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POLICY BRIEF

Envisioning a Sustainable Water Resource Governance in the Sambunotan Watershed: Integrating GIS, Hydrology, Geology, and Water Quality Insights

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KEY POINTS

- The Sambunotan Watershed is essential for water supply, agriculture, and biodiversity in northern Dinagat. However, it faces natural and man-made disruptions that include deforestation, mining, unsustainable farming, and climate variability, putting ecosystem services and the community well-being at risk.
- A revised watershed boundary corrected discrepancies in earlier delineations and revealed that the Sambunotan River is not its primary tributary.
- With approximately 70% of the watershed classified as Alienable and Disposable (A&D), 30% as timberland, and no protected areas, combined with mining tenements covering more than 75% of its area, the watershed is highly vulnerable to environmental degradation.
- Hydrological modeling highlighted seasonal water dynamics, with a total baseflow of 71.60 million cubic meters (MCM), while water quality analysis linked land use, particularly tree cover, to improved water parameters, underscoring the need for sustainable land-use practices.
- Key recommendations include designating protected areas or local conservation areas, regulating mining and land use in A&D zones, improving water and sediment monitoring, enhancing reforestation in riparian zones, and renaming the watershed to align governance with its true ecological and hydrological features.

Keywords: *Sustainable Water, Watershed Governance, Sambunotan Watershed, GIS, Hydrological Analysis, Geological Mapping, Water Quality Assessment, Watershed Management*

1 Introduction

Governance to manage water resources is crucial for preserving ecological balance and supporting the livelihoods of communities that depend on them (Annisa et al. 2023). The Sambunotan Watershed, located in northern Dinagat, Mindanao, Philippines, is a critical resource by providing clean water and sustaining agriculture and biodiversity (Crismundo 2020, Naïve et al. 2019). In recent years, the environmental conditions of the watershed have deteriorated (Crismundo

2020), with the most pressing threats being timber poaching, charcoal production, grass fires, and other unsustainable practices (Bagayas 2020). Moreover, the watershed is increasingly threatened by deforestation, agricultural expansion, mining activities, and the impacts of climate variability. If not addressed, these stressors could jeopardize the watershed's ability to provide essential ecosystem services, with potentially severe long-term consequences for the environment and local communities. Without immediate and coordinated action, the watershed's capacity to support biodiversity, agriculture, and water resources will continue to decline. This concern underscores the importance of achieving Sustainable Development Goals (SDGs) such as SDG 6 (Clean Water and Sanitation) to ensure sustainable water resource management, SDG 11 (Sustainable Cities and Communities) to enhance resilience and sustainability in human settlements that depend on the watershed, SDG 13 (Climate Action) to address climate-related impacts, SDG 15 (Life on Land) to protect and restore terrestrial ecosystems, and SDG 12 (Responsible Consumption and Production) to promote sustainable practices. A comprehensive and sustainable watershed management plan is urgently needed to integrate these SDGs into actionable governance interventions.

In this context, a collaborative effort between Caraga State University and KAISAHAN, Inc.,[1] a non-governmental organization, was initiated in 2021 to conduct a baseline study supporting the development of the Sambunotan Watershed Management Plan (SWMP). This policy brief highlights key findings from the study, which combined hydrological modeling, geological mapping, water quality analysis, GIS tools, advanced analytical techniques, and field surveys. Together, these approaches aided to comprehensively understand the Sambunotan Watershed's dynamics and vulnerabilities.

The following sections detail these findings, drawn from the terminal report (Makinano-Santillan et al. 2022) and related publications (Makinano-Santillan et al. 2024a; Makinano-Santillan et al. 2024b; Salcedo-Albores et al. 2023). Building on these findings, we explore policy implications and recommendations to address key risks and opportunities for intervention. This scientific foundation provides a basis for designing governance frameworks that tackle resource management challenges while fostering ecological conservation and community resilience. By adopting this collaborative, science-driven approach, we can support the long-term sustainability of the Sambunotan Watershed and its essential ecosystem services.

2 Major Findings and Insights from the Sambunotan Watershed Study

2.1 (Re)Defining the Sambunotan Watershed Boundary for Informed Policy and Management

The Sambunotan Watershed, delineated by the Department of Environment and Natural Resources (DENR)[2], covers approximately 2,819.59 hectares in the northern part of Dinagat Islands province, Caraga Region, Mindanao, Philippines (Figure 1). This estimate closely matches the 2,819 hectares reported by Crismundo (2020) but slightly differs from the 2,820.99 hectares cited by Bagayas (2020).

Recognizing the need to address discrepancies in reported watershed areas, enhance physical characterization, and support hydrological modeling and analysis, a precise delineation of the Sambunotan Watershed boundary was conducted. Using a 5-meter spatial resolution Digital Terrain Model (DTM)[3] and advanced GIS-based watershed delineation techniques (Makinano-Santillan et al. 2022), the refined boundary (Figure 1b) adheres to the definition outlined in Presidential Decree No. 705: "a land area drained by a stream or fixed body of water and its tributaries having a common outlet for surface run-off" (The LAWPhil Project 2022).

The refined delineation reveals a total surface area of 2,823.96 hectares[4] — substantially more extensive than previously reported estimates. This increase is attributed to the use of high-resolution topographic data, which allowed for a

[1] Kaisahan Tungo sa Kaunlaran ng Kanayunan at Repormang Pansakahan, Inc.

[2] The watershed boundaries, obtained from the DENR and provided as a GIS shapefile, were supplied to the project by KAISAHAN, Inc.

[3] A DTM is a type of a Digital Elevation Model (DEM). It is a representation of the Earth's bare surface topography, devoid of vegetation, buildings, and other surface objects. The Interferometric Synthetic Aperture Radar (IfSAR) DTM from the National Mapping and Resource Information Authority (NAMRIA) was utilized in the refined watershed boundary delineation.

[4] GIS-computed area, with the Universal Transverse Mercator (UTM) Zone 52, World Geodetic System 1984 coordinate reference system.

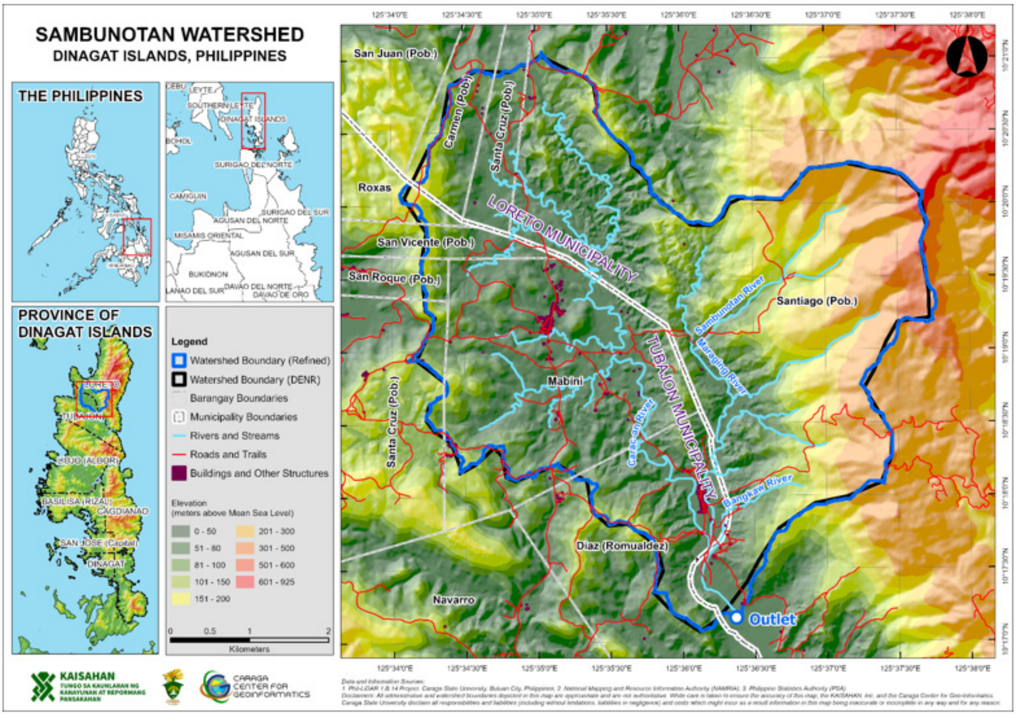


Figure 1. Map showing the boundaries of the Sambunotan Watershed. The black line represents the boundary delineation provided by the DENR, while the blue line indicates the refined boundary derived from a 5-meter spatial resolution Digital Terrain Model (DTM).

more accurate identification of natural watershed boundaries. Based on the refined boundary, approximately 63% of the watershed is within the Loreto municipality, while the remaining 37% is within Tubajon. Three barangays of Loreto and six barangays of Tubajon have boundaries within the watershed[5]. This refined understanding of the boundary provides a stronger foundation for the watershed's policy development, resource management, and sustainable planning efforts.

2.2 Hydrological and Geographical Features of the Sambunotan Watershed

The Sambunotan Watershed constitutes a significant portion of the Malinao Inlet Basin (Figure 2), covering approximately 23% of its total area of ~12,277 hectares (Makinano-Santillan et al. 2022). All water from the Sambunotan Watershed flows downstream into the middle part of the Malinao Inlet Basin, ultimately discharging into the Malinao Inlet, which highlights the watershed's critical role in sustaining downstream water resources, influencing the basin's sediment transport, water quality, and ecological health.

A GIS analysis of the watershed's drainage network reveals a total length of rivers and streams measuring approximately 67 kilometers, corresponding to a drainage density of 2.38 km/km². Elevation within the watershed varies from 0 meters near the main outlet to 665 meters above mean sea level (MSL), with an average elevation of 111 meters above MSL (Figure 3a). The average slope of 23% reflects predominantly rolling to moderately steep terrain. Notably, areas with steep slopes exceeding 30% are concentrated in the eastern part of the watershed (Figure 3b).

A further subwatershed delineation identified three major river systems and their corresponding subwatersheds (SW) within the Sambunotan Watershed (Figure 4): the Carac-an River SW, Maraging River SW, and Bangkaw River SW.

[5] These barangays are Santiago, Santa Cruz, and Carmen in Loreto, and Diaz, Mabini, Santa Cruz, San Roque, San Vicente, and Roxas in Tubajon.

Figure 2. Map showing the Sambunotan Watershed within the Malinao Inlet Basin, which spans the municipalities of Loreto, Tubajon, and Libjo.

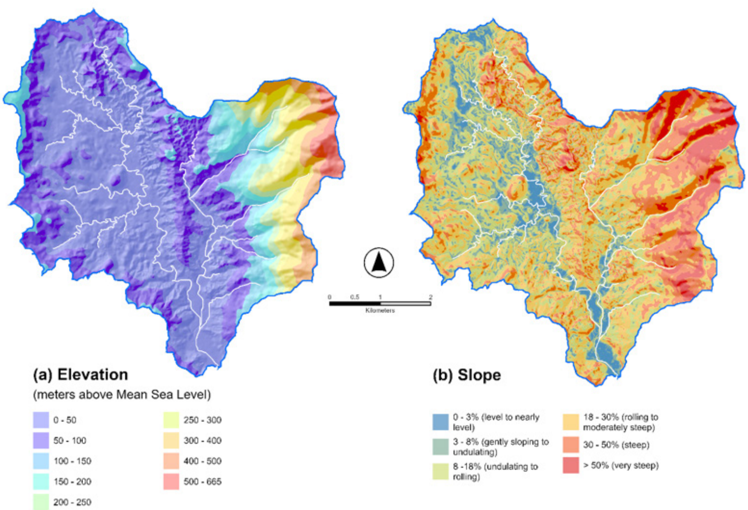


Figure 3. Elevation and slope maps of Sambunotan Watershed.

Among these, the Carac-an River SW is the largest, covering 1,527.44 hectares (54%), followed by the Maraging River SW with 1,064.94 hectares (38%). The Bangkaw River SW and other minor areas account for the remaining 8%.

Beyond identifying the major river systems and sub-watersheds, the delineation provided valuable insights to support better and more effective water resource governance within the watershed:

- The Sambunotan River's Role and Location: The Sambunotan River is not the major tributary of the watershed. Instead, it is an upstream river with its own drainage area within the Maraging River

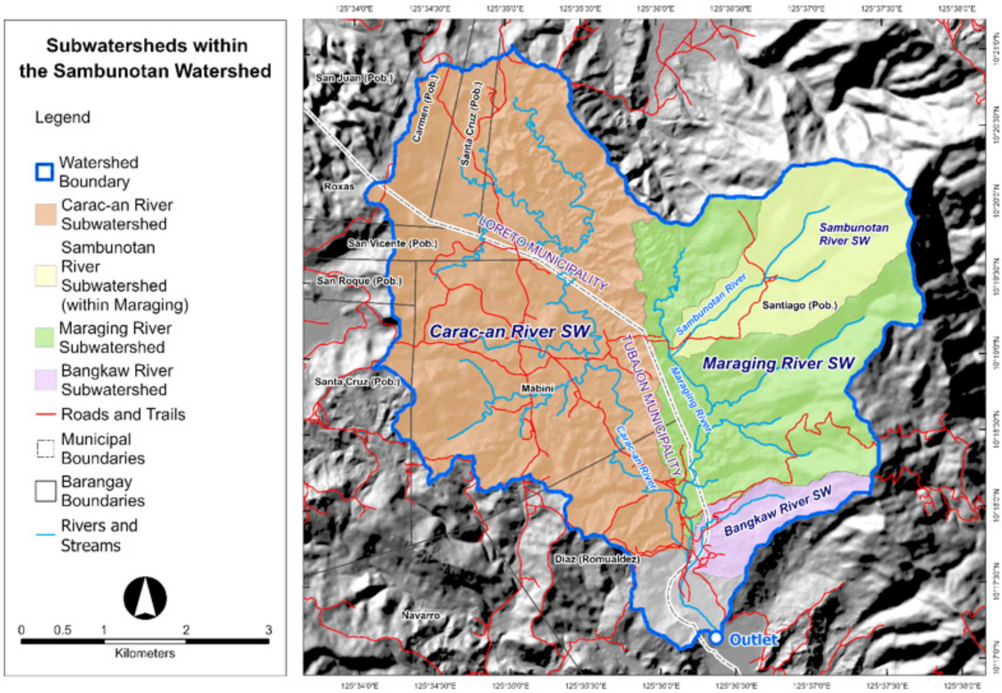


Figure 4. Subwatersheds within the Sambunotan Watershed.

SW, covering approximately 374.37 hectares. The Sambunotan River lies upstream of the Maraging River in Loreto municipality and is several kilometers from the watershed's primary outlet.

- Absence of a Dominant Tributary: No single river is the major tributary of the so-called Sambunotan Watershed. The Carac-an, Maraging, and Bangkaw rivers have distinct watersheds. Near the downstream portion of the watershed, the Carac-an River and Maraging River converge, further emphasizing the interconnected but distinct nature of the watershed's hydrological systems.

These findings highlight a critical issue with the name "Sambunotan Watershed," which inaccurately implies that the Sambunotan River is the primary tributary of this watershed. This misnomer can lead to confusion in watershed governance, potentially resulting in misaligned priorities and ineffective management plans. To address this, it may be necessary to adopt a more appropriate and representative name for the watershed—one that reflects its actual hydrological composition and the significant roles of the Carac-an, Maraging, and Bangkaw Rivers (e.g., Carac-an-Maraging-Bangkaw Watershed). Renaming the watershed appropriately could improve clarity, enhance stakeholder communication, and ensure management strategies align with the area's hydrological and ecological dynamics. Moreover, identifying the location of the actual Sambunotan River could enable more focused and effective management of its drainage area, should specific attention be required for its conservation or development.

Although we advocate for renaming the watershed, we will continue using the term 'Sambunotan Watershed' in the succeeding section for consistency in the discussion.

2.3 Land Classification and Land-use/Land-cover Dynamics in the Sambunotan Watershed

According to DENR data, approximately 70% of the Sambunotan Watershed is classified as Alienable and Disposable (A&D), while the remaining 30% is classified as timberland (Figure 5a). No part of the watershed is designated as a protected area. Within the watershed, there are about three Mineral Production Sharing Agreements (MPSAs) covering approximately 700 hectares (25% of the watershed), about two Exploration Permit Applications (EXPAs) covering approximately 800 hectares, an Application for

Production Sharing Agreement (APSA) covering about 280 hectares, and two declared Minahang Bayan[6] covering approximately 380 hectares (Mines and Geosciences Bureau Region XIII 2022) (Figure 5b).

The classification and land use activities within the Sambunotan Watershed provide context for understanding its evolving land cover. While significant portions of the area are allocated for mineral agreements and timberland, the dominant land cover remains relatively stable, as shown by our analysis of Esri Land-cover maps (Esri 2022) (Figure 6). From 2018 to 2021, trees consistently covered more than 60% of the watershed yearly, while rangeland accounted for over 20% but never exceeded 30% (Figure 6). Cropland and built-up areas remained the least prevalent, covering less than 10% of the total watershed areas (Makinano-Santillan et al. 2022).

Analysis of land cover changes (Figure 7) reveals that built-up areas in the watershed have not expanded significantly, with the largest extent recorded in 2020 at approximately 30 hectares, equivalent to 1.08% of the total watershed area. Cropland areas showed minor changes, decreasing from 2018 to 2020 and increasing slightly from 2020 to 2021. Rangeland increased from 2018 to 2019 but then decreased from 2019 to 2021. Conversely, tree cover decreased from 2018 to 2019 but recovered and increased from 2019 to 2021. Overall, these changes are relatively minor, and the land cover condition of the watershed can generally be considered stable over the past five years (Makinano-Santillan et al. 2022). These findings are based on Esri land cover maps, which may have accuracy limitations. Interpretations should be made cautiously and, where possible, supported by field validation.

2.4 *Baseline Hydrological Data and Modeling*

To further support the development of a comprehensive management plan for the watershed, baseline hydrological data was collected to support the hydrological modeling and aid in water management strategies (Makinano-Santillan et al. 2022, Salcedo-Albores et al. 2023). Rainfall, water level, and discharge measurements were

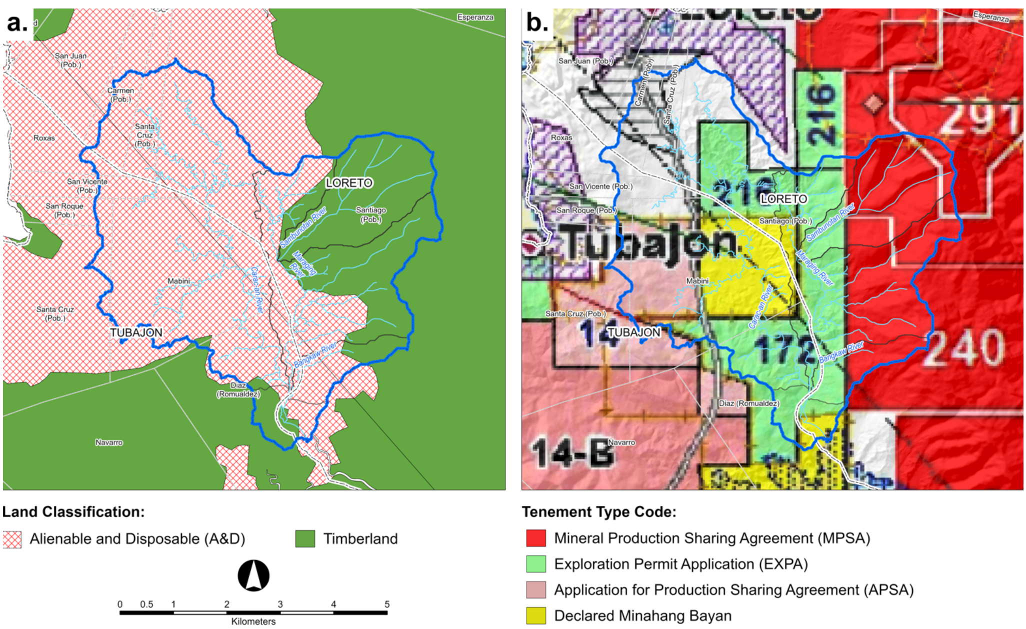


Figure 5. (a) Land classification and (b) mining tenements within the Sambunotan Watershed. The land classification data is sourced from the Department of Environment and Natural Resources (DENR) Caraga Region XIII, while the mining tenements data is based on the Mines and Geosciences Bureau (MGB) Regional Office No. XIII Mining Tenements Control Map as of October 31, 2022.

[6]According to the DENR Administrative Order No, 2015_03, "Minahang Bayan" or "People's Small-Scale Mining Area" refers to the entire area declared as People's Small-Scale Mining Area pursuant to Republic Act No. 7076, otherwise known as the “People’s Small-Scale Mining Act of 1991”.

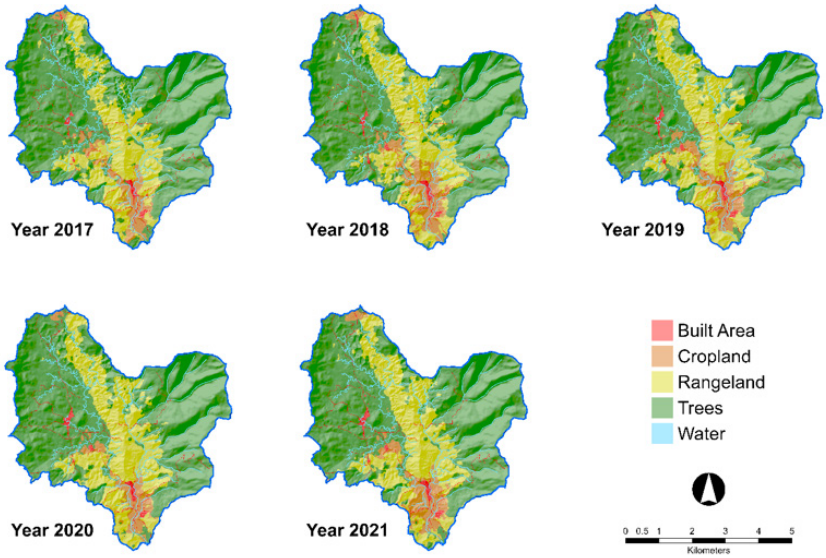
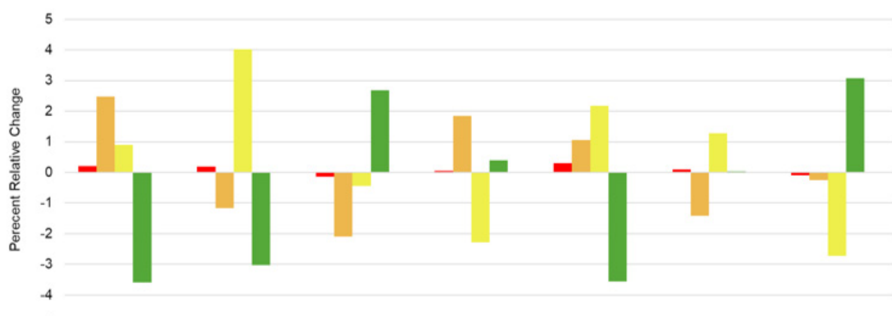


Figure 6. Land cover maps of the Sambunotan Watershed from 2017 to 2021, highlighting the distribution and changes in major land cover classes over time. Source: Esri Land Cover



	2017-2018	2018-2019	2019-2020	2020-2021	2017-2021	2018-2021	2019-2021
Built Area	0.20	0.18	-0.14	0.05	0.30	0.09	-0.09
Cropland	2.48	-1.16	-2.10	1.84	1.06	-1.42	-0.26
Rangeland	0.90	4.01	-0.45	-2.29	2.18	1.28	-2.73
Trees	-3.59	-3.03	2.68	0.39	-3.55	0.04	3.07
Water	0.01	0.00	0.01	0.01	0.02	0.02	0.02

Figure 7. Percentage of land cover changes in the Sambunotan Watershed relative to its total area.

conducted within the watershed, utilizing advanced equipment such as rain gauges, water level loggers, 2D velocity meters, and an Acoustic Doppler Current Profiler (ADCP). These tools captured data on both low and high flows. A rain gauge was strategically installed upstream to synchronize rainfall data with other sensor measurements.

The collected field data served as the foundation for calibrating a hydrological model based on the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) and generating hydrograph results for water balance analysis (Salcedo-Albores et al. 2023). This analysis examines current water resource availability and trends over time, providing valuable insights to strengthen water management decision-making. The model calibration was conducted using a field dataset collected from October 31, 2022, to November 2, 2022. The model's performance was assessed using three statistical measures:

- Nash-Sutcliffe Efficiency (NSE): 0.85, indicating excellent agreement between observed and simulated data.

- Percent Bias (PBIAS): 1.62, showing minimal deviation between observed and simulated data.

- RMSE-Observations Standard Deviation Ratio (RSR): 1.62, reflecting a high level of reliability.

These statistics collectively rated the model as "Very Good."

The study also highlighted the critical role of baseflow in sustaining ecosystems and water supply. The municipality of Tubajon, for instance, relies on water sourced from the Sambunotan Watershed. Using historical annual precipitation data, baseflow for individual subwatersheds was modeled using the calibrated hydrologic model, with the total baseflow volume estimated at 71.60 million cubic meters (MCM) (Table 1). Results indicate that larger subwatersheds, such as Carac-an, exhibit higher baseflow due to longer travel times to the main outlet.

These findings provide essential baseline data for water resource management within the watershed. They can also be used to estimate groundwater exploitation levels across wet and dry seasons, aiding sustainable water resource planning.

2.5 Water Quality Assessment

Water quality within the Sambunotan Watershed was assessed using in-situ measurements conducted in May 2022 using the Biobase Portable Multi-Parameter Water Quality Meter (Makinano-Santillan et al. 2022, Makinano-Santillan et al. 2024b). The spatial distribution of observed water quality parameters is illustrated in the accompanying maps (Figure 8). Key results showed a variability in temperature in both upstream and downstream locations, ranging from 25.6℃ to 27.95℃, as measured. Total Dissolved Solids (TDS) levels across all sampling sites remained below the 500 mg/L limit for Class AA surface waters, as set by DENR Administrative Order 34, series 1990. However, TDS levels varied significantly across sites. For instance, the elevated TDS levels observed in Stations 5 and 11 (Figure 8e) may be attributed to various human activities documented during field measurements. These include quarrying, construction, livestock farming, clothes washing, and garbage dumping along the riverbanks in the vicinity of these stations, which likely contribute to increased dissolved solids in the water.

Dissolved Oxygen (DO) levels were within acceptable limits for Class AA to Class C surface waters, with some upstream stations exceeding the 2 mg/L minimum threshold for Class C water bodies, ensuring the ability to sustain aquatic life. Statistical analysis highlighted the significant influence of land use and vegetation cover on water quality. For example, the tree cover percentage within the contributing area was positively correlated with pH levels, underscoring the importance of tree cover in maintaining water quality parameters.

These findings, derived from field measurements and statistical analysis (Makinano-Santillan et al. 2022, Makinano-Santillan 2023b), demonstrate the critical role of land cover classes—particularly cropland, built-up areas, and tree cover—in influencing water quality across the watershed.

2.6 Geologic Mapping, Potential Mining Impacts, and Erosion Dynamics in the Sambunotan Watershed

Geologic mapping and related field investigations, utilizing the latest modified lithologic map (Santos 2014, UNRFNRE 1993), validated that the significant river networks within the Sambunotan Watershed are structurally controlled, shaped by lineaments cutting through

Table 1. Baseflow volume computed through hydrologic modeling, in millions cubic meters (MCM). Data sourced from Makinano-Santillan et al. (2022).

Subwatershed	Dry Season Baseflow Volume	Wet Season Baseflow Volume	Total
	December to May, 2022	June to November, 2022	
Sambunotan	0.752	4.969	5.720
Maraging	9.938	18.580	28.518
Carac-an	8.086	28.423	36.509
Bangkaw	0.057	0.711	0.769
Others	0.004	0.082	0.085
Total	**18.837**	**52.765**	**71.601**

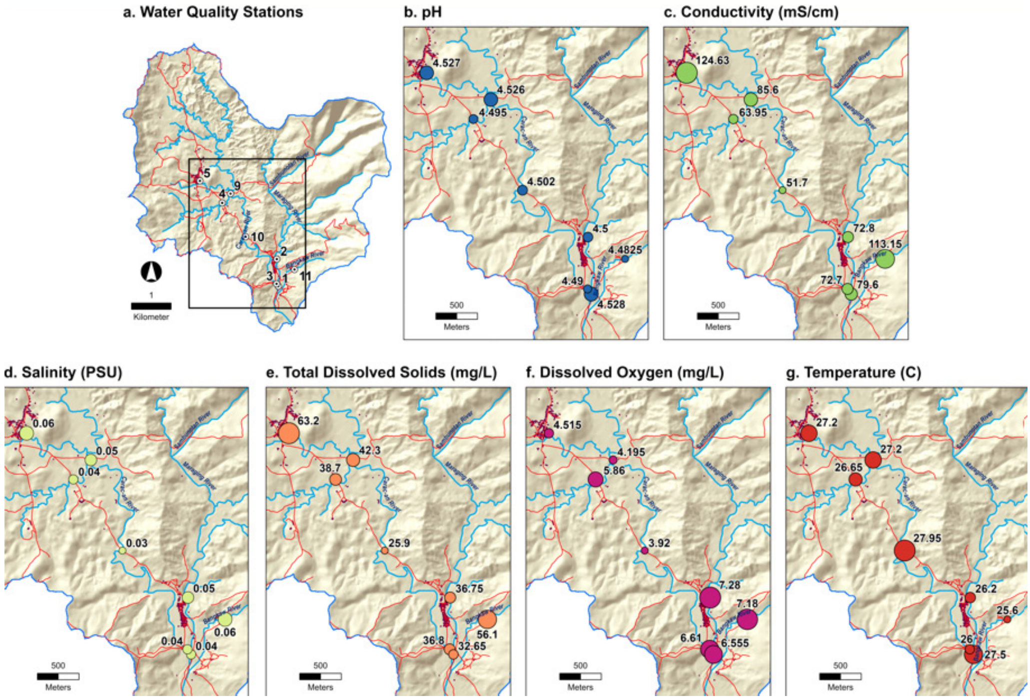


Figure 8. Spatial distribution of observed water quality parameters in the Sambunotan Watershed, May 2022. Data sourced from Makinano-Santillan et al. (2022).

the islands or lithologic contacts between different rock types. These planes of weakness act as pathways for water flow, influencing the watershed's hydrological system. Regions of limestone and clastic sediments, known for their high porosity and permeability, were identified as having the highest potential to serve as aquifers. This finding is supported by the concentration of water resources for the municipalities of Tubajon and Loreto within these rock types. Extending geologic mapping beyond the watershed boundary and overlaying the water resource location map of the two municipalities (i.e., Tubajon and Loreto) can provide clues on the possible groundwater resources in the area. Among the rock types found in northern Dinagat, the regions of the limestone and clastic sediments have the highest potential to become aquifers based on these units' high porosity and permeability. This finding is validated by the concentration of most of the water resources of the two municipalities in these two rock types (Makinano-Santillan et al. 2022, Makinano-Santillan et al. 2024a).

Mining activities within the watershed present significant risks to water quality. A Minahang Bayan and several mining tenements for chromite, nickel, and cobalt exploration, as shown in Figure 5, overlap with critical water sources. These metal resources are commonly associated with mantle rocks like harzburgite and dunite. All the Sambunotan River subwatershed and the headwaters of the Bangkaw River subwatersheds are in the Harzburgite region. These two watersheds are identified as the primary water sources of some barangays in Tubajon (i.e., Mabini and Diaz). All these points highlight that any development within these mining tenements (i.e., MPSA#3; MPSA#240, MPSA#291, EXPA#172; EXPA#216 in Figure 5) will have a significant impact on the overall water quality within the watershed (Makinano-Santillan et al. 2022; Makinano-Santillan et al. 2024a).

Erosion dynamics also vary across the watershed. The upstream portions of the Carac-an Subwatershed exhibit high to critical erosion levels, while downstream areas experience moderate erosion conditions. Correlation analysis (Table 2) indicates that cropland is positively associated with higher soil erodibility, while tree cover has a negative correlation, suggesting its importance in reducing erosion. These findings highlight the potential for significant changes in cropland areas to influence sediment transport within the watershed (Makinano-Santillan et al. 2022; Makinano-Santillan et al. 2024a).

Overall, the geological mapping and analysis results underscore the importance of sustainable land use practices in erosion-prone areas and the need to manage mining activities to preserve water quality carefully. Protecting aquifer-rich regions, such as limestone and clastic sediment areas, and promoting reforestation efforts in erosion hotspots can enhance water resource management and reduce sedimentation risks in the Sambunotan Watershed.

3 Policy Implications and Recommendations

The Sambunotan Watershed faces various challenges, from land use changes and erosion to impacts on mining and water quality degradation. Addressing these issues requires a science-based, collaborative approach to governance that balances development with ecological protection. The following policy implications and recommendations are directed toward local government units (LGUs) of Loreto and Tubajon, regional offices of national agencies such as the Department of Environment and Natural Resources (DENR) and the Mines and Geosciences Bureau (MGB), non-governmental organizations (NGOs), and other stakeholders involved in watershed management and policy formulation. These recommendations guide decision-makers in implementing effective and sustainable watershed management strategies.

3.1 On the Sambunotan Watershed Boundary

Accurately defining the boundaries of the Sambunotan Watershed is a fundamental step toward effective governance and resource management. The refined boundary provides a reliable basis for policy formulation, addressing discrepancies in previous estimates and ensuring that management strategies align with the true extent of the watershed.

Recommendations:

- Officially adopt the refined Sambunotan Watershed boundary to standardize planning and resource management across municipalities.
- Form a joint Watershed Management Board with representatives from Loreto and Tubajon LGUs, DENR, and other stakeholders involved in watershed management to collaboratively manage and govern the watershed, leveraging the updated boundary data to guide decision-making.
- Integrate the refined watershed boundary into local development and land-use plans to ensure alignment with sustainable management objectives.

3.2 On the Naming of the Sambunotan Watershed

The Sambunotan Watershed's name implies that the Sambunotan River is its primary tributary, despite evidence that this river is a minor upstream feature within the Maraging River Subwatershed. Instead, the watershed comprises three distinct river systems: the Carac-an River, Maraging River, and Bangkaw River, each with unique hydrological and ecological roles. This misnomer can confuse governance, leading to misaligned priorities and ineffective management strategies. A more accurate and representative name would reflect the watershed's hydrological composition, improving stakeholder communication and coordination.

Recommendations:

- Conduct consultations with stakeholders, including LGUs, communities, and experts, to discuss the watershed's renaming to reflect better its hydrological composition (i.e., Carac-an-Maraging-

Table 2. Correlation Between Erodibility Index (EI) and Land Cover Distribution in the Sambunotan Watershed. Data sourced from Makinano-Santillan et al. (2022).

	Builtup	Cropland	Rangeland	Trees
Pearson Correlation	0.689	**.899***	0.551	-0.849
Sig. (2-tailed)	0.198	0.038	0.335	0.069
Sum of Squares and Cross-products	4.445	27.717	12.813	-45.046
Covariance	1.111	6.929	3.203	-11.261
N	5	5	5	5

**. Correlation is significant at the 0.05 level (2-tailed).*

Bangkaw Watershed).

- Adopt a new, representative name through an official declaration or resolution to improve clarity and align management strategies with the watershed's dynamics.
- Develop educational campaigns and materials to communicate the rationale behind the name change, ensuring all stakeholders understand its significance for effective governance and resource management.
- Identify and map the Sambunotan River and its drainage area, enabling focused and informed interventions for its conservation or development, if necessary.

3.3 On the Watershed's Hydrology and Geography

The hydrology and geography of the Sambunotan Watershed play a critical role in sustaining downstream ecosystems, influencing sediment transport, and supporting communities reliant on its resources. Targeted management in vulnerable areas, particularly steep slopes and high-drainage regions, is vital to mitigate erosion risks and maintain ecological balance.

Recommendations:

- Implement soil and water conservation measures, such as reforestation and contour farming, in areas with steep slopes and high erosion risks.
- Develop a sediment monitoring program to assess and mitigate sediment transport impacts on downstream water bodies.
- Incorporate hydrological data into disaster risk reduction plans to address flooding and erosion risks.

3.4 On the Watershed's Land-use and Land-cover Dynamics

The land classification and land-use dynamics within the Sambunotan Watershed present opportunities and challenges for sustainable management. While the watershed's land cover has remained relatively stable in recent years, the absence of a protected area designation and extensive Alienable and Disposable (A&D) lands, timberland, and mining tenements expose the watershed to significant risks. A&D areas are particularly vulnerable to unregulated development, while timberland faces pressures from deforestation and unsustainable practices. Furthermore, mining activities in critical zones overlap with key water sources, posing threats to water quality and ecosystem health. These factors highlight the urgent need for targeted policy interventions to protect the watershed's ecological and hydrological functions while supporting sustainable land use.

Recommendations:

- Propose the designation of critical portions of the watershed as protected areas under existing laws, such as the Expanded National Integrated Protected Areas System (E-NIPAS) Act.
- Implement stricter regulations on activities in A&D and timberland areas to ensure land use aligns and adheres to sustainable practices.
- Comprehensive Environmental Impact Assessments (EIAs) are required for all mining tenements, focusing on their effects on water quality, erosion, and biodiversity.
- Strengthen monitoring and enforcement mechanisms to prevent illegal activities, such as timber poaching and land clearing, particularly in timberland areas.
- Promote sustainable land-use practices, such as agroforestry, to balance development needs with conservation goals.

3.5 On the Baseline Hydrological Data and Modeling

The availability of robust baseline hydrological data is crucial for informed decision-making and long-term water resource management. Hydrological models offer predictive insights into water availability, distribution, and seasonal variability, providing a strong foundation for effective planning and intervention. Monitoring water levels in river systems is also essential to tracking changes over time and adapting management strategies accordingly.

Recommendations:

- Use hydrological modeling data to optimize the placement of future water infrastructure, such as reservoirs and irrigation systems.
- Conduct periodic updates to the hydrological model to incorporate new data and improve decision-making accuracy.
- Establish a regular water level monitoring program for the watershed's river systems using automated sensors and manual verification to ensure continuous data collection for trend analysis and

emergency preparedness.

- Integrate water level data into the existing hydrological model to refine predictions and enhance resource planning across dry and wet seasons.

3.6 On the Watershed's Water Quality

Maintaining water quality is a key priority for the Sambunotan Watershed, as it directly impacts biodiversity, agriculture, and human health. Water quality is significantly influenced by land-use practices and human activities, requiring targeted interventions to address point and non-point pollution sources. Trees play a crucial role in maintaining water quality, emphasizing the need for reforestation and conservation. Addressing pollution sources and promoting sustainable land use can mitigate risks and safeguard water resources for future generations.

Recommendations:

- Enforce regulations to control quarrying, garbage dumping, and livestock farming near riverbanks.
- Launch community-based reforestation programs focusing on riparian zones to enhance water filtration and stabilize riverbanks.
- Establish a water quality monitoring network to regularly assess and address pollution hotspots.

3.7 On the Watershed's Geology, Potential Mining Impact, and Erosion Dynamics

The geological characteristics of the Sambunotan Watershed shape its hydrology and groundwater potential while influencing erosion and sediment transport. Geologic features, such as aquifer zones, provide essential water resources but are at risk from mining activities. Erosion in cropland areas threatens soil productivity and increases sedimentation in water bodies. Addressing the impacts of mining and soil erosion requires strategic interventions to protect critical water sources and maintain land stability.

Recommendations:

- Designate limestone and clastic sediment zones as critical aquifer recharge areas and regulate activities that could disrupt these zones.
- Strengthen enforcement of mining regulations to minimize environmental damage, particularly in harzburgite regions supplying critical water sources.
- Promote soil conservation practices in cropland areas, such as cover cropping and no-till farming, to reduce erosion and sedimentation.

4 Concluding Remarks and Further Study

This policy brief synthesizes key findings from scientific analyses and field investigations in the Sambunotan Watershed, offering actionable recommendations to guide decision-makers in addressing these challenges. By adopting the recommendations presented, stakeholders can develop a comprehensive and sustainable watershed management plan that balances ecological preservation with socio-economic development. Such a plan will protect the watershed's ecosystem services and enhance its beneficiaries' well-being, ensuring long-term water security, resilience to climate impacts, and sustainable growth for the region.

While the inclusions of critical maps, such as high erosion zones, recommended protected regions, water quality hotspots, and limestone and clastic sediment zones, are essential for decision-making, unfortunately, this study did not generate them. The generation and development of these maps require additional data and analyses beyond the scope of this research. We recommend their inclusion in future studies to provide a more comprehensive basis for watershed management planning.

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Statement of Conflict of Interest

The authors declare no conflict of interest associated with the submission and publication of this manuscript.

Author Contribution

MM Santillan: *Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review and Editing, Supervision, Project administration, Funding acquisition*. AC Gagula: *Conceptualization, Writing - Original Draft, Writing - Review and Editing*. RP Varela: *Conceptualization, Writing - Original Draft, Writing - Review and Editing*. JR Santillan: *Conceptualization, Formal analysis, Investigation, Writing - Original Draft, Writing - Review and Editing, Visualization.*

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