REMOTE SENSING AND GIS-BASED DEVELOPMENT AND CALIBRATION OF A HYDROLOGICAL MODEL FOR THE SAMBUNOTAN WATERSHED, PHILIPPINES

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KEY WORDS: Deficit Constant Loss Method, Hydrologic Model, Watershed Management

ABSTRACT: The Sambunotan Watershed, spanning 28 sq. km. is located at Tubajon and Loreto municipalities, Philippines. The main objective is to calibrate a hydrologic model and generate hydrograph results for water balance analysis. The Hydrologic Modeling System (HEC-HMS) is employed, utilizing raster data derived from a digital elevation model (DEM). The Loss Method, integrated within the subbasin, is used for actual infiltration calculations, accounting for ongoing variations in moisture content using a single soil layer. Continuous simulation is made possible through the Deficit Constant Loss Method. After the initial simulation, a comparative analysis between the observed and simulated flow is performed. Model calibration is accomplished by adjusting the parameters until the simulated graph aligns with the observed data, evaluated at the gaged point in the model. Field data collected last November 2022, including cross-section surveys and sensor deployments for long-term hydrologic data (water level and velocity), is utilized for model calibration and validation. The accuracy assessment of the calibrated model resulted in a "very good" rating, with an average error of 0.3 and RMS Error of 0.8. This research provides essential baseline hydrological data for the Sambunotan Watershed Management Plan (SWMP), supporting the government's initiative for a more conservative and collaborative approach to managing the watershed. The findings contribute to a comprehensive development of the SWMP and serve as a relevant reference for future conservation efforts in the region.

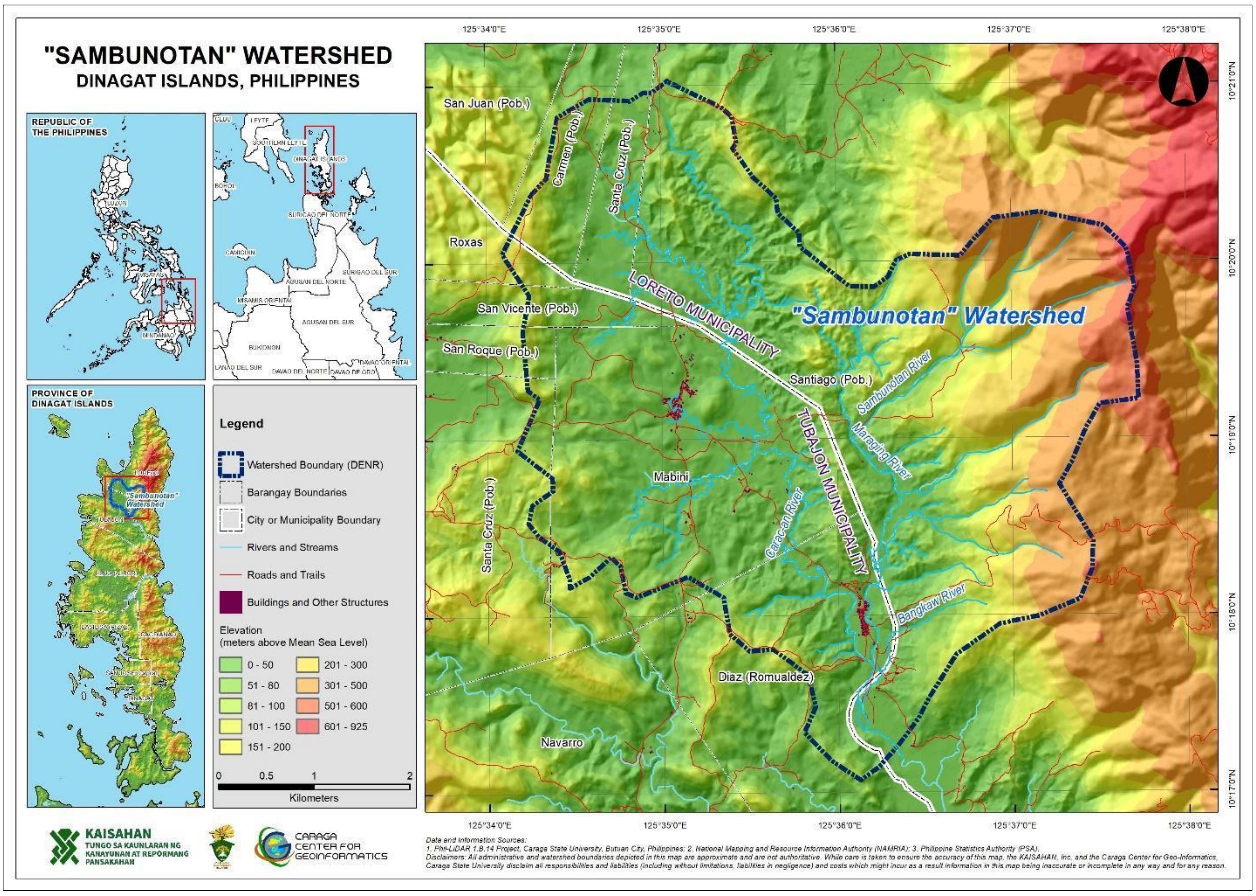
1. INTRODUCTION

1.1 Background of the Study

To craft a comprehensive development of the SWMP, establishing baseline hydrological data for the watershed is crucial. Thus, field data were gathered as the basis for the calibration of the hydrologic model and for generating hydrograph results for water balance analysis. A water balance analysis is used to examine the present status and trends in the availability of water resources in a region over a certain period and strengthen water management decision-making.

1.2 Study Area

The Sambunotan Watershed covers an area of 28 sq. km. within the Tubajon and Loreto municipalities as shown in Figure 1. In Loreto, the watershed is within Barangays Carmen, Sta. Cruz, and Santiago. In Tubajon, it traverses Barangays Malinao, Mabini, Diaz, San Vicente, San Roque, Roxas, and Navarro. The watershed also covers parts of Mt. Redondo-Mt. Cambinliw Mountain Ranges in the north and Paragua Mountain Ranges in the south. Sambunotan watershed is the source of potable water for six barangays within Tubajon. It is also the source of irrigation water for agricultural production. Sambunotan is home to both threatened and endemic flora and fauna. It is the pilot site for the National Convergence Initiative for Sustainable Rural Development in CARAGA Region.



Data and Information Sources:
1. Phil-LiDAR 1.B.14 Project, Caraga State University, Butuan City, Philippines; 2. National Mapping and Resource Information Authority (NAMRIA); 3. Philippine Statistics Authority (PSA).
Disclaimers: All administrative and watershed boundaries depicted in this map are approximate and are not authoritative. While care is taken to ensure the accuracy of this map, the KAISAHAN, Inc. and the Caraga Center for Geo-Informatics, Caraga State University disclaim all responsibilities and liabilities (including without limitations, liabilities in negligence) and costs which might incur as a result information in this map being inaccurate or incomplete in any way and for any reason.

Figure 1. Sambunotan Watershed Boundary based on DENR GIS shapefile.

1.3 Objectives

The objectives of this study are multifaceted and revolve around the calibration of a hydrologic model, particularly employing the Hydrologic Modeling System (HEC-HMS), to generate hydrograph results for comprehensive water balance analysis.

2. METHODOLOGY

The hydrologic model used in this study was pre-processed using ArcGIS and uses input data such as satellite-derived land cover maps and manually delineated river networks. To achieve accurate model calibration, the study relies on data collected from field measurements and observations. Field data, such as rainfall measurements, streamflow data, and land cover, play a pivotal role in ensuring that the hydrologic model aligns with the actual conditions on the ground. This integration of field data enhances the model's reliability and its capacity to simulate real-world hydrological processes. Within the HEC-HMS framework, the study utilizes the Loss Method integrated within subbasins to calculate actual infiltration, which accounts for ongoing variations in soil moisture content. The study employs the Deficit Constant Loss Method to enable continuous simulation. Continuous simulation allows for the modeling of hydrological processes over extended periods, which is essential for assessing long-term water balance trends and understanding how various factors impact water resources over time.

2.1 Development of the Hydrologic Model in ArcMap 10.8

2.1.1 Drainage and Topographic Characterization: The LiDAR-derived drainage network data, which consists of rivers and streams within the watershed, was used to create the drainage map and to calculate the drainage density. The latter was determined by getting the sum of the lengths of the rivers and streams and dividing the value by the total area of the watershed.

The elevation and slope characteristics were determined using the IfSAR DTM. For the elevation, the GIS-delineated boundary was used to clip the IfSAR DTM such that only the portions of the watershed are included. The "Zonal Statistics as Table" tool in ArcGIS-ArcMap 10.8 was used to calculate the minimum, maximum, and average elevation of the watershed, referenced from the MSL, with the GIS-delineated boundary serving as the "zone" for the statistical calculations.

A "percent slope" raster was generated using the Spatial Analyst tool of ArcGIS-ArcMap 10.8 with the IfSAR DTM as the primary input data. The "Zonal Statistics as Table" tool was also used to calculate the minimum, maximum, and average slopes of the watershed. For slope map generation, the following slope classes were considered:

0 to 3%: level to nearly level
3 to 8%: gently sloping to undulating
8 to 18%: undulating to rolling
18 to 30%: rolling to moderately steep
30 to 50%: steep
> 50%: very steep

2.1.2 Land Cover Characterization: We utilized the multitemporal Esri Land Cover data in our watershed land cover characterization. The original land cover data were in raster format and converted to vector using ArcGIS-ArcMap 10.8 raster to vector conversion tool. The vector files were then clipped using the GIS-delineated watershed boundary. For the land cover mapping, the classes listed and described in Table 1 were utilized.

Table 1. Esri Land Cover classes used in the watershed land cover characterization.

Class	Modified Class Name/Class Names used in the Analysis and Maps	Description*
Built Area	Built Area	Human-made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings, and residential housing; examples: houses, dense villages/towns/cities, paved roads, and asphalt.
Crops	Cropland	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, and fallow plots of structured land.
Rangeland	Rangeland	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs, and tufts of grass, savannas with very sparse grasses, trees or other plants.
Trees	Trees	Any significant clustering of tall (~15 feet or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense, tall vegetation within savannas, plantations, swamp, or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).
Water	Water	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built-up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.

*Source: ESRI, 2022

2.1.3 Basin Processing using HEC-GeoHMS: One of the input data to prepare a basin model is the river networks which were manually ectracted from LiDAR data. Together with the Digital Elevation Model, these datasets served as inputs for HEC-GeoHMS, a geospatial hydrology toolkit designed to assist engineers and hydrologists with limited GIS experience. HEC-GeoHMS enables users to visualize spatial data, document watershed characteristics, conduct spatial analyses, delineate subbasins and streams, generate inputs for hydrologic models, and aid in report preparation. The initial step in developing an HEC-GeoHMS project involves terrain preprocessing, where a terrain model is employed to generate eight supplementary datasets describing the watershed's drainage pattern, facilitating stream and subbasin delineation. After the compilation and preparation of terrain data, HEC-GeoHMS proceeds to process watershed data, ultimately generating various input files for an initial HEC-HMS model once data assembly is complete.

2.2 Hydrologic Model Calibration using HEC-HMS

2.2.1 Hydrologic Model Preparation and Model Setup: The hydrological analysis is carried out using the Hydrologic Modeling System (HEC-HMS) of the Hydrologic Engineering Center (HEC), which is based on raster data from a digital elevation model (DEM). This water system model is used to study the hydrological characteristics, simulate the surface hydrological process, and predict the future surface hydrological situation. The hydrological analysis model can assist with flood scope analysis, source location for runoff pollution, and runoff geomorphological change prediction. It is widely employed in many areas and businesses, including road design, agriculture, forestry, and regional planning. In the Monalack watershed in west Michigan, Chu and Steinman (2009) employed the HEC-HMS model for both event and continuous hydrological modeling.

For more than 30 years, HEC-HMS has been used successfully and is accepted for a variety of governmental tasks, including determining the U.S.'s floodways. Agency for Federal Emergency Management. In the event-based and continuous simulation, the model was demonstrated to be reliable for geographically and temporally predicting watershed response (Buisan et. al., 2019).

HEC-HMS version 4.11 will be used to create the hydrologic model. The hydrologic process was simulated using the parameters shown in Table 2 below.

Table 2 Sub-models used in HEC-HMS Model Development

Parameter	Method
Loss	Deficit and Constant
Transform	Clark Unit Hydrograph
Baseflow	Recession Constant
Routing	Muskingum-Cunge

The actual infiltration calculations are carried out by a Loss Method embedded within the subbasin. The Deficit Constant Loss Method accounts for ongoing variations in moisture content by using a single soil layer. Continuous simulation is possible when using the Deficit Constant Loss Method. As the canopy draws moisture out of the soil, the soil layer will dry out in between periods of precipitation. The method's initial condition is the Initial Deficit. This is called the amount of water needed to fill the soil layer at the beginning of the simulation. The entire amount of water that the soil layer can hold is determined as an effective depth by the Maximum Deficit. The active soil layer's bulk thickness times the porosity gives an upper bound. However, the permanent wilting point and other factors that lower the water holding capacity must typically be considered when making such an estimate. The best way to gauge the depth of the active soil layer is through calibration. When the soil layer is saturated, the Constant Rate specifies the infiltration and percolation rates. As a rough estimate, saturated hydraulic conductivity is useful. It is possible to specify the percentage of the subbasin that is directly connected to an impervious area. The impermeable region does not undergo loss calculations; all precipitation in that part of the subbasin is considered excess precipitation and is, therefore, subject to surface storage and direct runoff.

While a subbasin element conceptually depicts infiltration, surface runoff, and subsurface processes interacting with one another, a Transform Method contained within the subbasin performs the surface runoff computations. A synthetic unit hydrograph technique is the Clark Unit Hydrograph. In other words, the user is not obliged to create a unit hydrograph by analyzing previously observed hydrographs. Instead of using a burst of precipitation, the translation hydrograph is constructed by employing a time-area curve. To consider the impacts of storage attenuation throughout the subbasin, the resulting translation hydrograph is directed through a linear reservoir. There are two sub-parameters under the Clark Standard Method Component Editor, time of concentration (TC) and storage coefficient (SC). The maximum travel time in the subbasin is determined by the Time of Concentration. The development of the translating hydrograph utilizes it.

The linear reservoir that considers storage effects uses the storage coefficient. The Storage Coefficient is calculated by multiplying the time of concentration by the reciprocal of a dimensionless ratio. The dimensionless ratio is often consistent over a region, according to much research.

The model developed in this study will use the Recession Baseflow Method, intended to simulate the normal behavior seen in watersheds when channel flow exponentially decreases after an event. The main purpose of this technique is event simulation. It may, however, be used for continuous simulation because it can automatically reset after each storm event. Within the subbasin, mass is not conserved. There are three sub-parameters for the method: First is the Initial Discharge; since we acquired actual data in the field, it will be a good reference for determining the initial flow in the channel. Second, the Recession Constant is defined as the ratio of the baseflow at the moment to the baseflow from the previous day. The rate at which baseflow decreases in between storm episodes is indicated by the Recession Constant. Third and last is the Ratio to Peak, in which the user should specify the flow ratio to the peak. When the current flow divided by the peak flow reaches the desired level, the baseflow is reset.

The routing method used in this study is the Muskingum-Cunge. The conservation of mass and the diffusion representation of momentum conservation serve as the foundation for the Muskingum-Cunge Routing Method. Because the routing parameters are updated at each time step in accordance with the channel characteristics and the flow depth, it is occasionally referred to as a variable coefficient approach. It can be applied in reaches with a slight slope and symbolizes the attenuation of flood surges. The sub-parameters needed for this method are already extracted in ArcMap during the preprocessing of the basin delineation (Bartles et. al., 2022).

2.2.2 Hydrologic Model Calibration: After running the first simulation, the user should check the difference between the observed and simulated flow. Model calibration is done by adjusting the parameters until the simulated graph fits the observed. This is assessed through the gaged point in the model. In hydrologic modeling studies, proper model calibration is crucial to reducing simulation uncertainty (Moriasi et.al., 2007). The following evaluation statistics are adapted for this study:

Table 3 HEC HMS performance rating (Moriasi et al. 2007, as cited in Santillan, 2019)

Performance Rating	**Statistics**		
	NSE	**PBIAS**	**RSR**
Very Good	$0.75 < NSE \leq 1.00$	$PBIAS < \pm 10$	$0.00 < RSR \leq 0.50$
Good	$0.65 < NSE \leq 0.75$	$\pm 10 \leq PBIAS < \pm 15$	$0.50 < RSR \leq 0.60$
Satisfactory	$0.50 < NSE \leq 0.65$	$\pm 15 \leq PBIAS < \pm 25$	$0.60 < RSR \leq 0.70$
Unsatisfactory	$NSE \leq 0.50$	$PBIAS \geq \pm 25$	$RSR > 0.70$

The Nash-Sutcliffe efficiency (NSE) represents how well the 1:1 line fits the observed versus simulated data plot. Percent Bias (PBIAS) assesses the typical tendency of the simulated data to differ from their observed counterparts in size or shape (Gupta et al., 1999, as cited in Moriasi et al., 2007). RMSE-observations standard deviation ratio (RSR) is "calculated as the ratio of the RMSE and standard deviation of measured data".

3. RESULTS AND DISCUSSIONS

3.1 Drainage Characteristics

Figure 2 shows the drainage map of the Sambunotan Watershed. The rivers and streams depicted in this map were delineated from LiDAR data. The combined lengths of the rivers and streams are 67,132.12 m. The drainage density is estimated to be 2.38 km/km2.

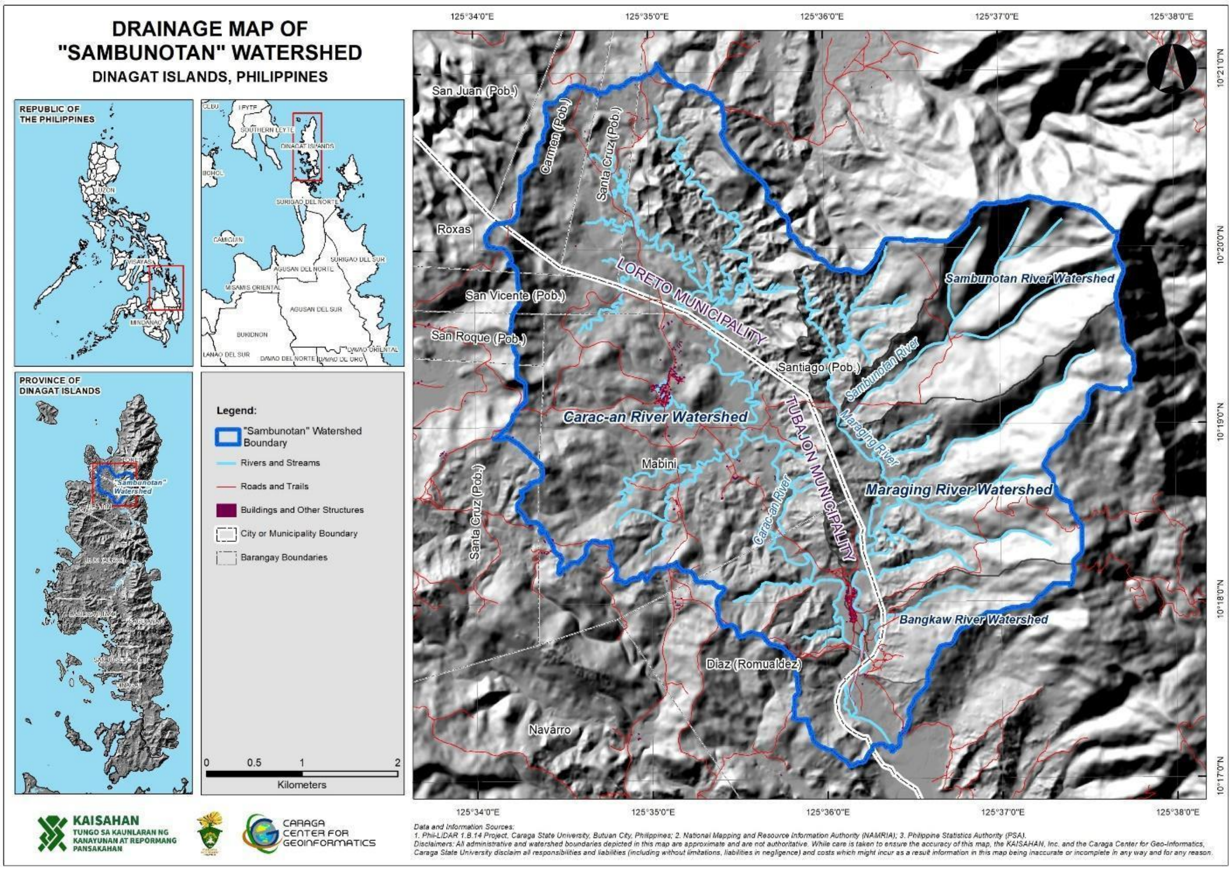


Figure 2. Drainage map of the Sambunotan Watershed.

3.2 Land Cover Characteristics

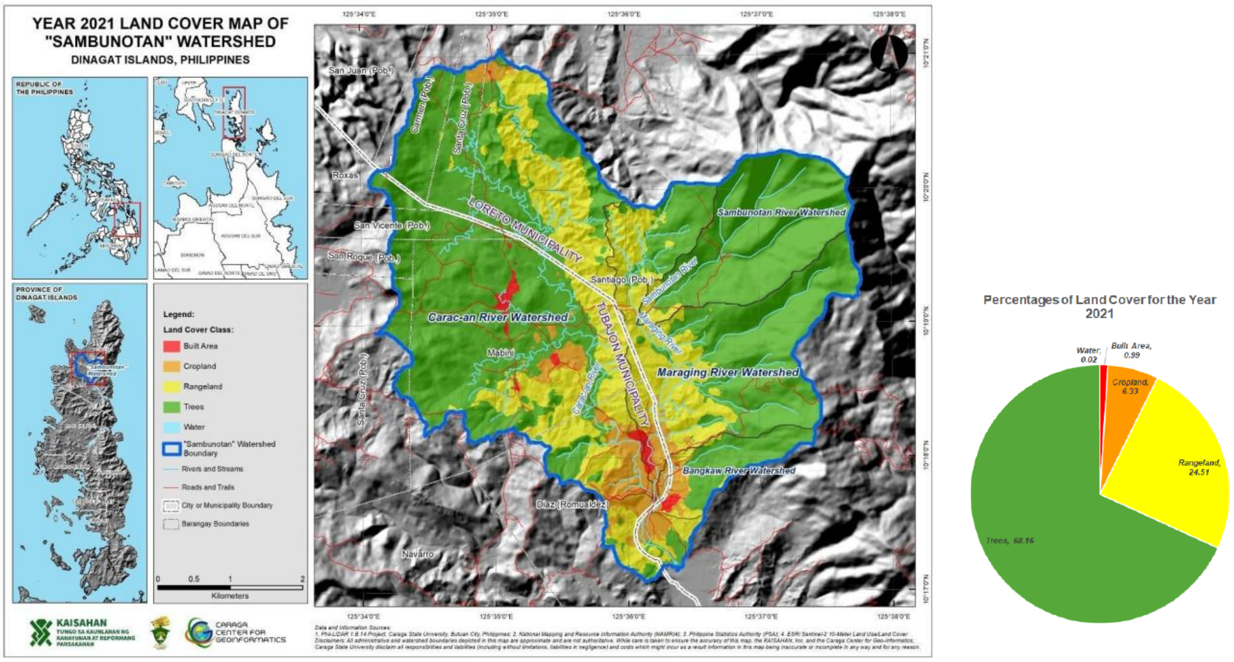


Figure 3. Year 2021 land cover map and statistics of the Sambunotan Watershed.
Landcover Data Source: Esri Sentinel-2 10-Meter
Land Use/Land Cover: Impact Observatory, Microsoft, and Esri under a Creative Commons by Attribution (CC BY 4.0) license.

3.3 Hydrologic Model Development and Calibration

The hydrologic model for the Sambunotan Watershed in Figure 4 contains 48 subbasins. The discharge point is located at 125°36'21.284"E and 10°17'10.854"N. The area upstream of the point is 25.23 km^2.

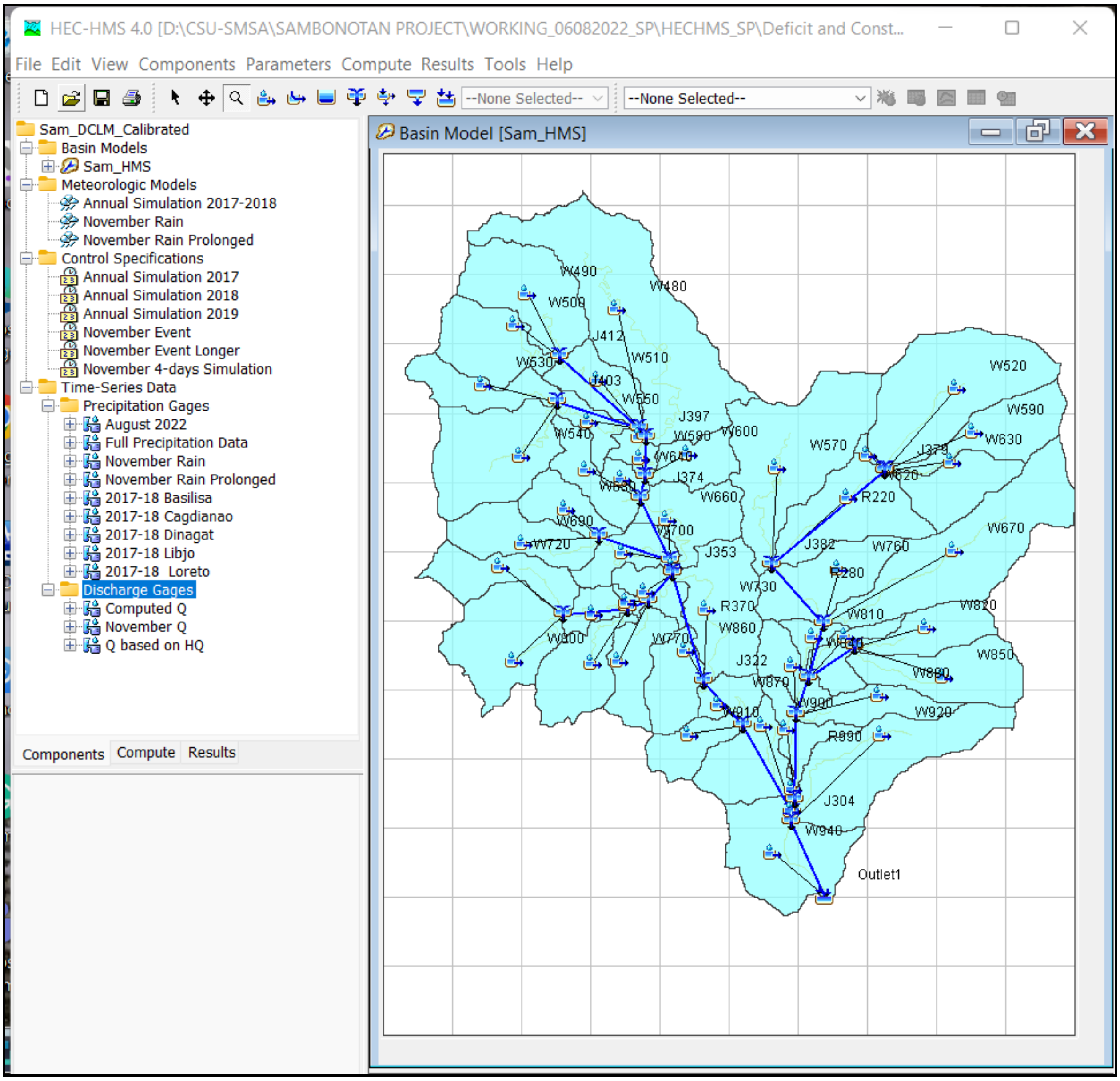


Figure 4. HEC-HMS Model Interface

The model calibration uses the actual field data from the field work conducted last November 2022. The calibration period is set from October 31,2022 1550H to November 2, 2022, 0840H. The observed data is plotted in the Figure 5 below. This is the processed flow data from the tandem depth gage and velocity meter deployed in the discharge point of the Sambunotan Watershed. The field measurement in this instance does not yield a value that can be entered into the program directly. However, based on past performance, the field measurement can offer a solid suggestion for a program parameter. Figure 6 shows the pre-calibration of the model in which the simulated value in blue did not peak and is not close with the observed value (black). Thus, calibration is needed to fit the two values.

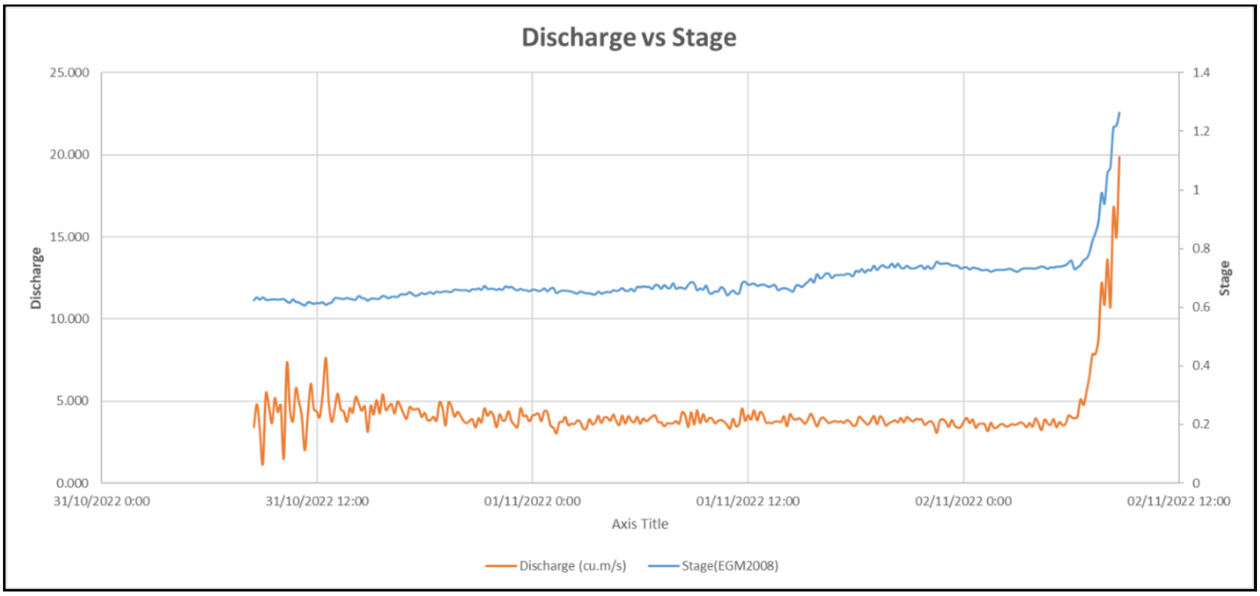


Figure 5. A graph showing the relationship between water discharge and stage.

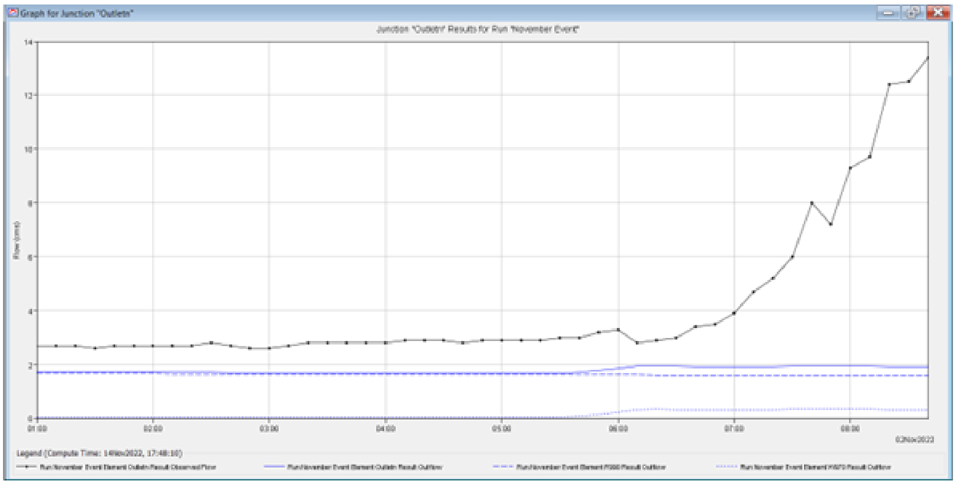
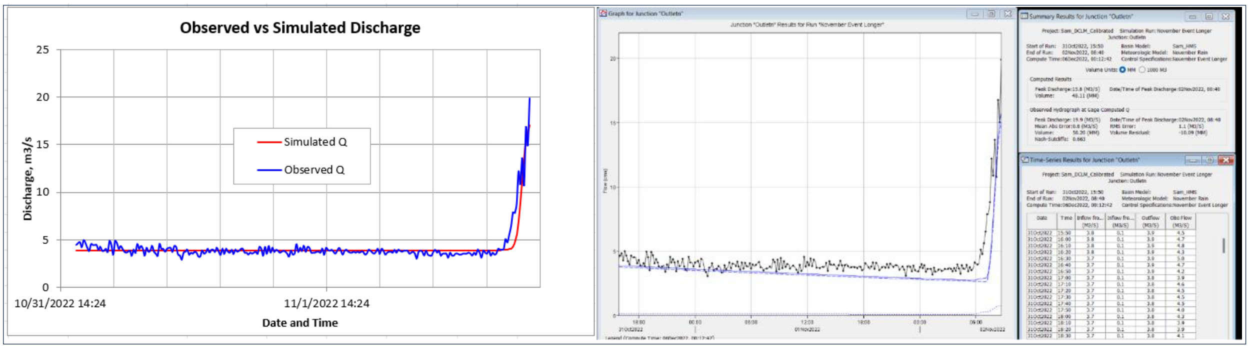


Figure 6. Pre-calibration result at Discharge Point

After several adjustments of the parameters as reflected in Table 4, the model yielded a good fit as can be seen in Figure 7 showing the observed (actual) and simulated (calibrated).



Project: Sam_DCLM_Calibrated Simulation Run: November Event Longer
Junction: Outlets

Start of Run: 31Oct2022, 15:50 Basin Model: Sam_HMS
End of Run: 02Nov2022, 08:40 Meteorologic Model: November Rain
Compute Time: 06Dec2022, 00:12:42 Control Specifications: November Event Longer

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge: 15.8 (M3/S) Date/Time of Peak Discharge: 02Nov2022, 08:40
Volume: 46.11 (MM)

Observed Hydrograph at Gage Computed Q

Peak Discharge: 19.9 (M3/S) Date/Time of Peak Discharge: 02Nov2022, 08:40
Mean Abs Error: 0.8 (M3/S) RMS Error: 1.1 (M3/S)
Volume: 56.20 (MM) Volume Residual: -10.09 (MM)
Nash-Sutcliffe: 0.863

Project: Sam_DCLM_Calibrated Simulation Run: November Event Longer
Junction: Outlets

Start of Run: 31Oct2022, 15:50 Basin Model: Sam_HMS
End of Run: 02Nov2022, 08:40 Meteorologic Model: November Rain
Compute Time: 06Dec2022, 00:12:42 Control Specifications: November Event Longer

Date	Time	Inflow fro... (M3/S)	Inflow fro... (M3/S)	Outflow (M3/S)	Obs Flow (M3/S)
31Oct2022	15:50	3.8	0.1	3.9	4.5
31Oct2022	16:00	3.8	0.1	3.9	4.7
31Oct2022	16:10	3.8	0.1	3.9	4.8
31Oct2022	16:20	3.8	0.1	3.9	4.3
31Oct2022	16:30	3.7	0.1	3.9	5.0
31Oct2022	16:40	3.7	0.1	3.9	4.7
31Oct2022	16:50	3.7	0.1	3.9	4.2
31Oct2022	17:00	3.7	0.1	3.8	3.9
31Oct2022	17:10	3.7	0.1	3.8	4.6
31Oct2022	17:20	3.7	0.1	3.8	4.5
31Oct2022	17:30	3.7	0.1	3.8	4.5
31Oct2022	17:40	3.7	0.1	3.8	4.5
31Oct2022	17:50	3.7	0.1	3.8	4.0
31Oct2022	18:00	3.7	0.1	3.8	4.3
31Oct2022	18:10	3.7	0.1	3.8	3.9
31Oct2022	18:20	3.7	0.1	3.8	3.9
31Oct2022	18:30	3.7	0.1	3.8	4.1

Figure 7. Calibration result at calibration/discharge point

Table 4. Model Parameters and Values

Parameters	Original Value	Calibrated Value
Impervious (%)	0.00084 – 0.61156	0.0012632 – 0.917334
Storage Coefficient (hr)	0.25718 – 2.4376	0.57866 - 5.4846
Time of Concentration (hr)	0.16074 - 1.5235	0.40184 – 3.80875
Initial Discharge (m3/s)	0.000149049- 0.10824	0.0012632-0.917334
Recession Constant	1	0.8
Ratio to Peak	0.5	0.5
Loss Parameters: Constant Rate (mm/hr) Initial Deficit (mm) Maximum Deficit (mm)	1.016 69.85 78.232	4 38 78.232

Once the model calibration result passes the error accuracy assessment, the model can be used in simulating historical rainfall records to assess the hydrologic condition of the watershed. Table 5 below shows an overall rating of ”Very Good”.

Table 5. Performance evaluation results before and after calibration at calibration point.

Statistics/Rating	Computed Error
NSE	0.85
RSR	0.38
PBIAS	1.62
Overall Rating	Very Good

4. CONCLUSIONS

This study has provided the baseline hydrological data for the Sambunotan Watershed, utilizing GIS and remote sensing in developing a hydrologic model. The utilization of the Deficit Constant Loss Method, in conjunction with the Canopy Method for moisture extraction and the Surface Method for surface water storage, emerges as a pivotal component in this study. This method's ability to account for continuous fluctuations in moisture content within a single soil layer facilitates uninterrupted simulation. Particularly noteworthy is the manner in which it addresses the drying of the soil layer between precipitation events as the canopy extracts soil water. The calibrated model's accuracy, with an average error of 0.3 and an RMS Error of 0.8 makes it a valuable resource for watershed management and future conservation efforts in the region.

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