

# 從山脊到珊瑚礁：於土地利用與氣候變遷情境

## 下之流域水文對沿岸海洋生態衝擊探討

### From ridges to reefs: hydrologic modeling of watersheds surrounding a global marine biodiversity hotspot under land use and climate pressures

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#### 摘要

本研究利用土壤與水文評估模式 (Soil and Water Assessment Tool, SWAT) 模擬 2004 年至 2022 年間之泥沙輸移情形，以評估環繞菲律賓維德島海峽 (Verde Island Passage, VIP) 共十一個流域之水文歷程。VIP 為全球海岸礁魚類生物多樣性最豐富的海洋廊道之一，本研究透過數值模擬探究泥沙對此地環境之影響，進而提供量化數據以供參考。模擬結果顯示，泥沙輸出量高峰多與連續強降雨事件密切相關，然各流域之泥沙產量與逕流強度的差異主要受地形坡度與土地利用型態所驅動。位於 VIP 南界之民都洛島 (Mindoro Island) 流域被辨識為泥沙之主要來源區。

為評估土地利用變遷之影響，本研究分別採用 2017 年與 2022 年之土地利用圖資 (LULC) 進行 SWAT 模擬比較。同時亦探討氣候變遷可能造成的衝擊，納入中度 (RCP 4.5) 與高度 (RCP 8.5) 溫室氣體排放情境下之降雨與氣溫變化進行模擬。模式輸出結果透過與衛星觀測資料及歷年洪災報導進行比對以進行驗證。統計分析結果顯示，集水區之水文指標 (如泥沙產量、地表逕流與蒸發散) 對土地利用變遷反應較為顯著；相較之下，出海口之相關變數 (如流量、泥沙負載濃度與基流) 則對氣候變化情境較為敏感。

本研究之成果提供具科學依據之實證，可作為規劃區域土地利用政策、流域管理策略與海洋保護區 (MPA) 規劃之重要參考依據。此外，結果亦強調建立完整且持續性水文監測體系之必要性，以支持長期規劃、促進調適性管理，並於環境與氣候條件持續變動之背景下，提升以模式佐證之決策準確。

**關鍵詞：**流域模擬、泥沙沖蝕、水文模擬、土壤與水文評估模式

## Abstract

The interplay between terrestrial and marine ecosystems is increasingly recognized as a central issue in global environmental science, particularly in regions where high biodiversity in the oceans is collocated against accelerating land-based pressures. Sedimentation is among the most significant land–sea linkages because of its direct impact on coral reef health, water quality, and the ecological integrity of nearshore environments. The Verde Island Passage (VIP) in the Philippines has been identified as the “center of the center” of marine shorefish biodiversity, hosting unparalleled levels of species richness and serving as a critical site for ecological and socio-economic resilience across the broader Coral Triangle. This marine biodiversity hotspot is also directly influenced by land-based processes occurring in adjacent watersheds whose hydrological behavior is shaped by both land use and climate dynamics. Despite the ecological and economic importance of the VIP, few quantitative assessments have been undertaken to evaluate the watershed drivers of sediment delivery to the marine environment, or to understand how these processes might change under future conditions of land cover modification and climate change. To address this critical knowledge gap, we employed the Soil and Water Assessment Tool (SWAT), a process-based semi-distributed hydrological model, to simulate water and sediment dynamics in watersheds surrounding the VIP between 2004 and 2022. Our study provides one of the most comprehensive hydrological assessments to date in this globally significant region, while also contributing to broader debates on ridge-to-reef management, climate adaptation, and the design of conservation strategies that integrate terrestrial and marine systems.

The SWAT modeling framework allowed us to disentangle the relative effects of land use/land cover (LULC) change and climate variability on watershed outputs (**Fig. 1**). We delineated eleven watersheds (**Fig. 2**) – eight from existing river gauge locations (Dacanlao, San Roque, Baco, Bucayao, Mag-asawang Tubig, Pula, Boac, and Libtangin) under the Department of Public Works and Highways, as well as three additional basins of ecological and conservation significance (Calumpang, Lobo, and Abra de Ilog). Geospatial inputs including a 30-m resolution digital elevation model, soil classifications from the FAO Digital Soil Map of the World, and land use land cover (LULC) maps from Sentinel-2 were incorporated. Climatological inputs were obtained from NASA Langley Research Center’s POWER Project database.

The effects of land use change were assessed by conducting separate SWAT simulations using LULC maps from 2017 and 2022. Projected provincial changes in rainfall and temperature under moderate (RCP 4.5) and high (RCP 8.5) emissions scenarios provided by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA)

were incorporated to examine potential impacts of climate change. Each watershed was simulated under six combinations of LULC and climate conditions, yielding a total of sixty-six model runs. Model calibration was constrained by the limited reliability of streamflow data from DPWH gauges, which restricted the statistical validation of SWAT outputs. As a workaround, model outputs were qualitatively validated through comparison with satellite-derived observations and documented flood reports. This provided confidence that the simulated hydrological dynamics, particularly peak flows and sediment pulses during extreme rainfall events, were consistent with independently observed patterns, even in the absence of continuous ground-based monitoring data. Outputs in this study shall be viewed as relative rather than absolute values, allowing us to compare trends across watersheds and scenarios. Output parameters of primary interest included basin-scale variables (sediment yield, surface runoff, and baseflow) and river mouth variables (discharge, suspended sediment load, and sediment concentration). Paired t-tests were employed to assess the significance of changes between scenarios.

Our findings highlight several key patterns. First, sediment yield and discharge peaks closely coincided with periods of intense, consecutive rainfall events, confirming the strong control of rainfall variability on sediment mobilization. While rainfall events clearly drive inter-annual fluctuations in sediment yield, the magnitude of sediment outputs varied substantially across watersheds, largely as a function of slope and land use distribution. Mindoro Island watersheds, especially Baco and Abra de Ilog, consistently produced the highest sediment yields and river mouth discharges, underscoring their disproportionate contribution to sediment inputs into the VIP. This pattern is attributable to their steeper topography and greater extent of agricultural and grassland areas which enhance erosion potential compared to the relatively gentler and more urbanized landscapes of Batangas.

Second, changes in land use between 2017 and 2022, most notably the expansion of urban areas, had measurable but differentiated effects on hydrological processes. Basin-scale variables were significantly more responsive to LULC change than river mouth variables. Increases in urban cover had the tendency to elevate surface runoff and reduce baseflow, consistent with the reduction in infiltration capacity due to impervious surfaces. However, in several watersheds these effects were moderated or even offset by simultaneous gains in forest area which enhanced infiltration and reduced erosion potential. Sediment yield responses to urbanization were complex: while impervious surfaces directly reduce soil exposure and hence sediment supply, short-term phases of land clearing and construction may temporarily elevate erosion and sediment delivery, effects not fully captured in static LULC representations.

Third, climate change scenarios demonstrated stronger impacts on river mouth parameters than on basin-scale processes. Adjustments in rainfall and temperature under RCP 4.5 and 8.5

consistently produced significant differences in discharge, suspended load, and sediment concentration, with baseflow also emerging as a climate-sensitive parameter. Interestingly, the direction and magnitude of change were not uniform across watersheds or seasons. For instance, while projected rainfall during wet months under RCP scenarios was generally lower than historical values, higher temperatures increased soil erodibility and evapotranspiration, producing nonlinear and sometimes counterintuitive effects on sediment delivery. In certain watersheds, elevated temperatures compensated for reduced rainfall by intensifying erosion, whereas in others, evapotranspiration-driven reductions in runoff attenuated sediment transport. These findings emphasize that climate-driven changes in watershed outputs cannot be reduced to a simple rainfall–sediment relationship, but instead reflect a complex interplay of climatic and land surface factors.

Fourth, long-term trends from 2004 to 2022 reveal gradual increases in both sediment yield and river mouth discharge across all watersheds. These trend trajectories suggest a cumulative intensification of sediment delivery to the VIP over time, consistent with observed increases in rainfall and temperature in the western Pacific. The fact that these rainfall-temperature increases exceed reported global averages reinforces claims that the Philippines is among the countries most vulnerable to climate change, and that nearshore ecosystems such as coral reefs in the VIP will face mounting pressures from terrestrial sedimentation.

Overall, this study demonstrates that land use changes exert more immediate effects on basin-scale hydrologic processes, while climate change predominantly reshapes river mouth dynamics. This distinction is crucial for understanding sediment delivery to marine ecosystems. The increasing urban footprint across VIP watersheds is likely to alter infiltration-runoff balances, whereas climate change will modulate the magnitude and timing of sediment fluxes entering the passage. Importantly, the two drivers interact: LULC changes alter baseline watershed conditions, which in turn modulate the sensitivity of river mouth variables to projected rainfall and temperature regimes.

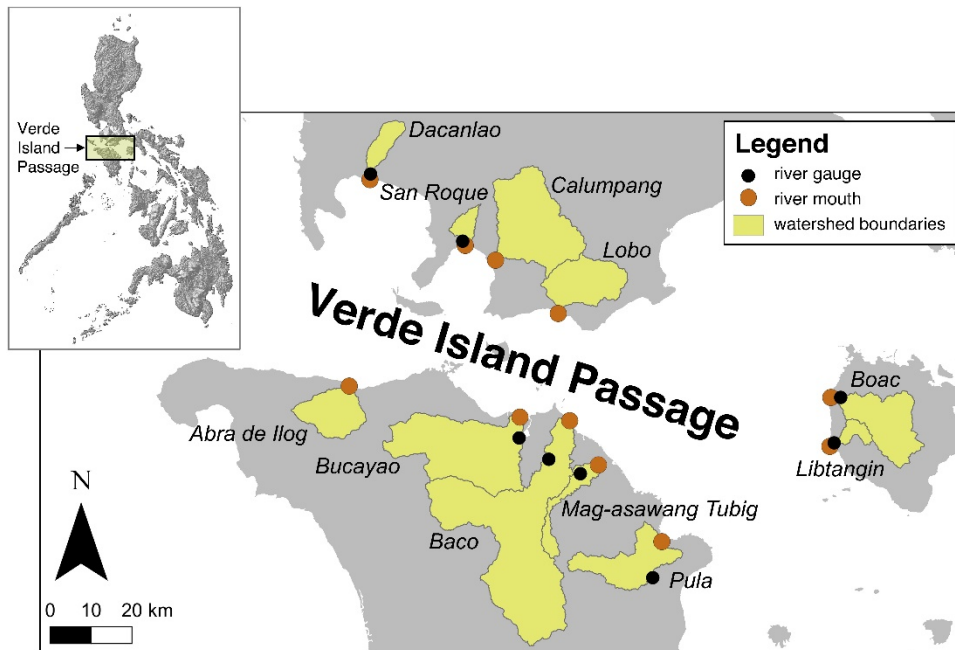
Beyond technical findings, this research underscores pressing challenges in environmental monitoring and management. The lack of reliable long-term streamflow datasets limits the calibration of physically based hydrological models such as SWAT in the Philippines. Strengthening hydrological monitoring infrastructure, ensuring data quality, and expanding climatological networks are essential steps for enhancing future modeling and supporting adaptive watershed management. At the same time, the study highlights the value of scenario-based modeling for anticipating watershed responses in data-limited settings, providing a scientific basis for evidence-informed land use planning, watershed protection, and marine protected area (MPA) management.

From a policy and management perspective, the results of this study offer several insights. First, the identification of Mindoro watersheds as major sediment contributors highlights priority areas for soil conservation measures, reforestation initiatives, and erosion control interventions. Second, the finding that basin-scale variables are more sensitive to land use change suggests that land management strategies (such as controlling urban sprawl, protecting forest cover, and adopting sustainable agricultural practices) can yield rapid benefits in reducing sediment mobilization. Conversely, the greater sensitivity of river mouth variables to climate change implies that marine management efforts, such as the design and placement of marine protected areas (MPAs), must incorporate future climate projections to anticipate changes in freshwater and sediment fluxes. Third, the nonlinear interactions among rainfall, temperature, and land use highlight the importance of adaptive, flexible management strategies that can respond to context-specific dynamics rather than relying on one-size-fits-all solutions.

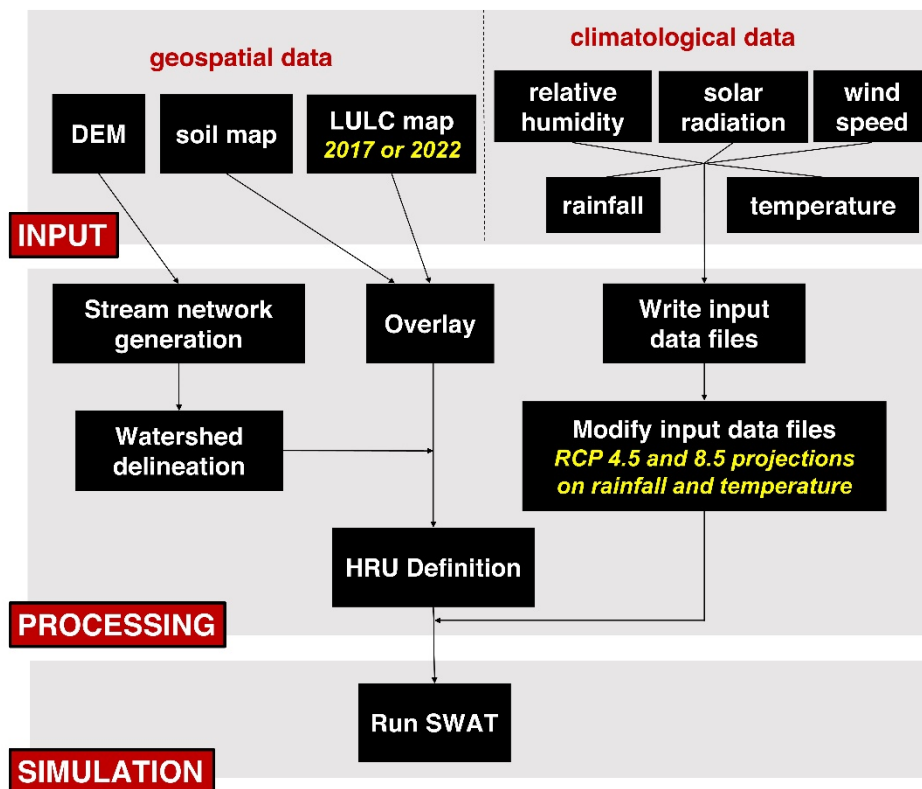
This study makes several contributions to the literature. It is among the first to systematically compare the relative effects of land use change and climate change on hydrological processes at both basin and river mouth scales in the VIP region. It demonstrates the feasibility of applying SWAT in data-limited tropical environments, while also illuminating the limitations imposed by weak monitoring systems. By linking ridge-to-reef processes, it provides a framework for integrated management of terrestrial and marine ecosystems in one of the world's most important biodiversity hotspots. It also advances methodological discussions about how to interpret and apply hydrological model outputs when calibration data are insufficient, advocating for a focus on relative comparisons and scenario analysis rather than absolute predictions.

In conclusion, our analysis demonstrates the utility of SWAT for exploring sediment–watershed–reef linkages in a data-limited yet ecologically critical region. We show that Mindoro watersheds are major sediment contributors to the VIP, that urbanization and forest expansion produce divergent basin-scale hydrologic effects, and that climate change intensifies river mouth sensitivity to rainfall and temperature shifts. Together, these findings underscore the need for integrated, cross-sectoral strategies that bridge land and sea, anticipate climate futures, and are supported by strengthened monitoring and data systems. Protecting the biodiversity and ecosystem services of the Verde Island Passage requires not only marine-focused conservation, but also a proactive ridge-to-reef approach that addresses the upstream drivers of sedimentation. By situating our analysis within this broader framework, the study contributes to advancing both the science and practice of sustainable watershed and marine management in the Coral Triangle and beyond.

**Keywords:** catchment simulation, soil erosion simulation, hydrological process simulation, SWAT model



**Fig. 1** The Verde Island Passage and selected watersheds for SWAT modeling (inset: location within the Philippines)



**Fig. 2** Schematic workflow of SWAT modeling showing LULC and climate change integration