GIS-AIDED PERFORMANCE SIMULATION OF GIGAQUIT DAM: A COMPARATIVE ANALYSIS OF HYPOTHETICAL FLOODING

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ABSTRACT: This study aimed to simulate hypothetical flooding in Gigaquit, Surigao del Norte, to assess how the dam affects the intensity of flooding events through series of simulations under six extreme rainfall scenarios. In this study, the 2D HEC-RAS model integrated with geographic information system (GIS) application has been employed. The flood simulation was conducted using the unsteady flow module of the HEC-RAS model. On the other hand, GIS has been fundamentally used to produce a digital elevation model (DEM) for visualization and analysis of possible flood propagation and flood effects. After the simulation was made, post-processing facilitated the automated flood plain delineation based on the simulation output. The dam's performance showed promising results in lessening the flooding effect in the downstream reach, especially on rainfall events of 50%, 20%, 10%, and 4% annual probability. However, rainfall events with 2% and 1% probabilities did not seem to have contributed a significant difference. In the present day, this kind of advanced modeling technology is becoming a potent tool for the decision-making process.

1. INTRODUCTION

Floods can be considered the most frequent natural disaster with an occurrence higher than any other natural hazard and affect more people than all other natural hazards combined (Kobe, 2009). River floods, for instance, are recognized as one of the major causes of economic damages and loss of human lives worldwide (The Human Cost of Weather-Related Disaster 1995-2005 Report). Furthermore, the adverse impact of floods in the next decades could dramatically increase due to the ongoing socio-economic and ever alarming climatic changes. Climate change is expected to amplify both the magnitude and frequency of extreme precipitation events, leading to more intense and frequent river flooding.

Over these past few years, excessive rainfall in the Caraga region has been notable for causing flooding in many areas. Earlier this year, tropical storm Basyang brought havoc in Surigao province. In the municipality of Gigaquit, the LGU has implemented strict protocols to help mitigate the negative impacts of flooding whenever alert levels and warning forecasts are raised. However, many citizens are repulsive when such protocols are carried out because they assured themselves that the Gigaquit dam could withhold the stress of extreme rainfall events. It is a fact that dams do not eliminate the risk since flooding may escalate at an incredible speed, especially if excessive rainfall happens for a relatively long period.

The researcher believes that no price can be put on the lives that have been lost and could be lost in the future by providing a false sense of security and encouraging settlements or economic activity in hazard-prone areas (S. N. Jonkman and I. Kelman, 2005). For such reason, the researcher finds it interesting to evaluate the efficiency of the dam in suppressing floods. As introduced in this study, the use of advance and efficient modeling software like HEC-RAS and GIS to simulate probable flooding events can play a significant role in safeguarding lives and valuable resources against such disasters. Hence, the performance analysis of the Gigaquit dam becomes somewhat the most important information for disaster preparedness. The researcher hopes to accomplish this throughout this attempt.

The main objective of this study is to analyze the performance of the Gigaquit dam in flood mitigation through a comparative simulation of hypothetical flooding. Specifically, this is also intended to (i.) develop models capable of simulating flood scenarios due to the occurrence of extreme rainfall events, (ii) compare the flooding effect due to a considerable amount of rainfall with and without the presence of Gigaquit dam; and (iii) determine the degree of flood depth in the municipality by generating flood hazard maps considering the presence and absence of the dam.

Presented also in this paper is the methodology employed by the researcher, which utilizes the 2D HEC-RAS model integrated with geographic information system (GIS) application. While flood simulation was conducted using the unsteady flow module of the HEC-RAS model, generation of digital elevation model (DEM) for visualization and analysis of possible flood propagation and flood effects were performed in GIS. The simulation of extreme rainfall events included 2, 5, 10, 25, 50, and 100-year return periods using two DTMs – with and without the presence of the Gigaquit dam.

This study helps raise community awareness of the likelihood of flooding among the public, local authorities, and other organizations, especially the LGU of Gigaquit. It has them notified whether the flood control mechanism of the dam is effective or not whenever extreme rainfall event occurs. The performance analysis leads to the formulation of a proper emergency action plan, generation of a more accurate flood risk assessment and flood management options, civil engineering developments for the reinforcement of dam, construction of dikes for rerouting of water flow, an accurate base for calculation of financial risk, improved evaluation on flood risk, and reliable flood warning forecast.

2. MATERIALS AND METHODS

2.1 Data Acquisition

Data acquisition involves gathering information on the variables of interest, including readily available datasets from appropriate offices, internet downloadable data, and other reliable sources (Table 1).

Besides the characteristics of the Gigaquit dam and its reservoir, the present study required high-quality satellite imagery and a digital elevation model (1-meter resolution DEM) to identify areas susceptible to untoward flooding. Google Earth also drew the GIS layers defining the stream centerline, stream bank lines, and dam structure.

Table 1. Data used in the study and their sources

DATA SOURCES	DATASETS ACQUIRED
1. Geo-SAFER Caraga	HEC-HMS 3.5 software HEC-RAS 5.0.1 software Magallanes DSS File Magallanes River/Stream Networks MagallanesSubasin Gigaquit calibrated LiDAR DTM and DSM
2. DENR, Butuan City	Gigaquit Land Cover
3. NIA Regional Office	Dam profile and structure

2.2 Generation of Two DTMs With and Without Dam

The original calibrated DTM with dam could already be used in setting up the domain of the model. The only thing left to do was to generate a new DTM without the dam. The dam was removed from the system through interpolation in ArcMap. The dam must be digitized first. The vertices after digitization should be converted to points and manually interpolated to smoothen the surface of the dam. Lastly, the interpolated portion had to be mosaicked back to the original DTM. After mosaicking, a new DTM without a dam was generated, ready to be used as input in the HEC-RAS.

2.3 Development of the Hydraulic Model

The hydraulic modeling software, HEC-RAS version 5.0 Beta (HEC-RAS-v5) with 2D capabilities, was used in this study to simulate unsteady flow analysis. It is an American model and one of the most popular hydraulic models developed by the U.S. Army Corps of Engineers (USACE). HEC-RAS is free software with a friendly graphical user interface that was successfully used for flood studies (M. Knebl, Z. Yang, K. Hutchison, and D. Maidment, 2005). First, the storage area was carefully delineated in ArcGIS through the HEC-geoRAS extension covering the entire flood plain of the study area based on the Magallanes river basin. It was later on imported into GIS format in HEC-RAS and was converted into a 2D flow area. The maximum flow rates that the hydrological model achieved, 1-m spatial resolution calibrated DTM with and without a dam, as well as the hydraulic elements (river networks and inflow points) were added as input data in the HEC-RAS model. Likewise, land cover classification was significantly meaningful in assigning manning's n values or roughness coefficient values for each land cover class.

The comparative nature of this study required the development of two hydraulic models, one with the presence of a dam and the other without a dam.

2.4 Flood Simulation

The flood simulation was conducted using the unsteady flow module of the HEC-RAS model. A closed polygon defined the computing domain, and the computation cells were created inside the polygon. The computation mesh cells may be arranged in a staggered or a non-staggered grid composed of polygons between 3 and 8 sides. The present study used a staggered grid composed of rectangular cells 40 m by 40 m. Such a grid was selected to stay close to the original DEM and to attain a higher accuracy level. HEC-RAS-v5 can be used either as a fully 2D model or as a hybrid 1D2D model when the main rivers are modeled as 1D, and the floodplains are modeled as 2D. However, only a full 2D model was used in this present study because the overflow locations were unknown.

The scenario considered in this study describes a situation when there is an extreme amount of rainfall causing a flood event. It corresponds to an extreme precipitation value of 2, 5, 10, 25, 50, and 100 years return period with a probability of 50%, 20%, 10%, 4%, 2%, and 1% respectively. The present study used three boundary conditions: flow hydrograph boundary condition, normal depth boundary condition, and precipitation. Besides the boundary mentioned above conditions, it is also important to define an energy slope that is used for distributing the discharge over the cells that integrate the boundary; the distribution was based on the specified slope and the pre-processed hydraulic properties of each cell.

The simulation was performed one at a time because HEC-RAS models were the longest to run. Regarding this vital matter, the computer must be optimized because the processor's speed is everything. The researcher started with the dam first, followed by without the dam for every return period. Upon successful simulation of the unsteady flow, the HEC-RAS results were exported back to the GIS platform for post-processing and further analysis.

2.5 Flood Hazard Mapping

One of the key stages in flood management is the identification of areas with potential flood risk. Flood risk is the product of flood hazards and flood vulnerability. Hence, the threat to personal safety and gross structural damage caused by floods depends mainly upon the speed and depth of floodwaters. The greater these factors become, the greater the danger to people and property.

3. RESULTS AND DISCUSSION

3.1 Generated DTMs With and Without Dam

Digital Elevation Model (DEM) such DTM is one of the most essential parameters for flood modeling. As such, the reliability and accuracy of the generated model are immensely dependent on the accuracy and resolution of the DEM data being used. DEM resolution and accuracies highly influence flood simulation results, such as inundation extent, flow velocity, flow depth, and flow patterns (Abdullah, A. Rahman, and Z. Vojinovic, 2017). Accurate and high-resolution DEM data can produce the most accurate and reliable flood inundation map compared to the inaccurate DEM course (P. Alho and H. Hyyppa J, 2009).

With DTM with a dam (Figure 1), a new DTM without a dam was generated through interpolation (Figure 2).

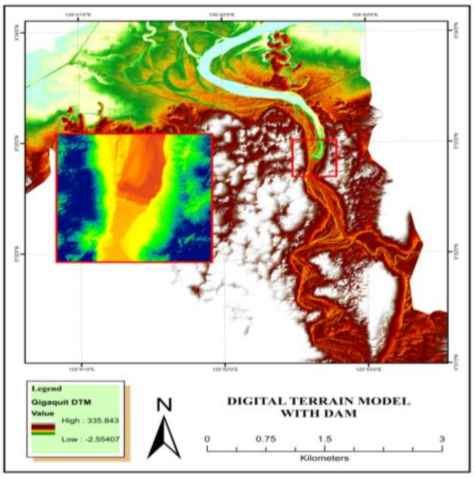


Figure 1. DTM with Dam

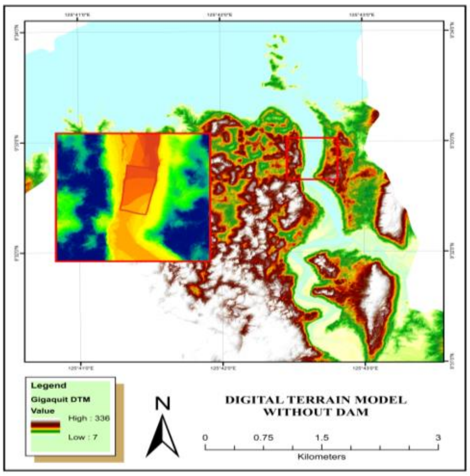


Figure 2. DTM without Dam

The simultaneous simulations were done based on the following extreme precipitation values in the Surigao del Norte station. Each station has a different river basin, thus different tolerance of precipitation as well. Compared to other stations, the Surigao station has higher values of precipitation in every recurrence interval. In real terms, this means that Surigao province experiences frequent extreme rainfall events than the other stations across the Caraga region (Table 2).

Table 1. Extreme values of precipitation for 24 hours

RETURN PERIOD (YRS)	SURIGAO STATION (MM)	PROBABILITY PER YEAR (%)
2	188.70	50
5	286.50	20
10	351.20	10
25	433.00	4
50	493.70	2
100	553.90	1

The resulting flood inundation maps are presented both derived from hypothetical rainfall events with and without a dam in 2, 5, 10, 25, 50, and 100-year return periods as shown in Figures 3, 4, 5, 6, 7, and 8, respectively.

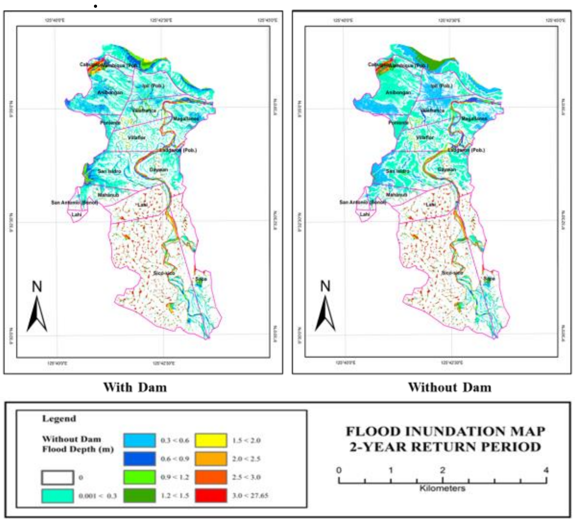


Figure 3. Flood inundation map for 2-year return period with and without dam

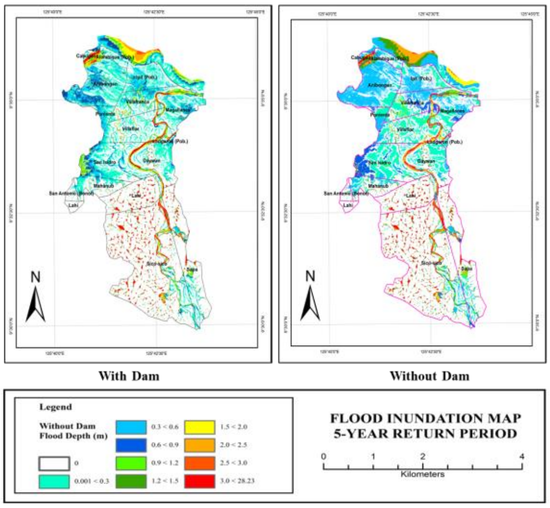


Figure 4. Flood inundation map for 5-year return period with and without dam

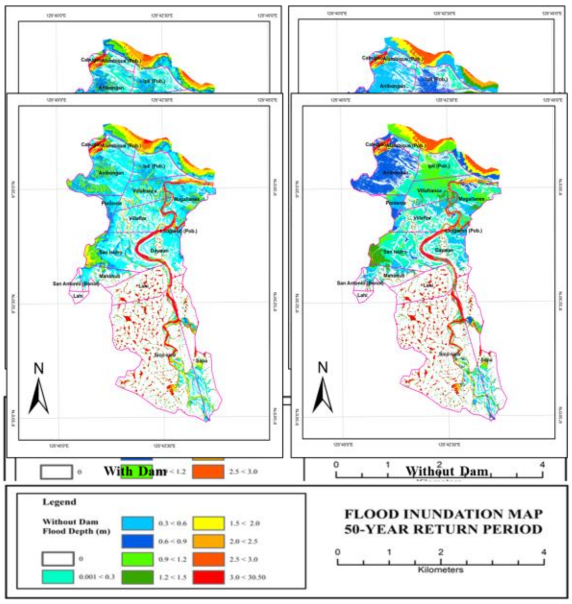
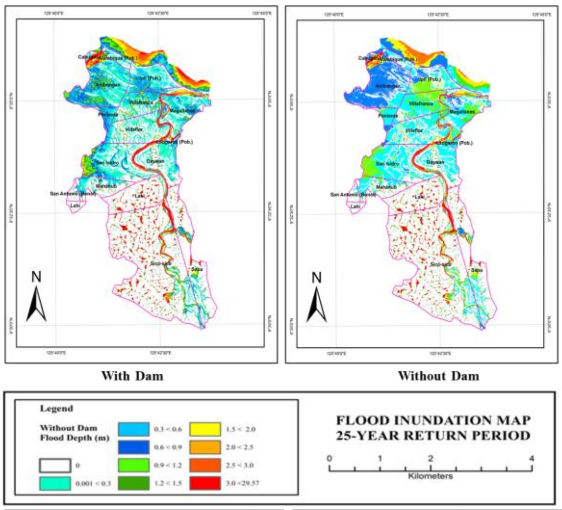


Figure 7. Flood inundation map for 50-year return period with and without dam



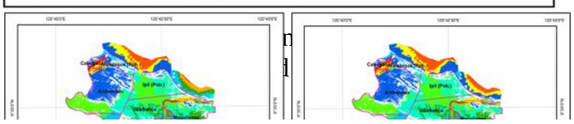
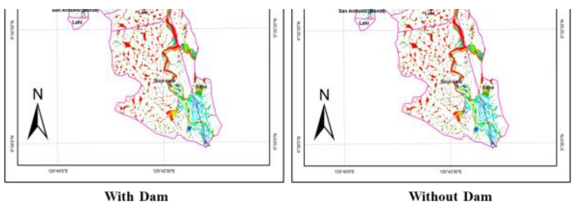


Figure 8. Flood inundation map for 100-year return period with and without dam



In the case of a 5-year return period rainfall scenario, the critical values of flood depths are at 0.001< 0.3m and 0.3< 0.6m, as shown in Figure 9, these values are dramatically changing with and without dam while leaving the other ranges almost identical.

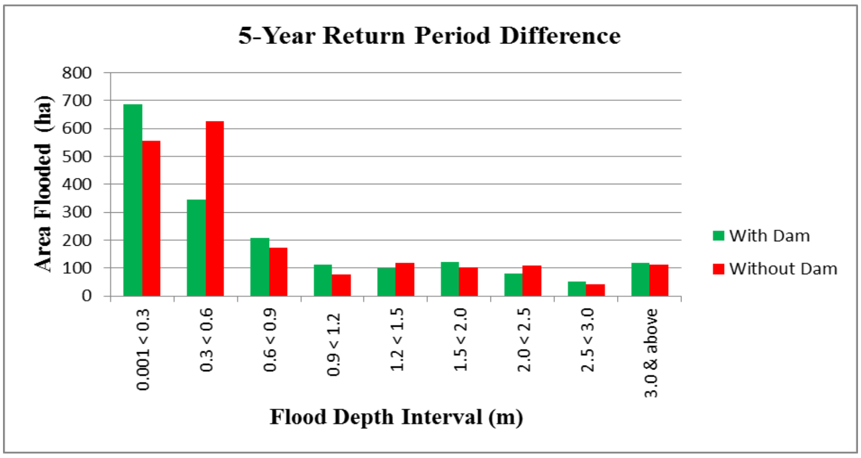


Figure 9. Comparison of the flooded area with and without dam

With the presence of a dam, areas flooded with 0.001< 0.3m are larger by 128.9 hectares (18.81%) compared to those without a dam. However, it cannot be overlooked that at flood depth of 0.3< 0.6m, without dam is also way larger by 283.81 hectares (82.61%). These apparent differences of values suggest that higher flood depths are likely to be experienced without a dam. Moreover, the same scenarios occurred in the other year's return periods.

The total flooded area with a dam is roughly 1,818.86 hectares, while 1,911.01 hectares without a dam – an increase of 5.07% (Table 3).

Table 2. Summary of the total flooded area in every hypothetical rainfall event

Return Period (yrs)	With Dam (ha)	Without Dam (ha)	Difference (ha)
2	1,549.26	1,752.33	203.07
5	1,818.86	1,911.01	92.15
10	1,930.06	2,010.47	80.41
25	2,100.93	2,139.43	38.50
50	2,262.06	2,282.17	20.11
100	2,293.81	2,294.62	0.81

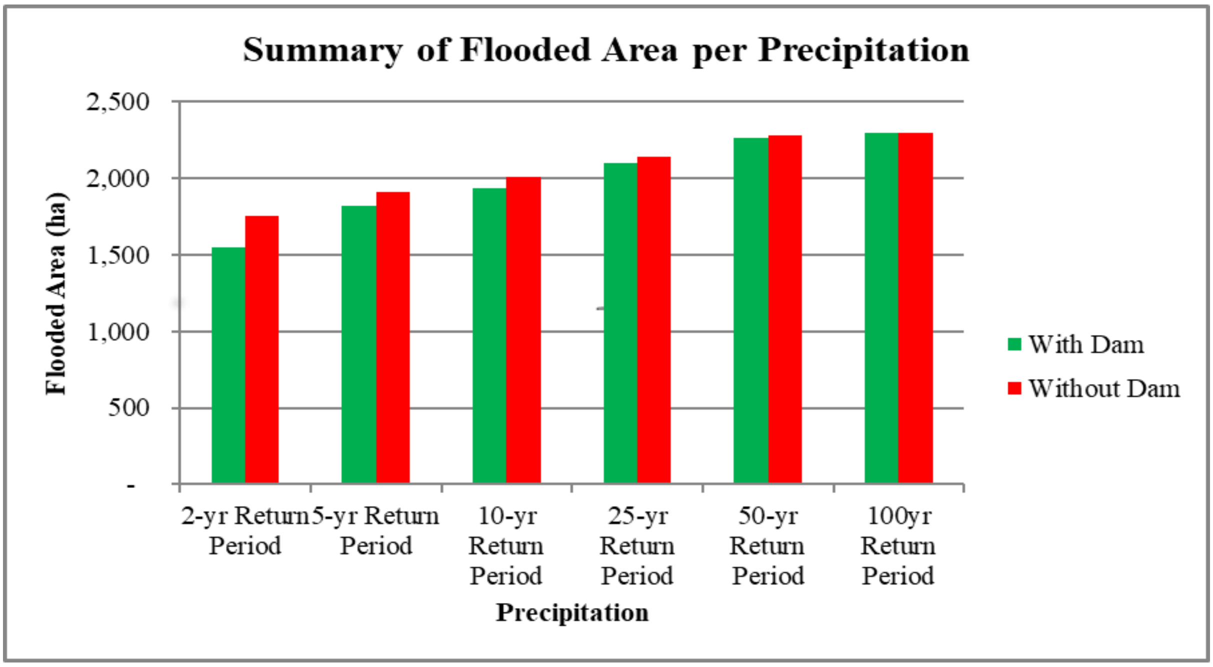


Figure 10. Summary of the flooded area in every hypothetical rainfall event

Table 3 and Figure 10 show that there are disparities in terms of flooded areas between with and without dams. For a two-year return period, precipitation, roughly 203.07 hectares difference of flooded area is observed. In the succeeding simulations for 5, 10, 25, and 50-year return periods, it is notable that the differences are drastically decreasing from 92.15 hectares, 80.41 hectares, 38.5 hectares, and 20.11 hectares, respectively.

However, the 100-year return period does not seem to display a discernible difference; only a 0.81-hectare difference of flooded area has been detected by the simulation so far. It can be inferred from Table 3 the inverse relationship between the return period of precipitation and the dam's efficiency. The difference between the flooded area with/without dam decreases as the return periods increases.

On the other hand, if the flood depths were evaluated for each return period, another set of quantitative values are obtained. Some barangays may have the same flooded area, but the flood depths may vary. Flood depth with a dam is different from without a dam. Floods experienced without a dam are noticeably higher than those floods with a dam.

4. CONCLUSION

Frequent tropical storms hitting the Philippines have triggered flooding in many areas, lost human lives, left many others missing, and brought relentless damage to properties. Due to this alarming trend, technological advancement has taken a massive leap towards improving flood prediction models through simulation.

The research shows that the models developed can be applied equally well to the specified extreme rainfall scenarios. Through the simulation, the performance of the dam has been quantified. From all six rainfall scenarios, it is clear that the dam's existence somehow lessens the flooding effect (e.g., flooded area and flood depth). Some floodwaters are impounded in the dam contributing to a pronounced difference of lesser flooding in the downstream reach.

It can be stated that the novelty of this model can viably derive more promising results especially in identifying flood-prone areas which is a pivotal aspect in locating flood shelters for evacuees. Hence, reconstruction or reinforcement of the dam should be encouraged as it helps regulate untoward flooding.

However, the researcher identified a range of areas for attention to make the result of the study more reliable and credible. Where possible, a flood map validation survey should be conducted to facilitate better results and accuracy assessment. Also, the use of outdated data diminishes the quality of the result, so the use of up-to-date datasets was recommended.

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