Bridging borders for sustainable river basin management: Lessons from the Cagayan River Basin

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ABSTRACT

The Cagayan River Basin is one of the 18 major river basins in the Philippines. These basins are considered the lifeblood and driver of the Philippine economy thus need to be managed sustainably following an integrated river basin management approach to address several concerns related to watershed conservation, flood mitigation, secure clean water supply and irrigation development. In 2018, a cooperative research project amongst Philippines, Vietnam and Japan was established aimed at developing innovative approaches and techniques in integrated flood, sediment, and water resources management for sustainable development in ASEAN river basins. This paper highlights results of said collaborative studies on impacts of climate change and human activities using the SWAT model and projected that climate change and land use changes will significantly reduce water resources during dry years leading to droughts and increase of sediment inflow during wet years. A bathymetric survey in the Magat dam was conducted to validate the extent of sedimentation in the reservoir. Further, the rainfall-runoff-inundation (RRI) model was locally optimized as a decision support tool for flood inundation forecast and upgrading dam discharge protocol during extreme rainfall events.

INTRODUCTION

Vietnam and the Philippines are two of the countries in the world most affected by climate change and fluctuation (Principe 2012; Souvignet et al. 2014). Extreme floods and droughts are anticipated to become more powerful and frequent as a result of climate change (Hoanh et al. 2010). Floods have become increasingly common in the Vu Gia-Thu Bon River basin in Vietnam in recent years, with higher flood peaks and more severe flooding (Do et al. 2018; Nga 2019). For example, the average number of floods increased from 2.7 in 1989 to 5.6 from 2005 to 2010. As a result, climate change poses a serious threat

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to the security of communities, economic activities, ecological services, and water supply to a variety of users in the Vu Gia-Thu Bon and Cagayan River basins (Vo and Gourbesville 2018), which are two of Vietnam's and Philippines' most important river basins, respectively.

Furthermore, human activities like dam construction, irrigation expansion, deforestation, sand mining, and land use change have exacerbated the effects of climate change. River and coastal erosion are caused by reservoir sedimentation and sand mining, which restrict sediment discharge and disturb sediment transport (Ponsioen 2015; JICA 2018). Because of reservoir sedimentation, the Magat dam in the Cagayan River basin has lost 62.7 percent of its designed dead storage capacity after 17 years of operation (for a designed life of 100 years). Climate change may cause sedimentation in the Magat reservoir to increase by 29%. As a matter of fact, the Cagayan River is eroding at a rate of 6-28 m/year. Moreover, riverbank and coastal erosion are severe in many places along the Vu Gia-Thu Bon River, particularly on the Thu Bon river's Cua Dai beach, which is eroding at a rate of 25-63 m/year, and in (JICA 2002; Viet at al. 2015; Do et al. 2018).

Due to climate change, deforestation combined with heavy rainfall during the flood season accelerates reservoir sedimentation, resulting in reservoir storage capacity decreasing. As a result, downstream populations in the Vu Gia-Thu Bon and Cagayan River basins are anticipated to be vulnerable to severe floods and droughts (JICA 2002; RBCO 2013), inflicting serious damage to agriculture, aquaculture, and people's assets (Nga 2015). Water shortages in the dry season are also exacerbated by land use changes and irrigation expansion, particularly in El Nino years.

An integrated flood and sediment management approach is required for sustainable development in a river basin, in which all water-related issues must be addressed and managed appropriately in a coordinated manner throughout the basin. The tri-lateral research project investigated the effects of climate change and human interventions on reservoir sedimentation, flood inundation, agricultural practices, and river and coastal erosion in the Vu Gia-Thu Bon and Cagayan River basins, which are two of Vietnam's and Philippine’s most important river basins, respectively. Because these basins are regarded as the lifeblood and engine of each of the countries’ economies, they must be handled in a sustainable manner. To address numerous challenges linked to watershed conservation and rehabilitation, flood prevention, a reliable source of clean water, as well as livelihood and economic prospects in the area, an integrated river basin management method must be used.

This paper aims to present efforts to develop and implement integrated flood and water resources management strategies in the Magat and Cagayan River Basins through international collaboration, hydrological modeling, capacity-building initiatives, and the establishment of an association for climate change adaptation and disaster risk reduction, with the goal of improving water supply management, mitigating flood risks, and addressing sedimentation challenges under future climate change scenarios.

MATERIALS AND METHODS

Study Area

The study was conducted in the Magat and Cagayan River Basins, which are critical water resources in the northern Philippines. The Magat Reservoir provides water for irrigation, hydropower, and flood control, while the Cagayan River Basin is prone to flash floods, particularly during the wet season. These basins are highly sensitive to sedimentation and extreme weather events, both of which are expected to intensify with climate change. This study focuses on hydrological modeling and sediment management strategies to ensure sustainable water supply and flood mitigation in these basins.

Collaboration Framework and Project Structure

Isabela State University, in collaboration with Kyoto University (Japan) and Thuyloi University (Vietnam), established a partnership through a formal memorandum of agreement to address issues in integrated flood and sediment management in river basins in the Philippines and Vietnam. Following a field visit and workshop held on November 29, 2019, which included stakeholders such as the Department of Science and Technology (DOST), National Irrigation Administration (NIA), Department of Agriculture, and local institutions, a comprehensive methodology was outlined (Figure 1). This framework was subsequently refined and presented during a meeting in Hanoi on January 18, 2020, among the collaborating universities.

The project was structured into four primary components, each addressing key aspects of river basin management, with an additional cross-cutting component on capacity building and partnership development. This study focuses on the assessment of climate change impacts and the optimization of the Rainfall-Runoff-Inundation (RRI) model for the Cagayan River Basin, intended as a decision support tool for flood forecasting and dam discharge protocols during extreme rainfall events. Additionally, the study includes the results of a bathymetric survey of the Magat Dam reservoir to assess sedimentation rates and recommend sedimentation control interventions.

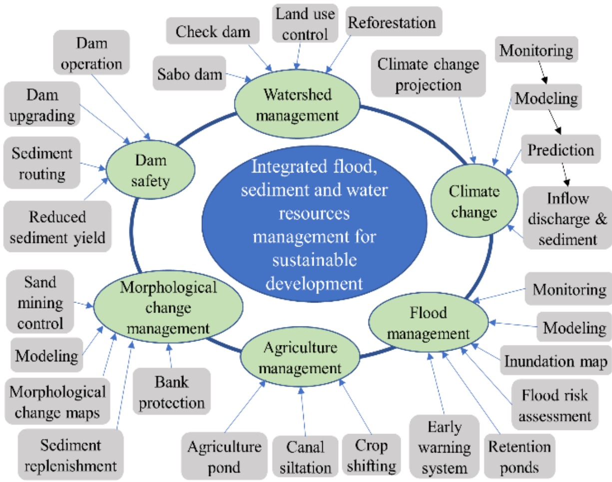

Figure 1: Schematic Framework for Integrated flood, sediment, and water resources management for sustainable development in river basins.

Hydrological Modeling for Water Supply Projection

To assess long-term water supply under future climate scenarios, the Soil and Water Assessment Tool (SWAT) model was employed. The SWAT model simulates the hydrological processes within the Magat River Basin, including surface runoff, groundwater flow, and reservoir inflow.

Model Setup

The model used a digital elevation model (DEM), land-use data, soil properties, and climate data from the basin to simulate monthly inflow into the Magat Reservoir. All relevant data from monitoring stations, field surveys, and satellites were collected. The spatial data that were used in the study included a 5x5 m resolution Digital Elevation Model (DEM), a 2015 land use/cover map, soil classification, and 31-year historical climatic/weather data. The input parameters for reservoir and dam operation were obtained from the NIA-MARIIS-Dam and

Reservoir Operation. The DEM of the Magat watershed which was extracted from the Digital Terrain Model (DTM) issued by NAMRIA was subjected to watershed delineation. Moreover, the weather data were taken from the meteorological station of PAG-ASA, while the daily rainfall data were provided by the NIA-MARIIS DRD specifically from the two rain gauge stations inside the basin. On the other hand, the land cover map was obtained from NAMRIA, while the soil map was sourced from the Bureau of Soil and Water Management (BSWM). Some of the soil and land cover data were validated and gathered from the field survey around the sub-basin.

Calibration and Validation

Calibration was performed using historical inflow data from 2000 to 2015, applying both manual adjustments and SWAT-CUP, a tool for parameter optimization. Seventeen key parameters related to groundwater, soil properties, HRU factors, and watershed management were fine-tuned. Model performance was assessed using Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), root mean square error (RSR), and percent bias (PBIAS). Validation was conducted with inflow data from 2016 to 2020.

Climate Change Scenarios

The model projected future water supply under two Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5, which represent moderate and severe climate change scenarios, respectively. These scenarios allowed for an evaluation of future inflow patterns and water availability under changing climate conditions. A hydrological model called Soil and Water Assessment Tool was calibrated and validated using the local weather, soil, land cover, and topography in Magat River Watershed. This was done to estimate the dam inflow and runoff from the catchment, considering the effects of climate. Climate projections from the CLIRAM tool of PAG-ASA were used as climate change scenarios.

Flood Forecasting Using Rainfall-Runoff-Inundation Model

For flood forecasting and flood risk assessment in the downstream Cagayan River Basin, the Rainfall-Runoff-Inundation (RRI) model was applied. The RRI model simulates the movement of water during rainfall events and estimates inundation levels based on terrain and hydrological conditions.

Model Setup

The RRI model was calibrated using data from Typhoon Ulysses (November 2020), which caused widespread flooding in the region. The model was setup using local inputs on hourly rainfall, land cover, and topography to estimate the runoff and flood inundations in the Cagayan River Basin.

Calibration and Validation

Calibration was performed using inflow data from the Magat Dam and water levels from the Buntun Bridge in Tuguegarao City. The model was tested on additional events, including Typhoon Tisoy (2019) and the monsoon rains of December 2020, to validate its predictive capability. Statistical indices such as NSE, R^2, PBIAS, and RSR were used to evaluate model accuracy.

Flood Simulation

The model was used to predict flood heights and inundation extents during extreme weather events, providing a basis for flood risk management and early warning systems. During the rainy season, flash floods have occurred in the Cagayan River Basin (CRB) downstream. The Cagayan Valley is a 27,000-square-kilometer elongated watershed. The lack of hydrological monitoring stations in CRB's tributaries and sub-watersheds makes flood forecasting difficult. Flood forecasting is critical for avoiding and minimizing flood damage. During extreme weather events, accurate, simple, and user-friendly rainfall-runoff models for estimating input from the upstream region of the Cagayan River Basin are required. The Japanese-made Rainfall-Runoff-Inundation (RRI) Model was calibrated and validated in this project to be used as a decision support tool to upgrade dam discharge protocol and improve flood inundation forecast during extreme rainfall events.

Bathymetric Survey and Sediment Management

To quantify sedimentation in the Magat Reservoir, a bathymetric survey was conducted to determine the extent of sediment deposition between 2016 and 2021. The 2021 survey was limited to the reservoir's main storage areas, covering ranges 1-8 (Figure 2).

Sediment Volume Calculation

The survey measured sediment volumes in both the live storage (elevation 147 m to 193 m) and dead storage (below 147 m) zones. These measurements were compared to a 2016 baseline to calculate the total volume of sediment accumulated.

Remaining Storage Capacity

The remaining live and dead storage capacities were calculated based on the survey data, providing critical information for water supply management. The sediment data also informed the design of sediment catchment structures (Sabo dams) aimed at reducing sediment inflow to the reservoir.

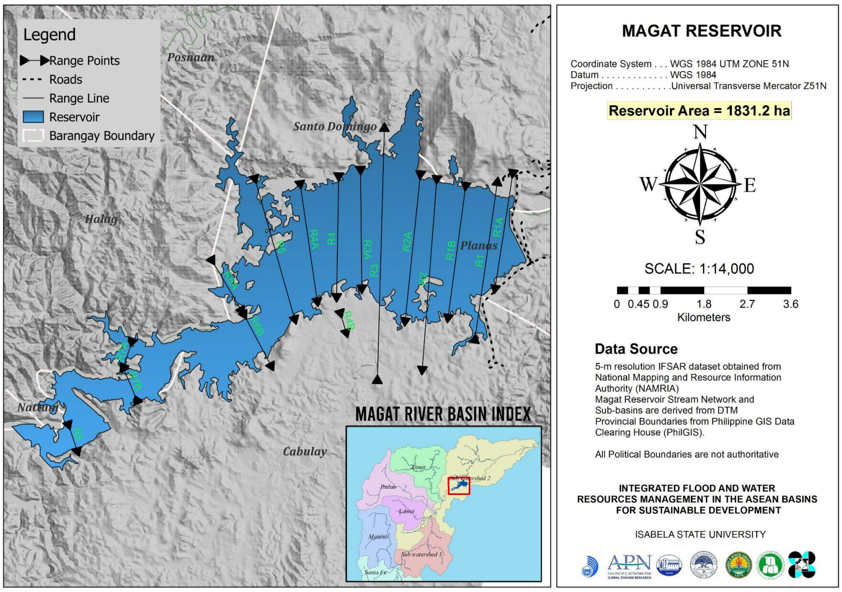

Figure 2: Range 1 to 8 of the main reservoir where the Bathymetric Survey was conducted.

Capacity-Building and Knowledge Transfer

As part of the project's overall objective to build capacity in integrated water resources management, several training programs and workshops were conducted. During the project course, international workshops, seminars, meetings, and training courses or internal meetings were organized and conducted by each member country. These activities supported the development of young researchers and enhanced stakeholder engagement.

RESULTS AND DISCUSSION

International Collaboration for Integrated River Basin Management

The international collaboration between Kyoto University (Japan), Isabela State University (Philippines), and Thuyloi University (Vietnam) was formalized through a memorandum of agreement, forming the foundation for this integrated flood and sediment management project. This tri-lateral alliance aimed to address critical water resource challenges in river basins affected by climate change, sedimentation, and flood risks. The collaboration facilitated knowledge exchange and capacity building, enabling researchers and stakeholders from each country to develop solutions transferable to policymakers and stakeholders.

The collaborative framework fostered diverse partnerships at multiple levels, ranging from local communities to central governments. The network of stakeholders, including scientists, government officials, private sector participants, and local communities, contributed significantly to the rapid dissemination of project findings. This integrated approach ensured that project results, such as the optimized rainfall-runoff-inundation model for flood forecasting and sedimentation mitigation strategies for reservoirs, were not only scientifically robust but also aligned with the needs of decision-makers and local users.

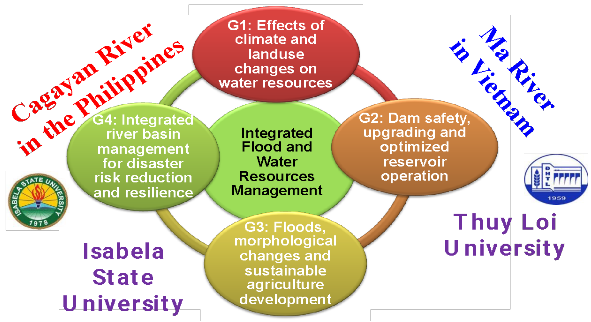

Figure 3: The Tri-lateral collaboration for integrated flood and water resources management

Hydrological Model Calibration and Validation

Simulation, Calibration, and Validation Results of SWAT Model

Based on the results of the study of Singson et.al. (2023), the 17 most influential parameters that were calibrated in the model using manual and SWAT-CUP Calibration parameters directly influence the inflow along the Magat Watershed into the reservoir. These parameters were related to groundwater (ALPHA_BF, GW_DELAY, GWQMN, GW_REVAP, RCHRG_DP), soil properties (SOL_AWC, SOL_K, SOL_BD), HRU factors (HRU_SLP, LAT_TIME, ESCO, EPCO), routing (CH_K2, ALPHA_BNK), watershed management (CN2) and basin management (SURLAG). The calibration and validation resulted in a satisfactorily acceptable model. Calibration showed that the model had an NSE of 0.73, R2 of 0.74, RSR of 0.52, and PBIAS of 8.38 which were all considered statistically acceptable when compared to the indices that were set. From the figure 4, the graph shows that the model generally underestimated the peak flows. This is one of the known limitations of the SWAT model. Although studies pertaining to the modelling of the inflow of a reservoir are very limited in the country, studies regarding streamflow, which is mostly associated with and similar to inflow, are conducted. For instance, Alejo and Ella (2019) satisfactorily calibrated and validated a SWAT Model in Maasin River Watershed in Laguna, the Philippines using actual streamflow. The calibration process resulted in 0.82 R2, 82% NSE, 0.024 RSR and PBIAS of -3.7%. This suggests that SWAT can be locally applied in river basin conditions in the country.

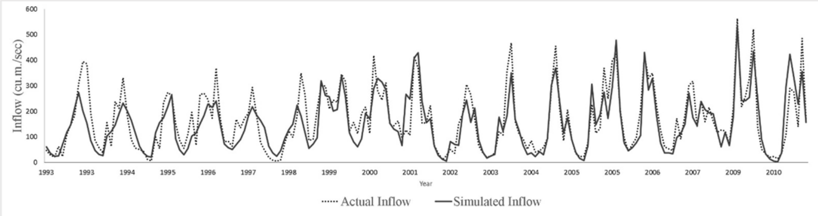

Figure 4: Simulated vs actual monthly inflow data during the calibration period.

Moreover, the validated SWAT Model yielded satisfactory results. The model had an NSE of 0.56, R2 of 0.62, RSR of 0.66, and a PBIAS of 17.3. This means that the model satisfactorily predicted the inflow of water to the Magat Reservoir based on the validation results. However, like the calibration results, the model underestimated most of the peak flows as seen in Figure 5. Validation results showed model accuracy values on NSE, R2, PBIAS, and RSR of 0.41, 0.57, 25.09%, and 0.71, respectively. Although the model was considered satisfactory, it can be observed that there was a drop in the performance of the validation results compared to the calibration results.

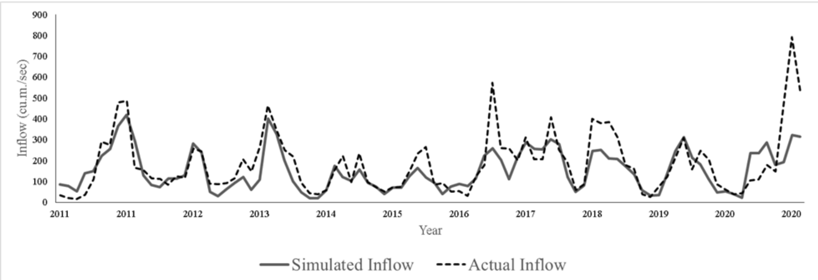

Figure 5: Simulated vs actual monthly inflow data during the validation period

Future Water Supply Projections under Climate Change Scenarios

The study found that if the climate change would worsen and reach the RCP 4.5 and RCP 8.5 scenario in the basin level, there will be a significant decrease in inflow during their dry and normal years, but a substantial increase will occur during the wet years. These decreases in reservoir inflow during dry seasons serve as a clear warning that the reservoir may soon become dry. Water supply is suspected to be scarce.

However, a rise in the inflow might necessitate modifying the reservoir's operating guidelines in order to accommodate the new, shifting reality. Surplus of water may lead to necessary release of water into the downstream area. It may be harmless at some point, however, during these wet seasons, heavy rainfall and typhoons highly occur. Hence, there may be risk involved in releasing water supply such as river bank flooding. In addition, the highest inflow of water to the reservoir is anticipated from the month of September followed by October to December since this is already the rainy season in the country. With these results, it is necessary to properly manage the water through storage.

Flood Forecasting with the Rainfall-Runoff-Inundation Model

The downstream of Cagayan River Basin (CRB) has been experiencing flash floods yearly during the rainy season. Flood forecasting is vital in preventing and mitigating flood damages. Flood inundation can be simulated to forewarn the affected areas on the effect of flood brought by the heavy rainfall events. In this study by Alejandro (2021), the inflow in Magat Dam and water level in Buntun Bridge located in Tuguegarao City was simulated using the successfully calibrated Rainfall-Runoff-Inundation (RRI) Model using Typhoon Ulysses. The model satisfactorily estimated the inflow in Magat with RSR, NSE, PBIAS, and R2 equal to 0.36, 0.87, 6.90 & 0.88, respectively. Also, the RSR, NSE, PBIAS, and R2 with 0.50, 0.75, -0.39, and 0.75, respectively, showed good agreement with the measured river water level data. The RRI calibrated parameters were also tested and validated on Typhoon Tisoy in December 2019 and Monsoon Rains in December 2020. Results gave a satisfactory statistical index for both Magat Inflow and Buntun water levels. The RRI model estimated flood heights ranged from >=0 meters at locations relatively far from the riverbanks and >=6 meters along the Cagayan riverbanks which is almost the same as the gathered actual data ranged from 0.3 to 7 meters. The calibrated parameter of RRI could be used to forecast the inflow of Magat Dam and flood inundation in CRB during extreme weather events for effective protective planning, decision-making, and flood early warnings.

Sedimentation and Storage Capacity in the Magat Reservoir

The initial results of the 2021 Bathymetric survey were finalized by NIA DRD and found out that from the 2016 baseline, the accumulated volume of sediments in the Live Storage is 40.12 MCM while the accumulated volume of sediments in the Dead Storage is 25.23MCM. Hence, the Total Volume of Sediments Deposited in the Main Reservoir from 2016 to 2021 is 65.34 MCM (Table 1 and Figure 4).

Table 1: Total Volume Deposited in the Main Reservoir.

Volume of Sediment	Accumulated Sediment (MCM)		
	1982-2016	1982-2021	2016-2021
Live Storage ('El. 147 m to El. 193 m)	91.10	131.21	40.12
Dead Storage ('El. 147 m and below)	72.19	97.41	25.23
Sediments Deposited ('Up to El. 193 m)	163.28	228.63	65.34

Moreover, the remaining storage capacity for the Main Reservoir for its dead storage is 18.65MCM while for the live storage is 40.12 MCM as shown in Table 2. All in all, the remaining storage capacity of the reservoir is 58.77 MCM (Figure 7). The 2021 data was processed from the bathymetry data gathered from ranges 1-8. Ranges 1-8 are specifically chosen because it is considered as the main reservoir, covering the biggest area within the whole reservoir. There are 23 more remaining ranges that remain to be surveyed for bathymetry, but these sections are considered more like tributaries compared to the main reservoir.

Table 2: Remaining Storage Capacity of the Main Reservoir.

Storage Capacity	1982-2016 (MCM)	1982-2021 (MCM)	2016-2021 (MCM)
Remaining Live Storage	587.28	547.17	40.12
Remaining Dead Storage	49.17	30.52	25.23
Total Remaining Storage	636.45	577.68	58.77

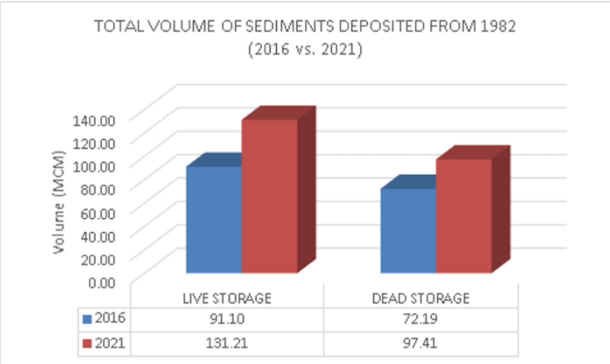

Figure 6: The total volume of sediments deposited based on the Bathymetric survey of 2016 and 2021.

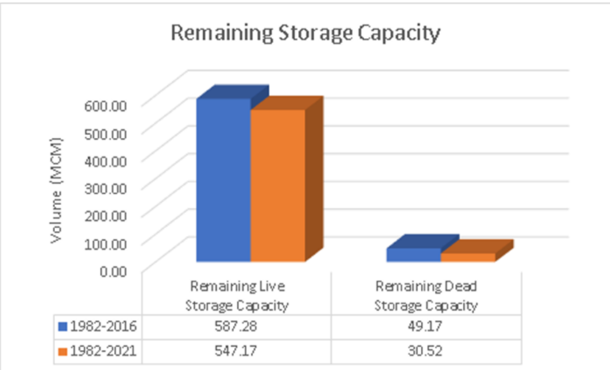

Figure 7: The remaining Storage Capacity of the Main Reservoir is based on the Bathymetric survey of 2016 and 2021.

The reduced storage capacity underscores the need for sediment management interventions. The construction of Sabo dams in the Magat watershed is one such measure, aimed at trapping sediment before it enters the reservoir. As of 2021, 12 sediment catchment structures have been completed, with additional structures under construction (Figure 8). These efforts, combined with plans for reservoir dredging, are expected to help mitigate sedimentation and preserve water storage capacity.

Figure 8: Sediment catchment structures in Diadi, Nueva Vizcaya (top photos) and Cordon, Isabela (bottom photos). Photo Source: NIA-MARIIS

Capacity Building and Collaboration for Integrated Water Management

Throughout the project, capacity-building activities were conducted to enhance local and regional expertise in flood and water resources management. Workshops, training courses, and seminars, organized in collaboration with Kyoto University, Isabela State University, and Thuyloi University, provided stakeholders, researchers, and policymakers with valuable knowledge and tools for managing water resources under changing climatic conditions.

Additionally, the establishment of the International Association on Climate Change Adaptation and Disaster Risk Reduction Management (IO-CCA/DRRM), hosted by Isabela State University, serves as a platform for ongoing collaboration in climate adaptation and disaster risk reduction. This association will facilitate knowledge sharing and policy development across Asia-Pacific countries, ensuring that the results of this study contribute to broader efforts in climate resilience.

CONCLUSION

The results demonstrate the effectiveness of integrating hydrological modeling, sediment management, and flood forecasting tools to improve water resources management in the Magat and Cagayan River Basins. The SWAT and RRI models provided critical insights into future water supply and flood risks under climate change scenarios, while the bathymetric survey highlighted the need for urgent sediment management interventions. The capacity-building initiatives and establishment of an international association ensure that these efforts are sustained and expanded to other regions, promoting resilience to climate impacts across the Asia-Pacific.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

All authors made significant contributions towards the completion of the collaborative project and this paper.

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