Jurnal Kejuruteraan 36(5) 2024: 1805–1812
https://doi.org/10.17576/jkukm-2024-36(5)-02

Optimizing Hydrological Research: Comparative Analysis of DEMs for Enhanced Catchment Area Delineation

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Received 26 January 2024, Received in revised form 28 April 2024
Accepted 28 May 2024, Available online 30 September 2024

ABSTRACT

Catchment area delineation is fundamental for hydrological modeling and research pursuits. Traditionally, delineating catchment areas entailed manual demarcation on topographical maps, a laborious task requiring skilled personnel. However, with the advent of Geographical Information System (GIS)-based software, this process has evolved, leveraging Digital Elevation Model (DEM) data for enhanced efficiency. Despite this advancement, selecting an optimal DEM remains pivotal, balancing quality with cost, given the substantial resources and approvals often necessary for high-quality DEM acquisition. This study, utilizing ArcGIS software, aimed to compare catchment area delineations derived from three distinct DEMs: Contour-based DEM, SRTM DEM, and IFSAR DEM across multiple locations. Using IFSAR DEM as the benchmark, this study demonstrate that both Contour-based DEM and SRTM DEM offer viable alternatives, exhibiting less than a 3.5% variance in delineated catchment area across all locations. Notably, SRTM DEM outperformed Contour-based DEM, boasting higher accuracy as evidenced by lower Root Mean Square Error (RMSE) values. Furthermore, this study elucidated the influence of geological and topographical factors on DEM accuracy in catchment area determination. This comprehensive understanding underscores the significance of selecting the most suitable DEM, considering factors such as cost, accuracy, and availability for future research. This study serves as a valuable resource for researchers, aiding in the judicious selection of DEMs tailored to specific research requirements, thereby enhancing the precision and efficiency of hydrological investigations.

Keywords: DEM; GIS; Watershed delineation; Automatic delineation

INTRODUCTION

Catchment area delineation is a process to define the land area whereby all its surface water will eventually flow to a single outlet. (Castronova & Goodall, 2014; Obida et al. 2019). This process benefits various fields, including biology, ecology, infrastructure, flood control, and engineering (Haag et al. 2018; Cacal et al. 2023). It has become so important that the area delineated and the data acquisition process have become fundamental elements in modeling hydrology-related issues. In contrast, the boundary for the catchment area determined is the main component and input for numerous hydrology-based decision support systems (DSS) (Tesfa et al. 2011; Castelli et al. 2022).

Qualitatively, catchment area delineation could help determine the source of pollution in certain polluted rivers. This can be done by checking the activities conducted in the river's catchment area. By doing so, the location and source of pollution could be detected, and further legal action can be taken to prevent the matter from being aggravated. For example, research done by Falconer, Telfer, and Ross (2018) has successfully determined the amount of non-point source pollution in their study area by utilizing a catchment area as the boundary for their study area. In terms of quantitative, it can be observed in most of the manuals that the size of the catchment area and its rainfall intensity are two important factors to consider when designing a drainage system or on-site detention, OSD for a specific construction project.

One of the main functions of catchment area delineation is dam construction. The catchment area must be predetermined before the dam's design and construction. With the increasing dam construction throughout the last few decades, catchment area delineation has also been gaining importance. These dams are usually built to supply water to residents to cater to their crops and daily life usage, generate hydroelectrically, and act as a flood control mechanism (Zarfl et al. 2014; Tang 2020). Although there might be some controversies over the negative impacts of the construction of dam (Kirchherr et al. 2018), the statistics from Renewables 2016 Global Status Report show that the capacity of hydroelectric generated had increased by about 39% from the year 2005 to 2015, which is equivalent to annual growth of 4% (Erias et al. 2016).

Moreover, hydroelectric remained the primary renewable energy source at the end of the year 2015, which comprised up to 70% of the total renewable energy in the world (Raturi, 2015). This is further supported by a Renewables 2018 Global Status Report, saying that the full hydroelectric capacity is expected to increase by 125GW by 2023, and hydroelectric will remain the most significant renewable source of energy by that time (Erias et al. 2016). In summary, the importance of catchment area delineation cannot be underestimated, as it could provide a surge in the field of hydrology if fully utilized.

The process of catchment area delineation can be divided into two main methods: manual delineation and automatic delineation. Traditionally, the catchment area's boundary is manually delineated based on the contour in the topography map. It is a tedious, time-consuming process and requires skilled workers with basic knowledge of how contour works, the natural direction of water flow, and also taking into consideration any man-made feature such as drainage, road, or railways (Han & Hammond 2006; Vrebos 2019; Dibs et al. 2023). On the other hand, automatic delineation provides more advantages. The software can be easily obtained, and most of the required input data can be acquired from open source for free (Kumar & Dhiman, 2014; Datta et al. 2022). According to Baker et al. (2006), automatic delineation also serves as a practical, repeatable, cost-effective, and consistent alternative when a large sample catchment area is needed for assessment (Miller et al. 2021). Automatic delineation required less processing time, and the results also show higher consistency especially involving the earth's surface with higher elevation and more tributaries (Kumar & Dhiman, 2014; Datta et al. 2022).

However, one drawback of automatic delineation is that it requires a type of input data called the Digital Elevation Model (DEM). DEM is electronic data that consists of elevation data of an area. Besides the algorithm used in each software, the accuracy of automatic delineation also depends on the quality of DEM (Khan et al. 2014; Polidori, & El Hage, 2020). Gopinath et al. (2014) also stated that although the process of automatic delineation is faster, the accuracy of watershed delineation is heavily dependent upon the accuracy and quality of DEM used (Munoth & Goyal 2019).

With the current emergence of modern technology, the production of high-resolution DEMs is also increasing. Nowadays, there are different qualities of DEM in the current market, each with other resolution, cost, and availability. Although one may think it is better to use a high-resolution DEM to achieve better results, this often requires higher cost, more extensive storage in the computer, and higher demanding performance (Charrier & Li, 2012; Rocha et al. 2020). Along with other factors to be thoroughly considered, more and more experiments and research have been done from time to time to assist users in selecting an optimum DEM, especially in terms of quality, cost, and availability.

This paper aims to determine the difference in catchment area delineated using Geographical Information System (GIS)-based software with different qualities of

DEM as input, namely Interferometric Synthetic Aperture Radar (IFSAR) DTM, Shuttle Radar Topography Mission (SRTM) DTM, and contour-based DTM. An optimum DEM will be determined based on the result. This paper will also discuss other factors that could affect the accuracy of DEM in catchment area delineation.

METHODOLOGY

SOFTWARE

In this study, ArcGIS software version 10.7 has been chosen to delineate the catchment area automatically. The main reason why this software is being used is it has the most basic and general function or algorithm to generate catchment area based on DEM (Abbas 2023). The system and interface incorporated are also user-friendly. The steps required to create a catchment area are straightforward, and no coding is needed, thus making the repetition process much more manageable. At the same time, the system requirement is also low specification, making it almost compatible with every computer. Last but not least, AutoCAD and Microsoft Excel were also used to aid in data collection and perform any calculations needed.

SOURCE OF RAW DATA

For the input data, as mentioned earlier, three types of data will be used for comparison, namely IFSAR DEM, SRTM DEM, and contour-based DEM. IFSAR DEM was generated from IFSAR data, and the resolution is up to 10 meters x 10 meters (m). On the other hand, contour-based DEM was generated from contour with 20m intervals produced by the Department of Survey and Mapping Malaysia (JUPEM). Both were secondary data acquired from open source and JUPEM, respectively. Lastly, the SRTM DEM was downloaded from the website https://opentopography.org/. This method has advantages in terms of procedures for obtaining data compared to the most common ways used, that is, through the official portal of the United States Geological Survey, USGS, because users do not have to go through the registration and log-in process. SRTM DEM with a resolution of 30m x 30m was used in this study.

STUDY AREA

In this study, catchment areas for three different rivers have been chosen for comparison, including (i) Galas River, (ii) Nenggiri River, and (iii) Lebir River. These rivers are all located in the state of Kelantan, Malaysia. This river spans about 248km and has a catchment area of about 13000km^2, including almost the whole of Kelantan. The vast area covered allows analysis to be done on how the software responds to different environments and how it affects the process of catchment area delineation.

PROCEDURE

Before the modelling process starts, the contour data has to undergo conversion using Topo to Raster tool in ArcGIS software, which converts the contour data to raster or DEM data. After that, the three DEMs underwent a series of steps, such as Fill, Flow Direction, Flow Accumulation, Snap Pour Point, and Watershed. The generated catchment area by each DEM was visualized in ArcGIS software. This process was repeated for three different rivers, as mentioned above. All the results overlapped; therefore, any differences in their shape and size can be observed. These results were exported to AutoCAD to obtain the raw data for statistical calculation, and each coordinate was recorded manually on its boundary. These coordinates were plotted where the y-axis was fixed, and the x-axis was recorded with a constant interval on the y-axis. By doing this, each catchment area corresponding to their respective DEM will have a different x coordinate to compare the differences among each other while having the same y coordinate. During the coordinates extraction, the whole catchment area is further divided into east and west, and a minimum of 50 points were extracted on each side for better results. Finally, statistical calculations were carried out in Microsoft Excel based on these data.

DATA ANALYSIS

Since IFSAR DEM has the highest resolution among the three DEMs, it is considered benchmark during the whole analysis process. The data were analyzed using Equation (1) and Equation (2), as shown below. The percentage difference of area delineated, δA, is defined in Equation (1), where A is the area of watershed delineated using SRTM DEM or contour-based DEM and A_{IFSAR} is the area of watershed delineated using IFSAR DEM. While the root mean square error, RMSE is defined in Equation (2), where X_1 is x coordinate for watershed delineated using SRTM DEM or contour-based DEM, X_2 is x coordinate for watershed delineated using IFSAR DEM, and n is the total number of points extracted.

$$\delta A(\%) = \frac{A - A_{IFSAR}}{A_{IFSAR}} \times 100\% \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_1 - X_2)^2}{n}} \tag{2}$$

In order to examine the factors that could affect the accuracy of DEM during catchment area delineation, the elevation data and stream in the catchment area were also displayed together with the boundary. Analysis based on observation was done to detect the relationship between these geographical factors and the accuracy of DEM.

RESULT AND DISCUSSION

COMPARISON BASED ON OBSERVATION

Figure 1, Figure 2, and Figure 3 show the catchment area of Galas River, Nenggiri River, and Lebir River, respectively, each with elevation data displayed on it. From these results, two main factors that could affect the accuracy of DEM in catchment area delineation were determined based on observation, which are (i) height and shape of terrain in an area and (ii) the proximity of the nearby river to the boundary of the catchment area. For all three locations, catchment area delineation for all three DEMs shows a high level of similarity at high ground or summit compared to low and wide areas. This is because rainwater that drops on the elevated area will have a clear flow path to the nearby river due to the natural surface of the elevated area. In contrast, a flat surface will cause the rainwater to flow slowly and have an uncertain flow path.

Moreover, Mikelonis et al. (2021) mentioned that the vast area also contributed to the increase of possible pathways for stormwater flows and caused the determination of catchment area boundary to be inconsistent. All these factors could be seen in the following places: northwest, southeast of Galas River (Figure 1); south, west, and north of Nenggiri River (Figure 2); southwest, south, southeast, and northeast of Lebir River (Figure 3), where catchment area delineated at these places were quite similar for all three DEMs due to the existence of high grounds or hills. Whereas in some wide and low-lying areas, such as north of Galas River, the catchment area delineated using contour-based DEM slightly differed from the other two DEMs. This is partly due to less prominent features on the earth's surface or flat area and lower resolution than the other two DEMs.

Another factor observed to have caused the inconsistent catchment area delineation is the proximity of the nearby river. Han et al. (2019) and Wahyudi (2019) highlighted in their study that the closer the two rivers, the more restrictive the position or placement of the boundary. That catchment boundary will not cross or overlap with those rivers in any condition. Therefore, by referring to the results, it can be seen that the catchment area delineated from all three DEMs northeast of Nenggiri River and a small part west of Lebir River is very consistent. Conversely, south of Galas River, there is some variance in the boundary delineated among the three DEMs. These phenomena clearly show that the distance of the nearby river could influence the outcome of catchment area delineation.

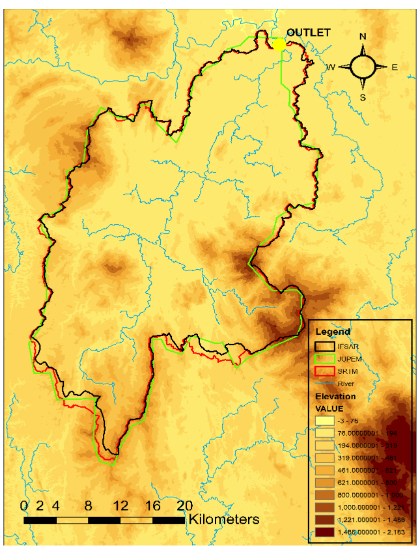

FIGURE 1. Galas River catchment area with elevation data

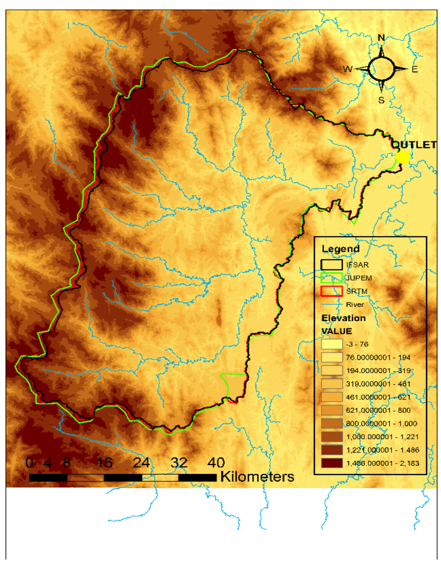

FIGURE 2. Nenggiri River catchment area with elevation data

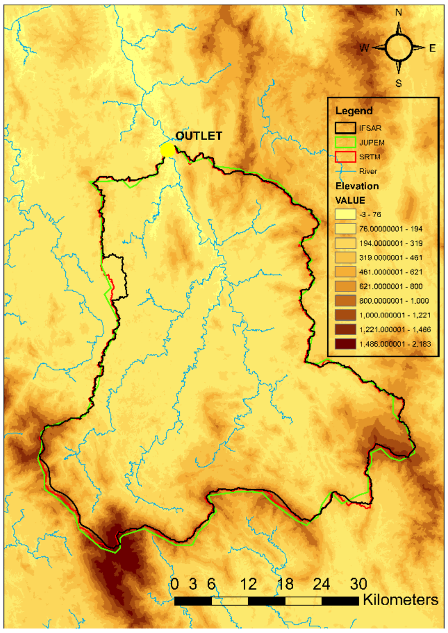

FIGURE 3. Lebir River catchment area with elevation data

PERCENTAGE DIFFERENCE IN AREA DELINEATED

Figure 4 shows the percentage of difference in the area delineated using contour-based DEM and SRTM DEM in each location. It can be seen that at Galas River, the percentage difference in the area delineated by contour-based DEM is much smaller. Still, the opposite trend happened regarding the Nenggiri River and Lebir River. These results do not reflect the different contour-based DEM and SRTM DEM at Galas River. As shown in figure 1, at the northern part of Galas River, contour-based DEM demonstrated that its catchment area differs significantly from the results of IFSAR DEM and SRTM DEM, yet still produces a low percentage difference in the area. This result shows that contour-based DEM and SRTM DEM can be used as alternative sources to create catchment areas due to the low percentage difference in the size of the watershed delineated, which is less than 3.5%. This value provides a general view of how much difference or wide the dispersion between these three data is in line with the research conducted by Fathy et al. (2019). Statistical calculations like root mean square error (RMSE) was performed to determine which data is more accurate.

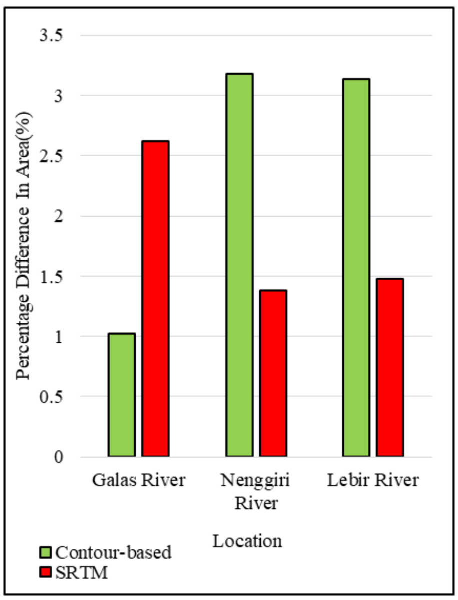

FIGURE 4. Percentage difference in the area in each location

ROOT MEAN SQUARE ERROR (RMSE)

Figure 5 shows the difference in RMSE for contour-based DEM and SRTM DEM in three areas of study. RMSE is an important parameter to be measured because differences at every coordinate on the boundary were calculated and identified, providing more reliable results that could determine better DEM accuracy. From the results, RMSE for SRTM DEM is lower than RMSE for contour-based DEM in every location. A lower RMSE means the accuracy difference between the data (SRTM DEM) and the benchmark data (IFSAR DEM) is more negligible. Also, it can be interpreted as having a high level of competency, as highlighted by Vansarochana (2020). Another additional information that could be noticed is that overall, at Nenggiri River, both contour-based DEM and SRTM DEM recorded the lowest RMSE compared to the RMSE in Galas River and Lebir River. These results parallel the findings obtained while comparing the catchment area delineated through observation. Contour-based DEM and SRTM DEM will show higher accuracy when applied in hilly areas.

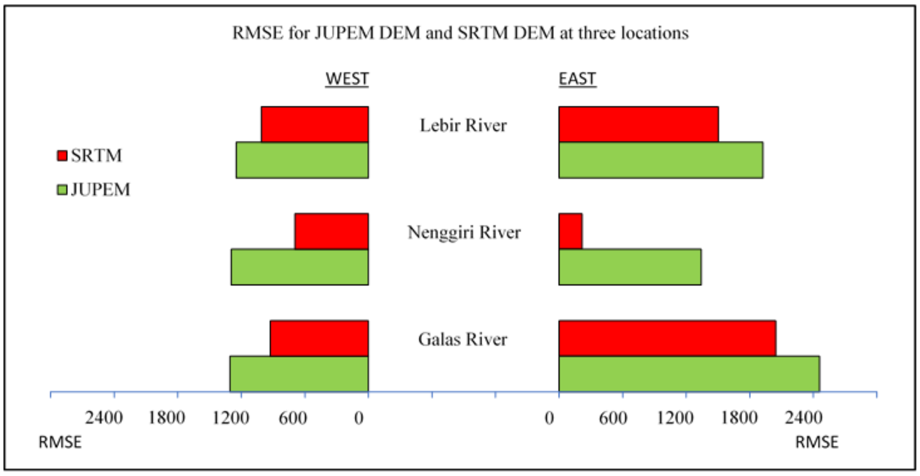

FIGURE 5. RMSE for contour-based DEM and SRTM DEM at three locations

CONCLUSION

As time passes, manual delineation of catchment areas has been slowly replaced by automatic delineation. While this method is often seen as a more efficient and time-saving method, its accuracy relies heavily on the availability and resolution of DEM. From the findings of this study, contour-based 20m DEM data and SRTM 30m DEM are reliable alternatives in catchment area delineation. In terms of optimum selection of DEM as input data for catchment area delineation, it is clear that SRTM DEM is a better choice because it can produce a more precise catchment area compared to contour-based DEM. The fact that SRTM DEM is available for free covers a wide area of nearly 80% of the earth's surface and could produce a catchment area similar to IFSAR DEM, a paid data (Preety et al. 2022). On top of that, SRTM DEM stands out as the optimum choice regarding the accuracy, cost, and availability.

Based on analysis of the results through observation, all three DEMs show a high level of accuracy in hilly areas as well as areas with compact river networks. This indicates that topographic and geographical factors can also determine the accuracy of a DEM during the process of catchment area delineation. However, to get more accurate results, considering IFSAR DEM should be made, especially involving a flat and broad location or a region with an isolated river.

Some suggested improvements are dividing the catchment area into more segments and using more coordinates with smaller intervals on the y-axis for more reliable results. This can be done using specific software to extract the coordinates, making the data collection process faster.

ACKNOWLEDGEMENT

The author would like to thank the Universiti Kebangsaan Malaysia (UKM) for the financial support under research grant GP-K012093 and the Department of Survey and Mapping Malaysia (JUPEM) for guidance.

DECLARATION OF COMPETING INTEREST

None.

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