ASSESSING DOWNSTREAM FLOOD RISK UNDER CHANGING CLIMATE FOR BAKUN DAM IN SARAWAK

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ABSTRACT

Rajang River Basin (RRB) comprise about 40% of the Sarawak State area in Malaysia. Any extreme storm event in the Upper RRB may cause a flood, affecting the downstream communities and infrastructures of the Rajang River. There are two large dams in a cascade scheme at upper RRB, Murum Dam and Bakun Dam. With the concern of changing climate impact, the future peak precipitation and peak river discharge are analysed in this study to assess the potential flood impact along the Rajang River. This study focused on developing flood modelling for downstream of Bakun Dam down to Belaga Town. The peak rainfall analysis was carried out to generate peak discharge for the return period of 1 in 50 and 1 in 100 years of historical and projected future storm events. The corresponding floodplains map pre- and post-Bakun Dam operations were generated using GeoHECRAS software. The study results show that the projected peak rainfall and peak discharge under future changing climate are increased between 6–27% and 7–30%, respectively, and this warrants attention from the relevant authorities and parties to access the flood risk downstream Bakun Dam continuously. The generated maps of pre- and post-Bakun Dam operation show that Bakun Dam can mitigate the flood from impacting the downstream structures and communities. The outcome from this study can be useful information to educate the local people and public about the benefit of having a Dam, not only for the source of power generation but also for flood mitigation.
Keywords: Bakun Dam, climate change impact, flood mapping, GeoHECRAS, peak flood discharge, peak rainfall, rainfall frequency analysis, Rajang River Basin, reservoir flood routing, RORB.

1 INTRODUCTION

Floods are a natural disaster and occur almost yearly in Sarawak, including the Upper Rajang River Basin (RRB). RRB constituted about 40% of the Sarawak state area and is located at the central of Sarawak. Due to its topography, RRB's climate is a mixture of wet and dry throughout the year. During the wet season, the rainfall intensity. Therefore, any heavy storm event upstream of the Rajang River will possibly cause a flood to the downstream communities. The flood event is commonly caused damage to properties, loss of economies and even loss of lives.

There is always a high possibility that flood events will occur again in the future. A study by Mubasher et al. [1] suggests increased annual precipitation in RRB by the end of the 21st century. In addition, logging activities and forest clearance for development upstream of RRB have caused significant sedimentation issues [2], further increased water levels during extreme precipitation, and led to flood events downstream of Rajang River.

With more hydrology and topography data available and increased concern on future precipitation impact under changing climate, the Rajang River's flood risk needs to be continuously assessed downstream [3]. Flooding is often unavoidable and unexpected; however, it can be controlled through appropriate measures to minimise losses and damage [4]. Therefore, the study of floodplains is necessary to assist Sarawak Energy and local authorities in ensuring proper mitigation measures, emergency response planning, and potentially limiting the potential destruction downstream of Rajang River communities and infrastructures [5].

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A hydrology study was carried out using RunOff Routing on Burroughs (RORB) software. Thiessen Polygon method estimates the spatial distribution of six (6) rainfall stations within the Bakun catchment. The peak rainfall for 1 in 50 and 1 in 100 year return period were derived using the rainfall statistical analysis; Pearson Type III, Log-Normal and Gumbel distribution. Rainfall-runoff routing modelling was undertaken with the RORB tool to estimate peak flood discharge (PFD) for 1 in 50 and 1 in 100 year return period.

For future precipitation under changing climate, the projected rainfall data from [1] is used for this study. The peak for rainfall and discharge are analysed using RORB, and the result becomes the input for hydraulic modelling using GeoHECRAS software. GeoHECRAS is a useful tool in floodplain mapping studies because of its capabilities in performing flood routing, hydraulic modelling and surface profile analysis in a single platform.

Reservoir flood routing through Bakun spillway and power station was carried out based on the data and operation rules from [6]. Reservoir capacity, inflow hydrograph and spillway discharge capacity were the input to generate inflow–outflow hydrograph. In addition, the flood mapping pre and post Bakun Dam operations were generated to see the impact of Bakun Dam in flood mitigation.

This study aims to (1) Analyse peak rainfall and PFD at Murum-Bakun Catchment for 1 in 50 and 1 in 100 years return period based on (i) historical rainfall and (ii) future projected precipitation under changing climate and (2) generate a flood map pre and post Bakun Dam operation for 1 in 50 and 1 in 100 year return period of historical and future projected flood event using GeoHECRAS software. The study areas extent includes the upper Rajang River reach until Belaga Town. It will also be a platform for assessing the capability of GeoHECRAS for flood mapping exercises in Sarawak.

2 STUDY AREA AND DATA DESCRIPTION

2.1 Study area

Rajang River is the longest river in Sarawak, Malaysia and extends approximately 565 km in length. Major towns located downstream of the Rajang River are Belaga, Kapit, Song, Kanowit and Sibu. This study maps Rajang River's floodplain to Belaga Town, and selection was made due to Belaga Town's vulnerability to the flooding risk.

Belaga is one of the districts in the Kapit division. Its centred area is Belaga Town, with a population of 44,500 people. The Town has a maximum elevation of 73 m above sea level and a minimum of 51 metres above sea level. It is also located in a tropical area with high temperatures and high rainfall experienced throughout the year.

Due to its location in the tropical area, the rainfall in Belaga Town is generally evenly distributed throughout the year as they are more sheltered from the influence of the monsoon, with an average annual rainfall of about 2,286 mm.

Being equatorial, the temperature is generally uniform throughout the year, with an annual variation of less than 2°C. Daily temperature variations can be large; however, extreme hot or cold temperatures are rare. Seasonal and spatial temperature variations are relatively small.

Mean monthly relative humidity is 70%–90%, depending on location and time of year. Daily variations can be significant, with mean daily minimums as low as 42% during dry months and as high as 70% during wet months. In 2010, Belaga had 20.3 Mha of natural forest, extending over 87% of its land area.

A locality map of the study area and rainfall stations in Murum-Bakun catchment is presented in Fig. 1.

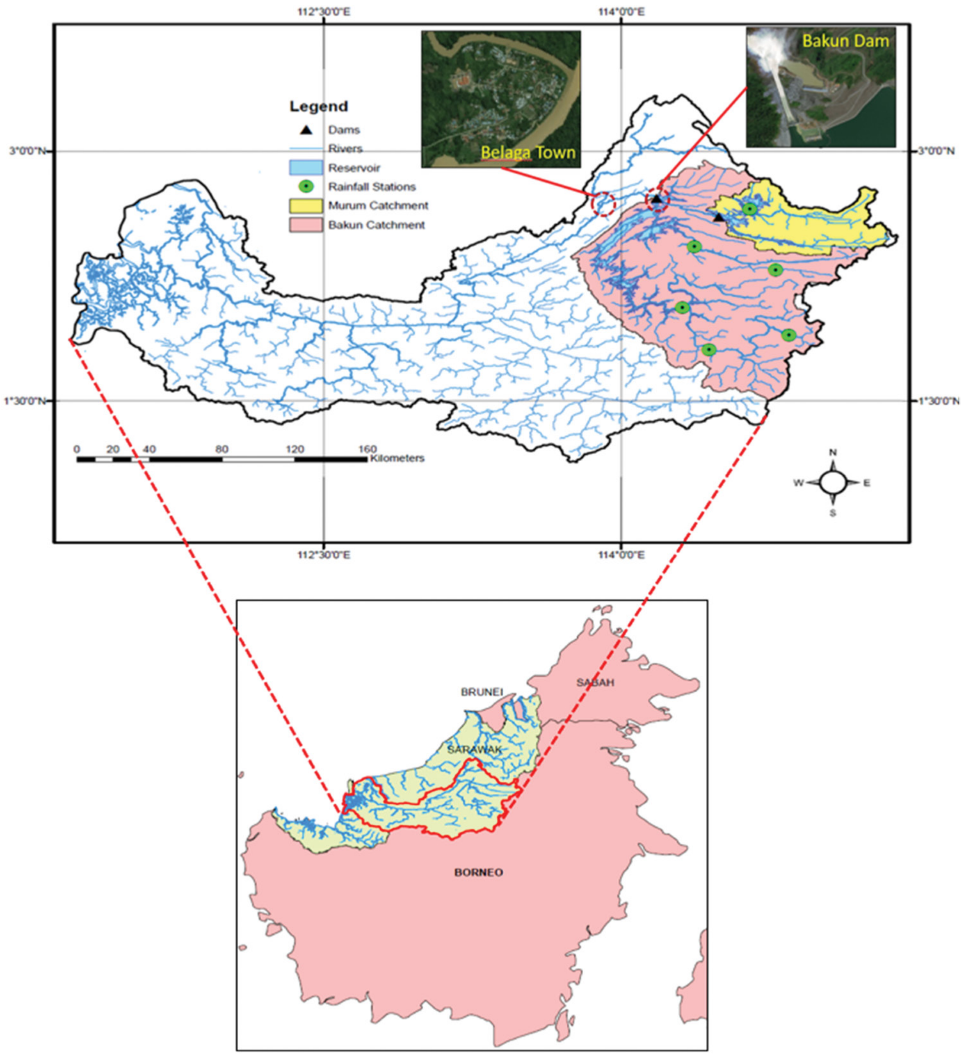

Figure 1: Locality map of the study area and rainfall stations in Borneo.

2.2 Data description

2.2.1 Rainfall and inflow data

The historical rainfall data from the 6 rainfall stations from 1976 to 2020 within the Murum-Bakun catchment were used to generate the peak rainfall for 1 in 50 and 1 in 100 year return period. These two return periods are selected as the flood boundary of the 50- and 100-year flood are often used in flood mitigation programs in high-risk flooding areas.

Climate change will impact the seasonal and annual precipitation over the RRB. Climate models are widely used for assessing climate changes impact that includes precipitation, temperatures and sea level. A global climate model simulation was referred to as the Climate Model Intercomparison Project (CMIP) [7]. The future rainfall data for this study was generated using Climate Model Intercomparison Project Phase 5 (CMIP5). This selection is because CMIP5 is the most up-to-date set of widely used climate models [7] and is widely used for assessing the global flood risk based on the multiple atmosphere-ocean general circulation model (AOGCM) [8].

In 2014, the RCPs were first used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as part of the final reports to deliver the findings. The RCPs use to encapsulate future trends. It predicts the changes in the concentrations of greenhouse gases in the atmosphere in future. The four RCPs range from very high (RCP8.5), average (RCP4.5) and (RCP2.6) are, representing the concentrations in 2100.

For this study, two Representative Concentration Pathway (RCP), representing 'medium' (RCP 4.5) and 'high' (RCP 8.5) scenarios to generate data in [1], were used to project precipitation for the year from 2022 to 2081.

2.2.2 Streamflow and outflow data

Sarawak Energy Berhad (SEB) has hydrometric stations at Murum Dam, Bakun Dam and downstream of Belaga Town. The hydrometric stations at Murum and Bakun dams record water level and inflow, and the data are stored in the centralised hydrological database. A hydrometric station downstream of Belaga Town is recording the water level. In addition, the river discharge was manually recorded from time to time to provide a rating curve for the elevation against discharge. All the inflow data has been checked for calibration and validation of the hydrological model exercise in RORB.

The required input for the Bakun reservoir flood routing calculation was obtained from Table 1 and the Bakun spillway operating manual [6].

The controlled release discharge parameters were incorporated into the reservoir routing model using the following information:

- Discharges from the Bakun Dam of 1,314 m^3/s have been assumed for normal operating conditions for electricity generation.
- The minimum operating water level of the reservoir is 195 m ASL. If the water level falls below this limit, it is assumed that normal operations will cease, and dam discharge will be limited to 150 m^3/s.
- The full supply level is 228 m ASL. If the water level exceeds this limit, it is assumed that the spillway will be opened to lower reservoir water levels. The spillway has a crest level of 209 m ASL and consists of 4 radial gates of 15 m width.

Table 1: Characteristics of Bakun HEP.

Reservoir parameter	Bakun HEP	Units
Catchment area	14,750	km^2
Full supply level (FSL)	228	m ASL*
Crest level	235	m ASL*
Minimum operating level (MOL)	195	m ASL*
Reservoir volume at FSL	35,895	Mm^3
Reservoir area (maximum flood level)	625	km^2
Active storage volume	16,466	Mm^3

* ASL – above sea level.

- Bakun releases water through the power station, via release valves or over the spillway to ensure a minimum combined release of 800 m^3/s when the reservoir level reaches EL 216 m and above to enable downstream express boat navigation.
- The reservoir application into the hydraulic model was partly conceptual, based on available topographic data and adjusted to include the specified depth-volume curves. Flow through the Bakun plant was described using two control structures in GeoHECRAS.

2.2.3 Topographic data

The delineation of catchment sub-basins and stream reaches was sourced from Interferometric Synthetic Aperture Radar (IFSAR) with a resolution of 3 m. For the river stretch from Bakun Dam to Belaga Town, Light Detection and Ranging (LiDAR) survey data were used. Both topography data are available within Hydro Department in Sarawak Energy Berhad.

3 METHODOLOGY

This study's two major components are (1) hydrology modelling – analysis for the historical and future precipitation to generate the peak rainfall and peak discharge under 50 and 100 years event and (2) hydraulic modelling – generating the flood plain mapping using GeoHECRAS, pre- and post-Bakun Dam operation for output of the first component.

3.1 Hydrology modelling

3.1.1 Areal catchment rainfall

There are six rainfall stations within the Bakun catchment. The rainfall recorded at each station represents only a specific catchment area. So naturally, the rainfall distribution is not uniform over the entire catchment, and there is a need to obtain average rainfall that can represent the entire catchment. Limin et al. [9] mentioned three conventional methods used to generate average areal rainfall: arithmetic, the Thiessen Polygon and the Isohyetal method.

Qing et al. [10] mentioned that Thiessen Polygon is one of the important methods for quantifying area rainfall. This method is also widely used because of its high accuracy on better-distributed rainfall stations, and the computation process is fast.

The Thiessen Polygon approach determines average precipitation over a Murum-Bakun catchment area. This approach was selected as it is suitable for the non-uniform distribution of rainfall stations in the Murum Bakun catchment area, which also factored in the weightage area for each gauge [11]. The World Meteorological Organisation [12], in the report, mentioned that the Thiessen polygon method was acceptable to be used for non-uniform rainfall station areas. In their research, Bruce and Clark [13] identify that the Thiessen Polygon method possesses value points for areas with fewer rainfall stations and non-uniform distributed areas. Ward and Robinson [14] view that the method has some spaces for non-uniform distribution of rainfall station and allow adjacent areas data to be incorporated in the average areas. Ahmed et al. [15] mentioned that the Thiesson Polygon method is more accurate for the non-uniform network of rainfall stations than the arithmetic method. The method is acceptable if the differences between the rainfall data are not significant. For this study, the result of average rainfall generated using the Thiessen Polygon method was not compared with other methods due to the constraint of time. Refer to Fig. 2 for the Sub-catchment area divided into polygons for the Thiessen Polygon method.

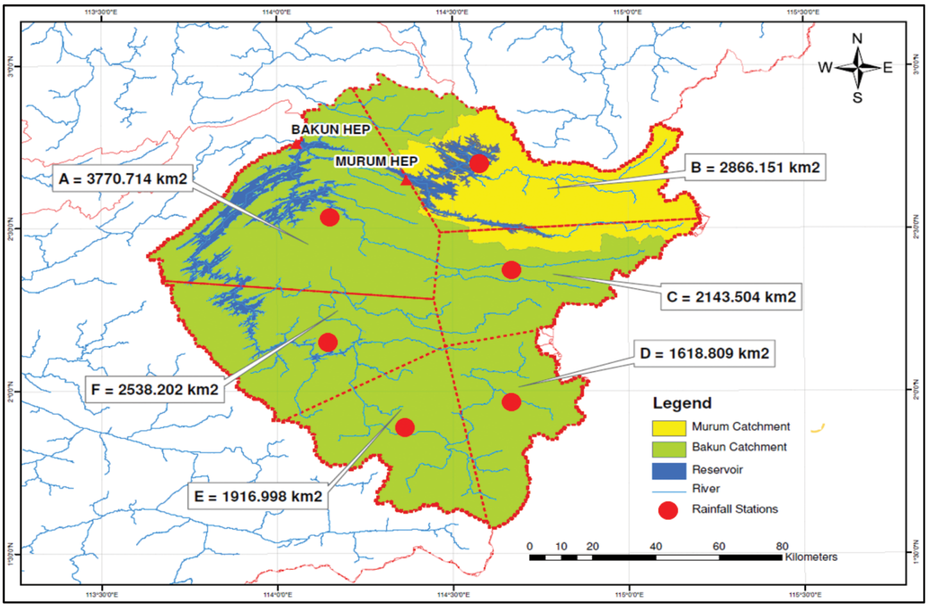

Figure 2: Sub-catchment area divided into polygons for Thiessen Polygon method.

3.1.2 Storm temporal pattern

There is a temporal pattern for the Sarawak region developed by the Department of Irrigation and Drainage (DID) through the publication of "Estimation of Design Rainstorm in Sabah and Sarawak" [16].

There are five regions in Sarawak with different Temporal Patterns, and the Bakun catchment is located in Region 3. Therefore, the temporal pattern data for Region 3 in the report was adopted for the rainfall analysis; refer to Fig. 3.

3.1.3 Analysis for peak rainfall based on historical data and future precipitation projection

Probability distribution and annual peak rainfall are commonly used to analyse the historical rainfall to manage better water resources, including flood mitigation [17]. Khudri et al. [18] stated that selecting the best fit for probability distribution to assess the extreme rainfall estimates depends on the rainfall characteristics and the selected area. Authors [19], [20] and [21] reported that normal, log-normal, log-Pearson type-III and Gumbel distributions commonly analyse peak annual rainfall. Authors [22] and [21] mentioned that Log Pearson Type III (LPIII) is the overall best fit for probability distribution for one (1) day storm events. Baghel et al. [23] consider Log-Normal (LN) and Gumbel (GBL) distribution as the best fit in their study.

For this study, Log Pearson Type III, Log-Normal and Gumbel were adopted and compared to fit maximum rainfall values in the Bakun catchment. Analyses were performed for storm periods of 1-day. Daily rainfall data from six stations for the 44 years (1976–2020) provided the basic data for the study.

3.1.4 Analysing peak discharge using RORB

There are many methods for estimating peak runoff or discharge in a catchment. One of the methods is through runoff routing technique using a network of storages like runoff routing on burroughs (RORB) model [24].

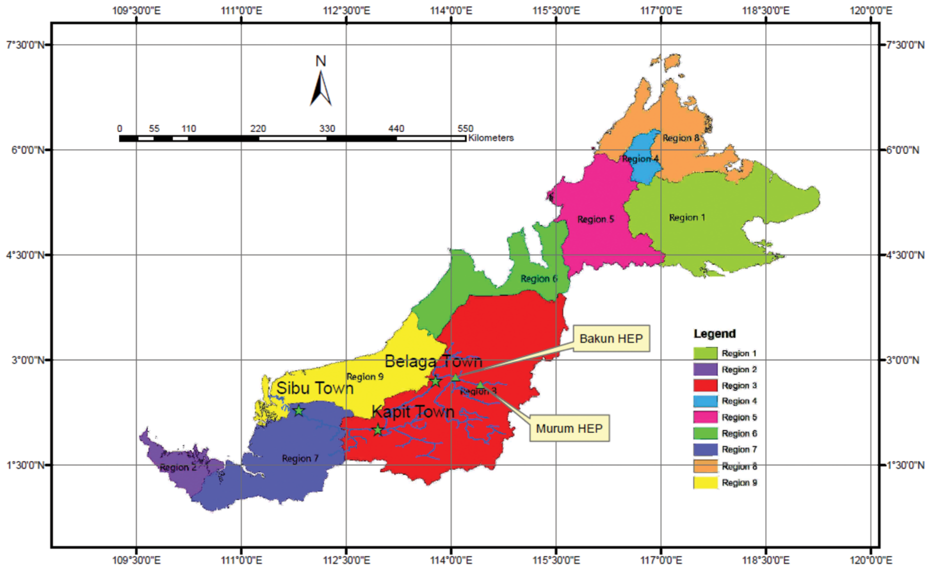

Figure 3: Region maps in Sabah and Sarawak, Malaysia.

RORB is an interactive, non-linear distributed runoff and inflow routing model. This software was chosen because of its widely recognised capabilities in flood routing. URS Australia [25] has used RORB in assessing the peak rainfall and flood routing to determine the peak discharge from 1 to 2 AEP to 1 to 2000 AEP for rivers in Bowen Basin, Australia. A similar exercise has been performed by a SMEC consultant using RORB to develop Baleh and Baram Hydro Electric Project (HEP) in Sarawak, Malaysia [26, 27]. The catchment area for these two projects carried by SMEC consultants is comparable to the Murum Bakun catchment.

The software is relatively easy to use and only require two inputs, K_c and m, for the user to determine. It has also been widely used in many catchments studies in the Asia Pacific and Malaysia for flood risk assessment. For example, Selvalingam et al. [28] found that the RORB model was able to simulate the runoff hydrograph and the result is well fitted with the recorded hydrographs in their study in Singapore. The step by step using RORB is detailed in sections 3.1.5–3.1.7.

3.1.5 Catchment delineation and reaches and nodes

RORB model setup begins with the catchment modelling. The catchment was divided into 114 sub-catchments, river links and nodes were connected utilising a combination of LiDAR and IFSAR survey data of the Murum–Bakun catchment [3]. The formed series of links and nodes represent the reaches of flow and the nodes of each sub-catchment, as shown in Fig. 4. Parameters like river length and sub-catchment area were defined and determined. The storage discharge relationship in the RORB model is:

$$S = 3{,}600 * K_c * K_{cri} * Q^m, \qquad (1)$$

where S = storage in reach (m^3), Q = discharge (m^3/s), K_c and m are main catchment parameters that can be obtained through trial and error fitting, known as a fit run in RORB model setup, while K_{ri} = relative routing lag parameter for the specific reach and storage [25].

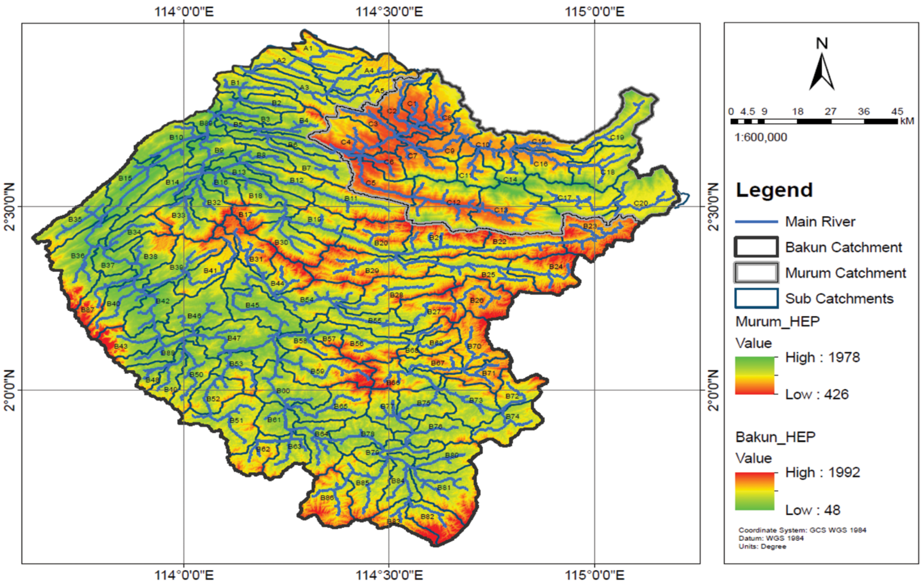

Figure 4: RORB model layout.

3.1.6 K_c and m values in RORB

In the RORB model, catchment lag and non-linearity are controlled by K_c and m, respectively. The selection of K_c and m values was performed through the fit run. A wide range of peak discharges of the recorded inflow was selected to estimate the K_c and m values. Trial and error methods were performed by adjusting the K_c and m values range to obtain the best fit of the recorded inflow hydrograph. The selected K_c and m values were tested against other peak discharge graphs and provided an acceptable fit with accuracy within +/-15% [24], which is considered good accuracy. Among all the fit runs, the m value of 0.75, K_c value of 152 and 0 for initial loss were adopted as the best fit for all the storm events in the study area.

3.1.7 Reservoir flood routing

Reservoir routing is an arithmetical process to determine the magnitude changes over time and shape of a transitioned flood wave passed dam structure. The flood wave travels from the reservoir's surface level to the outflow structures such as spillways, low-level outlets and turbines at the power station. Complex calculations are made factoring in the elevation storage and elevation-discharge data of the reservoir.

There are two common methods used in flood routing; hydraulic and hydrological. A hydrological method is selected for this study as it is simpler and only requires an inflow hydrograph to generate outflow. One of the hydrological methods used is Modified Puls. It was selected for this study because the reservoir eliminates its suitability in flood wave impact.

A study by Ogbonna et al. [29] stated that the prediction for outflow and measured outflow are close and have low standard error compared to other models. Modified Puls routing also is typically used for reservoir routing where a unique storage-outflow relation is available [30]. Reservoir flood routing will be performed based on a relationship between reservoir storage and outflow. The continuity form for each time step will be calculated using equation (2):

$$\left(\frac{S_t}{\Delta t}+\frac{O_t}{2}\right)=\left(\frac{I_{t-1}+I_t}{2}\right)+\left(\frac{S_{t-1}}{\Delta t}-\frac{O_{t-1}}{2}\right), \tag{2}$$

where S_t = storage for each increment, I_t = inflow, O_t = outflow and t = time step.

3.2 Hydraulic modelling

3.2.1 Generate flood using GeoHECRAS

GeoHECRAS is a useful tool in floodplain mapping studies because of its capabilities in performing food routing, hydraulic modelling and surface profile analysis in a single platform [5]. In addition, it saves much time compared to a more standard approach using HEC-RAS coupled with Geographic Information System (GIS) tools.

Digital elevation map of the study area was obtained from LiDAR data and processed using GeoHECRAS to get the elevation grid. A downstream of Rajang River reach until Belaga Town was selected to cover resettlements along the river and assess the flood risk to Belaga Town.

A river centreline was drawn along the river alignment displayed on the base map layer using the Draw River Reach tools in GeoHECRAS software. Then, the next step is to draw cross-sections on the pre-determined intervals. Finally, Manning's *n* values were assigned for the main channel and over banks based on the software's default values.

The boundary condition for downstream and upstream river reach was selected, and the software calculated the boundary slope. Flood flows under 1 in 50 and 1 in 100 years return periods were specified in steady-state flow data, and analysis was performed using a computed steady function in GeoHECRAS.

The rating curve for Pelagus gauging station was selected for calibration as it has the most actual discharge measurement compared to other gauging stations downstream of Bakun Dam. The observed water surface level (WSL) of the peak discharge at the Pelagus gauging station was obtained from the available rating curve of elevation-discharge data. It was then compared with the simulated WSL in the software. This is done in a steady flow calibration function. If these two data were found to have a significant difference in value, the model needs to be calibrated by adjusting Manning's n values for both the main channel and the over banks. Once the model is calibrated, flood maps under different return period floods were generated for visualisation in a GIS map.

4 RESULT AND DISCUSSION

4.1 Current and future rainfall analysis

The peak rainfall for 1 in 50 and 1 in 100 years return period was analysed as per Section 3.1.3. Figure 5 shows the rainfall depth at different return periods computed using statistical analysis methods. The maximum rainfall for Bakun catchment for 1 in 50 years return period is 148 mm, and 171 mm for 1 in 100 years return period based on the historical rainfall. The same would be expected for the projected rainfall under RCP 4.5 and RCP 8.5. However, looking at Fig. 5 for 1 in 100 years event. The peak rainfall for the RCP4.5 2022–2051 is higher than RCP4.5 2052–2081. The result does not behave as expected and does not align with the result for RCP4.5 under 50 years event. The difference could be due to some errors in input for perturbation exercise in CMIP5 modelling. The next study on this subject will reassess and fix the difference mentioned above.

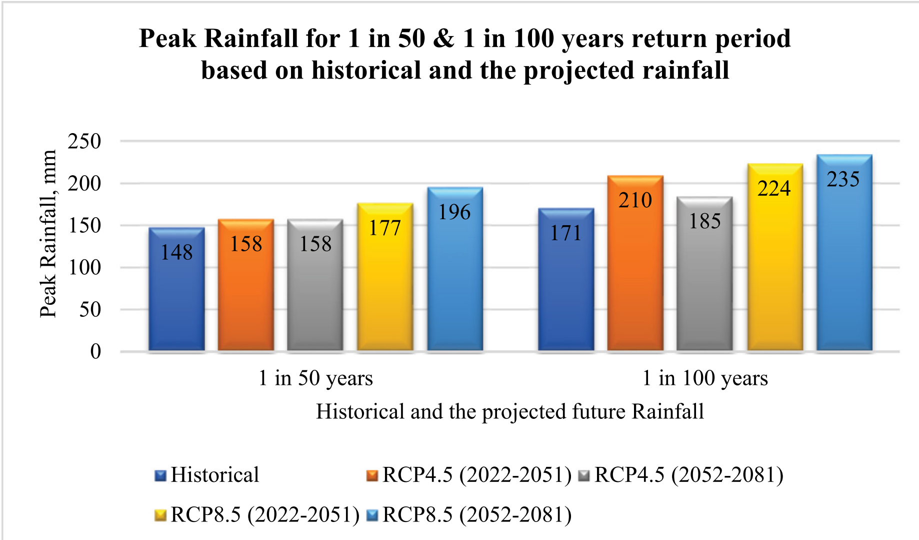

Figure 5: Peak rainfall for 1 in 50 and 1 in 100 years return period based on historical and projected rainfall.

There are increases in precipitation observed for the latter part of the 21st century, under RCP4.5 and RCP8.5 for 2022–2051 and 2052–2081. For RCP4.5 2022–2051 and 2052–2081, the peak rainfall is increased about 6–22% each under 1 in 50 years return period and 1 in 100 years return period. Meanwhile, for RCP8.5 2022–2051 and 2052–2081, the peak rainfall is increased about 16–27% each under 1 in 50 and 1 in 100 years return period.

4.2 Peak flood analysis under historical and future precipitation

Methods employed to evaluate peak discharge in the upper RRB have produced a range of estimates of peak design discharge, as in Fig. 6. The peak discharge value is higher in the more significant return period and increases toward the 21st century. For example, the peak discharge for 1 in 100 years return period from historical data, 8,714 m^3/s, is higher than 7,358 m^3/s, a peak discharge for 1 in 50 years return period. The peak discharge values under RCP4.5 and RCP8.5 for 2022–2051 and 2052–2081 are higher, about 7–31%, than peak discharge from historical data. Again, the peak discharge for RCP4.5 under 100 year events of 2022–2051 compared to 2052–2081 are directly affected by the peak rainfall from the same parameter.

4.3 Flood mapping for pre- and post-Bakun Dam operation

The WSL (m) for the peak discharges of 1 in 50 and 1 in 100 return periods for the Pelagus gauging station was generated using the available rating curve of average discharge (m^3/s) against the WSL (m) graph for Pelagus gauging station. These levels were categorised as observed WSL. In addition, the WSL generated from the simulation of steady flow simulation was categorised as calculated WSL.

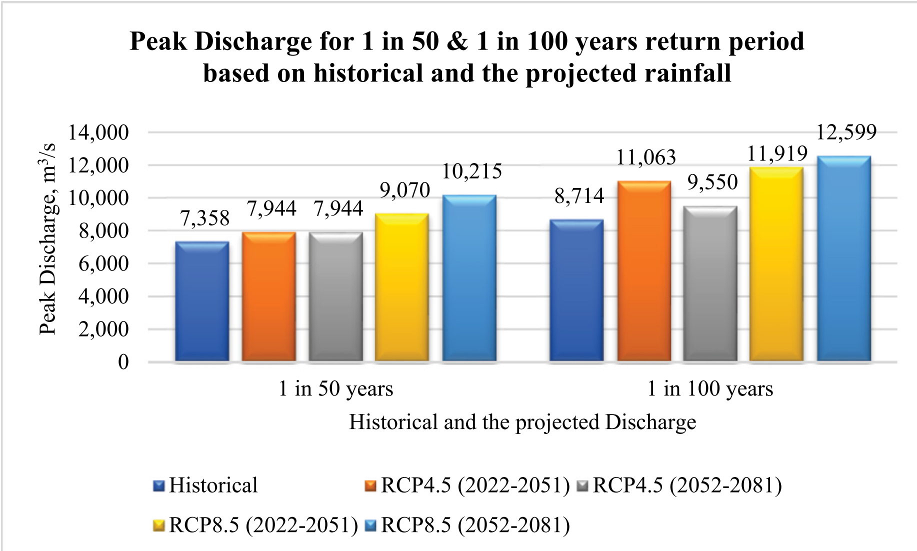

Figure 6: Peak discharge (m³/s) in 1 in 50 & 1 in 100 years return period based on historical and the projected future discharge.

The first step for calibration involves assigning default Manning's value, *n*, for the river cross-section [31]. The default value of 0.032 was used for the main channel and 0.045 for the over banks in the steady flow analysis step. Next, the observed WSL will be compared against the calculated WSL. There are differences at the first analysis run, and the model needs to be calibrated. The calibration was completed with *n* values of 0.032 and 0.040 for the main channel and river overbank.

The peak discharge recorded at Pelagus gauging station was 4,390 m^3/s with a WSL of 21.55 m. The calculated WSL for 4,390 m^3/s using GeoHECRAS was 20.94 m, and these two figures are quite close to each other.

The calibration model was evaluated using Nash-Sutcliffe efficiency (NSE) for model performance. Moriasi et al. [32] mentioned that NSE rating can be categorised as NSE = 1.0 is the perfect fit, NSE > 0.75 is a very good fit, NSE = 0.64–0.74 is a good fit, NSE = 0.5–0.64 is a satisfactory fit and NSE < 0.5 is an unsatisfactory fit. In general, an NSE of more than 0.5 is considered satisfactory in performance rating. The NSE formula has calculated NSE value was 0.88, which falls under a very good fit category. The observed and calculated WSL for different return period floods for the river reach at Upper Rajang River are presented in Table 2.

Figure 7 shows the Belaga Town condition impacted by the flood under 1 in 50 years and 1 in 100 years return period based on peak discharge data from historical RCP4.5 and RCP8.5 pre-Bakun Dam operation. The figure shows that more than 50% of the Belaga Town area is inundated or submerged under the water under these flood events.

However, Fig. 8 shows that with Bakun Dam is in operation, the potential flood impact at Belaga Town is mitigated. This is because the extreme discharge upstream due to storm events is contained by Bakun reservoir. When the reservoir level reaches full supply level (FSL) of 228 mean above sea level (masl), the water will be released through spillway and

Table 2: Observed and calculated WSL at Pelagus gauging station for different return period floods

Flood event (year)	Discharge (m^3/s)	Observed WSL (m)	Calculated WSL without reservoir routing (m)	Calculated WSL with reservoir routing (m)
Calibration	4,390	21.55	20.94	Not Applicable
1 in 50	7,358	23.94	23.72	16.88
1 in 100	8,714	24.76	24.83	16.88
RCP4.5 (1 in 50)	7,944	24.31	24.22	16.89
RCP4.5 (1 in 100)	11,063	25.95	26.59	16.89
RCP8.5 (1 in 50)	10,215	25.55	25.98	17.09
RCP8.5 (1 in 100)	11,919	26.61	27.59	17.09

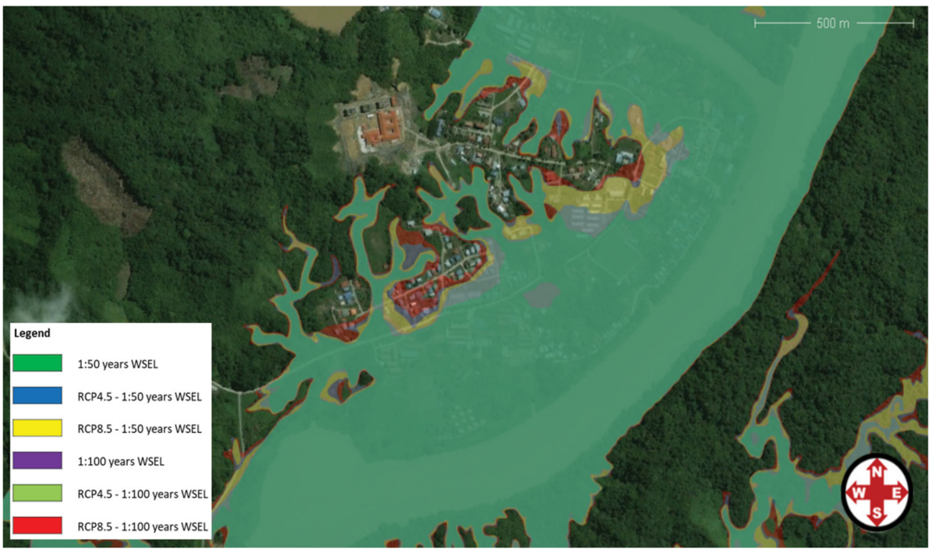

Figure 7: Flood plain map for Belaga Town under 1 in 100 years return period for historical, RCP4.5 and RCP8.5 pre-Bakun Dam operation.

turbines. Figure 6 also shows that with Bakun Dam's existence, the simulated water level at Pelagus gauging station is about the normal water level, showing the efficiency of Bakun Dam in mitigating the extreme flood under 1 in 50 and 1 in 100 years event.

5 CONCLUSIONS AND RECOMMENDATION

This study analyses the peak rainfall under historical data (1976–2020) and projected future precipitation of 2022–2081 for Murum Bakun catchment from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Figures 4 and 5 observed that peak rainfall and peak discharge are increased between 6–27% and 7–30%, respectively, compared to peak rainfall

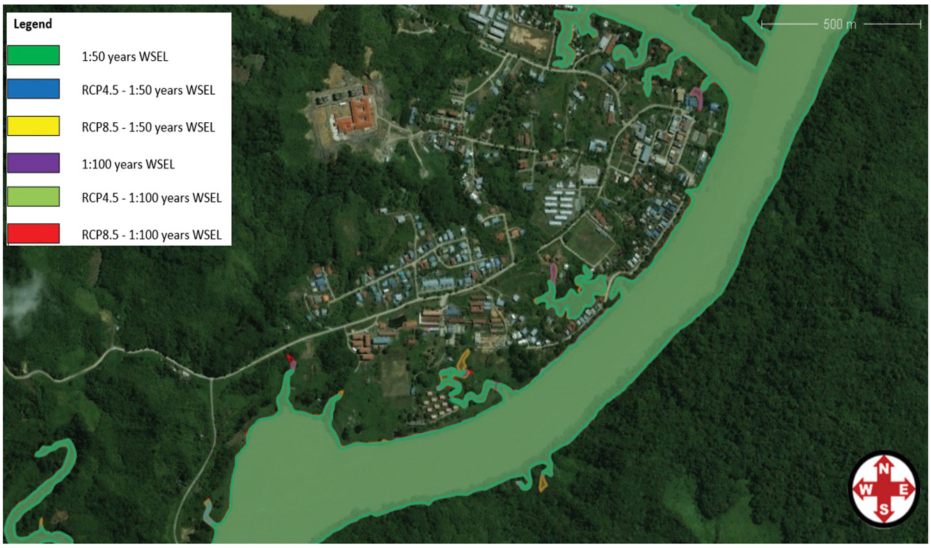

Figure 8: Flood plain map for Belaga Town under 1 in 100 years return period for historical, RCP4.5 and RCP8.5 post Bakun Dam operation.

and peak discharge based on historical data. The increase in future precipitation projection warrants the relevant authorities and asset owners' attention to assess the flood risk continuously in the future toward the structures and communities downstream of Bakun station.

Figures 7 and 8 shows the flood plain mapping under 1 in 50 years and 1 in 100 years return period for Belaga Town pre and post-Bakun Dam operation. Post Bakun Dam operation, the flood risk is reduced significantly as the Dam collects and holds the reservoir waters until the level reaches FSL at 228 m ASL. When they reach 228 m ASL, the reservoir waters will be released back to the downstream river at a controlled speed through the spillway. Therefore, with Bakun Dam in operation and with a properly planned and controlled release of water downstream of the Dam, it was concluded that the flood occurrence to the downstream communities would be further minimised, especially in Belaga Town.

With frequent flood events in the past at upper RRB and the increased precipitation projection, this study's findings will provide useful information for flood mitigation and preparation for emergency action plans. Therefore, the recommendation for the next steps of the study are summarised as follows:

1. To extend flood plain mapping under the peak discharge up to Probable Maximum Flood (PMF) for historical and future precipitation of RCP4.5 and RCP8.5 for 2022–2081 to assess Belaga Town susceptibility toward the most extreme flood risk.
2. To generate the flood mapping post-Bakun operation for item 1 to assess the functionality of Bakun station in mitigating flood to the downstream river.

Floodplain mapping is crucial in development planning, sustainable water resource management and advanced emergency action plans. The software used for this study, GeoHECRAS, demonstrates a useful and user-friendly tool in hydraulic modelling and flood mapping exercise. The software also is capable of performing flood routing, hydraulic modelling and surface profile analysis in a single platform. All the hydraulic modelling and flood plain mapping process is done in a single software and has saved much time compared to the most commonly used method, a combination of HEC-RAS and GIS tools.

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