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Integrating Remote Sensing and GIS Techniques for Flood Modeling in Sparsely Gauged Catchment

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ABSTRACT

Reproducing past flood occurrences can help us better understand the behavior and patterns of floods to develop effective flood mitigation plans. However, modeling flood events at sparsely gauged catchments remains challenging due to insufficient catchment information and incomplete climate records, especially in developing countries. To address these limitations, remote sensing products have come under the spotlight due to recent advancements in satellite sensors and assimilation algorithms. This study intends to explore the feasibility of integrating remote sensing and GIS techniques for flood modeling in the sparsely gauged Lebir sub-catchment, which is the upper catchment of Kelantan River Basin in Malaysia. Four quantitative statistics were applied to evaluate the performance of flood model in simulating the hydrograph and inundation extent during December 2014 flood event. The results reveal good agreement between observed and simulated hydrographs for the Lebir catchment. The calibration of model parameters also further improves the model accuracy, indicating better simulation of the peak flow. In addition, the hydraulic model performs reasonably well in generating the inundation extent during the floods in comparison to the observed inundation level. The collective findings highlight the potential usefulness of remote sensing products when integrated with GIS techniques in hydrological modeling to achieve acceptable accuracy in sparsely gauged catchments. Future studies should explore how uncertainty properties change when propagating from precipitation data to rainfall-runoff processes.

1. Introduction

As the water cycle continues to intensify under warming climate, natural disasters, such as pluvials and floods, occur more frequently around the world. According to the annual disaster statistics published by Guha-Sapir D. *et al.* [1], water related disasters account for more than half of the natural disasters that happened between 2006 and 2015, causing fatality, economic losses, and disruption of human livelihood. Every year, more than 5,000 deaths and 40 % of total economic losses due to natural disasters are associated with flood incidents. As such, it is crucial to understand the

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behavior and occurrence process of floods to lessen their socioeconomic impacts and build climate resilience. This can be achieved by conducting hydrologic modeling, which is capable of simulating the occurrence of such events and estimating the inundation extent and flood water level [2]. Previous research has demonstrated the importance and usefulness of flood modeling in the sustainable management of flood hazards by enabling policymakers to develop appropriate strategies for their adaptation and mitigation [3-5]. However, accurately simulating or predicting floods can be challenging when catchment data is insufficient, especially in developing countries.

One such example is the incomplete records of historical flood events due to the challenges in collecting the rainfall, discharge, and water level data during peak flow events. Flood monitoring instruments at hydrological stations are often destroyed by large debris in floodwaters, leading to operational downtime and the loss of important hydrological information during peak events. Apart from their susceptibility to equipment failure, ground-based gauges also have limited spatial coverage, despite having high accuracy at their specific point locations. This is particularly evident for rainfall data in tropical regions, where rainfall can vary greatly over short distances, causing existing gauges unrepresentative of rainfall amounts in surrounding areas. In addition, most of the catchments in developing countries are sparsely gauged, which presents an enormous challenge to the researchers in conducting hydrologic studies [6].

Given the existing limitations, it is necessary to explore and assess alternative sources of data, such as remote sensing products, for their feasibility and potential application in flood modeling in sparsely gauged catchments. Most of these products have large spatial coverage and are accessible online. Recently, several satellite precipitation products have gained increasing popularity to address the limitations in rainfall data due to their high resolutions with global/quasi-global coverage [7]. Although several studies have been conducted to examine the use of remote sensing products in flood modeling, only few have integrated GIS techniques into this process [8-10]. Moreover, studies that describe the entire process of flood modeling based on integrated remote sensing and GIS approaches are scarce, especially in Southeast Asia. It is anticipated that this integrated modeling approach could address the existing limitations and challenges faced in sparsely gauged catchment by providing reliable estimates of hydrology.

Therefore, this paper intends to model a historical flood event by integrating both remote sensing data and GIS technique in the sparsely gauged Lebir sub-catchment, which is the upper section of the Kelantan River Basin in Peninsular Malaysia. The flood event between 15 and 25 December 2014 was selected as the study period to demonstrate the modeling process by using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model.

2. Methodology

Figure 1 outlines the overall methodology of this study. Catchment parameters and boundary conditions required for hydrological analysis were derived from digital elevation models (DEM), land cover, soil, and rainfall data sourced from remote sensing products. The flow hydrograph generated was then applied in hydraulic analysis to produce the flood inundation map.

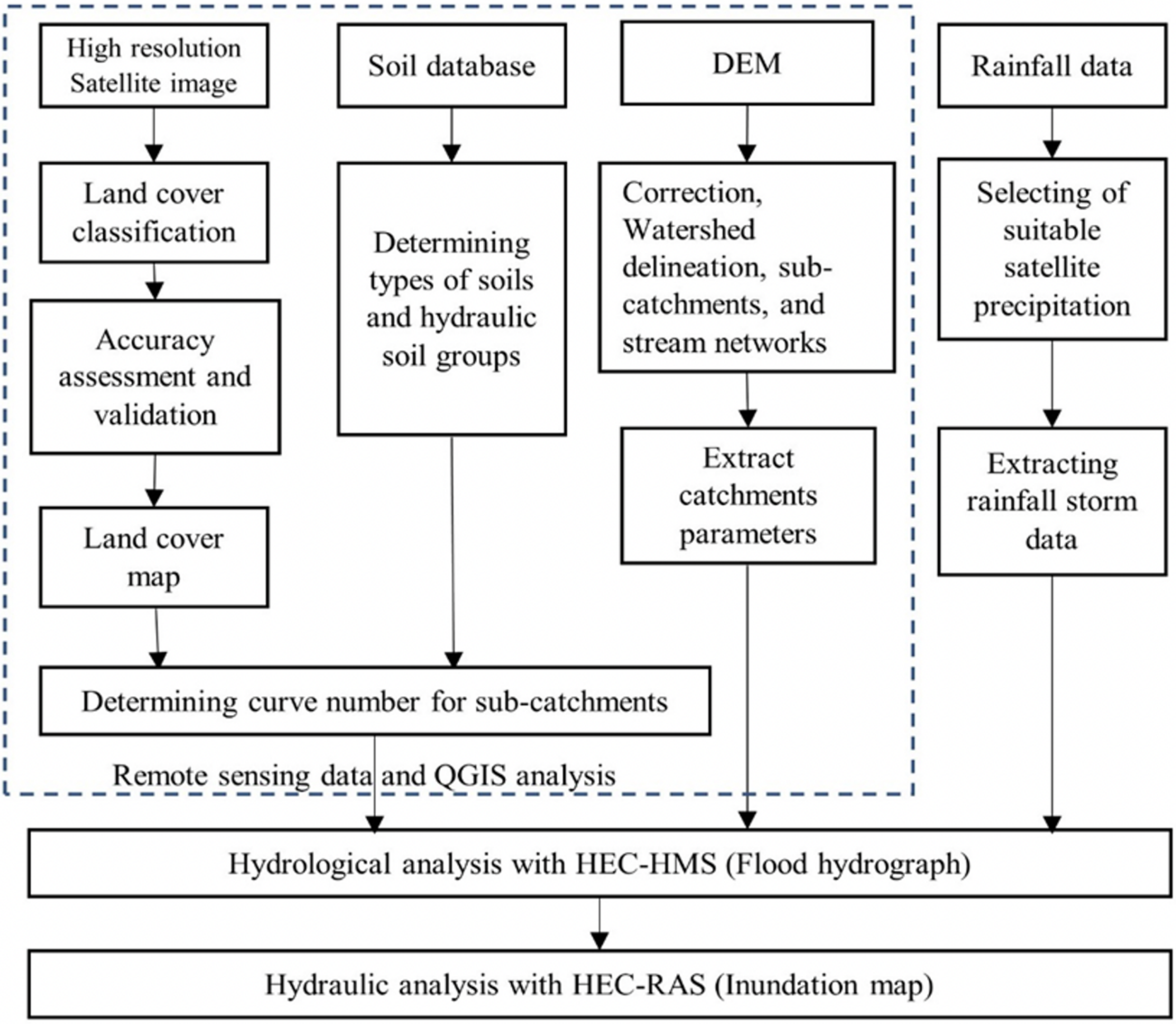

Fig. 1. Flowchart of the overall approach

2.1 Study Area

Kelantan is located east of Peninsular Malaysia between 101.17˚–102.7˚E longitude and 4.5˚–6.5˚N latitude, which has a total area of 15,060 km^2. There are 1.539 million people living in the state; they are spread out across the ten districts of Kota Bharu, Pasir Mas, Tumpat, Bachok, Tanah Merah, Pasir Puteh, Kuala Krai, Machang, Gua Musang, and Jeli. The average annual temperature of Kelantan is 28°C, with 2500 mm of rainfall annually [11]. The north-east monsoon, which lasts from November to March, is the wettest season with frequent flooding [11; 12]. The catchment area of Kelantan River Basin occupies 86 % of the whole Kelantan administrative area. The main rivers that drain the state include the Kelantan, Lebir, Galas, Nenggiri, and Pergau, of which the Kelantan River is the largest and receives most of its flowing water from the Lebir and Galas catchments. Nenggiri and Pergau are the major tributaries of the Galas River. The main Kelantan River starts from the confluence of the Galas and Lebir rivers at the Kuala Krai district and runs around 105 km downstream through several cities with higher population density and development until reaching its estuary in the South China Sea located north of Kota Bharu. It has an average width of 180 m to 300 m [13] and an average basin runoff of 500 m^3/s [14; 15]. The upper catchment of the Kelantan River consists of four sub-catchments, namely the Lebir, Galas, Nenggiri, and Pergau sub-catchments as depicted in Figure 2.

For this study, hydrologic modeling was conducted for the Lebir sub-catchment, while the flood inundation was simulated up to Kuala Krai.

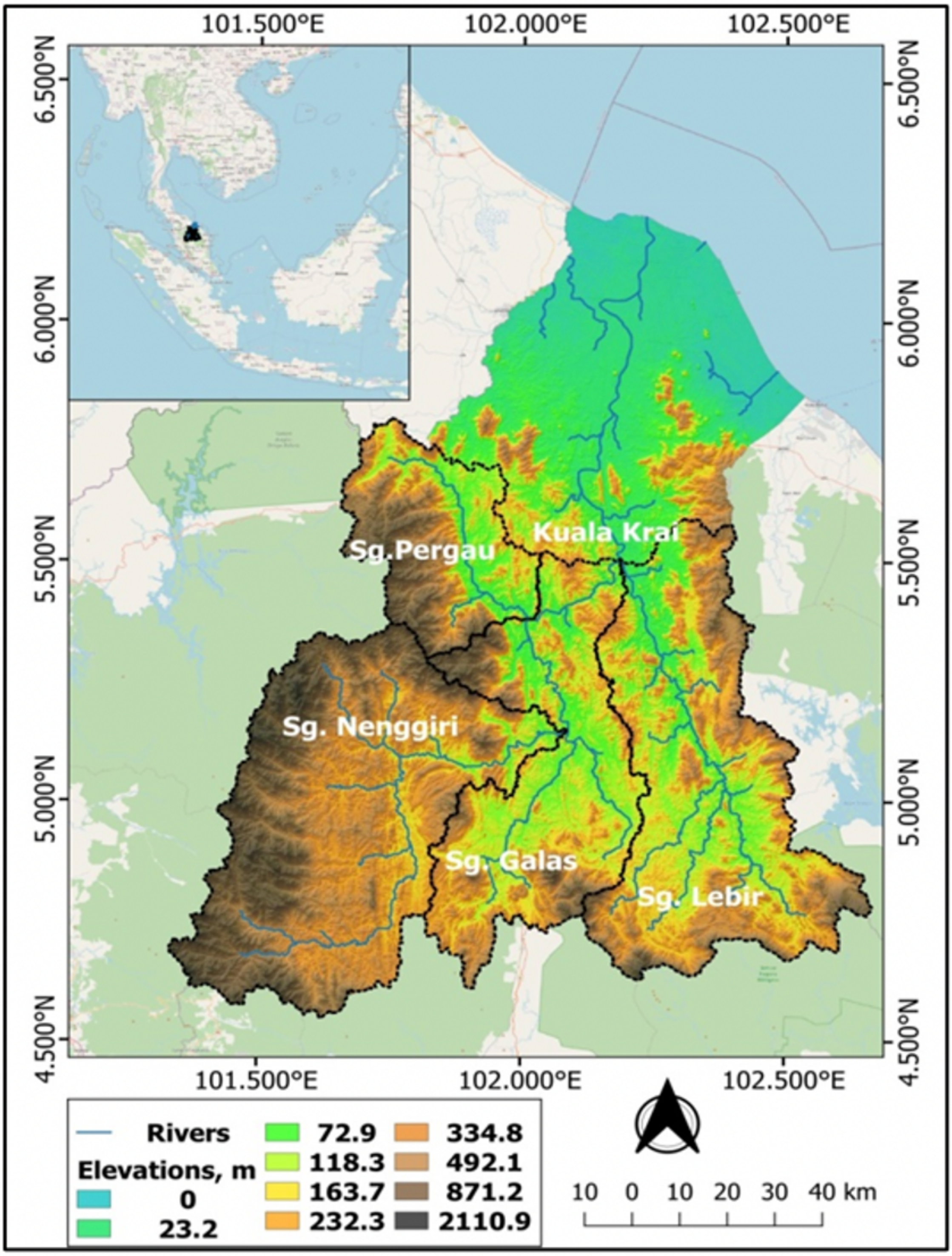

Fig. 2. Topographical map of the study area

2.2 Data

2.2.1 Rainfall and discharge data

This study utilized the state-of-the-art remote sensing rainfall dataset, the TRMM 3B42RT v7 (near real time) dataset, due to its high level of agreement with the gauge observations in Kelantan [16; 17]. TRMM is the first satellite mission dedicated to monitoring tropical and subtropical precipitation [18]. It has higher accuracy compared to the other products due to its high spatiotemporal resolutions and good algorithm that combines both precipitation measurements from various satellite systems and gauge observations. Its superiority and advantages over the other satellite precipitation products in estimating tropical rainfall makes it a suitable source of rainfall input data for flood modeling application. For calibration and validation of simulated flow hydrograph, good quality observed discharge records at the outlet point of the Lebir River catchment area was obtained from the Department of Irrigation and Drainage (DID) Malaysia for the flood event during December 2014.

2.2.2 DEM, land cover and soil data

DEM is typically used for delineating watersheds and deriving the stream network, elevations, slopes, and several other catchment-related parameters for hydrological modeling and flood mapping. This study applied the widely used Shuttle Radar Topography Mission (SRTM) DEM of 30 m resolution for hydrological modeling. All DEM cells that cover the entire Kelantan state were downloaded, merged, corrected, and clipped to match the catchment boundaries using GIS techniques. The streams network was then extracted, and the sub-catchments for the required rivers were delineated as shown in Figure 2. The parameters derived from DEM include the catchment area, longest river length, average slope, and time of concentration for each sub-catchment. The Advanced Land Observing Satellite (ALOS) DEM of 12.5 m resolution was applied as terrain data in the RAS Mapper for the 2D unsteady flow calculation and inundation mapping.

The land cover classification map for the study area was derived from Landsat 8-OLI-TIRS satellite images of 30 m resolution by the United States Geological Survey (USGS) [19]. Different blocks of multiband Landsat-8 images were downloaded and pre-processed for analysis using QGIS. The Semi-Automatic Classification Plugin (SCP) [20] was used for the pre- and post-processing and the supervised classification of the Landsat-8 band set. Landsat 8-OLI-TIRS comes with 11 bands. Bands 1, 8, 9, 10, and 11 were excluded from the processing and the calculation process [20], and the remaining bands were converted to reflectance and used as a band set for the classification process. The land cover types of the study area were classified into four main categories, namely water bodies, vegetation, built-up areas, and bare soil.

The soil map and hydrologic soil group map (HSG) for the study area were prepared using data from the Harmonized World Soil Database (HWSD) [21]. The HWSD is a global raster database of 30 arc-second resolution that contains information on more than 15,000 different soils for hydrologic applications [22]. The HSG map was constructed by matching the study area map with information from the HWSD raster in the QGIS environment. The curve number (CN) grid was then constructed according to the land cover map, HSG map, and standard CN lookup tables.

2.3 Hydrological Analysis and Inundation Mapping

This study used the HEC-HMS model for hydrological modeling. It is a numerical event-based model that was developed to simulate the hydrological processes for different types of watersheds.

The input data for the basin model, including DEM, streams network, sub-catchment areas, and CNs, were initially processed using the QGIS software and were then imported to the HEC-HMS model. The HEC-HMS model incorporates several methods of rainfall loss and transformation, including the SCS-CN method for loss and the Clark Unit Hydrograph Model for transformation. In the basin model, four sub-basins and two reaches were selected according to the main rivers. Typically, the main output of the hydrological model at this stage of analysis is the hydrograph of the flood event, which describes the values and timing of peak flow at the selected outlet.

The HEC-River Analysis System (HEC-RAS) model was used in this study to simulate the inundation during the selected flood event and to supplement the flood modeling process with spatial information (flood extent). HEC-RAS allows users to perform river hydraulic computations for steady flow and 1D/2D unsteady flow based on geo-referenced terrain data, floodplain roughness (Manning's coefficients according to the land cover data), and flood hydrograph as an input boundary. Both HEC-HMS and the HEC-RAS by the US Army Corps of Engineers are available for public use [23].

2.4 Evaluation Framework

The performance of the model was evaluated using quantitative statistics, namely coefficient of determination (R^2), root mean square error-observations standard deviation ratio (RSR), percent bias (PBIAS), and Nash-Sutcliffe efficiency (NSE). These evaluation metrics are widely used to measure the skills of hydrologic models [24; 25]. R^2 describes the proportion of the variance in measured data explained by the model; RSR reflects the standardized differences between a statistical model's predicted values and the actual values; PBIAS measures the average tendency of the simulated data to be larger or smaller than the observed data; NSE determines the relative magnitude of the residual variance compared to the measured data variance. These evaluation metrics were calculated as follows:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (O_i - O_m)(S_i - S_m)}{\sqrt{\left[\sum_{i=1}^{n} (O_i - O_m)^2\right]} \sqrt{\left[\sum_{i=1}^{n} (S_i - S_m)^2\right]}} \right\}^2, \tag{1}$$

$$RSR = \frac{RMSE}{STDEV_{Obs}} = \frac{\sqrt{\left[\sum_{i=1}^{n} (O_i - S_i)^2\right]}}{\sqrt{\left[\sum_{i=1}^{n} (O_i - O_m)^2\right]}}, \tag{2}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (O_i - S_i)}{\sum_{i=1}^{n} (O_i)} \times 100\right], \tag{3}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - O_m)^2}\right], \tag{4}$$

where *O* is the observed value; *S* is the model-simulated value; *n* is the number of data; *m* is the mean value. R^2 ranges from 0 to 1, with higher values indicating less error variance, and values greater than 0.5 are considered acceptable [26; 27]. RSR ranges from 0 to ∞, with 0 being the optimum value that indicates zero residual variation. NSE ranges from −∞ to 1, with 1 being the optimal value. NSE value between 0 and 1 is considered as acceptable levels of performance, whereas negative value indicates that the mean observed value is a better predictor than the simulated value [25]. PBIAS ranges from

−∞ to ∞, with 0 being the optimum value. Positive PBIAS value indicates model overestimation bias, while negative value indicates model underestimation bias.

3. Results and Discussions

3.1 Peak Flow Identification

Figure 3 shows the observed hydrograph at the outlet point of the Lebir River catchment area. Two notable peaks are observed from the graph, which indicates that Kelantan experienced two waves of floods from 14 to 24 December 2014 that is in agreement with the timeline reported by previous findings [28]. The first flood wave was attributed to the water flowing from the Lebir and Galas rivers, whereas the second flood wave was caused by the water flowing from the Lebir, Galas, Nenggiri, and Pergau catchments. However, the curve of the observed hydrographs remains flattened beginning from 23 December 2014, which may be due to the saturation of the subsurface. According to Gupta [29], runoff may travel laterally below ground through the unsaturated zone toward the river channel or infiltrate deeper to replenish the groundwater flow and discharge as baseflow into the river channel. As the flood period lengthened, the subsurface became saturated and infiltration rate was reduced, thus lengthening the time taken for the water level to drop to its normal stage. Given that the subsurface flow was not considered in the analysis, the subsequent evaluation was established between 14 and 22 December.

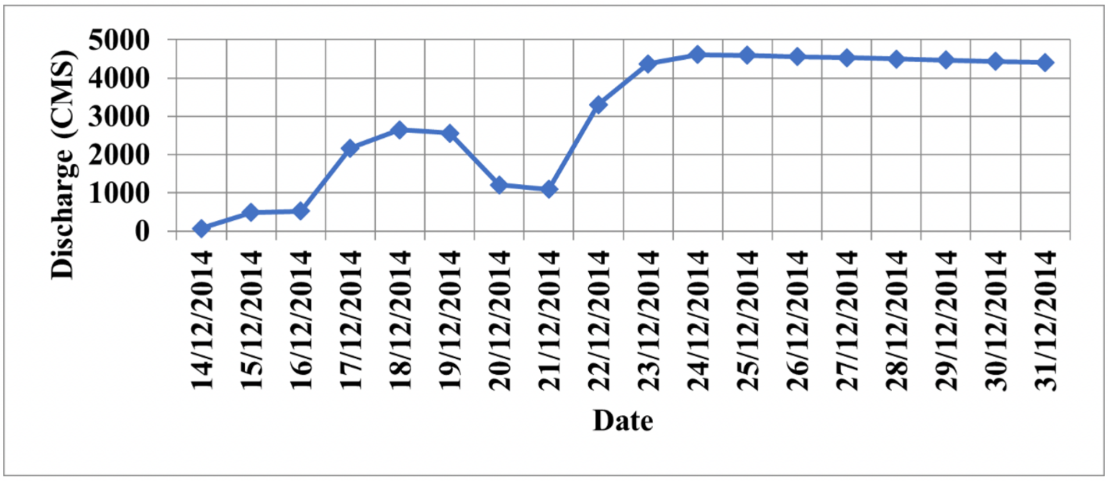

Fig. 3. Observed flow hydrograph at the outlet point of the Lebir catchment

3.2 Flow Hydrograph and Inundation Map Simulations

For evaluation, the simulated discharge from the model was compared with observed discharge using quantitative statistics. Figure 4 presents the simulated hydrographs for the Lebir River before and after calibration, while Table 1 shows the values of the statistical parameters for evaluation. The simulated flow shows considerably good agreement with the observations before the calibration, and improvement in all quantitative statistics are observed after the calibration. The results suggest that the model is well-calibrated and displays high skills in simulating the flood hydrograph during the 2014 flood event. Nevertheless, the model still exhibits a slight underestimation of the flow discharge after calibration, suggesting that simulating the full scale of flood severity for this record-breaking event remains challenging.

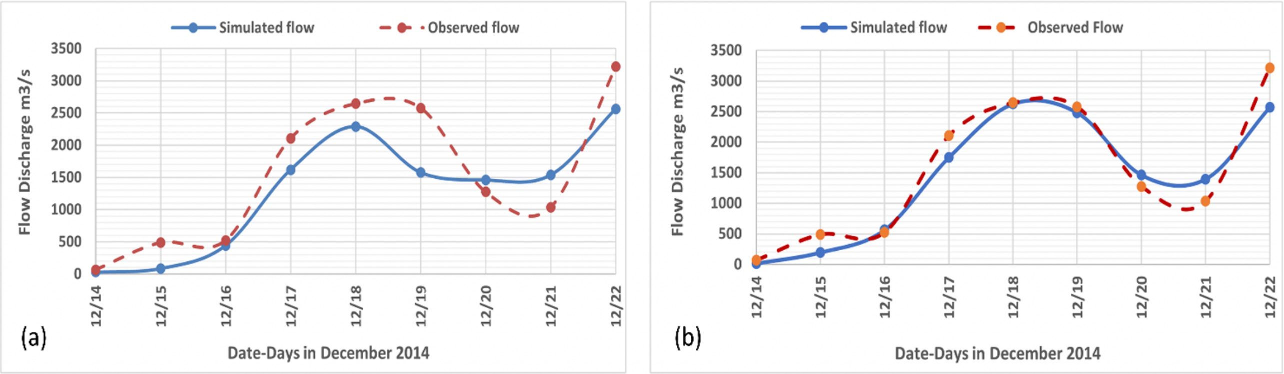

Fig. 4. Observed and simulated hydrographs of the Lebir River (a) before and (b) after calibration

Table 1
Model performance assessment based on quantitative statistics

Statistics	Before Calibration	After Calibration
Coefficient of determination (R^2)	0.67	0.85
Root mean square error divided by the standard deviation of observed data (RSR)	0.6	0.4
Nash-Sutcliffe efficiency (NSE)	0.606	0.844
Percent bias (PBIAS)	-19.70%	-3.64%

Figure 5 displays the spatial inundation pattern for the December 2014 flood event in Kuala Krai-Kelantan. The reach of the selected river for the inundation analysis started from the point close to the river confluence (Lebir and Galas rivers) and ended at the administrative boundary of the Kuala Krai district (around 18 km). The HEC-RAS model was adjusted for the adequate time step based on the Courant condition criteria to ensure an accurate numerical computation. Previous studies reported approximately 12 m maximum observed flood depth at the Kg Aur Duri area (marked by red rectangle) in the Kuala Krai district during the December 2014 event [30], which is consistent with the simulated inundation depth as shown Figure 5. The results suggest a high level of agreement between the modeled hydraulics and the actual morphological characteristics of river channels.

Despite the promising results, uncertainties may arise during the modeling process. It can be attributed to several sources, such as from DEM data of low resolution, as well as the discharges contributed from minor tributaries that were neglected during the modeling process. DEM data, including ASTER, SRTM, and ALOS, come in different resolutions ranging from 12 m to 90 m. The accuracy of the applied DEM greatly affects the accuracy of the simulated flood depth and extent in the hydraulic model. These DEMs should therefore be corrected with ground truth reference points or sections by means of site surveys to accurately reflect the flood extent. In this study, SRTM data with a resolution of 30 m was used for hydrological modeling, and ALOS data with a resolution of 12.5 m was used for inundation mapping. Both datasets were geometrically corrected to fill sinks and voids using QGIS. The delineated catchment and river networks were checked by comparing them with the satellite imagery (OSM and Google) and with the available data from the literature on the study area. However, the DEM should ideally be corrected based on river bathymetry, if available, or by referencing a sufficient number of control points from an on-site ground survey. Additionally, using satellite precipitation and remote sensing earth data for flood modeling in sparsely gauged catchments may introduce certain levels of uncertainty. Despite large spatial coverage, their accuracy may vary in space and time depending on the satellite constellation, their data sources, processing algorithm, interpolation techniques and the geographical features of the study area. Therefore, the suitability of remote sensing products needs to be carefully assessed by referring to ground-based benchmarks before being applied in hydrological modeling.

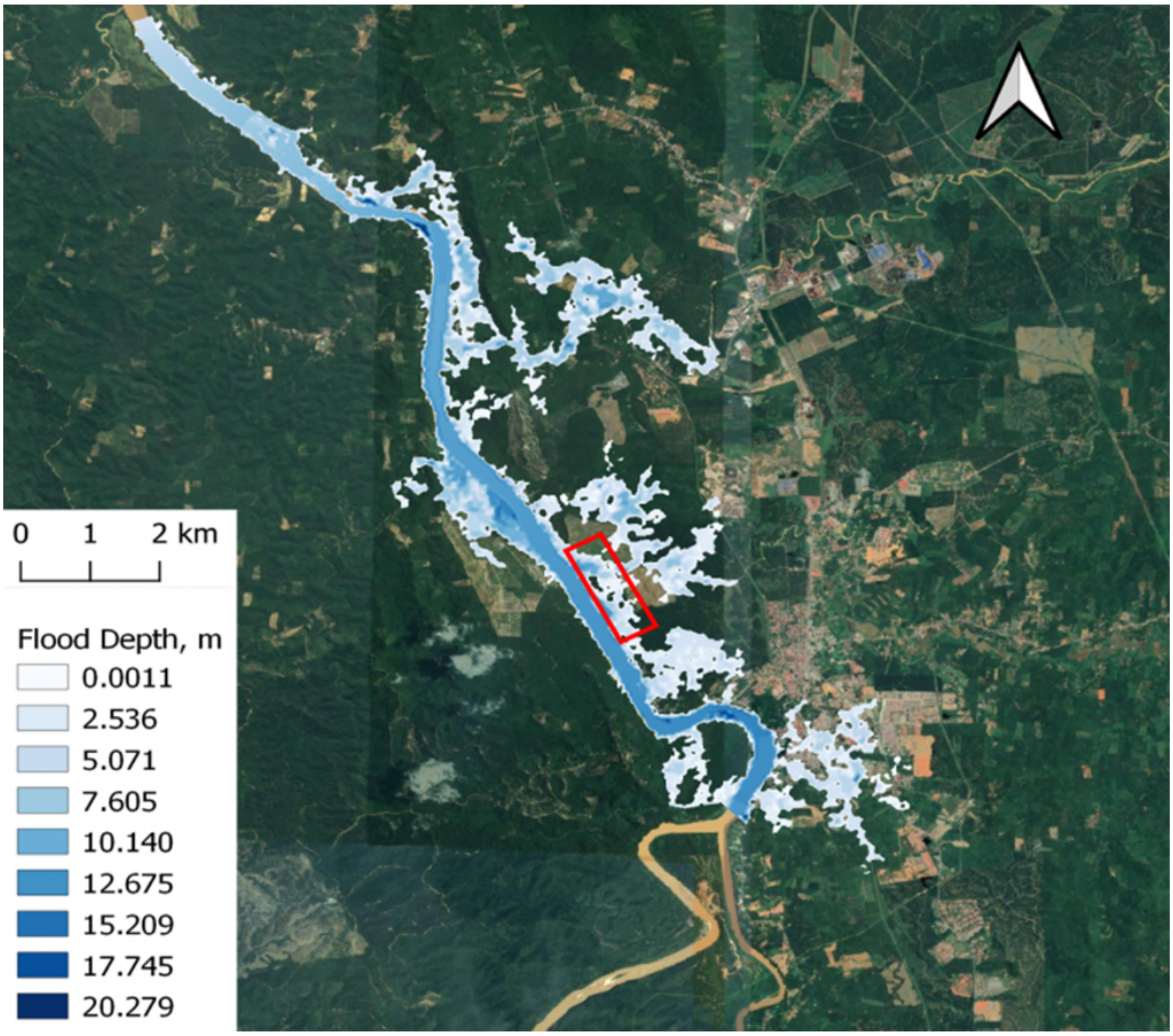

Fig. 5. Simulated inundation map of the December 2014 flood event in Kuala Krai, Kelantan. The red rectangle indicates the Kg Aur Duri of the Kuala Krai district

4. Conclusions

Understanding and modeling flood occurrence in sparsely gauged catchments is challenging due to limited catchment information and incomplete climate records, particularly in developing countries. Considering recent advancements in remote sensing techniques and assimilation algorithms, this study applied various remote sensing products in combination with GIS technique to model the hydrology of flood event in Lebir sub-catchment, upper section of Kelantan River Basin, Malaysia during December 2014. Four evaluation metrics were applied to evaluate the performance of the flood model in simulating the hydrograph and inundation extent during the December 2014 flood event. The hydrological modeling results, based on quantitative statistics, indicate good agreement between observed and simulated flows generated by the HEC-HMS model for the Lebir catchment. Calibrating the model parameters further improved the evaluation statistics, indicating better simulation of the peak flow. In addition, the HEC-RAS model performs reasonably well in generating the inundation extent during the floods in comparison to the observed inundation level. Nevertheless, considering the flow from minor tributaries within the floodplain could further improve the accuracy of the model. Improving the accuracy of delineated catchments, river networks, and DEM data through on-site ground surveys or field investigations could also reduce the uncertainty. Additionally, the feasibility of remote sensing products should be carefully assessed by comparing them with ground observations before applying them in hydrologic modeling.

The outcome of this research contributes to the understanding of flood patterns in the study area for future development of mitigation measures. The collective findings also highlight the potential usefulness of remote sensing products when integrated with GIS techniques in hydrological modeling to achieve acceptable accuracy in sparsely gauged catchments. Future studies should explore how uncertainty properties change when propagating from precipitation data to rainfall-runoff processes.

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