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Analysis of the Sis and Icán Basins in Guatemala: Recommendations for Disaster Prevention

Análisis de las Cuencas Sis e Icán en Guatemala: Recomendaciones para la Prevención de Desastres

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ABSTRACT: Guatemala, due to its geographic location and recurring extreme events, faces significant natural risks, with flooding being a historical threat. The objective of this study is to analyze the hydrological characteristics of the Sis and Icán river basins, employing qualitative and quantitative approaches. The research integrates climate and flow data with hydraulic modeling and stochastic analysis. Meteorological data were collected from stations such as INSIVUMEH and ANACAFE, using HEC-RAS software to hydraulically model the basin. Among the results, the identification of vulnerable areas stands out, obtained through modeling that considered return scenarios and resulted in a final zoning based on extreme flows. The comprehensive approach reveals key details: the total basin area is 929.89 km², with a perimeter of 156.49 km; average slopes range between 3% and 3.35%; The maximum annual rainfall was 5259.8 mm in 2021. The average annual surface runoff is 336 million m³ for the Icán River and 160 million m³ for the Sis River, totaling a potential water availability of approximately 497 million m³ per year. Flood modeling results indicate flood-prone areas, improving the understanding of potential impacts on the Sis-Icán basin.
Keywords: hydraulic modeling, Geographic Information Systems, watershed management.

RESUMEN: Guatemala, por su ubicación geográfica y eventos extremos recurrentes, enfrenta riesgos naturales significativos, siendo las inundaciones una amenaza histórica. El objetivo de este estudio es analizar las características hidrológicas de la cuenca de los ríos Sis e Icán, empleando enfoques cualitativos y cuantitativos. La investigación integra datos climáticos y de caudales con modelado hidráulico y análisis estocástico. Se recopilaron datos meteorológicos de estaciones como INSIVUMEH y ANACAFE, utilizando el software HEC-RAS para modelar hidráulicamente la cuenca. Entre los resultados, se destaca la identificación de áreas vulnerables, obtenida mediante la modelación que consideró escenarios de retorno y resultó en una zonificación final basada en caudales extremos. El enfoque integral revela detalles clave: el área total de la cuenca es de 929,89 km², con un perímetro de 156,49 km; las pendientes promedio oscilan entre 3% y 3,35%; la precipitación anual máxima fue de 5259,8 mm en 2021. La escorrentía superficial anual promedio es de 336 millones de m³ para el río Icán y 160 millones de m³ para el río Sis, sumando una disponibilidad hídrica potencial de aproximadamente 497 millones de m³ al año. Los resultados de la modelación de inundaciones señalan áreas propensas a inundaciones, mejorando la comprensión de los posibles impactos en la cuenca Sis-Icán.
Palabras clave: gestión de cuencas, modelación hidráulica, Sistemas de Información Geográfica.

INTRODUCTION

Conducting hydrological research is essential for the growth of a community, a region, or even a country. These studies allow us to understand water behavior in a given area, its distribution within the region, and its availability to different stakeholders or for use in specific sectors. Likewise, it contributes to the planning, design, construction, and operation of a project (Rivera *et al.*, 2021).

This progress must ensure sustainability and environmental preservation, with particular attention to water protection and the implementation of strategies for land-use planning and design. Improving water resources is a fundamental requirement for achieving sustainable urban planning (Machacuay & Lozano, 2025).

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According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is defined as a modification of the climate caused directly or indirectly by human activities, which alters the composition of the global atmosphere and is in addition to natural environmental variability over a comparable time period. This phenomenon increases the likelihood of extreme weather events, such as intense rainfall that can cause floods, landslides, hurricanes, and cyclones; as well as increases in temperature, sea level rise, and a decrease in freshwater sources (Gallo & Sánchez, 2021; Suazo & Torres, 2021). Currently, it is a pressing issue for the governance of any nation and is addressed by the scientific community as one of the trends of postmodern society (Bósio & Rodrigues de Oliveira 2023).

Guatemala is a country in the Central American isthmus, located in a tropical climate zone, where hydrometeorological threats are recurrent and have significant impacts. The 2017 Global Disaster Risk Index ranked the country ninth in terms of socio-economic impacts from natural disasters Cabrales & López (2023); therefore, promoting ecosystem conservation and protection against natural disasters is one of the objectives of the Development Bank of Latin America and the Caribbean (De Miguel & Sánchez, 2023).

Sis-Icán River basin, as this basin possesses the necessary conditions for conducting a hydrological analysis through flood modeling. This modeling helps identify vulnerable areas and enables effective flood risk management and mitigation strategies. This tool supports decision-making by providing valuable information on the potential impacts of flooding (Vallejo *et al.*, 2024).

Within the Sis and Icán river basins, there is a growing need for a study to determine the behavior of these rivers, as well as to promote a basin management program to reduce the risk of pollution and flooding in the lower reaches. The objective of this study is to analyze the hydrological characteristics of the Sis and Icán river basins for flood modeling, enabling the identification of flood-prone areas based on a comprehensive analysis of the biophysical, climatic, and morphometric characteristics of the study area.

MATERIALS AND METHODS

This research was conducted using a mixed qualitative and quantitative approach, with a non-experimental and correlational design to address the complexity of the basin (García *et al.*, 2021). The study combined longitudinal analyses to assess the temporal variability of hydrological variables and a descriptive-diagnostic component to characterize the current state of the basin and its flood threats, integrating primary and secondary information through Geographic Information Systems.

Study area

Sis-Icán River basin, located in southwestern Guatemala. The Icán River is a coastal river that originates in the Sierra Madre mountains, on the slopes of the Santo Tomás volcano (Suchitepéquez), and flows into the Pacific Ocean. It runs parallel to the Sis River, also in Suchitepéquez, which connects with the Sis Chiquito and Se rivers before joining the Icán River. The Sis-Icán River basin covers a total area of 919 km².

Data collection

Meteorological, hydrometric, and spatial information was collected from various institutional and field sources:

- Meteorological data: daily and monthly records of precipitation, tank evaporation, temperature and relative humidity were obtained from the following stations: National Institute of Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) “Mazatenango Station”; National Coffee Association (ANACAFE) “Buena Vista Station”; Private Institute of Research on Climate Change (ICC) “Tululá , Lorena, Naranjales, San Nicolás and Providencia Stations”.
- Hydrometric data: flow series were acquired from the La Franja and La Máquina hydrometric stations (INSIVUMEH). This information was supplemented with data from the ICC and with regional flood analyses.
- Spatial and field data: digital elevation models, satellite imagery (Google *Satellite)*, and existing geological and geomorphological maps were used. Fieldwork was essential to verify vegetation cover, land use, geomorphological characteristics, and hydrological conditions *in situ,* as well as to calibrate the information obtained in the office.

Instruments and software

The following tools were used for processing and analyzing the information:

- Monitoring stations: meteorological and hydrometric stations of INSIVUMEH, ANACAFE and ICC for the acquisition of primary data.
- Hydraulic modeling software: the HEC-RAS software, along with its RAS Mapper add-on, was used to simulate the hydraulic behavior of the rivers and delineate the flood areas.
- Geographic Information System (GIS): ArcGIS was used for the management, analysis and spatial representation of information, including the creation of thematic maps of land cover, land use, slopes, geology and the final zoning of flood areas.
- Analytical tools: spreadsheets and statistical software were used to perform hydrological, stochastic, and water balance calculations.

Biophysical and morphometric characterization of the basin

The biophysical and morphometric characterization of the basin was carried out in detail based on fieldwork and spatial analysis with ArcGIS (Cobeña *et al.*, 2023). This included:

- Relief survey and geological verification: for mapping abiotic features.
- Morphometric analysis: parameters such as total area, perimeter, length of the main river, drainage classification, average altitudes and slopes were calculated, following Horton's method.
- Geomorphological analysis: this was carried out by comparing historical satellite photographs to identify changes in the morphology of the basin.

Climatological and hydrological characterization

To characterize the hydroclimatic regime of the basin and quantify the availability of water resources, the following analyses were performed:

- The climatic variables precipitation and temperature were analyzed, segmenting the basin into upper, middle and lower parts, contextualizing it with information from the neighboring basin of the Nahualate river.
- Intensity-Duration-Frequency (IDF) curves: were used to describe the probabilistic behavior of precipitation, using data from the Mazatenango station as a base.
- Surface runoff analysis: the methodology of Villón (2004) was used from data from the La Franja and La Máquina hydrometric stations to calculate flows and analyze the behavior of runoff in different segments of the drainage network.
- Schosinsky methodology was applied to estimate the water balance of the basin.

Statistical and stochastic analysis of extreme flow rates

In order to determine design flows for different return scenarios and evaluate the probability of extreme hydrological events, a statistical and stochastic analysis of maximum flows was developed using the following procedures:

- Estimation of maximum flows: the Soil Conservation System (SCS) method was used to calculate maximum flows Lozano y Valeriano (2022), considering the soil classifications and hydrological conditions observed in the field.
- Frequency analysis: a stochastic analysis of the maximum daily flows was performed for a full hydrological year, generating frequency curves. To calculate maximum design flows with return periods of 50 and 100 years, Pearson Type III and Gumbel probability distributions were applied, using historical data from the hydrometric stations.

Hydraulic modeling and flood zoning

To evaluate the hydraulic behavior of the channels under extreme events and to delimit the areas susceptible to flooding in the basin, a hydraulic model was developed with HEC-RAS Vallejo *et al.* (2024) and subsequent zoning in ArcGIS, considering the following aspects:

- Model configuration: a steady-flow hydraulic model was constructed for three key segments: the Sis River, the Icán River, and their confluence at the estuary. HEC-RAS was used with data from: channel cross-sections, derived from topography and the digital elevation model; Manning roughness coefficients for each reach, based on field observations and the digitization of satellite images (Google Satellite); and, as boundary conditions, the estimated maximum flows for the different scenarios were entered (period 2003-2022, and return periods of 50 and 100 years).
- Simulation and zoning: hydraulic simulation allowed for the determination of flood maps for each scenario. These results were exported to ArcGIS, where they were integrated with geological and geomorphological information to generate a zoning map of flood-prone areas. This map was compared and validated with the flood hazard mapping of the Institute of Agriculture, Natural Resources and Environment (IARNA).

RESULTS AND DISCUSSION

Analysis of the biophysical and morphometric characteristics of the basin

The study of biophysical aspects identified three relief ranges in the Sis-Icán River basin: 25-50%, 12-25%, and 0-12%. The steepest slopes (25-50%), located in the upper part, comprise 4.48 km², equivalent to 0.48% of the total area. The drainage network is subdivided into the sub-basins of the Icán, Sis, Nimá, and Seco rivers, which converge in the El Tulate estuary to the south. Geologically, volcanic formations and alluvial deposits (Qa), typical of the Guatemalan Pacific slope, predominate.

Soil analysis, based on previous studies, identified eight soil series, with the Ixtán (Ix) series being the most representative. This soil has a loamy texture, low stoniness, good drainage, high fertility, and a significant mineralogical component, conditions that enhance agricultural productivity. Consistent with these characteristics, land use reflects intense human interaction: annual agriculture, grazing, and rubber cultivation cover approximately 70% of the watershed, with sugarcane plantations, emblematic of the southern coast of Guatemala, being particularly prominent (Vásquez *et al.*, 2025).

In geomorphological terms, plains, fills, floodplains, and alluvial fans were identified. These units are linked to depositional surfaces, shaped by fluvial and aeolian action. The northern part, dominated by the Santo Tomás volcano and its slopes of volcanic material, adds complexity to the landscape, while a marshland zone develops at the Pacific outlet. This geomorphological configuration, characterized by its alluvial nature, is common in Pacific basins, where fluvial transport from the highlands generates water accumulation over extensive areas of the middle and lower reaches (García *et al.*, 2021).

Morphometric analysis

Morphometric analysis determined that the Sis-Icán basin has a total area of 929.89 km² and a perimeter of 156.49 km (Sandoval y Rodríguez, 2021). The average altitude and average slope of the basin were calculated at 3.35%, indicating a predominantly gentle topography. A comparative analysis with the neighboring Ocosito River basin reveals significant contrasts in their hydrological behavior. While the Ocosito basin has a shape factor of 4.34 (classified as rounded), which implies a rapid hydrological response with high flows over short periods, the Sis-Icán basin exhibits a shape factor of 0.15. This low value is characteristic of an elongated morphology, which favors predominantly parallel runoff and a more moderate hydrological response, with outflows occurring over a longer period (Moretto y Gentili, 2024).

Regarding drainage density, the Sis-Icán basin has a low value (0.60 km/km²), similar to that of the Ocosito basin. This similarity is attributed to the nature of the soil composition, typical of coastal areas with high infiltration capacity and primary permeability (Villón, 2024). The low average slope of the basin (3%) limits drainage capacity and the rate of surface water runoff.

Furthermore, the analysis of geomorphological changes in the Icán River reveals a significant displacement of its river mouth and a reduction in its opening cross-section, attributable to sedimentation processes. This dynamic contrasts with the stability observed at the mouth of the Tulate Estuary, a key aspect for the management of the river's mouth.

Climatological and hydrological analysis

Climatological analysis revealed a marked precipitation gradient across the basin. In the upper reaches, the maximum annual precipitation was 5259.8 mm (2021) and the minimum was 2821.4 mm (2018), with an annual average of 397.3 mm and peak rainfall in June. The middle reaches recorded an exceptional peak of 6313.0 mm in 2010, associated with Tropical Storm Agatha. In the lower reaches, maximums reached 1100.4 mm (2021) and minimums 856.8 mm (2018). The average annual temperature showed little variation: 26.1 °C in the upper reaches, 25.8 °C in the middle reaches, and 27.4 °C in the lower reaches. In all areas, precipitation exceeded evapotranspiration, generating annual water surpluses (Maldonado *et al.*, 2021).

Nahualate River basin, consistent patterns are observed. Precipitation in the middle or foothills of the Nahualate (up to 3000 mm annually) is similar to that of the middle zone of the Sis-Icán basin (3661 mm annually). Likewise, in the lower reaches, the ranges are comparable (500-1000 mm in Nahualate and 972 mm in Sis-Icán). This similarity suggests that the climatic behavior responds to regional factors, such as the collision of Pacific and North winds, which generate condensation points and river recharge in the upper and middle reaches of both basins (Rodríguez *et al.*, 2023).

Analysis of surface runoff and water supply

The analysis of surface runoff, based on records (2003-2022) from hydrometric stations, shows the transition of high-volume rivers from the upper to the lower reaches. The La Franja station (middle section) recorded a maximum flow of 6230.29 m³/s in the 2010-2011 period and a minimum of 1956.35 m³/s in 2004-2005. Meanwhile, the La Máquina station (middle-lower section) reported a maximum of 4886.56 m³/s in 2005-2006 and a minimum of 789.12 m³/s in 2017-2018.

Based on these data, an average surface water supply of 506 million m³/year was calculated for the entire basin. However, the specific calculations of this research, which incorporate more detailed runoff analyses, refine this figure to 497 million m³/year. This supply is distributed as follows: 336 million m³/year for the Icán River and 160 million m³/year for the Sis River.

Delving deeper into the discrepancy with INSIVUMEH data: When comparing these values with the water supply of 30,053 million m³/year reported by INSIVUMEH for the entire Pacific slope, a substantial discrepancy emerges. This difference, rather than a contradiction, stems from different scales of analysis. While the INSIVUMEH data includes all the basins draining into the Pacific (a much larger area), this study is limited to the micro-scale of the Sis-Icán basin. Therefore, the comparison underscores the importance of using data at the appropriate scale for local water resource management and avoids extrapolations that could lead to an overestimation of water availability in a specific territory (Moran *et al.*, 2024).

Regarding flow rates, the historical average reported for the basin is 33.74 m³/s (Olivet y Tobar, 2023). However, the most recent records from this study indicate variability that places the current average flow rate at 15.75 m³/s. This difference is explained by the inclusion in the historical series of years with seasonal anomalies and periods of lower precipitation, which directly impacts the representativeness of the average flow rate. For risk management, a maximum design flow rate of 188.51 m³/s was determined for a 100-year return period, a crucial reference value for infrastructure planning and the delineation of hazard zones.

Water balance analysis

The application of Schosinsky 's methodology allowed for the quantification of the water balance by zones (Table 1). The results show a remarkable capacity for generating water resources, although with marked differences between the parts of the basin.

In the upper reaches, the Suchitepéquez and Samayac soils (silty loams, with a high infiltration capacity of 412 mm/day) and an average root depth of 1500 mm (forests and coffee plantations) favor a surface runoff of 1416.87 mm/year (40% of the precipitation) and a potential recharge of 425.73 mm/year (12%). These values, considered moderate to high, confirm this area as a key water recharge zone (Saldaña *et al.*, 2023).

Table 1. Water balance

Region	Soils	Surface runoff (mm/year)	% PP	Potential recharge (mm/year)	% PP
High	Suchitepéquez, Samayac	1416.87	40	425.73	12
Average	Mazatenango, Cuyotenango	1810.04	44	561.28	14
Low	Ixtán	337.52	35	270.12	17

The middle section, dominated by Mazatenango and Cuyotenango soils (silty loams, infiltration rate of 320 mm/day) and sugarcane cultivation (roots infiltration rate of 1300 mm), exhibits the highest generation of surface runoff at 1810.04 mm/year, representing 44% of the total precipitation (PP) and the highest potential recharge in the basin (561.28 mm/year; 14%). This local maximum in recharge is attributed to a favorable combination of factors: still abundant rainfall, soils with good permeability, and a topography that, although less steep than in the upper section, facilitates infiltration before the water concentrates in the watercourses.

In the lower reaches, the Ixtán soil (clay texture, infiltration rate of 245 mm/day) and the corn and bean crops (shallow roots, 250 mm) limit infiltration. Furthermore, potential evapotranspiration (1561.73 mm/year) exceeds precipitation (971.93 mm/year). As a result, surface runoff (337.52 mm/year; 35% of potential precipitation) and potential recharge (270.12 mm/year; 17%) are numerically lower. Despite this, due to its size and topographic characteristics, this area provides a significant water reserve, both surface and groundwater, which sustains ecosystems and productive activities.

In global terms, the Sis-Icán basin generates a total of 3564.43 mm/year of surface runoff and a potential recharge capacity of 1257.13 mm/year, confirming its importance as a reservoir and water regulator on the Pacific slope.

Analysis of hydraulic modeling, flood zoning and risk management

The application of the HEC-RAS model allowed for the simulation of river flooding under 50- and 100-year return period scenarios, using the Pearson III and Gumbel distributions for inflow rates. The modeling confirmed that energy losses in the analyzed reaches are due to flow contractions and expansions, a typical phenomenon in channels with variable geometry (Gutiérrez *et al.*, 2022). Both probability distributions proved reliable for long-term predictions, consistently identifying flood-prone areas in the middle reaches of the Sis and Icán rivers, as well as in the El Tulate estuary.

The final zoning (Figure 1), resulting from the integration of flood maps (for an extreme flow of 928 m³/s) with geomorphological information and land use data, determined that 64% of the total basin area is classified as high flood hazard, 14.39% as medium hazard, and 21.5% as low hazard (Table 2). This zoning map was qualitatively validated by comparison with the IARNA hazard mapping, finding a good correspondence in the areas of greatest risk.

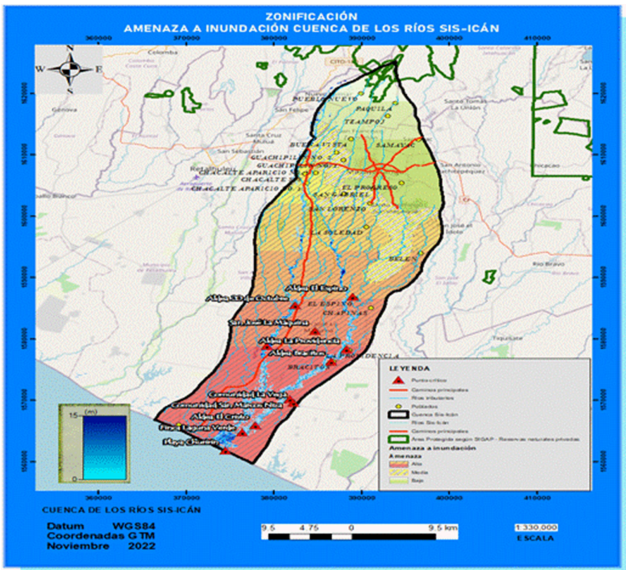


Figure 1. Final zoning of areas with flood threat.

The detailed analysis identified 11 critical high-risk areas requiring priority intervention (Table 2). These include villages, farms, community centers, and urban sections whose vulnerability necessitates the development and implementation of an emergency plan. Based on these findings, the following risk management measures are proposed:

- Protection and monitoring works: construction and maintenance of riverbank defenses, and structural monitoring of bridges.
- Territorial planning: relocation of communities in areas of high, unmitigable risk and updating of construction regulations that restrict development in flood-prone areas.
- Community strengthening: implementation of ongoing education and training programs in risk management.
- Alert systems: management before the National Coordinator for Disaster Reduction (CONRED) for the installation of an early warning system for extreme rains, which allows the activation of evacuation protocols with sufficient advance notice.

Table 2. Critical points with threat of flooding in the Sis-Icán River Basin.

High-threat point	Name	Geographical coordinates	River
Village	Aldea El Cristo	14.1583380, -91.6310309	Ican
Estate	Finca Laguna Verde	14.148107, -91.645178	Ican
Beach	Churirín	14.1208915, -91.66282529	Etero Tulate or confluence of the Sis-Icán rivers
Village	Bracitos	14.253162, -91.551325	Ican
Community center	Comunidad San Marcos Niza	14.197594, -91.595165.	Ican
Village	Comunidad La vega	14.191930, -91.591067	Ican
Village	La Providencia	14.270796, -91.535482	Ican
Village	El Espino	14.348862, -91.528893	Ican
Municipal guardhouse and group of houses	Garita Municipal y conjunto de casas de San Andrés Villaseca	14.2758203, -91.619876	Sis
Village	Aldea 20 de Octubre	14.3353172, -91.5902713	Sis
Municipality	San José La Máquina	14.298012, -91.569135	Sis

This study therefore provides valuable and scientifically based information so that local and municipal authorities can plan and implement preventive and response measures, thereby reducing the vulnerability of communities to the risk of flooding (Boza y Tenorio, 2021)

CONCLUSIONS

Sis-Icán River basin allows us to understand its hydrological and hydraulic behavior and to identify areas susceptible to flooding. This analysis is based on the collection of climatic, hydrometric, and biophysical data for the basin, the diagnosis and analysis of water behavior, and the hydraulic modeling of the river channels.

The zoning of the basin helps to determine its hydrological and hydraulic situation, facilitating the development of measures for the prevention and mitigation of threats associated with floods, thanks to the great benefit provided by the use of geographic information systems.

The hydrological study demonstrates that the extreme flows estimated for high-magnitude events, particularly for 100-year return periods, exhibit significant variability depending on the calculation method used, which highlights the need to adopt multiple probabilistic criteria and not a single technical reference for structural decision-making in the basin.

Flood modeling confirms that the water threat is not distributed homogeneously across the territory, but is concentrated in specific sectors of the basin, where the recurrence of extreme events imposes the need to prioritize the precise identification of areas that must remain free of permanent occupation.

The study shows that flood risk management does not depend solely on structural hydraulic solutions, but requires the strengthening of social and regulatory instruments such as community education, land regulation and early warning systems as central components of any long-term adaptation strategy.

This research should be extended, delving deeper into the aspects identified here in order to refine the results and provide even more precise and appropriate tools for effective and sustainable flood risk management in the basin.

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