IMPROVEMENT OF OPEN-SOURCE SATELLITE DATA FOR LAND COVER AND FLOOD MAPPING IN THE KELANTAN RIVER BASIN, MALAYSIA

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by

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${\beta^0}_i$	Radiometrically calibrated backscatter value proportionally to the nominal vertical plane
Υ_i	Radiometrically calibrated backscatter value proportionally to the nominal height
${\sigma^0}_i$	Radiometrically calibrated backscatter value proportionally to the nominal horizontal plane
σ°	Backscatter coefficient
$\vec{P}$	Earth ellipsoid radius at the point below the satellite
$\vec{S}$	Satellite position vector
$\vec{V_s}$	Satellite velocity vector
$\vec{V_T}$	Backscatter velocity vector
c	Speed of light
$C\alpha$	Constant value derived from the standard normal distribution corresponding to the applied confidence level 100 (1 – α) %
dB	decibel
DN	Digital number
f	Flattening factor of the ellipsoid
f_0	Radar frequency
f_D	Doppler frequency
F_r	Range sampling rate
h	Local target elevation relative to the ellipsoid
k	Kappa coefficient
l_d	Difference image
N	Number of observations
n	Number of observations in the sample
n_i	Noise in the LUT found by bilinear interpolation
PRF	Scanner pulse repetition frequency

Q	Sen's slope
R	Range
R_e	Equatorial Earth radius
r	Pearson's correlation
RF	Rainfall
S	MK test statistics
t	Single way travel time for the SAR antenna to reach the first range pixel and the sample
t_a	Azimuth time
Tmax	Maximum temperature
Tmin	Minimum temperature
x	Observations
$\mathbb{Z}$	Significance of the statistics trend
(l, s)	Image coordinates

LIST OF ABBREVIATIONS

ALOS-PALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
AVHRR	Advanced Very High Resolution Radiometer
CGLS	Copernicus Global Land Services
DEM	Digital Elevation Model
ESA CCI	European Space Agency Climate Change Initiative
ECEF	Earth-Centered Earth-Fixed
FAO	Food and Agriculture Organization
FROM-GLC	Finer Resolution Observation and Monitoring – Global Land Cover
GAUL	Global Administrative Unit Layers
GEE	Google Earth Engine
GLASSGLC	Global Land Surface Satellite Climate Data Records Global Land Cover
GRD	Ground Range Detected
HH	Horizontal-Horizontal
IPCC	Intergovernmental Panel on Climate Change
JERS-1	Japanese Earth Resources Satellite
KRB	Kelantan River Basin
LC	Land Cover
LULCC	Land Use and Land Cover Change
LUT	Look Up Table
MK	Mann-Kendall
MMD	Malaysia Meteorological Department
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NOAA	National Oceanic and Atmospheric Administration
POK	Pixel-object-knowledge-based
RADARSAT	Canadian Space Agency Earth-imaging Radar Satellite
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
UN	United Nations
VV	Vertical-Vertical

LIST OF APPENDICES

PENAMBAHBAIKAN DATA SATELIT SUMBER TERBUKA UNTUK PEMETAAN LITUPAN TANAH DAN BANJIR DI LEMBANGAN SUNGAI KELANTAN, MALAYSIA

ABSTRAK

Pemahaman interaksi antara proses hidroklimatik dan guna tanah/pelitupan tanah (LULC) adalah penting untuk keberkesanan pengurusan risiko banjir dan penyesuaian iklim, terutamanya dalam lembangan tropika yang kekurangan data seperti di Lembangan Sungai Kelantan (KRB) Malaysia. Kajian ini bertujuan untuk meningkatkan kebolehgunaan produk pelitupan tanah *European Space Agency* (ESA) *Climate Change Initiative* (CCI) untuk penilaian kesan hidroklimatik dengan meyepadukan dataset pelitupan tanah dari sumber terbuka yang lain, serta mengkaji hubungan perubahan pelitupan tanah dengan pembolehubah iklim. Kajian ini dijalankan dalam tiga fasa. Dalam fasa pertama, peta pelitupan tanah ESA CCI telah diselaraskan dan digabungkan dengan *Copernicus Global Land Service* (CGLS), *Global Land Surface Satellite global land cover* (GLASSLC), *Finer Resolution Observation and Monitoring of Global Land Cover* (FROM-GLC), dan data ESRI2020 dengan klasifikasi semula dan penilaian ketepatan data dan seterusnya menjana peta pelitupan tanah yang diperbaiki dengan data yang lebih tinggi ketepatannya di KRB. Peta pelitupan tanah ini seterusnya dijadikan input untuk analisis perubahan pelitupan tanah. Bagi fasa kedua, model pemetaan banjir dibangunkan dengan menggunakan data satelit Sentinel-1 SAR yang tersedia pada platform *Google Earth Engine* (GEE) untuk mengesan kawasan yang terjejas banjir sewaktu musim tengkujuh. Bagi fasa ketiga pula, analisis statistik telah dijalankan untuk mengkaji hubungan antara perubahan pelitupan tanah dan perubahan iklim dari segi perubahan hujan dan suhu dianalisis dengan menggunakan pendekatan Korelasi Pearson untuk tahun 1992 hingga 2018. Dataset pelitupan tanah yang dibaiki menunjukkan bahawa penggabungan dataset lain meningkatkan ketepatan peta pelitupan tanah ESA CCI sebanyak 11.5%. Dalam tempoh kajian ini, kawasan pertanian di KRB menurun sebanyak 327.28 km^2, manakala kawasan hutan dan bandar meningkat sebanyak 320.94 km^2 dan 16.49 km^2. Pemetaan kawasan banjir dalam kajian ini mencapai ketepatan 57.6% untuk tahun 2014 dan 60.0% untuk tahun 2021. Secara umumnya, taburan hujan, suhu maksimum, dan suhu minimum di KRB menunjukkan trend peningkatan secara keseluruhan, walaupun hujan tahunan yang tidak tetap dari tahun 1979 hingga 2018. Suhu minimum menunjukkan trend peningkatan yang lebih ketara berbanding suhu maksimum. Perluasan aktiviti pertanian menyumbang kepada peningkatan trend hujan dan suhu maksimum, manakala penebangan hutan dikaitkan dengan kenaikan trend suhu minimum di dalam lembangan. Tuntasnya, kajian ini menyumbang kepada pembangunan pendekatan geospatial yang lebih baik dengan data sumber terbuka untuk pemantauan banjir dan menyediakan asas untuk membuat keputusan berasaskan bukti dalam lembangan sungai yang sensitif iklim.

IMPROVEMENT OF OPEN-SOURCE SATELLITE DATA FOR LAND COVER AND FLOOD MAPPING IN THE KELANTAN RIVER BASIN, MALAYSIA

ABSTRACT

Understanding the interactions between land cover and hydroclimatic processes is essential for effective flood risk management and climate adaptations, especially in data-scarce tropical basins like the Kelantan River Basin (KRB) in Malaysia. This study aims to improve the applicability of the European Space Agency (ESA) Climate Change Initiative (CCI) land cover product for hydroclimatic impact assessment by integrating multiple open-source land cover datasets and examining their relationship with climate variables. The study was conducted in three phases. First, the ESA CCI land cover maps were harmonized and merged with suitable Copernicus Global Land Service (CGLS), The Global Land Surface Satellite global land cover (GLASSLC), Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) and ESRI2020 data through spatial reclassification and accuracy assessment to generate an improved land cover product tailored for KRB where the data is used for land cover change assessment for the region. Secondly, a rapid flood inundation mapping model was developed using Sentinel-1 SAR data on the Google Earth Engine (GEE) platform to detect flood-affected areas during selected monsoonal events. Third, statistical analyses were conducted to examine the relationship between land cover changes and climatic changes in terms of rainfall and temperature was analyzed using the Pearson Correlation approach for years 1992 to 2018. The improved land cover datasets showed that merging other datasets improved the accuracy of the ESA CCI land cover maps by 11.5%. During the study period, agriculture land of the KRB decreased by 327.28 km^2, while forest and urban land increased 320.94 km^2 and 16.49 km^2. The flood inundation mapping in this study achieved accuracy of 57.6% for 2014 and 60.0% for 2021. In general, rainfall, maximum and minimum temperatures of the KRB reveals an overall increasing trend, despite the irregular annual rainfall from 1979 to 2018. Minimum temperature has shown a more pronounced increasing trend compared to the maximum temperature. The expansion of agricultural activities contributed to increased rainfall and maximum temperature trends, while deforestation was associated with a rise in minimum temperature trends within the basin. Overall, this study contributes to the development of better geospatial tools for flood monitoring with open source data and provides a foundation for evidence-based decision-making in climate-sensitive river basins.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Climate change is a significant global event in the recent decade in which the variations of the current and future weather patterns that is challenging to the ecology, environment, and socio-economy (Abbass et al., 2022; Abungba et al., 2020). Climate change can be observed through the increasing of the surrounding temperature, as well as the consequences in terms of rainfall variability and water availability (Thakur et al., 2020). The variation of the global land and ocean between 1983 – 2012 was the warmest in the past 800 years (IPCC, 2021a), that lead to extreme weather events and increased number of warm days and nights between 1951 – 2010 (Tang, 2019). The IPCC Sixth Assessment Report of the Intergovernmental Panel on Climate Change reported that the frequency and intensity of extreme precipitation has increased significantly in the past few decades (IPCC, 2021b), where there is more heat wave events in the Europe, Asia and Australia in the mid-20th century, and intensified flood events in the eastern Asia, northern and central Europe, and the western Mediterranean during the past five centuries (Avashia et al., 2020; IPCC, 2019).

Climate change has been discussed as the topic to cater the 13th goal – Climate Action in the Sustainable Development Goals by the United Nations (UN, 2021). The UN urges the country members to take urgent action to combat climate change and its impacts, where there is scientific evidence and future climate projections predicted that the intensifying extreme climate events would lead to the increase 40% of medium–to–large scaled natural disasters from year 2015 to 2030 (UN, 2015). Besides that, the warming climatic system could affect the availability of livelihood necessities, i.e., freshwater, food security, and energy source, where the impact will be more severe in the developing countries.

1.1.1 Climate Change

Climate change is a long-termed weather conditional variation. Scientists have proven climate change is an on-going process that happen globally statistically, and the key factors that leading the change is an issue that is often discussed (Tang, 2019). As climate change triggers the hydrology cycle on the earth, the implications of hydrological disaster that caused from the changing climate is gaining much more attention in the recent years, particularly in the tropical region.

There are two major hydro-climate disasters affecting the sustainability of livelihood in the tropical region – drought and flood (Tan et al., 2017). Over the last few decades, the variations of hydroclimate have brought severe disasters and the cause of the severity of the disasters often related to the anthropogenic changes in the area. Scientific studies have proven that the variations of hydroclimate in multiple interacting temporal scales are comparable to the magnitude of anthropogenic induced climate change, on decadal timescales (Stevenson et al., 2022). Thus, the construction of the relationship between the magnitudes of hydro-climatic variations and anthropogenic changes in each basin is important for solution and decision making to resolve the environmental issue in the urban planning (Nusrat, 2018).

Analyses of global hydro-climatic variations is the science of hydro climatology, while the analyses of hydro-climatic variations in watershed or smaller basin scales are much valuable continues to grow in importance (Koster et al., 2017). There is always a need for advancing researches to understand the hydroclimate changes in contemporary watersheds as changes on the land use can affect the mitigation strategies (Zeiger et al., 2018).

1.1.2 Flood

As the climate change has impacts on the magnitudes of the hydro-climatic variations, the combination of other factors that driving the ecological change of the environment is yet to be discovered for the global initiatives to fight climate change. Several studies done have been concluded that changes in temperature, moisture variability, hydrological changes and land use changes are the major contributor to the environmental change across the globe.

There are significant increasing trends on the number and intensity of extreme precipitation during the past decades, where this could led to more severe floods in the future (IPCC, 2021b). Flood has been listed as one the most damaging natural disaster globally, with a total of 5608 extreme flood events recorded from 1906 to 2021 worldwide (EM-DAT, 2022). The overall damage that these flood events caused about 7 million losses of lives, while affecting 3.9 billion people and total damage losses of USD 953 billion globally.

Generally, flood is a natural event when there is overflow of water from the river, lake or ocean submerging the land within the catchment area, or accumulation of excessive water resulted from the heavy precipitation. Flood occurrence is not avoidable, but it can be predicted, and protection facilities can be done to manage the destruction of the disaster (Mengistu et al., 2022). Accurate flood prediction is crucial to reduce the loss of resources and lives, hence, evaluation of the flood occurrence as well as the flood management studies has been categorized as the primary concern in flood related hydro-climatic studies.

1.2 Problem Statement

Accuracy of the hydro-climatic studies highly depending on the precision of the recorded hydro-climate data and information, particularly in rural areas (Mengistu et al., 2022). The global-scale hydro-climatic modelling requires gridded models of observed meteorological data derived data, that available for decades (Stevenson et al., 2022). Nevertheless, the availability of free and open-source hydro-climatic and land cover products enables more studies to explore the hydro-climatic dynamics worldwide. However, the coverage and quality of the data is a particular concern when using open data in analysis.

Loss of forest associated urban expansion is closely related to the occurrence of flood (Nusrat, 2018). Land cover data on a temporal scale is required for land cover change studies, at which detailed land cover data is a confidential data in most of the countries in the world. Hence, the availability of various open-sourced land cover data solved the limitations on studying data-limited areas. The open-source land cover data often generated by the author via remote sensing methodologies, or came in ready-to-use land cover products form that is available to be retrieved via the Google Earth Engine (GEE) (Amani et al., 2020; Gorelick et al., 2017).

The study of land cover change requires reliable land cover datasets. The land cover datasets produced by local agencies might have problems in terms of inconsistency and standardization across different sources and temporarily. The availability of various open-sourced land cover products has made land cover change studies easy for nonprofessional geospatialists. However, there might be errors and biases within the products on a local basis as the products were generated with large-scaled remote sensing digital image processing, for example, misclassification for some of the agricultural features whereby the pixel values were similar. This issue limits the direct application of the dataset, and these errors are possible to be resolve via further processing.

The accessibility of the historical land cover data is always the challenges in land cover change studies. Based on the study done by Saah et al. (2019), the key challenges of land cover data application from the stakeholders in South East Asia were insufficient commitment to the provision of resources, lack of data access and availability of technical capacity to manage the procedures of modelling and use of existing land cover maps, especially in tropical region where the sky always covered with thick cloud covers.

The Kelantan River basin is one of the most flood-prone regions in Malaysia during the Northeast Monsoon, where the recurring floods in the region exposed critical gaps in the flood preparedness capacity particularly in terms of real-time flood information. The disaster management agencies in Malaysia, the National Disaster Management Agency (NADMA) and National Adaptation Plan (NAP), produced post-disaster study results and the disaster management during the disaster events were relied on the static coarse-scaled hazard maps produced from the simulation models in the reports. The present practice hinders a gap in terms of temporal flood inundation information as flood may occur at different area for each flood events, especially in the Kelantan River basin with complex terrain and scattered rural settlements.

The availability of high resolution satellite data on cloud platforms allows the development of automated rapid flood inundation mapping that can be locally validated and regionally scalable, especially in the data-scarced areas. Therefore, the potential of tailored rapid flood inundation mapping with cloud platforms in the monsoon-driven tropical environment like Kelantan River basin is crucial to support the strengthening of local climate resilience.

Numerous scientific research on land use and climate interactions has been done under the National Policy on Climate Change 2009 and integrated catchment management and climate risk mitigation studies have been done under the National Water Resources Policy 2012, however, there is still lacking of comprehensive long-term integration of land use trends and rainfall and temperature variations in the Kelantan River basin. Understanding these interactions is crucial for informing evidence-based land management and climate adaptation strategies.

1.3 Research Questions

The research questions of this study are as below:

1. What is the effectiveness of integrating multiple open-source land cover datasets in enhancing the local accuracy of land cover information for the Kelantan River basin?
2. Is it possible to obtain the flood inundation area of an area with open-source approaches?
3. What is the spatial relationship between the land cover change and the hydro-climatic changes in a specific area?

1.4 Objectives of this Study

The application of the open-source land cover data is beneficial for data scarce areas; however, the accuracy of the global land cover products are the main challenges in local adoption of the global land cover products. The coarse spatial resolution of the products may cause information loss in the inconsistent pixels (Jin et al., 2022), causing errors in mapping the local land cover with the open source land cover products. In addition, the reduced number of bands in the reanalysis land cover products restricts the level of detail for classifying the local land cover accurately (Jin et al., 2022).

As the land cover products were developed by different data providers, the different classification system and classification method may contribute to information inconsistency especially when the land cover product is applied onto a specific region (Kinnerbrew et al., 2022). Hence, data fusion needs to be performed prior to application of the multisource land cover products to reduce the uncertainty in mapping the land cover of a region (Jin et al., 2022).

There is a growing interest in precise evaluation of hydro-climatic impact studies worldwide, where long records of climate data and land cover change data are needed for the spatio-temporal variability analyses. In this study, the application of open-source land cover products in studying the hydro-climatic impact is done based on the following objectives:

1. To improve ESA land cover product by integrating several open-sourced land cover data.
2. To develop a rapid flood inundation mapping model using Google Earth Engine.
3. To analyze the relationship of land use with precipitation, temperature and flood in the Kelantan River basin.

1.5 Significance of Study

This study is significant in several key aspects in terms of scientific and practical perspectives. The first two objectives of the study focuses on exploring the potential of the open sourced satellite images and analysis ready land cover data derived from the open sourced satellite images for land cover analysis and flood area mapping in the Kelantan River basin, while the third objective presents the simple statistical analysis approach to study the relationship between the hydroclimatic variations and the land cover change in the basin. Such approaches are crucial for regions like Malaysia, where obtaining thematically consistent data were often a challenge for non governmental researchers.

Most of the existing open-source land cover products are available in coarse resolutions, which limits the spatial detail of the features mapped and frequency of updating the dataset. Landscape heterogeneity, image processing, and classification methods may affect the accuracy of the dataset in terms of local accuracy (Chen et al., 2017). The inclusiveness of various product sources may help to improve the variability and precision of the features mapped, as the spectral differences in various images would be able to capture more spatial information. Therefore, in this study, the improvement of the open-source land cover products via data fusion is carried out to enhance the land cover dataset to be used in this study to minimize the uncertainties in the land cover representation of the study area, where this could provide a more reliable foundation for data preparation on the data-sparse regions.

Flood inundation mapping is one of the important elements for hydro-climatic disaster management (Merwade et al., 2008). Traditional flood modelling produces historical flood inundation maps for the specific flood event that was under investigation, the process can take weeks or months to complete with condition that extensive datasets and detailed parameter sets available for the modelling. Hence, inundation maps generated via traditional flood modelling approach were exposed to limitations in terms of data collection techniques and modelling computational capacity especially for floods with specific return period (Li et al., 2022). At such, remote sensing technology created a cost-effective and timely resource to map the precipitation and flood information over large area during flood events (Tew et al., 2022). In this study, the potential of the open sourced remotely sensed data for flood inundation mapping is explored to enhance the accessibility and efficiency of flood detection and mapping in the disaster-prone and resource-limited setting of Kelantan River basin.

As global population continues to increase, existing land use and land cover will continue to change. Past studies have proven that the alteration of land use and land cover in a basin has an impact on hydrological processes in terms of interception, infiltration rate, evapotranspiration, and water resource availability (Samal et al., 2021). At instance, the recent severe flood events that occurred in the KRB (Tew et al., 2022) is evident to the phenomenon of impact of land use change to the hydrological balance in the basin, and may exacerbate in the future time period. By exploring the relationship between land use change and land cover change, hydrological regimes of the basin in response to climate and land use and land cover changes can be evaluated. These insights are essential for designing adaptive land management and climate resilience strategies, especially under the increasing pressure of climate change and land use transformation in the Kelantan River basin.

Moreover, the outcomes of this study is align with the national development priorities under the Malaysian National Policy on Climate Change and the National Water Resource Policy, as well as fitting in the global agenda under the Sustainable Development Goals, particularly Goal 13 Climate Action and Goal 11 Sustainable Cities and Communities. Nevertheless, this study provides a comprehensive geospatial framework that not only improves scientific understanding of land-atmosphere interactions but also supports operational tools for flood risk reduction and sustainable land use planning in Malaysia and other similar regions.

1.6 Scope of Study

The occurrence of monsoon floods in the Kelantan River basin is one of the major natural disasters that affect the well-being of the local community. The land cover change processes and the variations of rainfall and temperatures in the basin may be inter-related, therefore, reliable land cover data shall be used to analyze the changes. In this study, the improved open-source land cover data is used to analyze the impact of land cover change onto the hydro-climatic changes, and thus identifying the cause of land cover change onto the flood areas. The abundance of literature on bridging land use and land cover changes towards flood hazard has shown the variation of land use and land cover changes is one of the major factors affecting the rainfall of a monsoon catchment (Adnan et al., 2016) and flood patterns (Abungba et al., 2020), however, there is still lacking of studies done by analyzing the particular change of land use and land cover patterns affecting the precipitation, temperature and flood extent, particularly in the flood prone area in Malaysia – the Kelantan River basin.

The research objective 1 in this study presents the methodology of obtaining reliable thematic consistent land cover information of the Kelantan River basin with open sourced ESA CCI land cover products. The annual land cover information is used to analyze the changes of land use and land cover precisely on an annual basis. The current land use and land cover maps available were found to be not adequate for long-term land use and land cover analyses, due to the information consistency of the spatio-temporal land use and land cover data (Liu et al., 2021). The advancement of remote sensing technology in monitoring the Earth's surface dynamic have enabled various ready-to-use open sourced land cover data derived from satellite images (Pham et al., 2024). Therefore, the accuracy and timeliness of the local land use and land cover data could be integrated with these open-sourced land cover products that shall gradually enhance the quality of the land cover change analyses.

The second research objective of this study presents the workflow of obtaining flood area extent in the Kelantan River basin with the Sentinel-1 SAR satellite data, where the developed cloud-based flood inundation mapping approach offers a practical and scalable tool for disaster response and mitigation planning for the action planners. One of the most-used open-sourced remote sensing Earth observatory image is the Sentinel images. The availability of the Sentinel-1 SAR data on the Google Earth Engine created a platform for users to explore the characteristics and functions of different operations onto the bands in the data for various land dynamic monitoring such as flood monitoring, vegetation changes, forest fire, and etc (Huang et al., 2020). As Kelantan River basin covers mountainous area that are persistently accessible, remote sensing technology is a considerate approach to obtain spatial information for the rural areas. Hence, the capability of extracting the flood area in the Kelantan River basin is adopted in this study to create a rapid method that generates timely flood inundation overview of the basin with the available Sentinel-1 data.

The results from the third research objective presents the relationship of how the rainfall and temperature variations varies according to the changes of land cover types on an annual basis. The land use and land cover of the Kelantan River basin has experienced gradual change due to the socio-economic development. However, the evidence of major flood occurrence in the basin has shown an increasing trend in the recent years. Hence, how is the change of the specific land use type in the basin that will affect the change in the precipitation and temperature of the basin is conducted through simple correlation analysis in this study.

1.7 Research Framework

Environmental change is a global process, where it affects the quality of human well-being on a long-term basis. This study integrates geospatial data science, remote sensing, and hydroclimatic analysis to assess and improve land cover data for better flood and climate related insights in the Kelantan River basin. The framework of this study is designed to reflect a three-phase process aligned with the research objectives:

1. Land cover data integration and enhancement where a refined land cover map is produced to generate the annual changes of the land cover class.
2. Development of flood inundation map by leveraging open-sourced satellite data to detect the flooded area during the major flood events. Result from the first process will served as the reference for the flood map to identify the type of land cover affected during the flood events.
3. The hydroclimatic and land cover change relationship analysis with statistical correlation analysis to determine how the changes in the land cover proportions influenced the hydrological responses under the varying climatic conditions in the basin.

The three phases are interlinked whereby the outputs from the first process served as the input for the subsequent analysis.

The research framework of this study has been constructed as below in Figure 1.1. This study aims to produce a harmonized open-sourced ESA CCI land cover product based land cover map that is tailored to the Kelantan River basin, an operational rapid flood mapping tool that is usable during every monsoon flood in the study area; and better insights of the interactions between the rainfall and temperature variations and the changes of land cover in the basin.

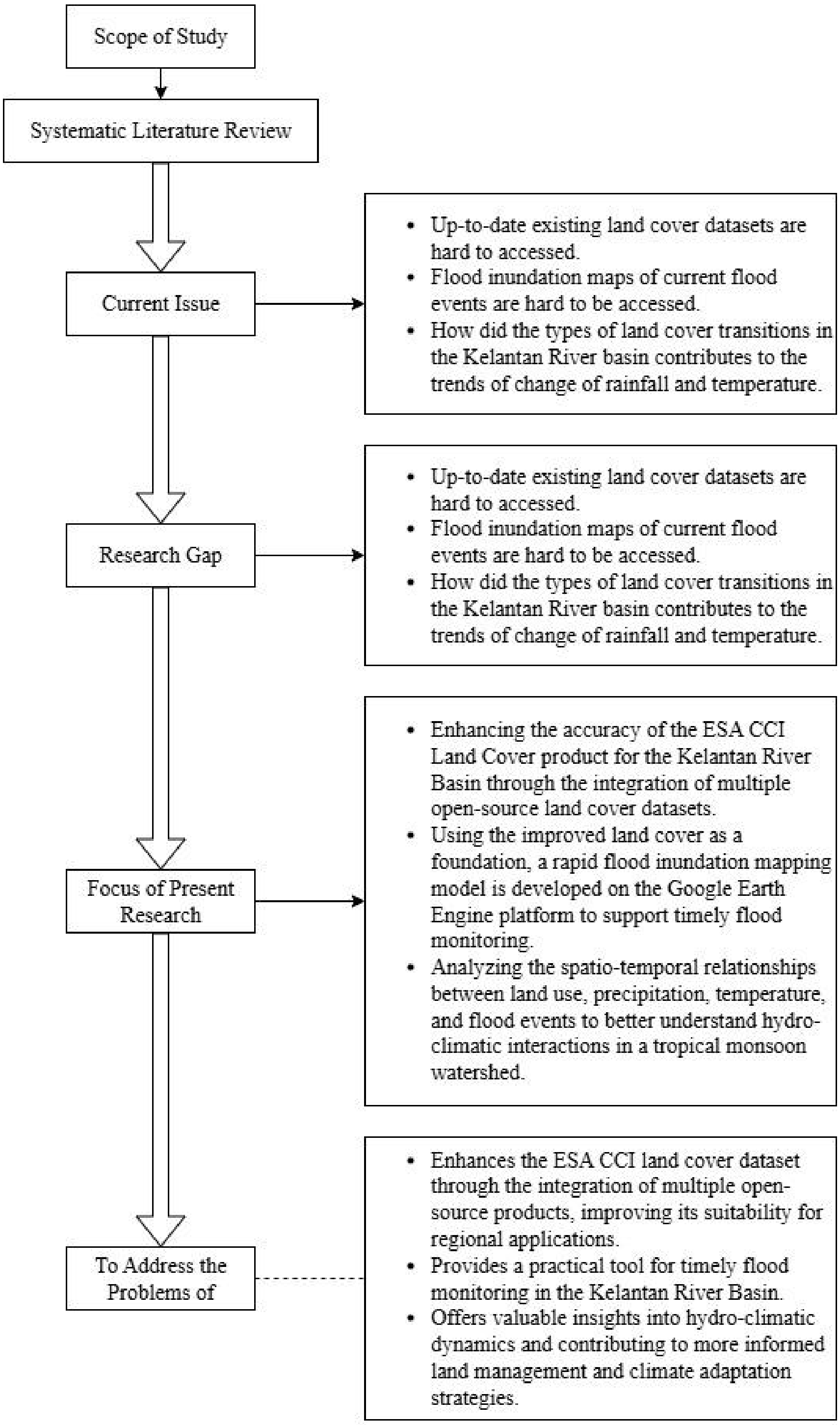

Figure 1.1 Research framework of the study.

1.8 Outline of the Thesis

The thesis comprises of six chapters that explained how the study was conducted by addressing the implementation of the spatial correlation of land use and land cover changes with the hydro-climatic changes over the KRB, highlighting on the rainfall extreme that leads to extreme flood events in the basin.

Chapter one introduced the general concept, problem statement, research objectives and gaps of the topic. Chapter two is a comprehensive literature review for the past studies done on the land use and land cover change associated hydro-climatic changes globally as well as tropical regions, that further elaborated towards analyzing the hydro-climatic hazards caused by the changes. This chapter also discussed the concepts, theories, and the pros and cons in the study approaches. Chapter three describes the methodology workflow and the data used in this study, while the results are presented in the following chapter. Chapter four discussed the results obtained in this study and the detailed result of each analysis were discussed in subsequent sections. The last chapter concludes the summary of the findings by revisiting the research hypothesis and significance in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a general overview about the theories on the focus of this study. This chapter is divided into three sections: the first section addressed the brief definitions of each component in this study including the hydro-climatic variations and land use and land cover change; the second section addressed the issues identified that are due from the variations, particularly the occurrence of flood events; and the third section reviews the application of various methods in analyzing the relationship between the variations globally and regionally, from the perspectives of the available free and open-source data and techniques to analyze the data.

2.2 Hydro-climatic Variations

Across all climate zones, hydrological drought is associated with some anomaly in the timing, occurrence or persistence of atmospheric circulation. These anomalies are often connected to large-scale ocean-atmosphere modes of variation such as the El Niño Southern Oscillation. The consequent meteorological water balance deficits often propagate into hydrological drought, but the connection is not always straightforward: land surface characteristics and feedbacks can be critical to hydrological droughts (Kingston, 2024). Based on the past literature, Langbein (1967) defined hydro-climatology as the study of influence of climate upon the waters of the land (Wendland, 1987). It discusses the total hydrology cycle and climate over various time scales. Generally, water cycle is a process whereby water is evaporated from the open water surfaces on Earth due to solar heating, then transported by moving air and thus condensed in the form of clouds and finally falls back to the Earth's surface through precipitation (Trenberth et al., 2014). The water in precipitation is stored temporarily as snow or soil moisture on the Earth's surface, while the excessive rainfall runoffs into streams and rivers and later discharged into the ocean (Trenberth et al., 2014).

The evaporation process has resulted in a large amount of water being transported in the air in the form of atmospheric water vapour that is strongly controlled by the atmospheric circulation. Bengtsson (2010) reviewed observational studies and numerical modelling and the study have proven that the atmospheric water vapour contents increase as the temperature increases, following the Clausius-Clapeyron relation. An increase of 1˚C in temperature at the lower troposphere will increase the water vapour by 6-7%. Moreover, the increase of water vapour in the global atmospheric hydrological cycle will lead to exchange of mass between the land surface that take place in the form of convection in the Tropics. The increasing water vapour according to Clausius-Clapeyron relation also indicating the intensified pattern of evaporation-precipitation (E-P). The increase of E-P gradient implies that wet regions get wetter and dry regions get drier as tropospheric water vapour increase proportionally to the temperature. The findings are key messages on how a warmer climate would change the patterns of precipitation in the future.

As amplification of the hydrological cycle is discovered to be related to the warming climate, the variations of global and regional precipitation pattern are among the most relevant aspects of climate change to be studied. Donat et al. (2016) studied the global precipitation pattern by analyzing the precipitation indices from observations and global climate model simulation and discovered that there are robust increasing daily precipitation extremes over both dry and wet regions. As discussed in the section earlier that precipitation intensity is related to the E-P gradient, the magnitude of atmospheric moisture convergence and divergence are expected to increase following the increase of water vapour content in the atmosphere due to the warming climate.

The rate of increase of precipitation extremes in the current climate is higher according to the Clausius-Clapeyron relationship. The extreme precipitation events are more likely to occur during monsoon seasons that was driven by the precipitation-temperature coupling effect during the monsoon seasons, especially in the tropical regions (Mukherjee et al., 2018). In the study done by Mukherjee et al. (2018), the frequency of extreme precipitation is projected to further increase in the late 21st century under the RCP 8.5 scenario, that would affect human activities in the infrastructure, agriculture, and energy sectors, as well as affecting the water resources availability.

As the discussion about the global warming induced hydrological cycle effects goes on, there is study found out the changes might be different from the theorized expectations in terms of water-holding capacity of the atmosphere under warmer conditions when the water availability is limited, and the affects were regional (Tabari, 2020). Extreme precipitation in humid regions have increasing rate with global warming at the Clausius-Clapeyron rate, meanwhile the flood intensity changes in-line with the extreme precipitation, and the flood intensity is projected to increase over land areas in the humid regions, according to the study done by Tabari (2020).

2.3 Land Use and Land Cover Change (LULCC)

Land Use and Land Cover Change (LULCC) is an indicator of human activities footprint, that is observed when the natural landscape of the region is altered for socio-economic development (Avashia et al., 2020). Examples of observed

LULCC are the change of vegetation type from natural shrubland into commercial crops, transformation of natural grassland into human settlement, change of cropland into human settlement etc. The assessment of the rate of LULCC is a way to determine the rapidness of urbanization of the area, forest losses, and how fast is the agricultural activity in the area is expanding (Li et al., 2020).

Lambin et al. (2003) concluded that land cover change is driven by climate dynamics, while land use change is driven by the need to produce more resources for human's daily lives. In order to measure the impact of LULCC towards the climate change at local scale, analysis of the observed changes in the physical, biological and anthropogenically impacts of the LULCC towards the changed climate variables should be correlated to understand the pattern of impact (Rosenzweig et al., 2013).

The recent climate study trends on global scale has focused on the effect of LULCC on temperature, where some local models have shown warming due to agricultural expansion, particularly in the Amazon when forest is sacrificed for crops planting and human settlement (Rosenzweig et al., 2013). At such, the distribution of latent and sensible heat and radiative changes of the ecosystem and the mass fluxes of the climate in terms of water vapour, gases and air particles strongly affected by human activities that resulted in LULCC (Kalfas et al., 2024).

According to the IPCC (2021a) report, approximately 60-85% of the world's forest cover has been transformed into other uses and covers, and this change has led to landscape, biomass, wildlife species, as well as soil organic matter changes of the Earth's surface. One of the notable LULCC studies with satellite imagery in the history is the detection of evidence for deforestation of Amazon by assessing the Landsat Multispectral Scanner (MSS) satellite images (Skole et al., 1993). The deforestation rate was found to be at 0.5% annually during the construction of huge highways in Brazil since year 1970 and the development of new human settlements to support the urbanization of the country, and until year 1993, approximately 50,000 km of forest loss is recorded in the Amazon basin (Mustard et al., 2013).

Worldwide urbanization is an irreversible process, as the world's population is projected to grow by 2.5 billion from year 2018 to 2050, with 50% of the world's population living in urban areas especially in the African and Asian continents (United Nations, 2023). Policies of sustainable cities and communities planning can be better implemented through modelled LULCC (Gaur et al., 2023). Historical changes of the LULCC derived from the satellite data is the key component in modelling the LULCC of a region, other than census data and maps of explanatory variables such as bio-physical changes of the environment, institutional development, socio-economic growth data, and proximity variables (Gaur et al., 2023).

Drastic LULCC can lead to trade-off of the ecosystem's benefit to human, particularly in arid regions (Liu et al., 2023). The analysis of MODIS derived NDVI from year 1990 to 2020 in Xinjiang has shown degradation of grassland into unused and cultivated cropland, as well as 22.63% expansion of construction land, where this LULCC in the region have led to wetland degradation and biodiversity reduction. For instance, assessing the depletion of land, forests, water, and other natural resources on the Earth's surface that can be obtained by analyzing satellite data, is a key indicator in quantifying climate change and environmental degradation (Nguyen et al., 2023).

Nevertheless, the Paris Agreement's AR5 related the significance of LULCC planning to the current initiatives to reduce climate change, particularly stressed on the importance of reducing emissions from deforestation and forest degradation in developing countries (REDD+) (IPCC, 2019). The advancement of remote sensing and image processing technology has enabled a more comprehensive and detailed

LULCC study at local scale to identify the types of LULCC that caused a particular environmental change in the area. Hence, it is crucial to include LULCC in assessment of hydro-climatic variation of a region using remote sensing technology.

2.4 Flood

Floods caused enormous damage globally every year, with recorded deceased victim of approximately 100,000 persons in the last decade of the 20th century (EM-DAT, 2022). Being the most costly and global climate-related natural hazard, floods have caused damage worth US$654 billion worldwide between year 1980 – 2009 (Eccles et al., 2019). According to the flood statistics, flash floods resulted in the highest average mortality per flood event, with most number of victim recorded during river floods in Asian region (Jonkman, 2005).

The United Nations Office for Disaster Risk Reduction (UNDRR) reported that for each 1˚C increase of global warming would intensify the extreme daily precipitation events by around 7% (IPCC, 2021a), with the 10 countries with highest prone towards flooding under the circumstances are located in tropical South and South East Asia, as well as countries in South America and Africa (UNDRR, 2023). As reviewed by Eccles et al. (2019) for the effects of climate change on riverine flooding, consistent increasing trend of flooding under the world's climate change in the future was predicted for South Asia, South East Asia and the western Amazon.

Referring to the review by Hirabayashi et al. (2013), the frequency of flood occurrence increases across large areas of South Asia, Southeast Asia, Northeast Eurasia, eastern and low-latitude of Africa, and South America that was determined from the decreasing multi-model median return period of the 20th century 100 year flood discharge in 21st century under RCP8.5. The direction of change of flood frequency for these regions was consistent with the change of the atmosphere-ocean general circulation model and river routing scheme, particularly in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes.

Floods can be categorized into different types, for example, the river floods that were induced by rainfall and snowmelt or debris flow, and the floods in deltas that were caused by storm surges, ice jam or dam break (Kundzewicz et al., 1999). One of the most devasting flood events in the 20th century was The Great Flood 1993 in the USA, where the Mississippi River was flooded for 81 days. The flood plain covers almost the whole river basin, with more than 10,000 families being relocated. This flood event has significant impact on the enforcement of policies for river basin management where the later flood studies focussed on the hydrological characteristics of the basin such as maximum flow, total volume of flood wave, duration of flow, inundated area, velocity of flood rise etc. The post flood assessment also suggested unnecessary development in flood prone areas to be avoided, as land use change in the basin could have impacted the flood characteristics in the flood plain (Kundzewicz et al., 1999).

River floods were generated by different geographic environmental factors, where the major cause of river floods was identified as extreme rainfall that exceeded the soil infiltration capacity or intensive rainfall onto saturated man-made ground (Arnell et al., 2016). The fast development of man-made features on ground over time would lead to variation in the accumulation of rainfall and evaporation, future floods may increase due to the socio-economic development of the basin. As the effects of climate change on floods vary across space and geographic factors, the changes in the frequency of extreme rainfall are the main determinant for the flood characteristics in the basin.

2.4.1 Floods in Malaysia

Malaysia is a Southeast Asian country, with total land area of 330,803 km² and population of approximately 34 million (as of the Malaysia Census 2020 (DOSM, 2022)). Situating in the tropical region, Malaysia exerts the equatorial climate that is hot and humid throughout the year, with the climate variability closely dependent to the Southwest (April to September) and the Northeast (October to March) Monsoons. The mean annual precipitation ranged between 2000 – 000 mm, with the mean temperature falls between 26˚C to 32˚C. At such, the Northeast Monsoon brings abundant precipitation to the country particularly at the east coast region of the Peninsular Malaysia (Hussain Shah et al., 2017; Tew et al., 2022). The direction of the wind during the Northeast and Southwest monsoons are as shown in the Figure 2.1 below.

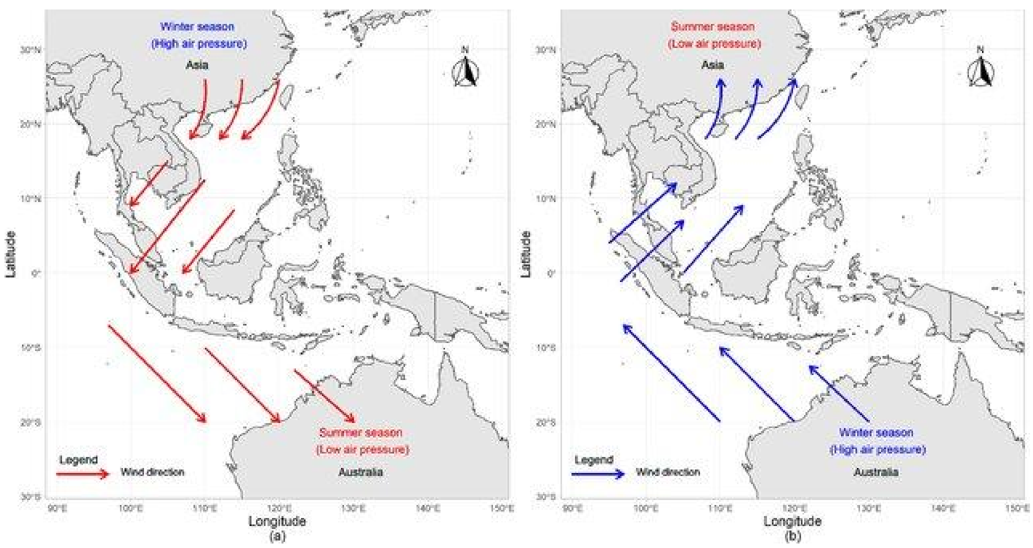

Figure 2.1 The wind direction during (a) Northeast monsoon; and (b) Southwest monsoon in the Southeast Asia region (Safari et al., 2022).

Climate change being the global phenomenon, Malaysia has undergone temperature rise and rainfall irregularities in the past two decades (Tang, 2019). According to the findings in the review done by Tang (2019), the annual mean temperature, extreme weather events and mean sea level rise shows increasing trend and the future projections shows the rise of temperature and mean sea level in Malaysia will continue to occur until the end of the 21st century, leading to increased frequency of extreme weather events.

Referring to the study done by Tan et al. (2020) on assessing the spatio-temporal changes of temperature extremes and their relationship to ENSO in Malaysia from 1985 to 2018, the results indicated a significant warming surface temperature throughout Malaysia particularly in the Peninsular Malaysia by 0.17˚C/decade. This phenomenon has led to climate-related risks in Malaysia including flood, water stress, agricultural productivity reduction and mosquito-borne diseases (Tan et al., 2020).

Malaysia consists of 189 river basins where 89 located in the Peninsular Malaysia, 22 in Sarawak, and 78 in Sabah. For instance, 85 (approximately 45%) basins are categorized as flood-prone regions (Hussain Shah et al., 2017). Floods in Malaysia is categorized as monsoonal, flash or tidal floods (Ibrahim et al., 2021), whereby the categorization was made by quantifying the time for the flood water to recede. For instance, monsoonal floods are floods that occurred during the monsoonal season; flash floods occurred during the sudden heavy rainfall; while tidal floods occurred during high tide events that inundated the low-lying area temporary (Durumin Iya et al., 2014).

Monsoonal floods were an annual natural disaster in Malaysia. As recorded in the Malaysian flood history, major monsoonal flood events happen during 1926, 1963, 1965, 1967, 1969, 1971, 1973, 1979, 1983, 1993, 1998, 2005, 2006, 2007, 2010, 2014, 2017, 2021 (Tew, Tan, Juneng, et al., 2022) and 2023. The major Malaysian northeast monsoonal flood events in the past decade are summarized in Table 2.1.

Table 2.1 Descriptions of the monsoonal floods in Malaysia for the past decade.

Year	**Date**	**States**	**Note**	**Reference**
2010	10 October – 19 November	Kedah Perlis	Triggered by a tropical depression and later aggravated by La Nina monsoon rains; 45,000 hectares of rice fields were damaged, and government pledged USD 6.5 billion to help the farmers.	Durumin Iya et al. (2014) Hussain Shah et al. (2017) Ibrahim et al. (2021)
2014	15 December 2014 – 3 January 2015	Johor Kelantan Kedah Negeri Sembilan Pahang Perak Perlis Sabah Sarawak Selangor Terengganu	Heavy rainfall as part of the northeast monsoon. The worst flood in Kelantan in history with 202,000 individuals evacuated; property damage of USD 560 million.	
2017	4 – 5 November	Pulau Pinang	Caused by Tropical Depression 29W on 3 November, flash flood in Pulau Pinang with maximum flood level 3.7 m.	
2021	16 – 31 December	Perak Selangor Kuala Lumpur Negeri Sembilan Melaka Johor Pahang Terengganu	Caused by Tropical Depression 29W on 14 – 17 December. Heavy flood in four states and minor flood in four other states; government estimated total of USD 1.55 billion in property damage.	BERNAMA (2021) Aiman (2021)