IMPACT OF CLIMATE CHANGE ON DROUGHT IN THE KELANTAN RIVER BASIN, MALAYSIA

DU HONGRONG

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IMPACT OF CLIMATE CHANGE ON DROUGHT IN THE KELANTAN RIVER BASIN, MALAYSIA

by

DU HONGRONG

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LIST OF SYMBOLS AND ABBREVIATIONS

ACDV	Annual Cumulative Deficit Volume
AHA	Assistance on Disaster Management
AM	Daily average temperature wave amplitude (^0C)
AMIP	The Atmospheric Model Intercomparison Project
ANFIS	Adaptive Neuro-Fuzzy Inference System
ARS	Agricultural Research Service
ASF	Atmospheric Stability Framework
BNI	Blue Nile
C'	The empirical copula function
CANFIS	Co-active neural fuzzy inference system
CAS	Chinese Academy of Sciences
CCM1	Community Climate Model
CDI	The comprehensive drought index
CDR	Carbon dioxide removal
CJDI	Copula-based Joint Drought Index
CMIP	The International Coupled Model Intercomparison Project
CO2	Carbon dioxide
CORDEX	Coordinated Regional Downscaling Experiment
CORDEX-SEA	Coordinated Regional Climate Downscaling Experiment—Southeast Asia simulations
CPC	Climate Prediction Center
d	Number of days (days)
DD	Attenuation depth of the soil (mm)
DEM	Digital elevation model

DHI	Drought hazard index
DI	Rainfall Deciles
DRI	Drought Risk Index
DVI	Drought Vulnerability Index
ECER	East Coast Economic Region
ED	Extreme drought
EDDI	Evaporative Demand Drought Index
eRDI	Effective Reconnaissance drought index
ET	Evaporation
G Annual	Annual groundwater
G i-j	Groundwater (January to June , for winter).
GCMs	General circulation models
GeoMIP	The Geoengineering Model Intercomparison Project
GeoMIP	The Geoengineering Model Intercomparison Project
GHG	Future greenhouse gas
GLENS	Geoengineering Large Ensemble
GLENS	Geoengineering Large Ensemble
GMDH	Group Method of Data Handling, were compared
GRACE	Gravity Recovery and Climate Experiment
GW	Groundwater
HIRLAM	High Resolution Limited Area Model
i	Day
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPCC AR	Intergovernmental Panel on Climate Change Assessment Report
KRB	The Kelantan River Basin

LAMs	Nested limited area models
LSC	Linear scaling
LUCC	Land use and covered change
MAHDI	Multivariable comprehensive meteorology–agriculture–hydrology drought index
MDHI	Modified Drought Hazard Index
MDSI	Modified Drought Severity Index
MJO	Madden-Julian Oscillation
MK	Mann–(MK) Kendall's trend test
ML	Machine learning
MLPNN	Multi-Layer Perceptron Neural Network
MLR	Multiple Linear Regression
MM4	NCAR Mesoscale Model version 4
MODIS	Moderate Resolution Imaging Spectro-Radiometer
MSARSPEI	Multi-Scalar Seasonally Amalgamated Regional Standardized Precipitation Evapotranspiration Index
n2	The count of samples that meet the condition C'
NADMA	The National Disaster Management Agency
MMEs	Multi-Model Ensembles
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized difference water index
NMDI	Nonlinear multivariate drought index
NO2	Nitrous oxide
NSE	Nash-Sutcliffe Efficiency
P_tri	The cumulative probability in three dimensions
PBIAS	Percent Bias

PDF	Probability distribution function
PDS	Palmer Drought Severity Index
PDSI	Palmer Drought Severity Index
PHDI	Palmer Hydrological Drought Severity Index
PNI	Percent of normal index
PSU	The Pennsylvania State University
QMM	Quantile mapping methods
R	Correlation coefficient
R2	Coefficient of determination
R95pF	Precipitation frequency
R95pT	Precipitation percentage
RCA1	Rossby Center Regional Atmosphere Model
RCMs	Regional climate models
RDI	Reconnaissance Drought Index
RDI	Reconnaissance Drought Index
ReDIM	Application of Regional drought identification model
RX1day	Maximum 1-day precipitation
ScenarioMIP	Scenario Model Intercomparison Project
sc-PDSI	Self-Calibrated Palmer Drought Severity Index
SDI	Streamflow Drought Index
SFI	Standardized Streamflow Index
SGI	Standardized Groundwater Index
SIndex	Seasonal (monsoon/winter) dominant rainfall index
SMannual	Annual soil moisture
SMi–j	Soil moisture (January to June)
SPEI	Standardized Precipitation Evapotranspiration Index
SPEI	Standardized precipitation evapotranspiration index

SPI	Standardized precipitation index
SPTI	Standardized Precipitation Temperature Index
SRES	The Special Report on Emissions Scenarios
SRM	Solar radiation management
SSFI	Standardized Streamflow Index
SSI	Standardized Streamflow Index
SSP	Shared Socioeconomic Pathway
SSP	Shared Socioeconomic Pathway
SSP	Shared Socioeconomic Pathway
SUFI-2	Sequential Uncertainty Fitting algorithm
SWAT	Soil and water assessment tool
SWAT+	Soil and water assessment tool plus
t	Length of time (days)
t (z,d)	Average daily soil temperature (^{0}C)
TCI	Temperature condition index
Td	Total number of droughts
TRCI	Precipitation condition index
TRMM	Tropical Rainfall Measuring Mission
TVDI	Temperature vegetation dryness index
Ty	Total number of years
USEPA	Environmental Protection Agency
VHI	Vegetation health index
VRGCMs	Variable resolution global models
WCRP	World Climate Research Program
WCRP	The World Climate Research Program
WMO	World Meteorological Organization

x	Amount of rainfall (mm)
z	Depth from the topsoil (mm)
Γ(α)	Gamma function
SW_t	Total water content (mm)
SW_O	Soil moisture content (mm)
R_{day}	Atmospheric precipitation on day
Q_{surf}	Surface runoff on day (mm)
E_a	Transpiration emission on day (mm)
W_{seep}	Infiltration and lateral flow at the bottom of the soil profile on day(mm)
Q_{gw}	Groundwater content (mm) on day
$\bar{t}$	Average annual temperature (^0C)

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IMPAK PERUBAHAN IKLIM TERHADAP KEMARAU DI LEMBANGAN SUNGAI KELANTAN, MALAYSIA

ABSTRAK

Pemanasan global telah menyebabkan perubahan ketara dalam corak taburan hujan serta peningkatan kejadian cuaca ekstrem di lembangan tropika, menimbulkan cabaran besar dalam pengurusan sumber air. Lembangan Sungai Kelantan (KRB), terletak di kawasan tropika, adalah sangat terdedah kepada bencana berkaitan air seperti banjir dan kemarau, menimbulkan cabaran utama terhadap bekalan air tempatan. Kajian ini menilai risiko kemarau masa hadapan di KRB di bawah dua senario pelepasan gas rumah hijau: SSP2-4.5 (pelepasan sederhana) dan SSP5-8.5 (pelepasan tinggi), yang digunakan secara meluas dalam kajian perubahan iklim dan sejajar dengan sasaran menahan pemanasan global sebanyak 1.5°C dan 2.0°C. Bagi memahami potensi intervensi iklim dengan lebih lanjut, eksperimen GeoMIP6 yang menggunakan pendekatan Pengurusan Sinaran Suria (SRM), khususnya senario G6solar dan G6sulfur, turut dipertimbangkan untuk perbandingan dengan senario SSP. Satu indeks kemarau komprehensif baharu (CDI), yang menggabungkan hujan, aliran sungai, dan kelembapan tanah berdasarkan simulasi model SWAT+, telah dibangunkan dan dibandingkan dengan Indeks Kejadian Hujan Piawai (SPI) dan Indeks Aliran Sungai Piawai (SSI). Unjuran hujan dan suhu ,daripada empat model GeoMIP, merangkumi senario SSP dan SRM, diintegrasikan ke dalam model SWAT+ untuk mengunjurkan aliran sungai dan kelembapan tanah masa hadapan di KRB.

Model SWAT+ menunjukkan prestasi yang bagus berbanding data aliran sungai cerapan (NSE = 0.76, R^2 = 0.78). Hasil kajian menunjukkan bahawa peningkatan aliran sungai dan insiden kemarau adalah lebih ketara di bawah senario SSP5-8.5 berbanding SSP2-4.5. Taburan hujan tahunan dijangka meningkat sehingga pertengahan abad ke-21, kemudian menurun, terutamanya di bawah senario G6sulfur. Kedua-dua senario G6solar dan G6sulfur menunjukkan bahawa SRM berpotensi mengurangkan pemanasan masa hadapan di bawah SSP5-8.5 ke tahap yang hampir sama dengan SSP2-4.5, dengan peningkatan suhu maksimum terhad kepada 1.01°C–2.07°C dan suhu minimum kepada 0.76°C–1.83°C berbanding tempoh 1985–2004. Walau bagaimanapun, penurunan ketara dalam indeks kemarau (SPI, SSI, dan CDI) di bawah SRM, terutamanya G6sulfur, menunjukkan bahawa walaupun SRM dapat menurunkan suhu permukaan, ia juga berisiko meningkatkan kejadian kemarau. Penemuan ini penting untuk pihak berkepentingan dalam merangka strategi pengurusan risiko dan mitigasi bencana secara berkesan.

IMPACT OF CLIMATE CHANGE ON DROUGHT IN THE KELANTAN RIVER BASIN, MALAYSIA

ABSTRACT

Global warming has led to significant changes in precipitation patterns and an increase in extreme events in tropical basins, posing serious challenges for water resource management. The Kelantan River Basin (KRB), located in a tropical region, is highly susceptible to water-related disasters, such as floods and droughts, which have created major challenges for the local water supply. This study evaluates future drought risk in the KRB under two greenhouse gas emission scenarios, SSP2-4.5 (intermediate emissions) and SSP5-8.5 (high emissions), which are widely used in climate change research and align with the global warming targets of 1.5°C and 2.0°C, respectively. To further explore the potential for climate intervention, GeoMIP6 experiments using Solar Radiation Management (SRM), specifically the G6solar and G6sulfur scenarios, were also considered in comparison with the SSP scenarios. A new comprehensive drought index (CDI), incorporating precipitation, streamflow, and soil moisture from SWAT+ model simulations, was developed and compared with the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI). Precipitation and temperature projections, from four GeoMIP models, covering both SSP and SRM scenarios, were integrated into the SWAT+ model to project future streamflow and soil moisture in the KRB. The SWAT+ model demonstrated good performance against observed streamflow (NSE = 0.76, R^2 = 0.78). Results indicate

that streamflow increases and drought events are more pronounced under SSP5-8.5 than SSP2-4.5. Annual precipitation is projected to rise until the mid-21st century, then decline, especially under the G6sulfur scenario. Both G6solar and G6sulfur demonstrate that SRM could reduce future warming under SSP5-8.5 to levels similar to SSP2-4.5, with maximum temperature increases limited to 1.01 –2.07°C and minimum temperatures to 0.76°C –1.83°C relative to the 1985–2004 period. However, substantial decreases in drought indices (SPI, SSI, CDI) under SRM, particularly G6sulfur, show that while SRM may reduce surface temperatures, it could also increase drought risk. These findings are important for stakeholders in formulating effective risk management and disaster mitigation strategies.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Global warming is widely known as a key factor influencing water resources and the hydrological cycle, with significant variations across different latitude zones (Wei et al., 2020). Drought remains one of the most persistent and severe threats to water resource management, a concern also highlighted in the findings of the Intergovernmental Panel on Climate Change (IPCC) reports (Parmesan, 2022). The Paris Agreement, adopted at COP21 in 2015, established an international framework to address the challenge of climate change. Its primary goal is to limit global temperature rise to no more than 1.5°C above pre-industrial levels, with a secondary upper limit of 2°C. Achieving the 1.5°C target would significantly reduce extreme weather events, mitigate the risk of sea-level rise, and help prevent substantial biodiversity loss. The 2°C threshold, being less stringent, is often regarded as another critical benchmark that, if met, would still help in reducing climate-related risks. It is essential to closely examine the differences between the impacts of these two warming thresholds, particularly when evaluating the increased risk of drought (Lehner et al., 2017). The IPCC AR6 report highlights that the period from 2011 to 2020 experienced a temperature anomaly ranging from 0.95°C to 1.20°C compared to the 1850-1900 baseline, following the intensification of extreme climatic events such as heatwaves, heavy rainfall, and prolonged droughts (Zhou, 2021). Apart from global warming, El Niño events lead to elevated sea surface temperatures in the central and eastern equatorial Pacific, disrupting atmospheric circulation and altering precipitation patterns. This has exacerbated droughts, particularly evident in 2010 and 2016 (Field et al., 2009; Thirumalai et al., 2017).

Southeast Asia has been especially vulnerable, with over 66 million people in countries such as Indonesia, Vietnam, Thailand, and Malaysia significantly impacted by drought (Zaki & Noda, 2022). From 2012 to 2019, the ASEAN Disaster Information Network, under the ASEAN Coordinating Centre for Humanitarian Assistance on Disaster Management (AHA), recorded 42 drought episodes across Southeast Asia (Tan et al., 2020a). Figure 1.1(a,b) illustrates the drought that affected Southeast Asia, leading to water shortages, wildfires and a decline in agricultural production (Al Jazeera, 2014). Figure 1.1(c) shows the drought conditions across Southeast Asia in March 2020 based on the Standardized Precipitation-Evapotranspiration Index (SPEI) (Masters, 2019). Lower SPEI values (in red) indicate more severe drought. The figure highlights significant rainfall deficits and severe drought affecting several countries in the region, including India, Thailand, and others. Drought is a prolonged and complex natural phenomenon that affects various sectors, especially agriculture and industry (Mishra & Singh, 2010). Directly observing the key variables of drought such as its affected areas and severity can be challenging. It is essential to develop a reliable drought monitoring system to enable timely and accurate assessments of regional drought conditions, enhance drought risk management, and mitigate the effects of drought (Wu et al., 2021).

Drought phenomena are classified into meteorological, agricultural, hydrological, and socioeconomic droughts, each affecting different sectors. Meteorological drought occurs when there is a sustained deficiency in precipitation, while agricultural drought arises from inadequate soil moisture, which directly impacts plant growth and agricultural productivity. Hydrological drought signifies a severe reduction in flow from surface waters or groundwater sources, and socioeconomic drought arises when water shortages cause challenges in production, consumption, and overall economic activities. These various types of drought are interconnected, with one type potentially exacerbating others. For instance, a persistent lack of rainfall can lead to meteorological drought, which, over time, reduces soil water content, subsequently lowering crop yields and causing agricultural drought. Hydrological droughts may result from ongoing rainfall deficits, which can also lead to significant decreases in surface and groundwater levels. When the negative impacts of the first three drought categories affect social production and economic growth, socioeconomic drought occurs (Liang et al., 2021b).

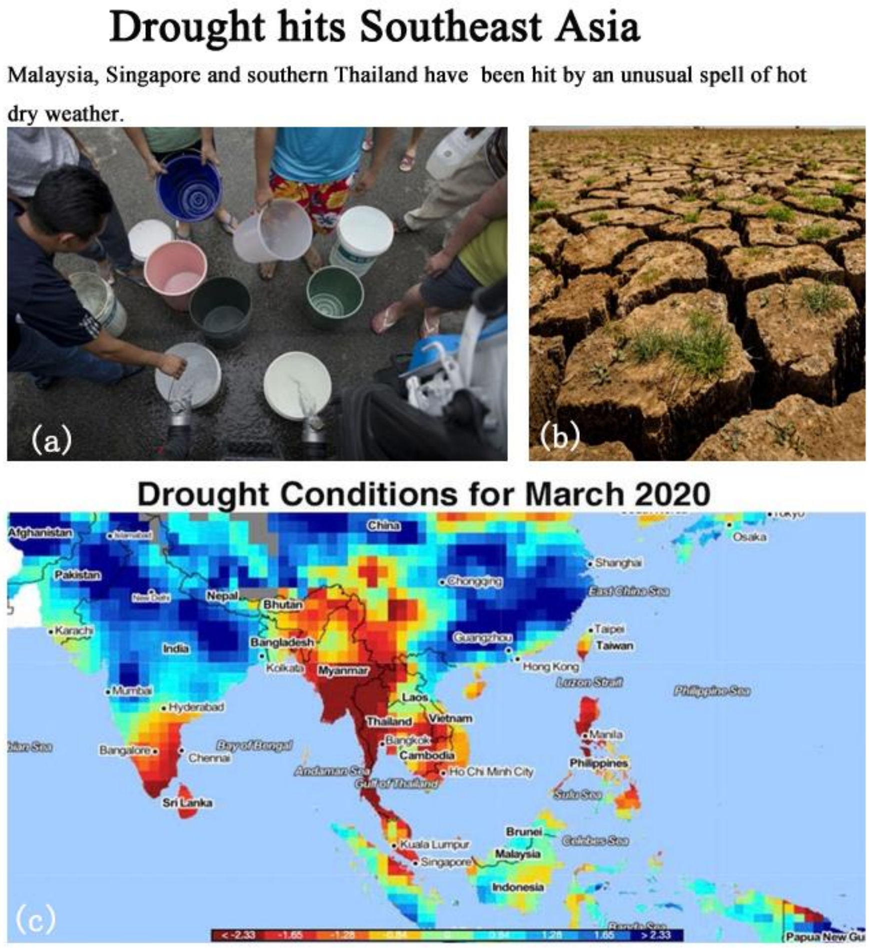

Figure 1.1 (a, b) Drought events in Southeast Asia, and (c) SPEI-based map representing drought severity.

Solar radiation management (SRM) aims to increase the reflection of incoming solar radiation back into space, thereby quickly inducing a cooling effect on the Earth. SRM is intended to counterbalance the heat trapped by greenhouse gases and reduce their harmful thermal effects (Crutzen, 2006; Masson-Delmotte et al., 2021). The Geoengineering Model Intercomparison Project (GeoMIP) is a component of CMIP6 that conducted to standardize the methodology for conducting modeling experiments related to SRM. In the sixth phase of GeoMIP, two experiments, referred to as G6solar and G6sulfur, were introduced to shift from high-emission scenarios for the global mean surface temperature under the Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5) to intermediate-emission scenarios represented by SSP2-4.5 (Meinshausen et al., 2020). The GeoMIP6 criteria stipulate that the average temperature of the Earth's near-surface air must remain within a 0.2 K range for the G6solar or G6sulfur scenarios, in comparison to the corresponding decade of each model's SSP2-4.5 simulation. This requirement is applicable to each decade starting in 2021 and continuing through 2100 (Kravitz et al., 2021).

The Kelantan River Basin (KRB) is a tropical basin situated in the northeastern region of Peninsular Malaysia, in close proximity to the equator, and characterized by warm temperatures and high amount of rainfall. Primarily during the Northeast monsoon season (November to January), which often leads to flooding. The National Disaster Management Agency (NADMA) Malaysia has reported on flood events in Kelantan multiple times (NADMA, 2024), numerous studies on floods have been conducted in this region (Chan et al., 2020; Hassan et al., 2018; Tam et al., 2019; Tam et al., 2023). The dry period of the KRB typically occurs during the second phase of the northeast monsoon, which runs from mid-January to February. This dry spell continues into the inter-monsoon period and extends through the southwest monsoon, lasting until around June. The region is particularly vulnerable to drought due to its tropical monsoon climate, significant climate variability, and the lack of major reservoirs or dams to store water during dry spells. Historical data highlights several severe drought events, such as those in 1998, 2014, 2019, and 2020 (Mahmud & Osawa, 2025; Suhaila et al., 2010), that resulted in widespread water shortages and significantly impacted local communities and agriculture. Despite these recurring challenges, comprehensive drought risk assessments in the region, remain scarce.

1.2 Problem Statement

Hydrological models are essential for simulating hydrological changes within a specific basin (Guo et al., 2016; Wei et al., 2020). The SWAT+ model offers greater flexibility compared to its predecessor, SWAT. In recent years, SWAT+ has been applied in various analyses, such as streamflow (Andaryani et al., 2021), sand production rates (Nkwasa et al., 2022), pesticide and metabolite concentrations (Rathjens et al., 2022), reservoir operations (Wu et al., 2020b), and highlands floodplains (Bieger et al., 2019). The SWAT model, developed by the U.S. Department of Agriculture, is primarily based on field studies conducted under the physical and climatic conditions of the United States. However, the hydrological and climatic characteristics of the tropical KRB differ significantly from those of the U.S. As a result, using SWAT with default parameter values as the rainfall-runoff transfer function can introduce substantial systematic bias (Yang et al., 2023a). Although SWAT and SWAT+ have shown good performance in simulating monthly streamflow in the KRB (Tan et al., 2023b), their effectively reliability in capturing extreme events and climate variability remains limited. This limitation persists due to the quality of precipitation data (Tan et al., 2018), gauge network density (Tan & Yang, 2020), and bias correction methods (Tan et al., 2023), hence some model enhancements, such as hybrid modeling with Bidirectional Long Short-Term Memory (Bi-LSTM), are adopted (Yang et al., 2023a).

Tan et al. (2023b) demonstrated that the SWAT+ model is suitable for climate change analysis in tropical basins like the KRB, its application has largely focused on general hydro-climatic trends. However, the ability of SWAT+ to assess drought-specific impacts and risk assessment under future climate change and SRM scenarios remains underexplored. Furthermore, previous studies have not integrated key variables such as precipitation, streamflow, and soil moisture into a unified drought assessment framework. This highlights a critical gap in understanding how SRM strategies such as G6solar and G6sulfur could influence drought conditions in vulnerable tropical river basins.

Drought indices are commonly utilized to evaluate drought severity. Indicators such as the Standardized Precipitation Index (SPI), Standardized Runoff Index (SSI), SPEI, and Standardized Soil Moisture Index (SSMI) are derived from precipitation, runoff, evaporation, and soil moisture data, among others. In Southeast Asia, drought studies have utilized SPI (Tan et al., 2020a) SPEI (Fung et al., 2020), Standardized Streamflow Index (SSI) (Luhaim et al., 2021; Suhana et al., 2023), temperature vegetation dryness index (TVDI), the normalized difference water index (NDWI) (Shashikant et al., 2021). Soil moisture plays a vital role in the growth and development of crops (Wang et al., 2024b). soil moisture in drought assessments is particularly important for agricultural regions. Previous studies that have integrated soil moisture with precipitation and other variables have mainly focused on dry and semi-arid areas (Liang et al., 2021b). There exists a significant gap in the comprehensive integration of key hydrological variables such as precipitation, streamflow, and soil moisture into index formulation, which is important to provide a holistic understanding of drought conditions in tropical regions.

At present, the effects of SRM on meteorological and hydrological droughts in tropical basins, particularly at smaller regional scales, remain unclear. The G6 scenarios, which include G6solar and G6sulfur, along with SSP2-4.5 and SSP5-8.5 in the GeoMIP project, provide valuable insights into future climatic conditions that can aid in exploring the impacts of SRM on these regions (Guo et al., 2016; Wei et al., 2020). SRM is considered one of the potential climate mitigation strategies, with the assumption that human intervention will maintain temperatures at 1.5℃. Therefore, incorporating SRM projections into hydrological model simulations is essential for understanding their effects on future drought conditions. Although the CMIP6 model provides data that can be used for basin-scale research to project future drought conditions, its coarse resolution poses a limitation (Dixit et al., 2022). To address this issue, CMIP model data are often refined through downscaling (Xu et al., 2021) or bias-corrected procedures (Oruc, 2022) prior to their application.

Global temperatures are projected to rise by 1.5˚C by 2030, following an increase of approximately 1˚C that has already been experienced. Findings suggest that limiting the temperature rise to 1.5℃ could significantly reduce the likelihood of drought and the risk of water scarcity. Under these conditions, precipitation levels in high latitudes, mountainous regions, East Asia, and eastern North America are expected to be higher than they would be with a 1.5°C increase (Karmalkar & Bradley, 2017; Levin, 2018). Additional research indicates that land areas in the Northern Hemisphere are warming at a rate faster than the global average, with predictions that this region will be the first to exceed a 2.0°C temperature rise (Joshi et al., 2011; Sutton et al., 2007). Most research on the impacts of global warming at 1.5°C and 2.0°C primarily conducted on global or Global North contexts, creating a significant gap in studies related to the Global South, which is more vulnerable to climate change, especially in the river basins of Southeast Asia.

Tropical regions are more susceptible to water-related disasters such as drought due to their climatic conditions and high exposure to climate variability (Pörtner et al.,, 2022). Overall, three main issues remain: (1) There is limited research on the application of the latest SWAT+ model for hydrological simulation and drought analysis in tropical river basins of Southeast Asia; (2) There is a lack of comprehensive drought indices that integrate both hydrological and meteorological factors for assessing drought in tropical regions; and (3) Most studies on the impacts of SRM and global warming on drought focus on the global scale or the Northern Hemisphere, whereas research on their effects in tropical river basins of Southeast Asia remains limited.

1.3 Research Questions

1. How effectively does the SWAT+ model simulate streamflow and drought conditions in the KRB?

2. How can a drought index be developed that incorporates climate data and SWAT+ model outputs for a comprehensive drought assessment in the KRB?
3. What are the impacts of SRM and global warming at 1.5°C and 2°C on hydro-climatic conditions and droughts in the KRB?

1.4 Research Objectives

This study aims to understand how climate change could affect historical and future hydrological conditions and droughts in the KRB. This can be achieved through three specific objectives as follows:

1. To evaluate the capability of the SWAT+ model in simulating historical streamflow and drought in the KRB.
2. To develop a comprehensive drought index that incorporates precipitation, streamflow and soil moisture simulated from the SWAT+ model.
3. To assess the impact of SRM and global warming at 1.5°C and 2°C on hydrology and drought conditions in the KRB.

1.5 Significance of the Study

Climate change has a significant impact on water-related disasters in tropical basins. In early 2014, Kelantan faced a severe drought that caused a sharp decline in water levels, impacting over 8,000 rice farmers and resulting in losses of approximately US$22 million. Additionally, the death toll from dengue fever in 2014 was three times higher than in 2013 (Tan et al., 2017c). Many countries have committed to the Paris Agreement through various climate mitigation strategies aimed at limiting global warming to 2°C, or preferably 1.5°C, above pre-industrial levels. In addition, some SRM mitigation strategies have been proposed to quickly reduce global warming. Understanding how different climate scenarios affect local hydro-climatic conditions and drought is crucial for local stakeholders to develop more effective climate adaptation and mitigation strategies to minimize the impacts of climate change.

Previous studies indicate that the pronounced seasonality of precipitation in the KRB increases the likelihood of droughts, despite the region's tropical climate. The KRB has experienced drought during several periods, including 1997–1998, 2002–2003, 2005–2006, 2007, 2009–2010, 2014–2015, and 2015–2016 (Tan et al., 2017c). Furthermore, the RMK 12 project for the Kelantan irrigation scheme, managed by the Division of Agricultural Irrigation and Drainage in the Ministry of Agriculture and Food Industry, indicates that agricultural water supply in many areas of the Kelantan Basin is insufficient to meet the needs of crop cultivation. The area of farmland in Kelantan has varied from 1992 to 2018, totaling 456,595 hectares as of 2020, according to the East Coast Economic Region (ECER) project under the 9th Malaysia Plan (Tew et al., 2022). As agricultural land expands, local water demand increases. Research has shown that climatic factors significantly influence agricultural production in Kelanta (Suhaila et al., 2010). Therefore, investigating the droughts in Kelantan is crucial for the effective management and utilization of water resources.

The SWAT model is a widely recognized and reliable hydrological tool, well-suited for accurately simulating tropical small watersheds and supporting watershed hydrological research. Its outputs, such as streamflow, rainfall, and soil moisture data, are crucial for various research purposes, including the development of a drought index. Developing a comprehensive drought index that integrates these variables can better represent the meteorological, hydrological and agricultural droughts in the tropical regions, offering new insights into drought evaluation in tropical basins. The drought index and modeling framework established in this study can be replicated in other river basins with comparable climate conditions, as well as in neighboring countries in Southeast Asia. Furthermore, this study analyzes the impacts of SRM and global warming on drought in the KRB, providing critical knowledge for understanding regional hydrological cycles and enhancing drought monitoring under climate change. The findings also contribute to the IPCC knowledge base and inform ASEAN policy-making, supporting local disaster risk reduction efforts.

1.6 Scope of the Study

The KRB was selected due to its access to reliable, high-quality long-term rainfall data, making it an ideal experimental site for studying basins with tropical climatic conditions. Another reason for choosing KRB is the successful application of the SWAT model in the basin (Tan & Yang, 2020). This provides a solid foundation for our investigation into the impacts of climate change on hydrological and drought. The KRB is highly susceptible to drought due to its tropical monsoon climate, pronounced climate variability, and absence of major reservoirs or dams to provide water storage during dry periods. Historical records indicate that the basin has experienced severe droughts, such as the 1998, 2014, 2019, and 2020 events, which led to widespread water shortages and adversely affected local communities and agriculture. Despite these challenges, systematic drought risk assessments remain limited for the region.

SWAT is an open-source, user-friendly hydrological model integrated with GIS tools, facilitating collaboration and efficient assessment of land use, management practices, and climate impacts to support decision-making. Although SWAT has been extensively applied and validated in over 4,500 studies, research specifically dedicated to the SWAT+ model remains relatively limited, with only 181 studies listed in the SWAT literature database as of 8 July 2025. SWAT+ was developed to offer greater flexibility than the original SWAT framework by restructuring the model into modular components (objects), making it easier to update and expand. In addition to its modular design, SWAT+ features several key improvements that enhance its overall performance. These include advanced capabilities for simulating land management, reservoir operations, irrigation, and point source pollution—enabling a more detailed and realistic representation of human interventions (Bieger et al., 2017; Yen et al., 2019). However, validation studies of the SWAT+ model in Peninsular Malaysia remain limited.

The comprehensive drought index (CDI) was developed by combining precipitation, streamflow and soil moisture data from the SWAT+ model with the Kendall distribution function. Drought characteristics were examined for various time frames of 1 month, 3 months, 6 months, and 12 months, covering both the historical period from 1985 to 2004 and the future period from 2025 to 2084. The Mann-Kendall test was used to evaluate the spatial variation trends of the three drought indices at the 3-month and 12-month scales throughout the entire KRB, using both historical and future data.

This article examines four models from the GeoMIP6 including CNRM-ESM2-1, IPSL-CM6A-LR, MPI-ESM1-2-LR, and UKESM1-0-LL. The linear scaling method, was selected to bias correct the GeoMIP6 models before incorporating into the SWAT+ model. The analysis investigates the changing characteristics of precipitation, maximum temperature, minimum temperature, and streamflow in the KRB over various time periods from 2025 to 2084 under different G6solar, G6sulfur, SSP2-4.5, SSP5-8.5 scenarios. In addition, the study also compares the impacts of global warming of 1.5 and 2°C as set in the Paris Agreement.

1.7 Organization of the Chapters

This thesis is structured into six chapters, each containing multiple sections, with a brief summary of the content for each chapter. Chapter 1 establishes the foundation of the study by providing a thorough overview, which includes the research background, research problems, research questions, objectives, explanation of the significance and scope of the study.

Chapter 2 introduces SRM, covering its experimental development history and related research trends. It further explores the invention and application of the SWAT model, along with the latest advancements in the SWAT+ model. Following that, a comprehensive review of drought disaster assessment methodologies, which includes the use of composite indices, multiple indices, and single indices. This chapter also presents a brief overview of drought research in Malaysia, with a specific focus on the Kelantan region.

Chapter 3 provides a description of the geography and climate of the KRB. It also explains the research methods and the data needed for this study. The chapter outlines the research data, which includes climate and streamflow data, land use data, and soil data, along with information from four models in CMIP6. Additionally, it covers how the data is processed, how the SWAT+ model is built, how the composite index is developed, the method for calculating a single index, and the techniques used to analyze drought characteristics such as intensity, severity, and trends.

Chapter 4 presents the primary findings of the study, focusing on the changing characteristics of meteorology and hydrology in the context of SRM and global warming at 1.5°C and 2.0°C, as well as the projections of future droughts. In this section, a new drought index is developed, and the SPI and SSI indices are employed for comparative analysis. The results from Chapter 4 are further discussed in Chapter 5. Finally, Chapter 6 concludes the research, summarizing the key findings and offering recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Climate change alters the hydrological cycle through shifts in precipitation patterns, evapotranspiration, and other factors, making it essential to understand potential future drought risks (Satoh et al., 2022). Climate model experiments offer insights into how climate change influences drought. Therefore, a thorough quantitative study is needed to assess future changes in meteorological and hydrological droughts under various warming scenarios, such as 1.5°C and 2°C, as well as emission pathways and geoengineering efforts. This is crucial for regional protection concerning ecological balance, environmental stability, and managing potential natural hazards (Zeng et al., 2022).

This chapter reviews research on hydrological models, drought analysis, different global climate models, geoengineering, and climate change. A solid understanding of how hydrological models function, how to estimate drought indices, perform trend analysis, and process global model data is essential to achieve the objectives of this study. This chapter also provides an overview of studies on meteorological and hydrological droughts in Malaysia and the KRB, as well as the conceptual framework of this study.

2.2 Climate Change

Climate change has attracted considerable attention in recent years. Climate change encompasses global warming along with broader alterations in climate patterns, such as changes in precipitation, increased frequency and intensity of extreme weather events, and shifts in atmospheric and oceanic circulation (Masson-Delmotte et al., 2021). While natural processes, such as variations in solar radiation and volcanic activity, can also influence these changes, while human actions have become the primary driver since the mid-20th century (Masson-Delmotte et al., 2021). The extreme vulnerability of humanity to climate change, stemming from global warming, is highlighted by climate-related disasters such as heatwaves, droughts, floods, cyclones, and wildfires (Marx et al., 2021).

The current rate of warming is increasing between 0.3°C and 0.7°C every 30 year, as illustrated in Figure 2.1 (Masson-Delmotte, 2022). By 2017, temperatures were 0.15°C to 0.35°C above the average level recorded over the 30-year period from 1988 to 2017. As global warming progresses, the frequency and intensity of heatwaves have risen globally. Additionally, marine heatwaves have doubled since the 1980s (Arias, 2021). In June 2021, unprecedented high temperatures in the Pacific Northwest of North America led to hundreds of excess fatalities in Washington State, Oregon, and British Columbia. Drought conditions affecting 95% of this region further intensified the occurrence of wildfires. During and after the heatwave, 93 major fires destroyed millions of acres of land across the western United States (Bartusek et al., 2022). An extreme heatwave in 2003 caused around 70,000 deaths, primarily in France and Italy. Similarly, a heatwave in Russia in 2010 resulted in approximately 55,000 fatalities, widespread forest fires, and significant crop losses (Marx et al., 2021).

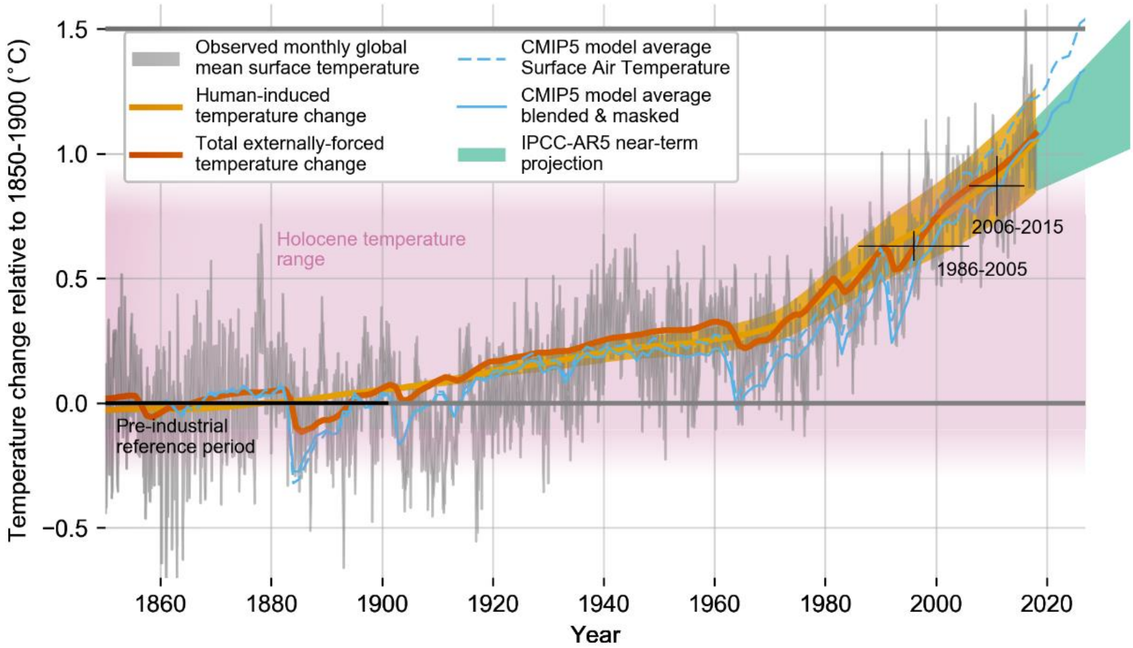

Figure 2.1 Evolution of Global Mean Surface Temperature (GMST)

According to high-end projections, regions such as East Africa, Northern Australia, Eastern North America, Central Asia, Central Europe, and Southeast South America will experience the greatest increase in heatwave frequency by the end of the 21st century. Regional warming is a key factor driving the variations in combined heatwave and drought events across most areas. It is anticipated that approximately two combined drought and heatwave events will occur each year in about 20% of the global land area, lasting around 25 days (Tripathy et al., 2023). Future changes in heatwaves in the most populous cities of 20 countries are projected using an ensemble of 44 members from 28 general circulation models (GCMs) from the CMIP5 archive under the RCP 8.5 emissions scenario. In absolute terms, heatwaves lasting 4-10 days are expected to be between 3.4°C and 6.6°C warmer in 2099 compared to 2006, regardless of their rarity and duration. The most significant increase is predicted for Paris, where the severity of a heatwave with a 100-year return level could rise by 3.4°C in average temperature, by 1.7°C for 10-day heatwaves, and by 130% in their occurrence (Brown, 2020). From 2000 to 2016, about 125 million people were affected by heatwaves (Klingelhofer et al., 2023).

The risk of flooding in coastal areas is intensified by rising sea levels (Buchanan et al., 2017; Vitousek et al., 2017). Global mean sea level is projected to rise between 0.30 and 0.65 meters by 2100, and between 0.54 and 2.15 meters by 2300, compared to the 1986-2005 period, under the RCP 2.6, with a central probability of 66%. Under RCP 8.5, the global mean sea level is expected to increase by 0.63 to 1.32 meters by 2100 and by 1.67 to 5.61 meters by 2300 (Horton et al., 2020). The tropics appear to be more vulnerable to extreme sea level events than northern latitudes (O'Neill et al., 2016). Over the past twenty years, marine heatwaves have occurred across all of Earth's ocean basins. Events that would have taken place only once every several hundred to several thousand years under pre-industrial climate conditions are now projected to occur as often as once per decade to once per century under 3°C of global warming (Laufkotter et al., 2020). There has been a 0.7°C increase in sea surface temperatures on the western side of the Arabian Gulf every decade. The coasts of all Arab countries along the Gulf are low-lying and could be at risk of submersion due to rising sea levels (Hereher, 2020).

The negative impacts of climate change on biodiversity have also been intensified, leading to the potential extinction of many species in the near future

(Rinawati et al., 2013). For example, during the severe 1997-1998 El Niño event, the variety of sun bear food trees in Indonesian Borneo declined by 44% due to drought and wildfires (Namkhan et al., 2022). Permafrost, which is land that remains frozen year-round, is present in various regions, including the Arctic, Siberia, Greenland, Alaska, Canada, and the Tibetan Plateau. The upper layer of this soil is rich in organic carbon, made up of decomposed plant material that could not break down because of the cold temperatures. As global warming progresses, the thawing of permafrost accelerates the microbial decomposition of these materials, leading to the release of additional carbon dioxide and methane into the atmosphere (Shivanna, 2022).

As warming trends continue, the frequency and severity of climate-related disasters are expected to rise significantly (AghaKouchak et al., 2020). More than 15% of the world's land is projected to become more vulnerable to heatwaves in the future, particularly in tropical regions and developing countries, impacting both human health and food production systems. Furthermore, the intensity and frequency of heatwaves are anticipated to increase substantially (Sun et al., 2020). In China, there has been a noticeable rise in extreme weather events, including prolonged heatwaves and heavier rainfall (Chen & Zhai, 2017; Wu et al., 2020a). Similar patterns of extreme precipitation and temperature events have also been documented in Central Asia over the past five decades (Hu et al., 2016; Peng et al., 2019; You et al., 2022). In Southeast Asia, the number of days with at least 2 mm of precipitation significantly decreased between 1961 and 1998, particularly in much of western and central South Pacific.

Most regions experienced a rise in the proportion of annual rainfall attributed to extreme events (Manton et al., 2001).

Health, agriculture, forests, biodiversity, and other components of the planet are all impacted by climate change as shown in Figure 2.2 (Solomon et al., 2007b). The number of severe hurricanes and heavy precipitation events will increase as a result of the global water cycle being altered by rising temperatures (Fischer & Knutti, 2016; Gualdi et al., 2013; Patricola & Wehner, 2018). Climate change's far-reaching repercussions extend to the global hydrological and hydrodynamic systems, amplifying the severity of water-related extremes, particularly droughts and floods (Dang & Pokhrel, 2024). Researchers have employed both coupled and uncoupled GCMs to probe the impacts of climate change on precipitation patterns and the occurrence of heavy rainfall events (Seager et al., 2012). With rising global temperatures, precipitation extremes are anticipated to become more pronounced, intensifying aridity in dry regions while exacerbating wet conditions in already moist areas (Chou et al., 2009).

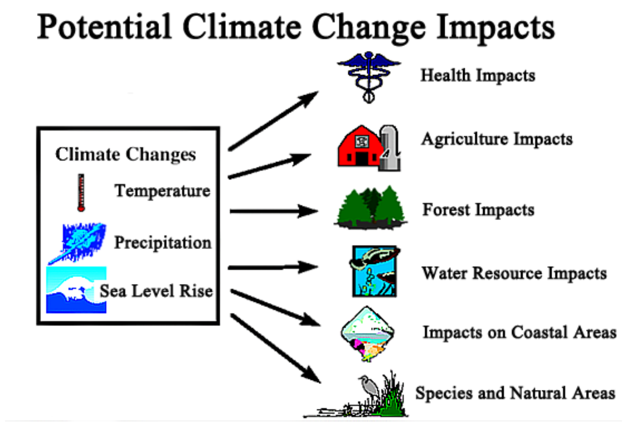

Figure 2.2 Climate change and its impacts

Studies on global extreme precipitation have found that global temperature is the most important factor influencing extreme precipitation indices worldwide, followed by regional temperatures. High-latitude regions of the Northern Hemisphere and Antarctica, which are strongly affected by global temperature changes, show a pronounced polar amplification effect. Other factors, such as the East Atlantic–West Russia pattern, the Atlantic Multidecadal Oscillation, and the El Niño–Southern Oscillation index, also contribute to changes in global extreme precipitation, but to a lesser extent (Li et al., 2024). West Africa is supposed to face a higher temperature increase than the global average this century (Todzo et al., 2020). In particular, with the trends of increasing rainfall in most regions, the frequency of drought has decreased significantly across all climate zones; the rate of reduction under a 1.5°C and 2°C warming scenario falls within ranges of -11.5%-6.1% and -57.1%-23.2%, respectively (Kim et al., 2020). Climate change is poised to significantly impact future water availability, compromising the intricate balance between water, energy, and food security, thus heightening the vulnerability of populations reliant on rain-fed agriculture (Dembélé et al., 2022).

2.3 Global Warming

The long-term increase in global average temperature, known as global warming, is primarily caused by greenhouse gas emissions such as carbon dioxide, methane, and nitrous oxide, which trap heat in the atmosphere through the greenhouse effect (Arias, 2021; Masson-Delmotte, 2021). As shown in Figure 2.3 (Britannica, 2024), these gases absorb outgoing infrared radiation and re-emit part of it back to the surface, enhancing atmospheric warming. Recent global warming studies continue to confirm that the Earth is warming due to the greenhouse effect caused by human activities. Between 1906 and 2006, the global average surface temperature rose from 0.6°C to 0.9°C annually. Millions of pounds of methane gas are produced through landfill operations, as well as the agricultural decomposition of biomass and animal manure. Various nitrogen fertilizers, including urea, ammonium phosphate, and other land management applications, release nitrous oxide into the atmosphere (Leiserowitz et al., 2018). The combustion of fossil fuels further increases greenhouse gas emissions.

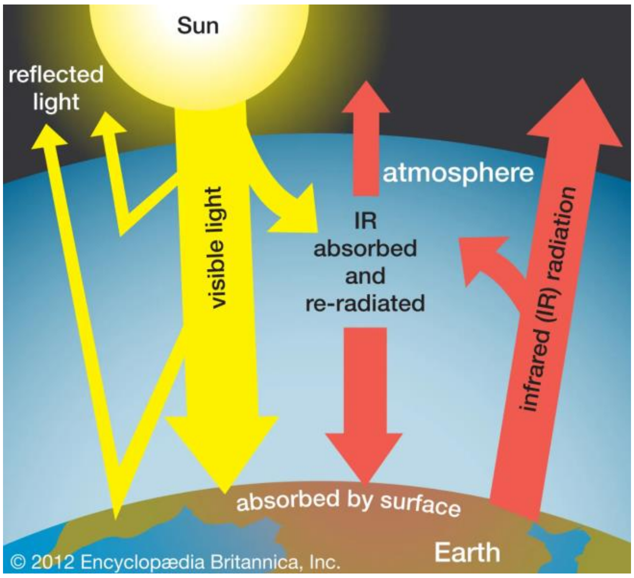

Figure 2.3 The greenhouse on the earth

Global warming has numerous adverse impacts, the foremost being drought. As temperatures rise, evaporation from land and oceans increases. In regions where the increase in evaporation exceeds that of precipitation, drought becomes more likely. This will result in decreased crop yields and potential famine in some parts of the world, particularly in areas already experiencing high temperatures (Arora, 2020). Secondly, glaciers around the globe are rapidly retreating, and ice loss appears to be occurring at a greater rate than previously anticipated (Rounce et al., 2023). Sea level rise has become one of the most serious consequences of global climate change. Furthermore, global warming may lead to more frequent heatwaves, more severe precipitation, and intensified storms and weather events. Global warming also increases the spread of diseases. Rising summer temperatures and longer warm seasons have resulted in an increase in mosquito-borne diseases such as dengue and malaria(Kulkarni et al., 2022). Additionally, global warming reduces biodiversity. Rising temperatures render habitats unsuitable for native species, causing species migration and impacting population reproduction (Brambilla et al., 2022).

The Paris Agreement proposes limiting global temperature rise to below 2.0°C above pre-industrial levels, with efforts to further limit the increase to 1.5°C (Building productive links between the UNFCCC and the broader global climate governance landscape). Accordingly, global scholars have conducted studies focusing on 1.5°C and 2.0°C global warming scenarios, primarily at global, Northern Hemisphere, and African regional scales (Betsill et al., 2015). For example, According to Shi et al. (2021), based on 29 CMIP5 global climate models, extreme precipitation was estimated using indices such as extreme precipitation frequency (R95pF), percentage (R95pT), and maximum 1-day precipitation (RX1day), to analyze the impact of global extreme precipitation events and socio-economic exposure. The results show that, in areas with high exposure to extreme precipitation events under 1.5°C warming, GDP