volume decreasing behavior as a whole; and a sharp decrease in their values from 2002 onwards.

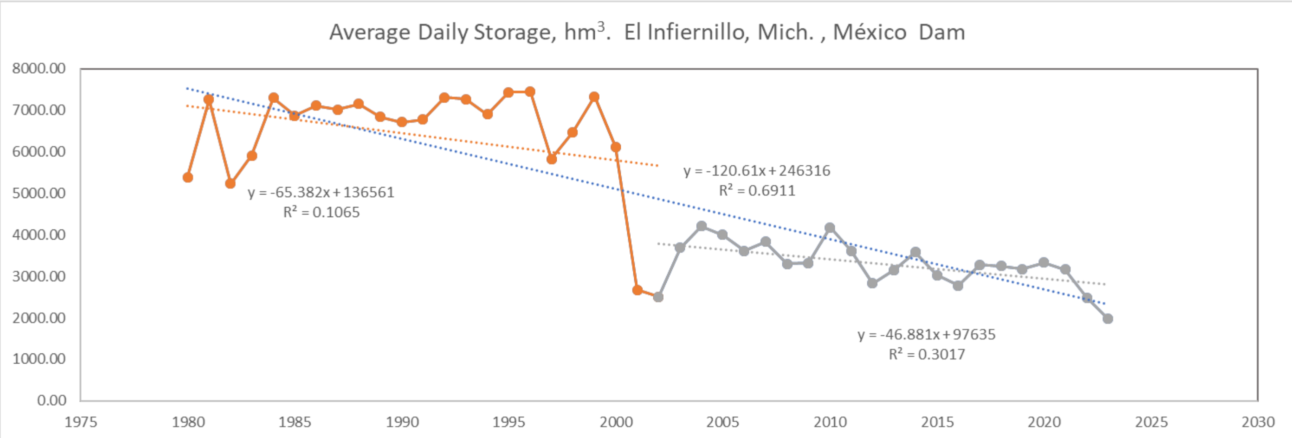

Fig. 2. Annual Average Daily Storage, El Infiernillo Dam, Mich, Mexico

Figures 3 shows a slight increasing trend in entry volumes to dam, both by own basin (OB) and by total basin (TB). Data series analysis for El Infiernillo dam storage volume revealed a downward trend since 1994, with a more pronounced reduction from 2002 (Figure 3).

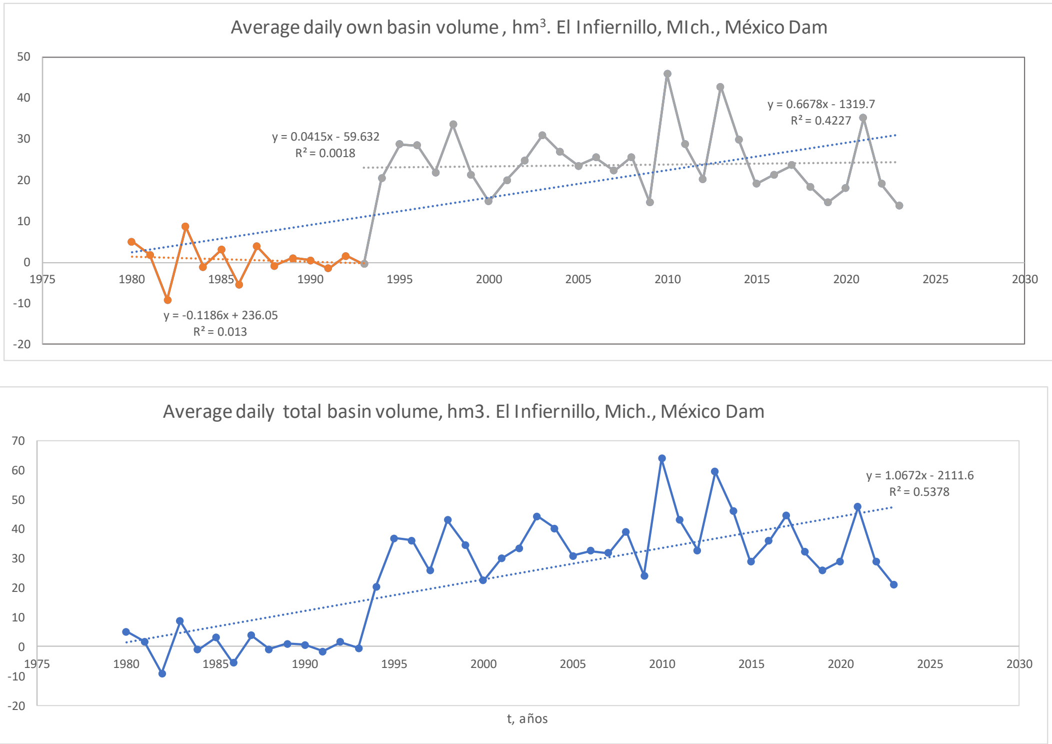

Fig. 3. Annual average daily inflow volume by own basin and by total basin, El Infiernillo dam, Mich, Mexico

This behavior can be attributed to several factors, including increase in evaporation and water withdrawals for agricultural and urban use (Figure 4). Evaporation, in particular, showed an increasing trend, suggesting that climate change could be influencing water stored dam loss. Figure 4 show an increasing behavior in average annual daily evaporation and also in extractions made to this reservoir.

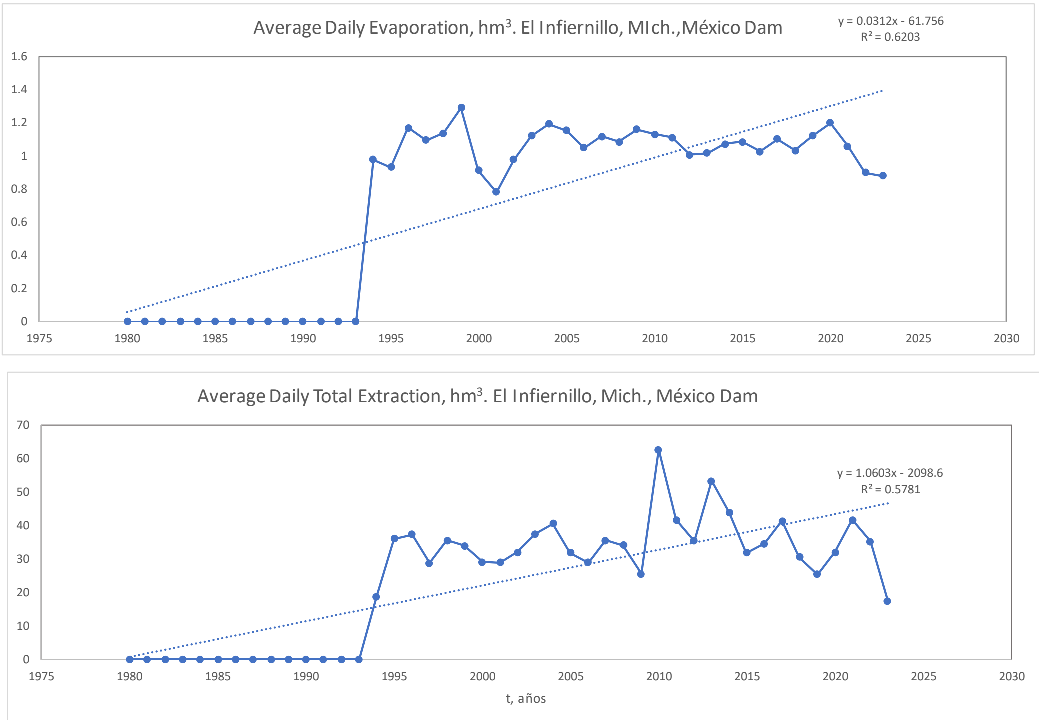

Fig. 4. Evaporated volume and annual average daily withdrawals, El Infiernillo dam, Mich, Mexico

Land use maps analysis

Analyzing land use maps from different years, such as Serie I (1980 year) and Serie VII (2018 year), is crucial for several reasons, comparing maps from different years helps identify deforestation, urban expansion, agricultural development, or industrialization.

It allows for quantifying changes in land cover, such as forest loss, water body reduction, or soil degradation.

Long-term land use changes can reveal ecosystem degradation, biodiversity loss, and increased vulnerability to natural disasters.

It helps assess the impact of human activities on climate change, water cycles, and soil erosion.

Comparing maps can highlight urban sprawl, road expansion, or industrial growth, helping urban planners manage sustainable growth.

It assists in preventing uncontrolled development that could lead to traffic congestion, pollution, or resource depletion.

Useful in environmental forensics, determining illegal land use changes, deforestation, or land encroachments. Evidence in legal disputes regarding land ownership, protected areas, or unauthorized constructions.

Helps in evaluating how land use changes increase flood risks, landslides, and desertification.

Supports the design of mitigation strategies by identifying vulnerable areas.

Detects changes in agricultural patterns, such as shifts from forest to farmland or urbanization of fertile land. Assists in water resource planning by monitoring changes in wetlands, reservoirs, or watershed areas.

Long-term land use analysis provides insights into carbon sequestration, deforestation trends, and changes in green cover, which impact climate models. This kind of analysis can gain a historical perspective on environmental trends and develop strategies for sustainable development, conservation, and policy-making.

Series I and VII Land Use Map Analysis

Series I and VII comparative analysis land use and vegetation maps for Bajo Balsas River basin (Figures 5 and 6 and Table 1) showed significant changes in land cover between 1980 and 2018. Among most notable trends are:

1. Increase in Irrigated Agriculture: An increase of 17.25% was observed in the area allocated to irrigated agriculture, which implies a greater demand for water for this sector. This increase could be putting pressure on the available water resources in the basin, contributing to the decrease in the volume of storage in the dam.
2. Expansion of Human Settlements: The area occupied by human settlements increased by 9,322.97%, reflecting an accelerated urbanization process. This urban growth may be affecting aquifer recharge and increasing surface runoff, which in turn reduces water infiltration into the soil.
3. Reduction of Forests and Jungles: There was a significant decrease in forests, as well as in low deciduous forest (-49.27%) and in Jungles (-44.26%). These natural areas loss affects soil capacity infiltration and contributes to an increase in surface runoff, which may be influencing the reduction in the volume of water stored in the dam.
4. Increase in Secondary Vegetation: A notable increase in secondary shrub vegetation was observed, especially in areas that were previously covered by Forest. This change suggests an original vegetation cover degradation, which may have negative implications on basin hydrological regulation.

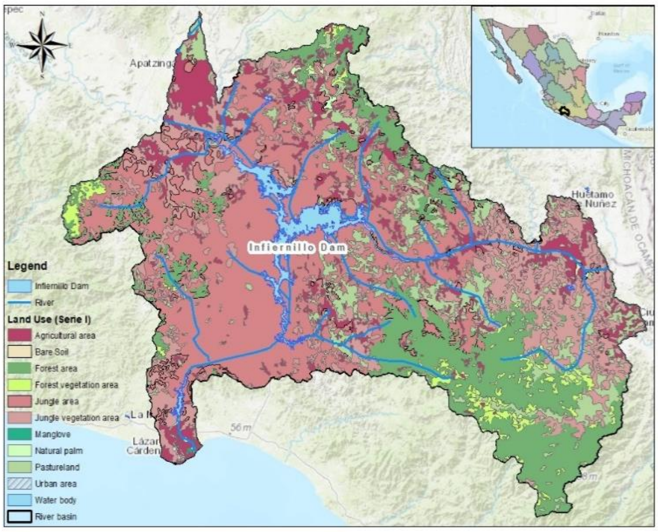

Fig. 5. Land Use Map Series I Lower Balsas River Basin

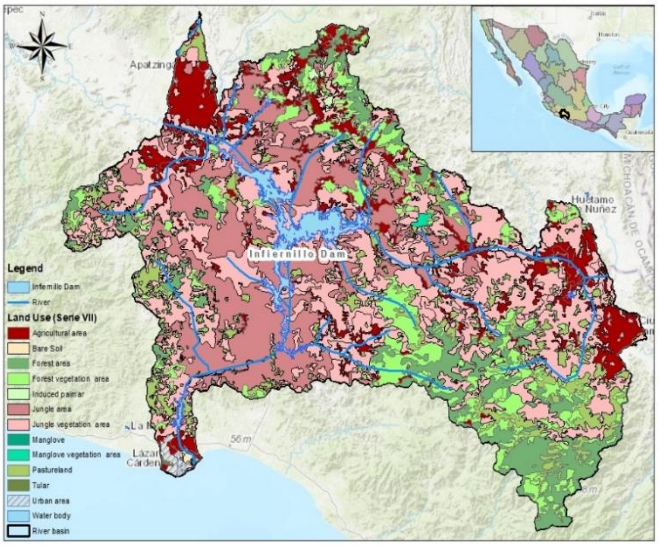

Fig. 6. Land Use Map Serie VII Lower Balsas River Basin

Table 1: Land use maps comparison from series I and VII generated by INEGI

Description	Serie I (Area Km^2)	Serie VII (Area Km^2)	Exchange rate %
Agricultural area	1,369.08	1,605.25	17.25
Bare Soil	13.45	12.92	-3.91
Forest area	2,439.28	1,237.32	-49.27
Forest vegetation area	373.54	1,459.49	290.72
Jungle area	5,132.93	2,860.97	-44.26
Jungle vegetation area	2,906.28	4,917.51	69.20
Manglove	3.59	4.54	26.63
Natural palm	26.06	29.00	11.29
Pastureland	1,399.39	1,391.15	-0.59
Urban area	1.09	103.02	9,322.97
Water body	280.03	320.39	14.41
Tular		3.15	100.00
Total Km^2	13,944.72	13,944.72	-

Land Use Changes Implications
Changes in land use identified in this study have important implications for water management in Bajo Balsas River basin. Natural vegetation cover reduction and the increase in area devoted to irrigated agriculture and human settlements are altering runoff and water recharge patterns. This, in turn, is affecting water availability in El Infiernillo dam, which could aggravate water scarcity situation for this region. In addition, forests and jungles loss may be contributing to rising local temperatures and increased demand for water in agricultural and urban sectors. These factors, combined with the climate change effects, could be exacerbating decrease in storage volume at dam.

5. Discussion

In this section, a detailed discussion of the results obtained from trends analysis in the storage of El Infiernillo dam, as well as changes in land use in the Bajo Balsas River basin, is presented. In addition, the results are contrasted with the conclusions of the study to offer a comprehensive view of the problem and its implications.
When reviewing Figure 7, no appreciable variations are observed in annual average daily area behavior reported in reservoir operation, only small positive slopes reach its trend lines, a change in the rule of areas correspondence from 2001 to 2002 is not clearly distinguished. As for elevations, there is a slightly downward behavior in series as a whole (line slope is negative), in separation by years intervals something similar happens, although it is not such an appreciable reduction that it is considered as a decrease cause in storage volume after the year 2002.

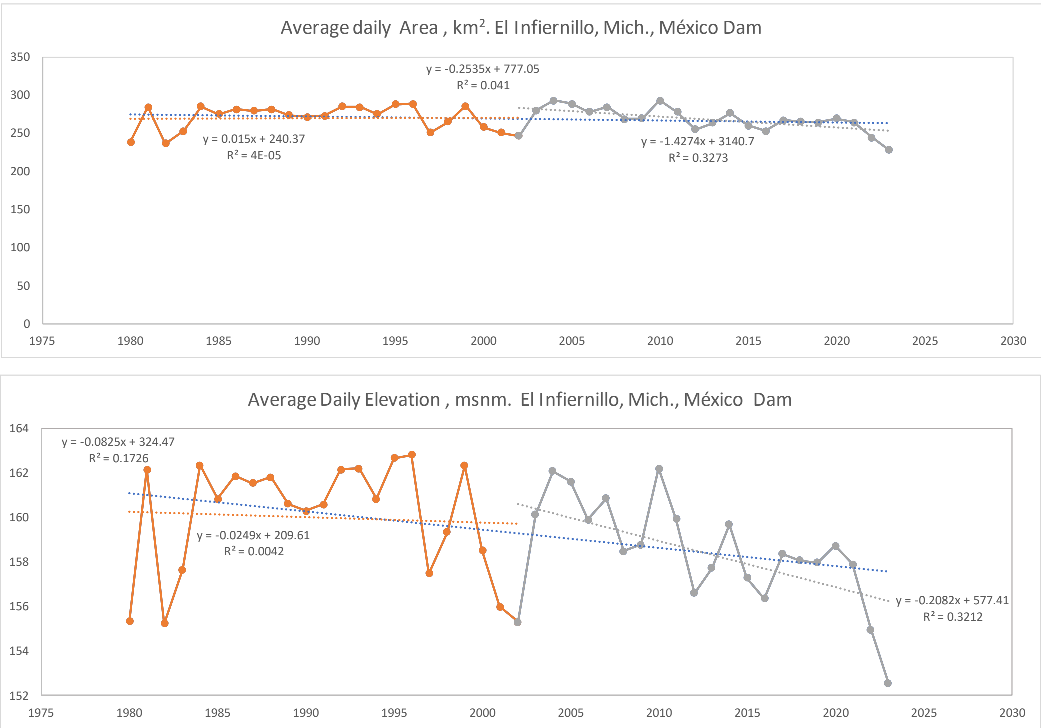

Fig. 7. Areas and Average Annual Daily Elevations, El Infiernillo Dam, Mich, Mexico

In addition, homogeneity and trend tests applied to data series indicated that most variables analyzed (storage volume, inputs by own and total basin) are not homogeneous and are temporally dependent (Table 2). This is due, to a large extent, to runoff exercised regulation by El Caracol dam, located El Infiernillo dam. Upstream. On the other hand, evaporation was the only variable that was homogeneous and independent, which reinforces the hypothesis that this factor is significantly influencing the decrease in storage volume.

Table 2: Results of homogeneity, trend and independence tests for the different variables

Variable	Data number	Homogeneity test								Conclusion
		Helmert	t the Student	Cramer	Pettit	Standard Normal	Buishand	By Neumman	Fisher	
V, Hm^3	30	X	X	X	X	X	X	✓	X	NH
OB, Hm^3	44	X	X	X	X	X	X	✓	X	NH
TB, Hm^3	44	X	X	X	X	X	X	✓	X	NH
Evap, Hm^3	30	✓	✓	✓	✓	✓	✓	✓	✓	H

Table 2: (continuation)

Name	Trend test		Conclusion	Independence
	Spearman	Mann Kendall		Anderson
V, Hm^3	✓	✓	T	D
OB, Hm^3	X	X	NT	D
TB, Hm^3	X	X	NT	D
Evap, Hm^3	✓	✓	T	I

Notes: T Tendency, NT No Tendency, D Dependent, I Independent

From homogeneity tests, only evaporation resulted in a homogeneous and independent series; remaining variables were non-homogeneous and dependent, a result that was expected due to regulation from existing runoff to El Caracol dam located at El Infiernillo dam upstream.
Table 3 presents an analysis of various scenarios, highlighting their results and the conclusions derived from them.

Table 3: Results Comparison

Analyzed Aspect	Results	Conclusions
Storage Trend	This trend has been declining since 1994, with a more pronounced reduction since 2002.	Increased evaporation and withdrawals are influencing the decrease in storage volume.
Land Use Changes	Increase in irrigated agriculture (+17.25%) and human settlements (+9,322.97%).	Agricultural and urban expansion is affecting hydrological basin dynamics.
Forest and Jungle Reduction	Decrease forest (-49.27%) and (-44.26%) jungle.	Vegetation cover loss is increasing surface runoff and reducing infiltration.
Impact on Water Availability	Reduction of storage volume in the dam.	The combination of factors is reducing water availability in the region.

6. Conclusions

This paper identifies a continuous decline in the El Infiernillo Dam storage volume since 1994, with a more pronounced reduction after 2002. The primary drivers of this decline are increased evaporation rates and higher water withdrawals for agricultural and urban use.
Land use changes in the Bajo Balsas River Basin, particularly the 17.25% expansion of irrigated agriculture and the 9,322.97% increase in human settlements, have significantly altered the region's hydrological balance. Natural vegetation loss including a 49.27% decrease in forests and a 44.26% reduction in jungle, has further exacerbated the situation by increasing surface runoff and reducing groundwater infiltration.
These combined factors are leading to a reduction in water availability, which poses a growing challenge for regional water security. To mitigate these impacts, it is essential to implement soil and water conservation strategies, improve water use efficiency, and integrate climate adaptation

measures into future water management policies. Additionally, continuous monitoring of seepage and hydrological trends will be crucial for sustaining water resources in the region.
This research provides a critical foundation for developing sustainable water management strategies that balance human demand with ecological conservation, ensuring long-term water security for the Bajo Balsas River Basin.

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