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Integrating Multiple Geospatial Datasets for Precise and Efficient Surface Water Extent Mapping in Malaysia

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Abstract. Accurate mapping of surface water extent is essential for several applications, including water resources management, climate modelling, biodiversity conservation, agricultural irrigation, hydropower, and food security. Inland water management is critical in Malaysia due to dams, river basins, and heavy rainfall. In a tropical country, mapping surface water is challenging due to cloud cover and dense vegetation. This study proposes an approach that uses rule sets in ArcGIS Model Builder to automate the identification of water bodies. At the regional scale, the extent of surface waters can be mapped by integrating multiple geospatial datasets, including surface terrain, global surface water data, and synthetic aperture radar (SAR) imagery. Accuracy is calculated by comparing the results to high-resolution optical imagery via the SecureWatch® application. The accuracy of 200 stratified random points is 95%, with a kappa value of 0.90 for water body and land area classes. This study maps a 12,563.95 km^2 study area covering several states in Malaysia. These results show that the integration of multiple geospatial datasets using rule sets and data modelling can map the extent of surface waters in Malaysia. The proposed approach could be applied in other tropical countries with similar topography.

1. Introduction

Surface water is the most valuable resource on earth, as it is generally encoded with social, economic, political, and environmental meanings. The global trend shows an increasing frequency of dry rivers, drought, and insufficient water [1]. Regular surface water monitoring and management are vital to sustainably support diverse sectors in Malaysia, including hydroelectric power, agricultural irrigation, flood mitigation, drinking water supply, recreation, and a raw water supply [2]. The temporal condition of surface water can vary from permanent, seasonal, and ephemeral. Surface waters are present in neither natural nor artificial forms of rivers, dams, lakes, springs, wetlands, and swamps. There are recorded 103 dams and 2,986, river basins throughout Malaysia with an average annual rainfall that exceeds 2,000 millimeters making water surface extent monitoring, and management important to maintain the water balance, thus preventing depletion and expansion of the quantity water surface [2, 3].

Malaysia is located at the Southeast Asia composes of two non-contiguous regions called Peninsular Malaysia, and East Malaysia (Sabah and Sarawak) at Borneo Island. In a tropical climate, Malaysia encounters moderate temperatures, high humidity, and year-round consistent rainfall, influenced by both the northeast monsoon and southwest monsoon seasons [4]. Tropical countries typically experience dense cloud coverage. As a result, microwave remote sensing has become a valuable tool for earth observation studies due to its ability to operate during both day and night, as well as in adverse weather conditions, thus enhancing earth observation capabilities [5]. For example, Canada's RADARSAT-2 satellite, with its technical specifications, data acquisition capabilities, and imaging resolution, has surpassed previous generations of radar satellites, making it one of the most complete and advanced in the field today [6].

Various studies have developed different methods to extract surface water. These include approaches such as single-band threshold analysis, use of ratios, spectral correlation techniques, segmentation, rate measurement, knowledge-based rule sets, and the water index method [7].

This study aims to create an innovative and automated method for precisely mapping the extent of surface water in Malaysia, considering the obstacles presented by cloud cover and dense vegetation and offers potential for adaptation in other tropical countries with comparable topography. The proposed method utilizes rule sets within the ArcGIS Model Builder environment to automate the identification and mapping of water bodies. By minimizing the need for manual intervention, this approach significantly enhances the analysis speed while ensuring the utmost accuracy. Consequently, the study aims to integrate multiple geospatial datasets, including the spatial terrain data, global surface water data, and Synthetic Aperture Radar (SAR) imagery from RADARSAT-2. This study seeks to accomplish two primary goals which are assessing the extent of regional-scale surface water within the study area and validating the accuracy of the final map classification product.

2. Study Area and Data Sources

In this section, we provide an overview of the geographic area under study and the diverse geospatial datasets utilized, emphasizing their importance and relevance to our research.

2.1. Study Area

The study area, spanning approximately 12,563.95 square kilometers, is at a regional scale and encompassed multiple states, including the northern part of Perak, Kelantan, and Terengganu. It bordered the southern part of Thailand and covered coordinates ranging from 5°50'41.892"N to 5°28'33.355"N latitude and 100°56'2.46"E to 102°31'20.741"E longitude (see figure 1). Notable features within the area include Temengor Dam in Perak, Bukit Kwong Dam, and Danau Tok Uban Lake in Kelantan. Two primary national forest reserves are situated within the study area, including the Royal Belum State Park located in Perak and the Gunung Stong State Park situated in Kelantan. Additionally, four major rivers, namely Perak River in Perak, Semerak and Kelantan Rivers in Kelantan, and Besut River in Terengganu, traversed the study area. The research area comprises a variety of land types, including wooded areas, lakes, grass fields, population settlements, urban areas, open land, scrublands, and agricultural areas, including oil palm and paddy, making it important for the socioeconomics.

Figure 1. The study area covers the entire scene of RADARSAT-2, situated in the northern regions of Perak, Kelantan, and Terengganu states, which share borders with southern Thailand. (RADARSAT-2 data and product © Maxar Technologies Ltd., 2020 – All rights reserved. RADARSAT is an official mark of the Canadian Space Agency).

2.2. Satellite Imagery

The RADARSAT-2 (R-2) is an operational satellite that was successfully launched on December 14, 2007. The RADARSAT-2 satellite is a collaborative effort between two entities, the Canadian Space Agency (CSA) and Maxar Technologies Ltd., formerly known as MacDonald, Dettwiler and Associates (MDA). It orbits in a sun-synchronous path at an altitude of 798 km, with an orbit period of 100.7 minutes and an inclination of 98.6 degrees [8]. RADARSAT-2 expands data product options beyond RADARSAT-1, introducing new modes such as quad-polarization and ultra-fine resolution. It also provides options for single and dual-polarization within the existing beams, utilizing the C-band microwave wavelength at a frequency of 5.4 GHz [9]. This enables the capture of crucial Earth observation data.

In this study, a single scene of a RADARSAT-2 extra-fine resolution beam mode is utilized to extract water bodies. RADARSAT-2's finer resolution beam mode enables wider observation coverage with a small angle of aim, maintaining high spatial resolution. However, it employs higher data compression ratios, which can result in increased noise levels [10].

The expert report [11] confirms that utilizing the SAR image beam mode with fine resolution and wide coverage provides substantial benefits for accurately mapping water in expansive areas. The report highlights the value of the horizontal-horizontal (HH) polarization mode in distinguishing between forested regions and submerged areas, as it effectively penetrates through tree cover. By selecting the HH polarization, researchers can achieve a higher level of accuracy in identifying and delineating flooded areas within the study region. Table 1 shows the detailed parameters of this RADARSAT-2 imagery.

Table 1. Parameters of RADARSAT-2 imagery.

Parameter	Description
Id	20201222_112154_XF0W1_HH
Beam mode	Extra fine (XF0W1)
Orbit	Ascending
Resolution (m)	3.125 m
Polarization	HH
Acquisition date and time (UTC)	2020-12-22T11:21:54.404602Z
Acquisition date and time (Local)	2020-12-22T19:21:54.404602H

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2.3. Topographical Data

The Shuttle Radar Topography Mission (SRTM) took place over an eleven-day period from February 11 to February 22, 2000. This mission utilized radar interferometry techniques and involved a collaborative effort among three nations, namely the United States, Germany, and Italy [12-14]. The SRTM data is available in two levels of spatial resolution, namely 90m (3-ARC) and 30m (1-ARC), with a vertical accuracy of 16m and a horizontal accuracy of 20m. The horizontal datum used is the WGS84 ellipsoid, and the vertical datum is the Earth Gravity Model 1996 (EGM96). These data can be accessed and downloaded from the website https://earthexplorer.usgs.gov/ belonging to the U.S. Geological Survey (USGS). For this study, six terrain raster tiles were utilized, and table 2 presents the terrain data parameters used.

In this study, SRTM 30m data (1-ARC) are used for analysis to assist the surface water extraction model for accurately removing false surface water detection from R-2 SAR imagery, especially in the hilly area where radar foreshortening and the layover exist at steep mountainous terrain due to relief displacement.

Table 2. The terrain data parameter.

Parameter	Description					
Entity id	SRTM 1N05E 100V3	SRTM 1N05E 101V3	SRTM 1N05E 102V3	SRTM 1N06E 100V3	SRTM 1N06E 101V3	SRTM 1N06E 102V3
Coordinate	5, 100	5, 101	5, 102	6, 100	6, 101	6, 102
Acquisition date	2000-02-11 00:00:00-06					
Publication date	2014-09-23 00:00:00-05					
Resolution	1-Arc (30 meters)					
Projection	Geographic					
Horizontal datum	WGS84					
Vertical datum	EGM96 (Earth Gravitational Model 1996)					
Vertical units	Meters					
Raster size	1-degree tiles					
C-band wavelength	5.6 cm					

2.4. The Dataset of Global Surface Water

The dataset pertaining to global surface water (GSW), a creation of The European Commission's Joint Research Centre under the Copernicus Program, has played a pivotal role in providing support for this study. This dataset encompasses a global scale and is accessible through the website https://global-surface-water.appspot.com. It is the result of meticulous documentation and production, involving the identification of surface water locations and their seasonality through inventories, national descriptions, statistical extrapolation of regional data, and the analysis of three million Landsat satellite images spanning a period of over 32 years [15]. The GSW dataset serves as a valuable resource for this study, providing control, guidance, and assistance in the extraction of surface water using R-2 imagery. Specifically, we utilized the transitions in surface water class 1984-2015 product, which was subset to focus solely on our study area. Table 3 provides detailed information regarding the dynamic nature of surface water classes.

Table 3. Description of transition in the surface water class 1984-2015 product.

Label Number Id	Class of Surface Water Dynamic	Description
1	Permanent	No change
2	New permanent	Conversion of land into permanent water
3	Lost permanent	Conversion of permanent water into land
4	Seasonal	No change
5	New seasonal	Conversion of land into seasonal water
6	Lost seasonal	Conversion of a seasonal water into land
7	Seasonal to permanent	Conversion of seasonal water into permanent water
8	Permanent to seasonal	Conversion of permanent water into seasonal water
9	Ephemeral permanent	Land replaced by permanent water that subsequently disappears
10	Ephemeral seasonal	Land replaced by seasonal water that subsequently disappears

2.5. SecureWatch® Imagery
The SecureWatch® application is an online service that offers access to high-resolution satellite images of any desired location, requiring a subscription for usage. This system operates on a secure cloud-based platform, ensuring robust security for users' data [16]. A Maxar satellite imagery can be viewed and accessed via ArcGIS by the ESRI platform with some security login. SecureWatch® service allowed the user to identify the best available images for any area of interest. The optical satellite image data accessible through the service includes a diverse array of sources, encompassing satellite images from WorldView-1 to WorldView-4, GeoEye-1 satellites, and other external sensors. SecureWatch® Imagery service allowed the user to identify the best available images for any area of interest.

3. Methodology
Figure 2 shows the flow of methodology to extract the surface water extent.

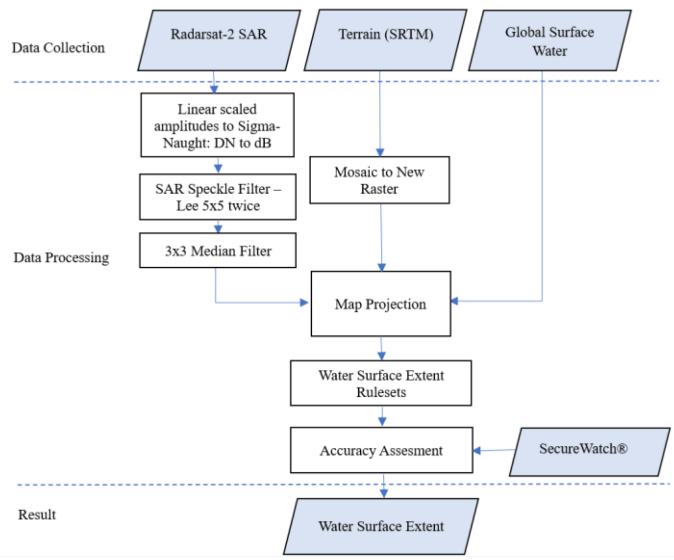

Figure 2. Overall workflow implemented to extract the water surface extent used for this study.

A detailed explanation of the workflow is provided in the following sections.

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3.1. Linear Scaled Amplitudes to Logarithmic Decibel (dB)

The initial step of data processing involves converting the R-2 backscatter into logarithmic decibels (dB) and representing the ground range instead of the slant range. The R-2 SAR backscatter data is stored as 16-bit unsigned integer values, utilizing a linearly scaled amplitude scale known as amplitude digital number (DN) [17]. These DNs need to be converted to a proper backscatter per unit area value of sigma-naught (σ˚), which can be expressed in either square meters per square meter (m^2/m^2) or logarithmic decibels (dB) [18].

Equation (1) presents the standard formula for converting the linearly scaled backscatter amplitudes to dB. This equation is used when the data is provided in linearly scaled backscatter amplitudes. By applying equation (1), the linearly scaled backscatter amplitudes can be transformed into logarithmic decibels (dB), which is a common representation for radar backscatter data.

$$\sigma^{\circ}(\mathrm{dB}) = 10 * \log_{10}(DN)^2 + K \quad (1)$$

Equation (2) is used when the data is provided in backscatter power. In this case, the backscatter power can be calculated using $DN_{power} = (DN_{amplitude})^2$, where DN_{power} represents the backscatter power and $DN_{amplitude}$ represents the backscatter amplitude. By utilizing equation (2), the backscatter power values can be obtained from the given amplitude data, enabling further analysis and interpretation.

$$\sigma^{\circ}(\mathrm{dB}) = 10 * \log_{10}(DN) + K \quad (2)$$

The DN represents the digital number for SAR amplitude image, and K is a calibration factor that varies depending on the SAR sensor type and processor system used for the study. For the R-2 SAR image, the calibration factor is -71.33 dB [19].

In this study, we exclusively employed PCI Geomatica EASI scripts to convert linear scaled amplitudes to decibels (dB). These automated scripts were specifically developed by MDA for the purpose of RADARSAT-2 image processing by the Malaysian Space Agency.

3.2. Speckle Noise Filtering and Smoothing

Speckle noise filtering is a crucial method for effectively removing unwanted speckles from SAR images, thereby safeguarding the accuracy of image classification tasks [20]. In this study, we applied the Lee filter with a kernel window size of 5x5 to perform two rounds of speckle noise filtering on the R-2 SAR image, ensuring the successful elimination of speckles from the image. Additionally, we performed a single pass of medium filtering using a 3x3-kernel window size to enhance the overall smoothness of the image's appearance [21]. Figure 3 illustrates the comparison between the R-2 SAR image before and after the application of a speckle noise filtering and smoothing process. The filtered image successfully enhances the water body features using this technique.

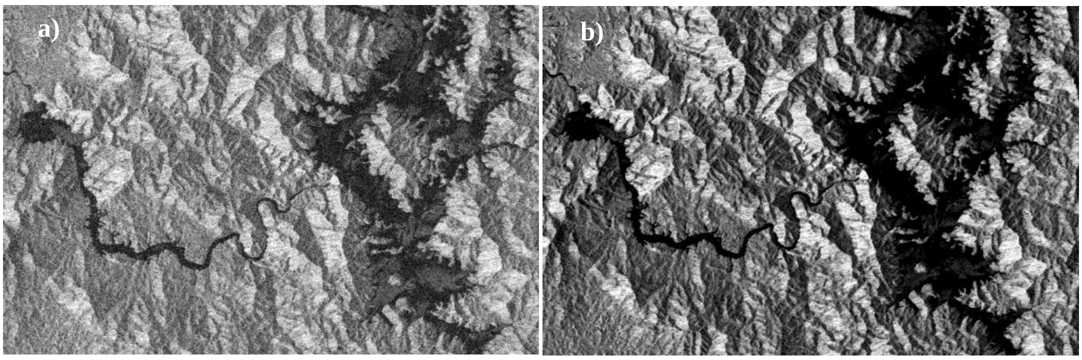

Figure 3. a) Original logarithmic decibels RADARSAT-2 SAR image with speckle noise (salt and pepper effect). b) Logarithmic decibels RADARSAT-2 SAR image after successful speckle noise

filtering. (RADARSAT-2 data and product © Maxar Technologies Ltd., 2020 – All rights reserved. RADARSAT is an official mark of the Canadian Space Agency).

3.3. Mosaicking
Image mosaicking merges the multiple adjacent raster datasets or overlapping images into a unified and larger composite image [22]. To create a comprehensive terrain raster dataset for the study area, data from all six terrain raster tiles was merged using the mosaic technique. This process resulted in the creation of a new and expanded terrain raster dataset.

3.4. Define Map Projection
As part of this study, it is essential to apply the map projection process to all the spatial data used. This ensures that distance, area, and volume calculations can be accurately performed on the spatial product [23]. They are of utmost importance for various applications in the field of spatial data analysis and visualization. In this phase, the main objective is to ensure the usability, precise alignment, and consistency of several spatial datasets that include RADARSAT-2 SAR (R-2) imagery, terrain, and global surface water. This focus is particularly important for a very large study area covering an area of approximately 12,563.95 square kilometers. Table 4 illustrates the careful definition of all datasets using the Rectified Skew Orthomorphic (RSO) projection, which was essential to achieve the desired results.

Table 4. Map projection parameter.

Parameter	Description
Projected coordinate system	Kertau RSO Malaya Meters
Projection	Rectified Skew Orthomorphic Natural Origin
False easting (m)	804671.29977500
False northing (m)	0.00000000
Scale factor	0.99984000
Azimuth	-36.97420944
Longitude of center	102.25000000
Latitude of center	4.00000000
XY plane rotation	-36.86989765
Linear unit	Meter
Geographic coordinate system	GCS Kertau
Datum	Kertau
Prime meridian	Greenwich
Angular unit	Degree

3.5. Rulesets for Waterbody Identification
In this study, a rule-based approach is employed to extract the surface water extent from R-2 SAR imagery. These extracted features are then merged with the SRTM and GSW datasets. For accurate representation of the surface water extent in the study area, careful selection of thresholding values is performed for each dataset. The developed rulesets for extracting surface water extent can be found in table 5.

Table 5. Rulesets developed to extract the surface water extent.

No.	Dataset	Rules
1	Ruleset for extract surface water extent from RADARSAT-2 (R-2) SAR	HH band <= -13 dB

No.	Dataset	Rules
2	Ruleset for extract surface water extent from terrain (SRTM)	Height <=700 m
3	Ruleset for extract surface water extent from Global Surface Water (transitions in surface water class 1984–2015)	1< Transitions Type <=10

The process of automating waterbody identification and mapping in Malaysia involved the utilization of rulesets within the ArcGIS Model Builder environment. This approach provides an innovative and efficient solution, reducing the need for manual intervention and improving analysis speed. Following rule validation, a model was created in ArcGIS Model Builder to facilitate various processing steps, such as attribute selection, mathematical operations (including Boolean operations), reclassification, raster to polygon conversion, and dataset merging (refer to figure 4). Multiple test runs were conducted to achieve the desired confidence level. Subsequently, the integration of multiple geospatial datasets was performed, resulting in the generation of the final surface water extent product.

3.6. Water Surface Extent Validation

In this study, the final product, which includes surface water extent and land classification, undergoes a thorough accuracy assessment to ensure it meets predefined standards for reliable use in various sectors and applications. This emphasizes the significance of employing appropriate methodologies [24, 25]. The results from this study are validated against a high-resolution optical imagery. The accuracy assessment uses the confusion matrix (or error matrix) method, which compares the product to the ground truth to demonstrate its accuracy. The ground truth input for the assessment includes two hundred stratified random ground control points (GCPs), with one hundred points allocated for the water and land area classes in the study area. The GCPs used in this study were extracted from optical imagery products with high spatial resolution (<50cm pixel size). These products include satellite images from WorldView-1 to WorldView-4, GeoEye-1 satellites, and other external sensors accessed through the SecureWatch® application. The error matrix is a widely accepted and frequently used technique for assessing the accuracy of thematic maps [26]. The matrix calculates the percentage of overall accuracy, the user's and producer's accuracy for each class, and the kappa coefficient. Kappa coefficient is a measure of the comparison between the results of the classification compared the values attributed. When the value of the kappa coefficient is high, it indicates a higher level of classification accuracy. From there, we know how many actual results match the predicted results. Figure 5 displays the complete distribution of two hundred stratified random points, with one hundred points allocated for each class in the study area. The points are evaluated against SecureWatch® imagery to assess the accuracy of the ground truth.

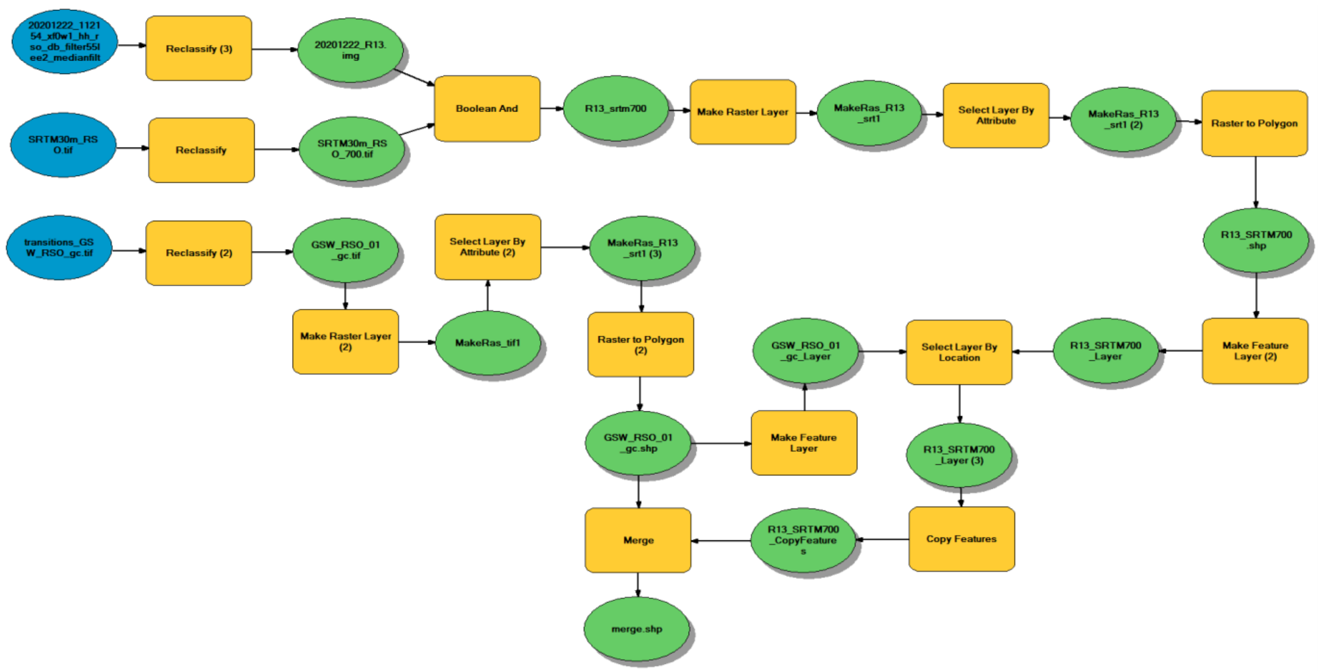

Figure 4. Surface waterbody identification rulesets created in ArcGIS Model Builder.

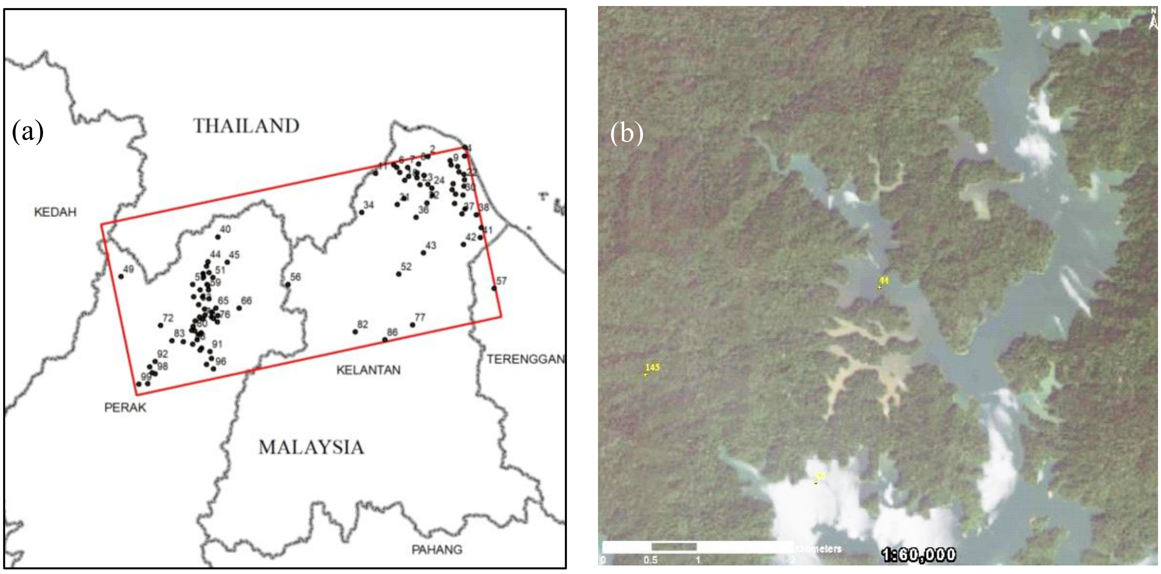

Figure 5. (a) Sample point distribution for conducting accuracy assessment within the study area. (b) Zoom-in SecureWatch® imagery of Worldview-2 dated December 20, 2021, for sample points id no. 44, 46 and 145 at the northern part of the Temengor lake, Perak. (© Maxar Technologies Ltd., 2021 – All rights reserved).

4. Result and Analysis

The findings of this study comprise two distinct outputs. The first output entails the results obtained from the extraction of surface water extent and land area. The second output encompasses the results of the accuracy assessment analysis.

4.1. Surface Water Extent and Land Area Extraction

The study employed proposed rulesets and data integration modelling approaches to effectively extract the surface water extent and land area in the designated study area. However, it is important to note that further data validation is required, which will be elaborated upon in the subsequent subtopic. Nevertheless, based on visual inspection of the results, it is evident (as depicted in figure 6) that the major reservoirs (Kenering, Temengor, Pergau, Bukit Kwong, and Danau Tok Uban Lake), rivers (Perak River, Semerak River, Kelantan River, and Besut River), and wet-paddy fields within the study area were successfully extracted. Table 6 shows the calculated extent area for all the major reservoirs that exist within the study area.

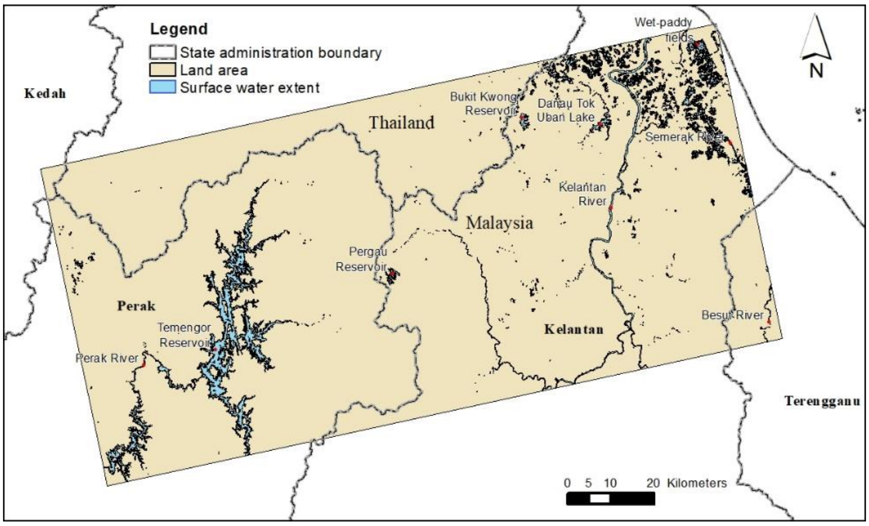

Figure 6. Extracted the surface water extent (in blue) and land (in brown) over the study area.

Table 6. Surface extent area for reservoirs within the study area.

Reservoir/ Lake	Area (km^2)
Kenering	32.80
Temengor	182.59
Pergau	3.51
Bukit Kwong	3.76
Danau Tok Uban	5.04

Table 6 presents data on the surface extent areas of five reservoirs in the study area. Temengor stands out as the largest, covering 182.59 square kilometers and serving as a crucial water source. In contrast, Pergau, which is an electricity dam, and Bukit Kwong are smaller with areas of 3.51 and 3.76 square kilometers, respectively, but still essential for local water supply, agriculture, and the environment [27]. However, larger reservoirs like Temengor can cause habitat loss and ecological changes, necessitating careful management [28]. Balancing water demand, conservation, and community needs is crucial when considering reservoir surface extent.

4.2. Accuracy Assessment

Table 7 summarizes the confusion matrix of the extracted water surface extent and the land area, respectively. The accuracy analysis involves comparing the final classification results with high-resolution images obtained from the SecureWatch® application, utilizing over 200 Ground Control Point (GCP) samples within the study area. From the results in table 7, it was found that the overall accuracy and the kappa statistics of the extracted water and land features are impressively high, with an overall accuracy of 95% and a Kappa Coefficient of 0.90, respectively. The Producer's Accuracy and User's Accuracy were also calculated to assess the model's performance.

Producer's accuracy (PA), also known as sensitivity, represents the ability of the classification model to correctly identify samples that belong to a specific class by measuring the proportion of correctly classified pixels or samples in the ground truth data for a particular class [29]. Meanwhile, user's accuracy (UA), also known as precision, reflects the accuracy of the model from the user's perspective by measuring the proportion of correctly classified pixels or samples for a specific class in the model's prediction [30]. For the "Surface Water Extent" class, the producer's accuracy was found to be 100%, indicating that the model correctly identified all samples representing surface water from the ground truth data. However, the user's accuracy for this class was 90%, suggesting that when the model predicted a pixel to be surface water, it was accurate 90% of the time. The slightly lower user's accuracy may indicate some misclassifications or false positives, which may require further investigation to improve the model's accuracy. On the other hand, for the "Land Area" class, the producer's accuracy was 90.90%, indicating that the model effectively identified 90.90% of the samples representing land areas. The user's accuracy for this class was an impressive 100%, indicating that all the pixels classified as land areas by the model were indeed land areas.

Kappa coefficient or kappa statistics, also known as Cohen's kappa or simply kappa, is a measure of inter-rater agreement or reliability for categorical data [31]. It is commonly used to assess the agreement between two or more raters or classifiers when they assign items into discrete categories. Kappa is particularly useful when evaluating the performance of classification algorithms, such as those used in remote sensing for land cover mapping. Kappa values shows in table 7 is 0.90 which is greater than 0.8 indicate very good to excellent agreement.

These results demonstrate that the developed approach is effective for determining the extent of surface water in Malaysia. The high overall accuracy and Kappa Coefficient validate the reliability of the classification process. However, to further improve the model's accuracy, it is essential to address the misclassifications in the "Surface Water Extent" class. Overall, the classification results provide valuable information for environmental monitoring and resource management, facilitating better decision-making in various remote sensing applications.

Table 7. Confusion matrix for classification result.

Class	Producer's Accuracy (PA)	User's Accuracy (AC)
Surface water extent	100%	90%
Land area	90.90%	100%
Overall accuracy	95%	
Kappa coefficient	0.90	

5. Conclusion

In conclusion, this study accurately determined the regional-scale extent of surface water in the northern regions of Perak, Kelantan, and Terengganu states in Malaysia. The findings provide valuable insights into the distribution and characteristics of surface water in this area. By integrating terrain data, global surface water data, and SAR imagery from RADARSAT-2 using rulesets in ArcGIS Model Builder, we developed an innovative and efficient approach to overcome challenges associated with tropical environments, such as cloud cover, vegetation, and dense canopy. This automated method successfully identified and mapped water bodies with an impressive 95% overall accuracy and a kappa value of 0.90, validated against high-resolution optical imagery.

As a suggestion for future research, we recommend incorporating multitemporal SAR imagery and proposing a water surface elevation study using SAR altimeter for inland water analysis. This approach can help analyse water dynamics under different climatic conditions, such as the northeast and southwest monsoons, which significantly impact Malaysia annually. This further research will enhance our understanding of surface water patterns in tropical areas and contribute to improved water resource management and environmental planning.

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