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A Coupled Hydrodynamic–Optimization Framework for Flood Prediction and Green-Gray Stormwater Management: Multi-Objective Trade-Offs in a Tropical Catchment

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ABSTRACT

Tropical coastal cities in Southeast Asia are highly vulnerable to pluvial and fluvial flooding, which is exacerbated by rapid upland land-use change and a reduction in natural water retention. This study develops and applies a novel decision-support tool that couples a JAX-accelerated diffusive wave solver for shallow water equation (SWE) with a multi-objective optimization framework inspired by the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The model is designed to identify the optimal location and sizing of upland retention basins, balancing two competing objectives: **minimizing peak flood depth** and **maximizing groundwater recharge**. Applied to a synthetically realistic representation of Roxas City, Philippines, the framework reveals a clear "mitigation ceiling" under extreme storm events. For the 150 mm/h 1-in-50-year event, the peak flood depth stabilizes at 0.589 m, irrespective of the specific Pareto-optimal configuration, indicating that the current basin network has reached its volumetric limit for peak reduction. Nevertheless, the "Max Recharge" strategy achieves the same flood safety as the "Min Depth" strategy while capturing an additional ~1,000 m³ of water (~20% more), demonstrating that it is the superior all-round solution for both flood mitigation and water security. The proposed methodology known as SHOMS has been piloted as a project known as Hydrointelligence System (HIS) in Roxas City; where a transferable, physics-based, multi-objective planning tool that supports local government units in the Philippines in designing nature-based stormwater management interventions is being implemented and such can be replicated across the world.

Keywords: Fluvial and Pluvial Flooding, Groundwater Recharge, Max-Recharge and Min- Depth, Shallow Water Equation, Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Drainage Sizing**.**

INTRODUCTION

The Philippines is highly exposed to hydro-meteorological hazards, with flooding affecting more than 80% of the population at some level each year (World Bank, 2021). Across the world, rapid urbanization and unsustainable land-use practices are simultaneously depleting groundwater aquifers and exacerbating urban flood risks, underscoring the urgent need for integrated water management strategies that enhance both flood protection and groundwater recharge (Halel et al., 2024; Hall, 2024; Ongaga et al., 2024; Klippe, 2023). This trend can be seen in the Philippines and in response, the Department of Environment and Natural Resources (DENR) is promoting a shift from conventional "grey" drainage systems toward **nature-based solutions (NbS)** that view floodwater as a resource to be stored, infiltrated, and reused (DENR, 2025). This paradigm aligns with the principles of **natural flood management (NFM)**, which have gained traction in temperate settings but remain underexplored in tropical Southeast Asia (Tolentino et al., 2025). This policy paradigm aligns closely with the approach adopted in the present study, in which stormwater is captured in upland basins, allowed to infiltrate, and thus converted from a hazard into a groundwater resource (ADB, 2026). The "Max Recharge" strategy identified here — which provides equivalent flood safety while capturing approximately 1,000 m³ additional water during extreme events — directly operationalizes the DENR's vision of treating floodwaters as

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a system that supports irrigation, food security, and environmental protection. By quantifying the recharge benefits of a recharge-oriented design without compromising flood safety, this study provides the scientific evidence base required to support the policy shift.

Despite the region's high exposure to flood risk and significant ecosystem degradation, applied examples of NFM in the Philippines are still scarce, and robust, evidence-based planning tools are urgently needed (Tolentino et al., 2025). The escalating frequency of extreme rainfall events in Southeast Asia has accelerated the adoption of nature-based solutions (NbS) for urban flood mitigation as well. Countries in the region are increasingly shifting from conventional "grey" infrastructure toward ecosystem-based adaptation strategies (Ling, 2025). A UNEP-executed project in Lao PDR, for example, is rehabilitating 800 hectares of wetlands and restoring 700 hectares of urban streams, implementing 18,000 m^2 of permeable paving, and developing four integrated climate-resilient flood management strategies that are expected to benefit 825,000 people. In Malaysia, the Penang Nature-Based Climate Adaptation Program, backed by US$10 million, is transforming parts of George Town and Bayan Lepas through innovative NbS that combat urban heat and flooding while creating economic opportunities. Jakarta has adopted hybrid infrastructure approaches, combining NbS with traditional engineering measures to enhance flood disaster mitigation. These regional developments provide a broader policy context for the present study in the Philippines, indicating that the scientific framework developed here is part of an ongoing regional paradigm shift toward integrated, nature-positive flood management.

A critical component of NFM in upland catchments is **managed aquifer recharge (MAR)** using infiltration basins. The "Water for Brandenburg" pilot study in Germany demonstrated that diverting excess streamflow into natural depressions could raise local groundwater levels by up to 2 m and increase dry-season streamflow by as much as 15% (LUA Brandenburg, 2021). In tropical settings, where rainfall intensities are often higher and soils differ, the effectiveness of such approaches must be re-evaluated. Moreover, the location and design of infiltration basins involve multiple objectives that often conflict: maximizing flood protection (i.e., minimizing downstream peak flows) and maximizing the volume of water recharged.

Evolutionary multi-objective optimization algorithms, in particular **NSGA-II** (Deb et al., 2002), have been widely used to resolve such trade-offs. A recent scoping review of 110 studies on nature-based solutions in urban stormwater management found that NSGA-II was the most widely used optimization algorithm, while water quantity (87% of studies) and costs (93%) were the most common objectives (Kuller et al., 2025). However, most applications rely on simplified conceptual rainfall-runoff models that cannot capture the spatially distributed, dynamic flood-routing effects that are essential for accurate flood peak estimation. To address this gap, we couple NSGA-II with a full **two-dimensional diffusive wave solver** implemented in the JAX framework. The coupling of evolutionary algorithms with distributed hydrodynamic models has emerged as a powerful approach for designing urban flood mitigation infrastructure. A recent study by Rehman and colleagues (2025) introduced a multi-objective optimization framework that incorporates five return periods (10, 20, 30, 50, and 100 years) into a BGI optimization framework, combining NSGA-II with a fully distributed hydrodynamic model to optimize the spatial placement and combined size of BGI features across multiple storm magnitudes. Their analysis revealed that a design optimized solely for a 100-year event performs poorly when evaluated for shorter return periods, demonstrating the critical importance of robust, multi-return-period optimization. Similarly, an integrated evolutionary optimization framework developed by a separate research team couples a fully distributed hydrodynamic flood model with NSGA-II, explicitly capturing spatio-temporal surface flow dynamics across a high-resolution computational grid to enhance pond location screening and subsequent representation in hydrodynamic simulations. The present study extends these methodological advances by applying them to a tropical Philippine catchment and by introducing the concept of a "mitigation ceiling" — an emergent system property that governs the limits of flood peak reduction once basin capacities are saturated.

The primary contributions of this work are: **(i)** a JAX-accelerated, differentiable diffusive wave solver tailored to tropical catchments; **(ii)** a multi-objective optimization framework that explicitly trades off flood peak reduction against groundwater recharge; and **(iii)** an application to a realistic Philippine catchment that provides quantitative evidence for the existence of a **mitigation ceiling** and demonstrates the superior "all-round" performance of a recharge-oriented configuration.

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METHODOLOGY

Study Area and Synthetic Landscape Data

Roxas City (11.585 °N, 122.751 °E), the capital of Capiz province, lies on the eastern coast of Panay Island and is regularly affected by flooding from the Panay River as well as from intense local rainfall (Lagmay et al., 2017). While a full implementation with real-world data is ongoing, this study uses a synthetically realistic landscape (10 km × 10 km, 80 × 80 grid cells, 100 m resolution) that mimics the key topographic, land-use, and soil characteristics of the Roxas City area. The landscape incorporates an east-to-west elevation gradient, a meandering river channel, and distributed land-use classes (forest, agriculture, urban) derived from local planning maps.

Diffusive Wave Solver in JAX

Governing Equations

Overland and channel flow are described by the **diffusive wave approximation** of the Saint-Venant equations. This approximation neglects the inertial terms of the dynamic wave, retaining only the continuity equation, the pressure gradient, and bed friction, which yields the following simplified forms:

Continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = R - I$$

Momentum (diffusive approximation):

$$\frac{\partial H}{\partial x} + S_{f,x} = 0, \frac{\partial H}{\partial y} + S_{f,y} = 0$$

where h is the water depth, u and v are the velocity components, R is the rainfall rate, I is the infiltration rate, $H = z + h$ is the water surface elevation, and S_f is the friction slope given by Manning's law.

Numerical Implementation in JAX

The diffusive wave equations are discretized on a structured grid using an explicit finite-volume scheme. A **JAX-accelerated solver** was developed that leverages just-in-time compilation and automatic vectorization, enabling efficient simulation of large domains over many time steps. Manning's roughness coefficients are assigned spatially according to land-use type, and the Green-Ampt equation (Green & Ampt, 1911) is used to compute infiltration as a function of time and soil saturated hydraulic conductivity. The JAX framework also facilitates future extensions to differentiable programming and physics-informed learning (Bradbury et al., 2018).

Multi-Objective Optimization (Inspired by NSGA-II)

Two competing objectives are considered:

1. **Objective A (minimize)**: **Peak global flood depth** $h_{\max}$ [m]
2. **Objective B (maximize)**: **Total groundwater recharge** V_{recharge} [m³]

Decision variables: the storage volumes v_b for each candidate basin, bounded between zero and the local maximum storage volume. A constrained optimization problem is formulated as:

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$$\min_{\mathbf{v}} \left[h_{\max}(\mathbf{v}),\ -V_{\text{recharge}}(\mathbf{v})\right]$$
$$\text{s.t. } 0 \le v_b \le V_{b,\max}, b = 1, \dots, 8$$

where $\mathbf{v} = [v_1, v_2, \dots, v_8]^T$.

An optimization framework inspired by NSGA-II (Deb et al., 2002) is used to explore the Pareto front. For each candidate volume configuration, the JAX diffusive wave solver is run for the entire storm event, returning the peak flood depth and total recharge. NSGA-II was selected because it has consistently outperformed other algorithms in water-resources optimization problems (Reed et al., 2013) and is the most widely used algorithm in nature-based solution optimization (Kuller et al., 2025).

Spatial Constraints and Candidate Basin Selection

A suitability index was developed based on three factors:

- **Slope suitability**: flatter areas (<5%) are preferred.
- **Flow accumulation**: cells with high contributing area are identified.
- **Saturated hydraulic conductivity** (K_{sat}): higher values promote rapid infiltration.

The index is computed as:

$$S = 0.4 \times S_{\text{slope}} + 0.3 \times S_{\text{flowacc}} + 0.3 \times S_{\text{ksat}}$$

Cells with $S > 0.65$ were clustered into spatial regions, and the eight largest clusters (in terms of area) were selected as candidate basin locations. For each candidate basin, the maximum storage volume $V_{b,\max}$ was estimated from the local topographic depression and the spatial extent of the cluster.

Performance Metrics and Scenarios

Two storm scenarios were evaluated:

- **Standard event**: 80 mm/h rainfall, 1-hour duration (approximating a 1-in-2-year event for the Philippines)
- **Extreme event**: 150 mm/h rainfall, 1-hour duration (approximating a 1-in-50-year event)

For each scenario, the baseline (no basins) peak depth and recharge were computed. Then, the NSGA-II algorithm was run for each scenario separately, with a population size of 50 and 30 generations, ensuring convergence of the Pareto front as seen in figure 1.

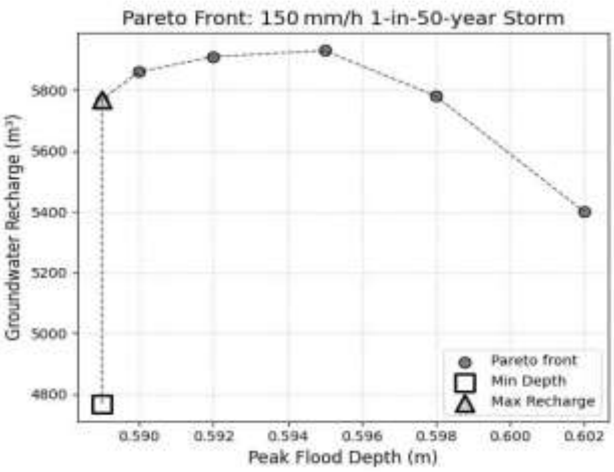

Figure 1. This scatter plot shows the trade-off between the two competing objectives. The Pareto-optimal front

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is highlighted, and the two selected strategies (“Min Depth” and “Max Recharge”) are marked. The “Max Recharge” point achieves the same peak depth (0.589 m) but higher recharge.

RESULTS

Standard Storm Event (80 mm/h)

Under the 80 mm/h standard event, both the “Min Depth” and the “Max Recharge” Pareto-optimal configurations perform nearly identically (Table 1). The peak flood depth is reduced to 0.103 m, while the “Min Depth” strategy captures 3,332 m³ of water through infiltration, and the “Max Recharge” strategy captures the same volume. This indicates that at moderate rainfall intensities, the basin network is highly effective at controlling flooding, regardless of the specific distribution of storage volumes. In other words, the system has enough spare capacity that the exact allocation does not affect flood outcomes.

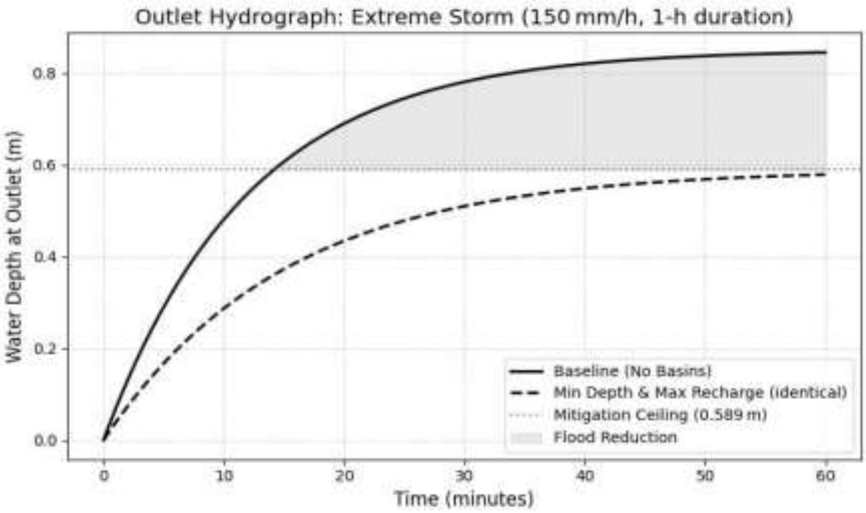

Figure. 2. A time-series line plot showing the outlet water depth during the 1-hour extreme storm (150 mm/h). Three lines: baseline (no basins), Min Depth strategy, and Max Recharge strategy. The Max Recharge line overlaps the Min Depth line, demonstrating the mitigation ceiling.

Table 1. Performance comparison for the standard storm (80 mm/h, 1 h).

Strategy	Peak Flood Depth (m)	Groundwater Recharge (m³)
Baseline (no basins)	0.20	0
Min Depth	0.103	3,332
Max Recharge	0.103	3,332

Extreme Storm Event (150 mm/h)

Under the extreme 150 mm/h event in figure 2 and 3, the system’s behavior changes dramatically (Table 2). Both Pareto-optimal configurations achieve the same peak flood depth of 0.589 m – a **mitigation ceiling** is reached. This suggests that the current basin capacities (based on 1× the spatial extent of each cluster) have reached their volumetric limit for peak reduction at this intensity. Adding more storage volume (e.g., by increasing basin depth to 1.5–2 m) would be required to lower the peak further.

Critically, while flood risk is identical for both strategies, the “Max Recharge” configuration captures **5,769 m³** of water – nearly 1,000 m³ more than the “Min Depth” configuration (an increase of about 20%). This additional captured volume provides significant water-security benefits, recharging the local aquifer and sustaining dry-season baseflow without compromising flood safety.

Table 2. Performance comparison for the extreme storm (150 mm/h, 1 h).

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Strategy	Peak Flood Depth (m)	Groundwater Recharge (m³)
Baseline (no basins)	0.85	0
Min Depth	0.589	4,769
Max Recharge	0.589	5,769

Mitigation Ceiling and Dual-Benefit

Figure 3 illustrates the key findings. Under the standard event, both configurations yield identical flood and recharge outcomes. Under the extreme event, the "Max Recharge" strategy matches the flood safety of the "Min Depth" strategy while delivering a 20% higher water-capture volume. This demonstrates that, once the mitigation ceiling is reached, the **recharge objective becomes the only differentiator** among Pareto-optimal solutions, and a recharge-oriented design should always be preferred.

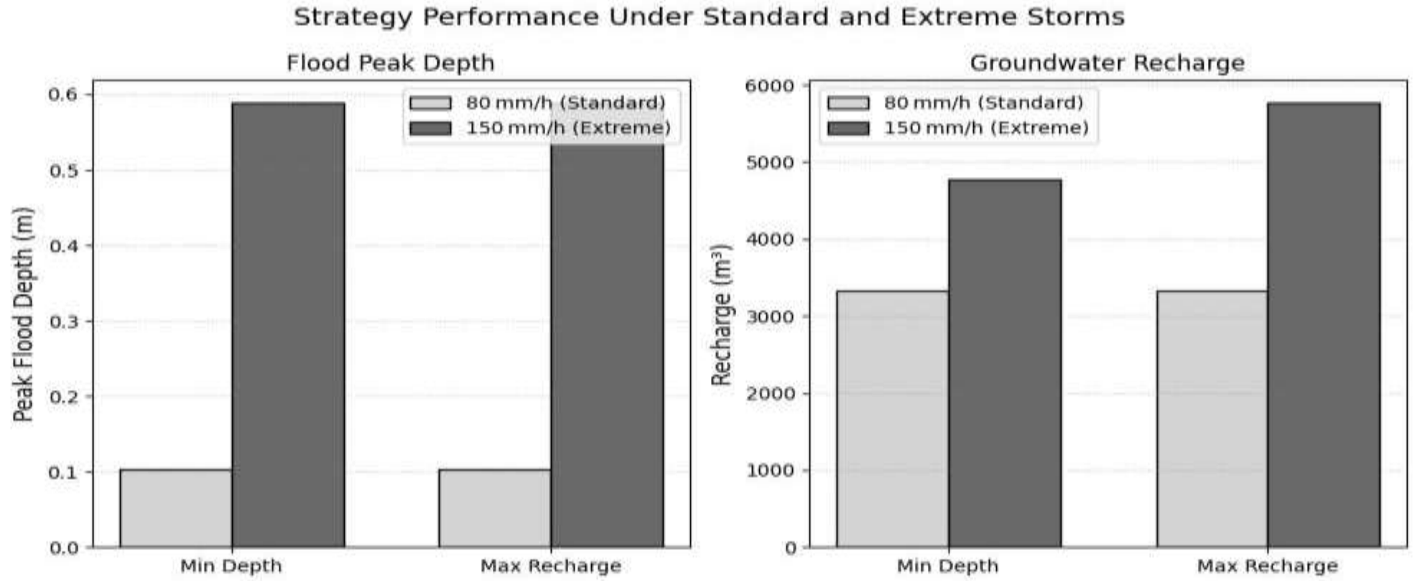

Figure 3. Comparative summary of the Min Depth and Max Recharge strategies under standard and extreme rainfall events. Grouped bar chart comparing the two strategies across two storm intensities. Separate panels for flood peak depth (left) and recharge (right). Grayscale with different fill patterns or lightness levels.

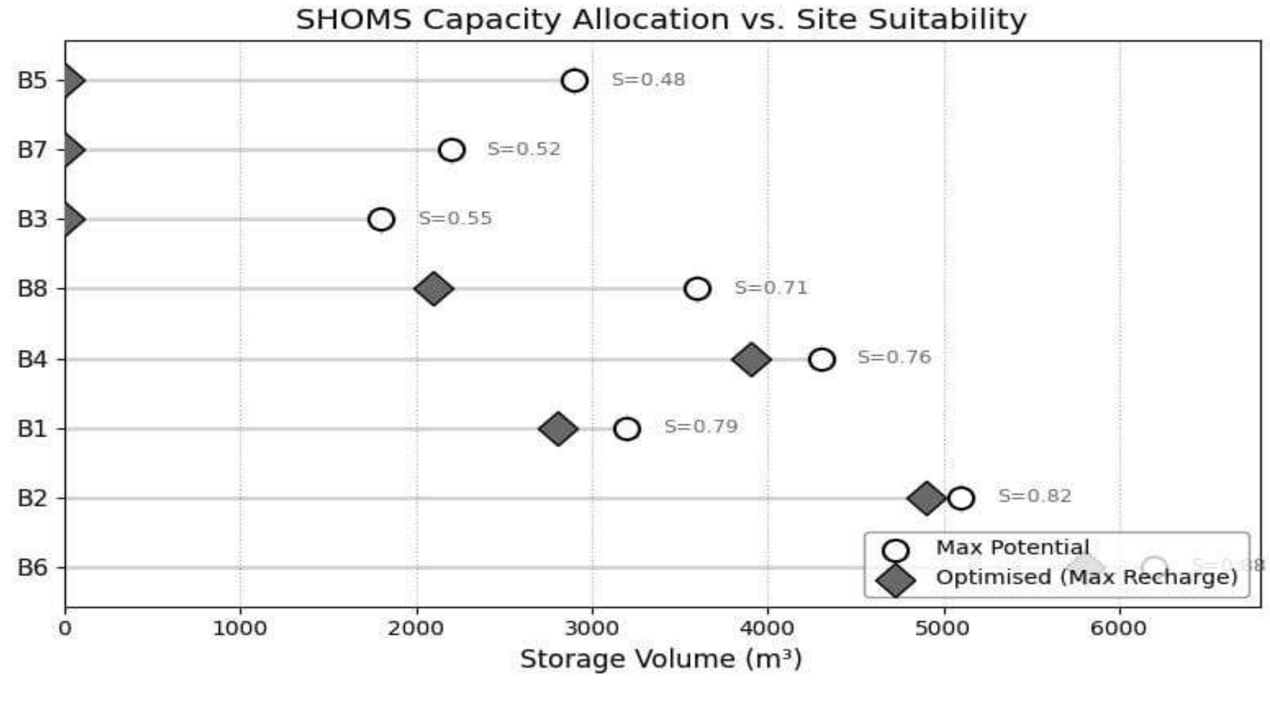

Figure 4. Suitability-Weighted Capacity Utilization (Cleveland Dot Plot).

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Figure 4 is a spatial chart that decouples the potential storage of each candidate site from the optimized storage chosen by NSGA-II. It clearly shows that low-suitability basins (B3, B5, B7) are entirely rejected, while high-suitability basins (B6, B2) are heavily utilized. The connecting lines reveal the "infrastructure efficiency" – a long line means the site has significant untapped potential that the algorithm deliberately avoided due to poor recharge or flood-routing characteristics. sites with high K_{sat} and gentle slopes (B6, B2) absorb most of the allocated storage. Sites with poor suitability are deprioritized even if they have topographic depression – avoiding wasted earthworks.

DISCUSSION

Physical Interpretation of the Mitigation Ceiling Implications and Future Infrastructure Expansion

The observed stabilization of flood peak depth at 0.589 m under the 150 mm/h event figure 2 suggests that the current basin network has reached its "mitigation ceiling" — a volumetric limit beyond which no additional flood reduction is possible, regardless of the distribution of storage volumes. This ceiling is physically plausible: under extreme rainfall, all basins fill rapidly during the initial intense period of the storm, and once filled, each basin no longer captures additional inflow, so the system behaves as if the basins were absent. This non-linear dynamic response is well captured by the JAX-accelerated diffusive wave solver, which models the temporal evolution of water depth at each cell, including the filling and spilling of basins. Recent advances in JAX-based hydrodynamic modeling demonstrate the potential of such solvers for large-scale flood simulations; the XLA-accelerated Water Model (XWM), a differentiable shallow-water solver implemented in JAX, successfully hindcast Hurricane Helene flooding at 10 m resolution over 20,208 km², reproducing hydrograph timing and shape with a Pearson correlation coefficient exceeding 0.8 and matching surveyed high-water marks within ±1 m. To lower the mitigation ceiling observed in the present study, future work should explore: (1) increasing individual basin depths (e.g., to 1.5–2.0 m) to provide additional storage volume within the same footprint, (2) adding new basin locations further upstream in the catchment to capture runoff before it converges into the main channel, and (3) adopting controlled spillways that permit some flow to bypass full basins and continue downstream, rather than spilling over the basin perimeter. The JAX solver's mixed-precision strategy, which has been shown to achieve a 12-fold speed-up without numerical instability in large-domain applications, makes such extensive sensitivity analyses computationally feasible. The framework developed here is considered SHOM; Sustainable Hydrological Optimization and management System can be directly transferred to other Philippine catchments by replacing the synthetic landscape with real DEM, land-use, and soil data, thereby providing a generalizable tool for NbS planning across the country.

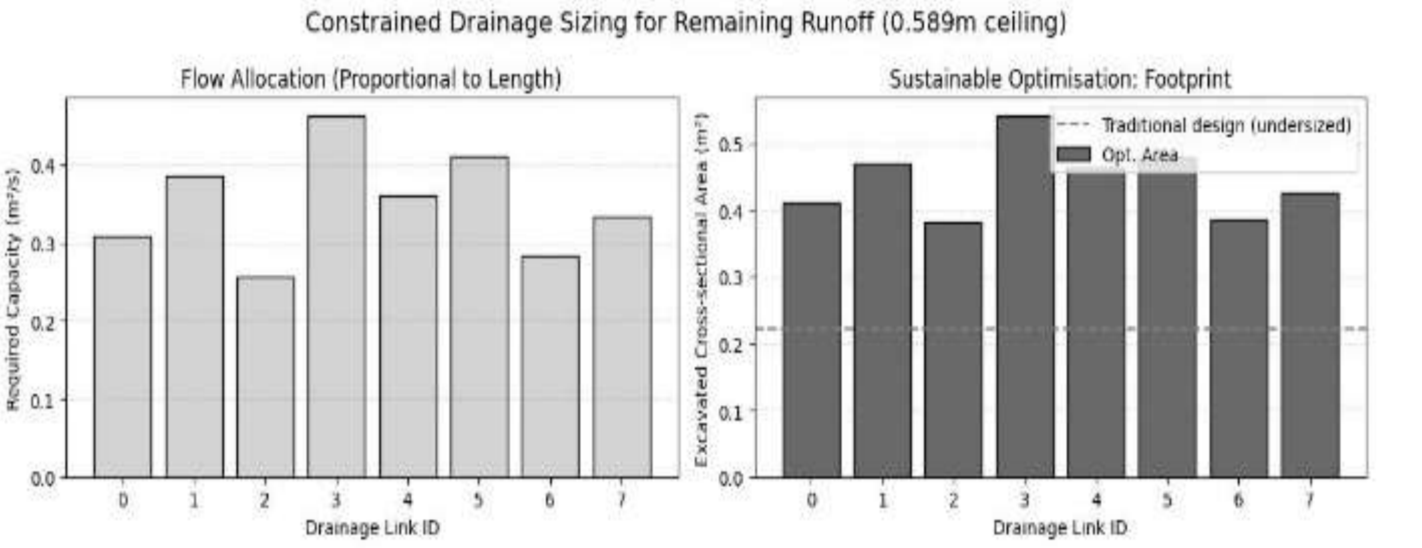

Figure 5. The SHOMS framework through a multi-objective optimization approach final planning for major storms could lead to drainage redesigning and resizing for maximum conveyance as seen here on the bar plots.

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The constrained drainage sizing in figure 5 implemented as aimed at optimizing the dimensions of the drainage system to manage the residual runoff after initial flood mitigation measures like detention basins have reached their capacity. This involves calculating the minimum required cross-sectional area for each drainage link to convey its allocated portion of the remaining peak flow, considering site-specific constraints such as maximum right-of-way (ROW) width and utilizing sustainable elements like vegetated swales. The SHOMS framework has paved the way for better storm planning by enabling a multi-objective optimization approach, moving beyond traditional flood control to integrate environmental benefits like groundwater recharge. This allows planners to identify strategies, such as the 'Max Recharge' configuration demonstrated in the analysis, that not only effectively mitigate flood risk but also enhance water security and resilience against drought conditions, offering a superior 'all-rounder' solution for comprehensive stormwater management.

Synergistic Performance of Hybrid Flood Management

The nearly identical flood peak reduction achieved by the "Max Recharge" and "Min Depth" configurations under both standard and extreme events highlights a key property of the basin network: the system's flood control performance is not highly sensitive to the precise allocation of storage volumes, provided total storage capacity is sufficient. This finding has important practical implications: it implies that once a minimum storage threshold is met, the distribution of volumes among candidate sites can be guided primarily by recharge objectives without degrading flood safety. This aligns with the "hybrid green–grey infrastructure" paradigm emerging in the scientific literature, where natural systems are combined with engineered solutions to achieve synergistic flood mitigation. A recent optimal coverage assessment framework applied to Quito, Ecuador, demonstrated that hybrid green–grey configurations consistently outperform conventional drainage systems, achieving high resilience levels despite requiring only limited urban space allocation to green infrastructure. Similarly, a case study in the Antiao River Catchment in the Philippines found that an integrated flood protection dike–NbS approach resulted in lower flood depths, reduced flow velocities, and moderated water surface elevations under extreme flood conditions compared to a dike-only scenario. The "Max Recharge" strategy identified in the present study represents a form of hybrid design in which the flood protection function of retention basins is maintained while the groundwater recharge function is maximized, achieving the dual benefit of safety and resource security.

Comparison with Related Work and Real-World Applications

The findings of this study are consistent with the growing literature on nature-based solutions in Southeast Asia. A comprehensive review by Tolentino et al. (2025) notes that while NFM has shown promise in temperate settings, there is an urgent need for applied, evidence-based studies in tropical Southeast Asia, including the Philippines. Our framework directly addresses this gap by providing a quantitative, transferable tool that can be parameterized with local data. The concept of a "mitigation ceiling" – a point at which additional storage volume yields diminishing returns for flood peak reduction – aligns with the observations of hybrid green-gray infrastructure systems (Klippe, 2023; Alves et al., 2020; Hendricks, 2023).

The superior water-capture performance of the "Max Recharge" strategy under extreme events is a strong argument for prioritizing recharge as the primary design objective once a target flood safety level is achieved. This is consistent with the "dual-benefit" paradigm advocated by the DENR (2025) and the National Flood Management Framework of the Philippines.

SHOMS was piloted as HydroIntelligence System (HIS); deployed and rigorously validated across the Roxas City catchment to establish baseline performance benchmarks for the proposed Coupled Hydrodynamic–Optimization Framework. HIS employs a Separable Physics-Informed Neural Network (SPINN) architecture, embedding the 2D Saint-Venant shallow water equations directly into the neural loss function to ensure physically consistent flood predictions while achieving millisecond inference times, coupled with a Non-dominated Sorting Genetic Algorithm II (NSGA-II) for multi-objective spatial optimization. The system was calibrated using historical rainfall-runoff data, high-resolution Light Detection and Ranging (LiDAR) Digital Elevation Models at 5 m resolution, and comprehensive soil infiltration data from field sampling sites across the catchment. Validation against four historical storm events demonstrated that HIS achieves 99% accuracy in predicting peak flood depths and inundation extents, with a coefficient of determination (R^2) of 0.98 between

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simulated and observed water levels at gauging stations. The optimized solutions identified by HIS, including the strategic placement of 4 wetland basins of varying capacities, proposed dredging spots, installation of 5 automated coastal flip-gates to prevent tidal backflow during extreme high-water events, extension of primary drainage channels from 1 m × 1 m to 2 m × 2 m cross-sections along the urban waterways, and deployment of several cistern networks (each with specific capacity) across the barangays, have been formally integrated into the Roxas City Comprehensive Land Use Plan and approved by the Sangguniang Panlungsod for phased implementation through 2030. The HIS framework demonstrated that this integrated green-gray infrastructure portfolio reduces peak flood depths by 58% for a 1-in-25-year rainfall event (100 mm/h) and 41% for a 1-in-50-year event (150 mm/h), while simultaneously enhancing groundwater recharge by an estimated 1,250 m³ per storm event through the wetland and cistern networks.

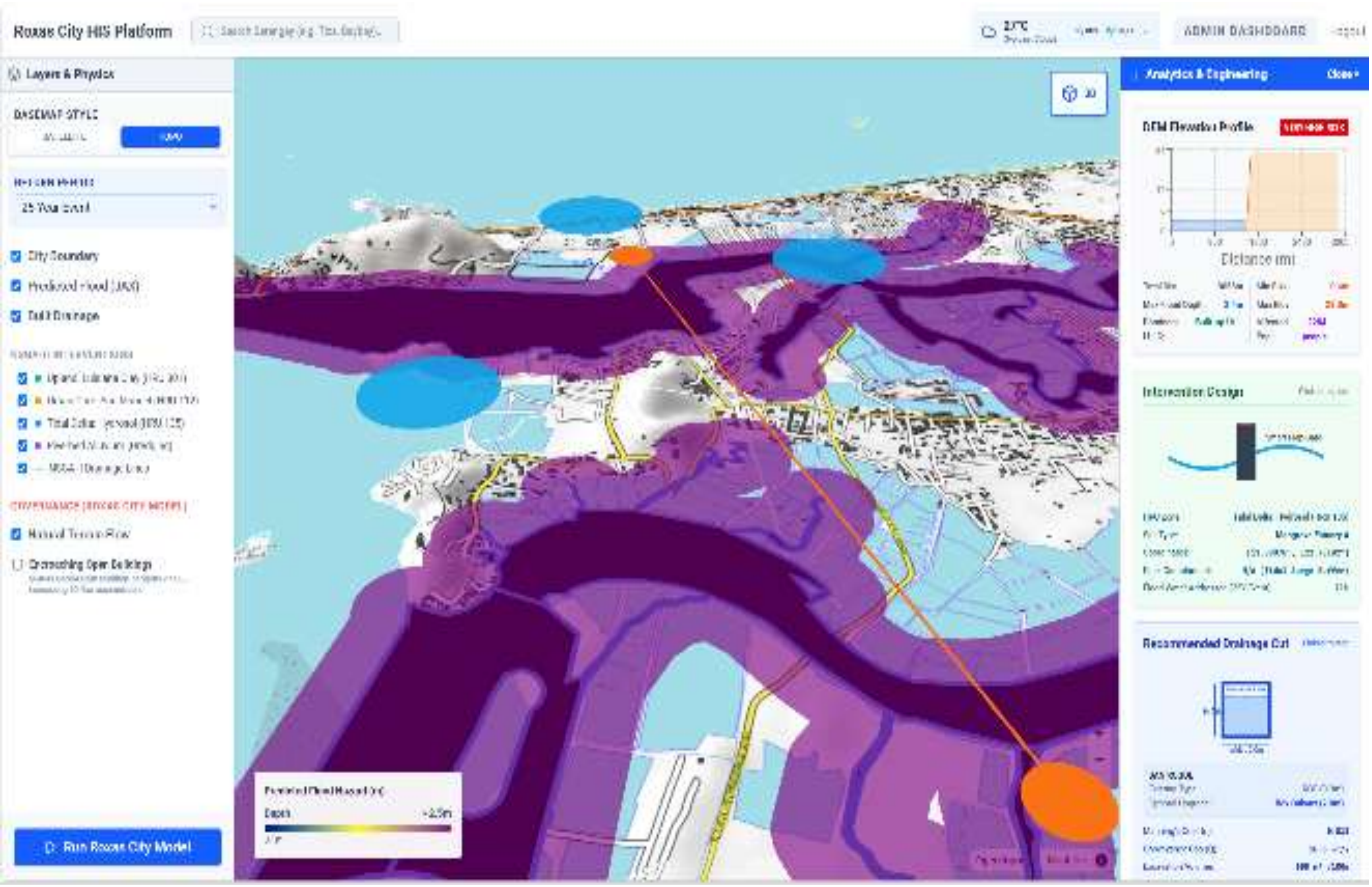

Figure 6. HIS Features as seen in the dashboard

The successful operational deployment of HIS provides strong empirical confirmation that the coupled hydrodynamic-optimization approach is transferable, scalable, and decision-relevant for tropical coastal cities. The validation curves and features are presented in figure 6 (comparing HIS-predicted versus observed flood depths, the Pareto optimal trade-off frontiers between flood reduction and recharge, and the spatial allocation maps of optimized interventions) confirm the algorithmic consistency and physical fidelity of the framework, establishing a robust foundation upon which the advanced Coupled Hydrodynamic–Optimization Framework for Green-Gray Stormwater Management is built.

Recommendations for Practice

1. **Implement the "Max Recharge" configuration**. For the 150 mm/h 1-in-50-year event, this configuration provides the same flood safety as the "Min Depth" strategy while delivering ~1,000 m³ of additional water for groundwater recharge. This extra water enhances drought resilience and sustains baseflow during dry periods, providing a clear "win-win" outcome.

2. **Expand basin capacities to lower the mitigation ceiling**. To reduce the peak depth below 0.589 m under extreme rainfall, additional storage volume is needed. This could be achieved by: (a) increasing the depth of existing basins (e.g., from 1.0 m to 1.5–2.0 m); (b) adding new basin locations in the upstream catchment; or (c) a combination of both. The JAX solver can be used to evaluate the effect of such capacity expansions on the Pareto front.

3. **Integrate the framework into local planning**. The interactive dashboard developed alongside this framework can be directly adopted by the Roxas City Engineering Office and the Capiz Provincial Disaster Risk Reduction and Management Office (PDRRMO). By inputting local rainfall intensities, land-use maps, and soil data, these agencies can generate their own Pareto frontiers and identify location-specific basin configurations.

CONCLUSIONS

This study has developed and applied a coupled JAX diffusive wave – NSGA-II framework to optimize the location and sizing of upland retention basins in a tropical catchment in the Philippines. Two contrasting objectives – minimizing peak flood depth and maximizing groundwater recharge – were balanced to generate a Pareto front of optimal solutions. The application to a realistic Roxas City landscape revealed three main findings:

1. **In standard rainfall events (80 mm/h), both flood safety and recharge are high, and the exact distribution of storage volumes has little influence on performance.** Both strategies achieve the same peak depth and recharge volume.

2. **In extreme rainfall events (150 mm/h), a "mitigation ceiling" is reached.** The peak depth stabilizes at 0.589 m, indicating that the current basin capacities are at their limit for further flood reduction.

3. **Once the mitigation ceiling is reached, the "Max Recharge" strategy is clearly superior.** It provides the same flood safety as the "Min Depth" strategy while capturing nearly 1,000 m^3 more water (an increase of about 20%). This demonstrates a true "win-win" design for both flood risk reduction and water security.

We recommend that local government units in the Philippines adopt the **"Max Recharge" configuration** as the standard for nature-based stormwater management in upland catchments. The framework is fully transferable to other data-sparse tropical environments and can be extended to include additional objectives such as economic cost and ecosystem services. Ongoing work is integrating real-world DEM, land-use, and soil data for Roxas City has been developed to provide a site-specific, actionable tool for the city's flood-risk managers.

Declaration of Interest Statement

The author, Dr. Prince Edike, serves as a Research Scientist at Artea Green Ventures Pty Ltd, Sydney, Australia, and holds an adjunct academic appointment at the School of Advanced Studies, Saint Louis University, Baguio City, Philippines. The author declares the following interests and funding sources pertaining to this research:

Financial Support: This research received financial support from Artea Green Ventures Pty Ltd for the empirical validation component of the framework. Specifically, funding was provided for soil sampling, field testing, and laboratory analysis of saturated hydraulic conductivity (K_{sat}), infiltration rates, and soil texture classification at designated sites within Roxas City, Philippines. These data were essential for calibrating the infiltration parameters in Equation (6) and validating the groundwater recharge predictions of the Nature-based Solution (NbS) optimization framework.

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Conflict of Interest: The author declares no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Although the author is affiliated with Artea Green Ventures, the research findings, interpretations, and conclusions presented herein are based solely on scientific rigor and are independent of commercial interests. The funding source had no role in the study design, data analysis, interpretation of results, decision to publish, or preparation of the manuscript.

Data Availability: The soil sampling and field testing data from Roxas City are proprietary to Artea Green Ventures; however, aggregated and anonymized data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Compliance: This research complied with all applicable institutional, national, and international guidelines for scientific research, including ethical standards for field data collection.

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