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Agro-Hydrological Modelling Systems in Peninsula Malaysia: A Comprehensive Review and a Guide towards Model Development

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Abstract

Agro-hydrological modelling systems play a vital role in understanding and managing water resources in agricultural landscapes. Incorporating hydrological processes and agricultural practices through modelling systems is essential for sustainable land and water management in Peninsula Malaysia, where agriculture is a significant industry. This article provides an overview of the agro-hydrological modelling systems implemented in Peninsula Malaysia and their applications, strengths, limitations, and future research directions. Various paper publications were considered, including papers listed in the Scopus database. Based on the findings, a key gap identified in Peninsula Malaysia is that the application of agro-hydrological modelling systems is still in its early stages. Additionally, few models incorporate long-term climate change projections and adaptive water management strategies. To address these limitations, the review proposes a flow chart for model setup and input data. These techniques, however, have the potential to significantly improve water management in the region. This paper aims to assist policymakers, researchers, and other stakeholders in making informed decisions about water management strategies in agricultural landscapes and to provide future research direction on agro-hydrological modelling.

Keywords: *Agro-hydrological, modelling, climate change, water management, Peninsula Malaysia.*

1.0 Introduction

The agricultural sector of Peninsula Malaysia is essential to the nation's economy and food security. It includes crop cultivation, animal husbandry, and aquaculture [1]. However, the sector's [1-3] Crop cultivation requires adequate water availability, whereas animal husbandry and aquaculture rely on water quality for animal health and production [4]. During dry seasons, irrigation systems are essential, and efficient methods are employed to maximize water use [5, 6]. Water scarcity and climate variability impact the availability of water in agriculture [7-10]. Government initiatives have been implemented to promote sustainable water management in agriculture [11]. The agro-hydrological modelling system is necessary to ensure the long-term viability of the agricultural sector in Peninsula Malaysia [7, 12-14]. Agro-hydrological modelling systems have the potential to be a valuable tool for enhancing water management in Peninsular Malaysia. More study, however, is required to increase the accuracy and utility of these models [7, 12, 14, 15].

Agro-hydrological modelling systems are utilized in agricultural systems to simulate water interactions and environmental conditions [6, 7, 14-17]. They can forecast water quality, crop yields, and other agricultural outcomes influenced by climate change, water management policies, and other factors.

Few studies in Peninsular Malaysia have employed agro-hydrological modelling systems to study these concerns. For example, [1] used an Excel-based model to assess the impact of climate change on streamflow in the Tanjung Karang Rice Irrigation Scheme. According to the study, under a high-emission scenario, more irrigation water will be required for the scheme in the future.

Another study employed the FAO-AquaCrop model to predict the impact of climate change on water productivity (WP) of irrigated rice in Malaysia by Houma. Using field trial data and the FAO-AquaCrop Model, this study assessed the WP of irrigated rice due to a changing climate in the North-West Selangor Rice Irrigation Scheme (NSRIS). According to the study, under three RCP emission scenarios (RCP2.6, RCP6.0, and RCP8.5), the WP of rice based on total water input applied irrigation, and real crop evapotranspiration will probably rise by 14–24%, 14–19%, and 17–29%, respectively, in the off-season.

These studies show that agro-hydrological modelling methods have the potential to inform water management decisions in Peninsular Malaysia [1, 18, 19]. However, several problems must be overcome before these models

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may be extensively employed. For example, the data requirements for these models might be considerable, and the models themselves can be challenging to utilize.

Agro-hydrological modelling techniques have the potential to be an effective tool for enhancing Malaysia's management of water resources on the Peninsula, despite these challenges. These models offer valuable insights into the intricate relationships between water, agriculture, and the environment, facilitating more effective and sustainable management of water resources.

By anticipating the consequences of climate change, identifying effective irrigation techniques, reducing soil salinity and waterlogging, and enhancing water quality, agro-hydrological modelling tools can aid in improving water management in Peninsular Malaysia.

[1, 12, 18-23].

The goals of this paper, however, are to examine the advancements and efficacy of agro-hydrological modelling systems on Peninsula Malaysia, assess their contribution to our understanding of hydrological processes, evaluate their role in improving irrigation practises, explore the integration of climate change scenarios, examine participation of stakeholders, identify challenges and constraints, and provide recommendations for further research and implementation. Moreover, the review examined the application of agro-hydrological modelling systems in Peninsula Malaysia, including the integration of various datasets, the improvement of temporal and spatial resolution, the incorporation of crop-water interaction modelling, the incorporation of climate change scenarios, stakeholder involvement, case studies, and recommendations.

2.0 Study Area

Peninsular Malaysia is roughly 3.9743° N latitude and 102.4381° E longitude. Peninsular Malaysia is situated in Southeast Asia, at the southernmost tip of the Malay Peninsula [24]. It is bounded to the north by Thailand, to the east and west by the South China Sea, and to the south by Singapore. Peninsular Malaysia is located in the southern part of the Malay Peninsula [25], as depicted in Figure 1.

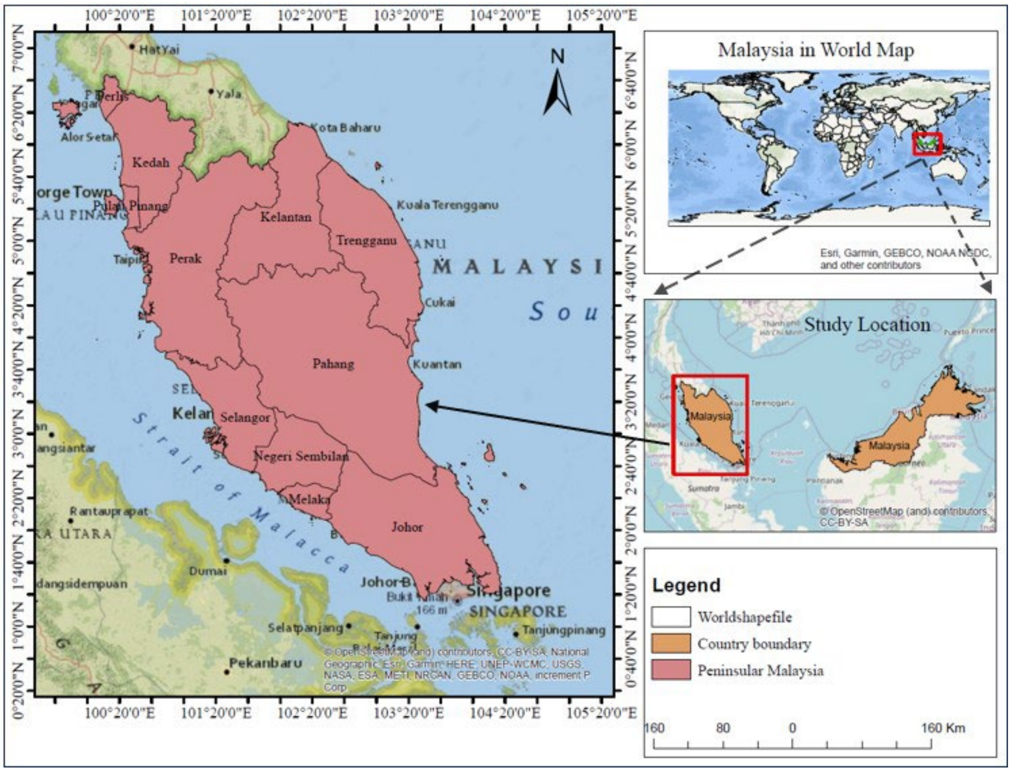

Figure 1: Map of Peninsular Malaysia

The climate in Peninsular Malaysia is tropical, characterized by consistently high temperatures and humidity throughout the year. March to October is the off-season, while November to February is the wet season [1, 26-29]. Malaysia's peninsular region is a key producer of oil palm, rubber, and cocoa. Rice, fruits, and vegetables are other important crops [1, 30-32].

3.0 Agro-Hydrological Modelling Concepts and Principles

The following are the fundamental concepts and principles of agro-hydrological modelling:

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Water movement through the environment, including the atmosphere, land surface, and subsurface, is simulated using hydrological models [6, 17, 33]. Precipitation, infiltration, evapotranspiration, runoff, and groundwater flow are frequently described using equations in these models [34-37]. The basic water balance equation used is expressed in Equation 1.1 [38].

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - ET - W_{seep} - Q_{gw}\right) \quad (1.1)$$

SW_t is the final soil water content (mm), $SW_0$is the initial soil water content (mm), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the surface runoff on day i (mm), ET is the evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile (mm), and Q_{gw} is the return flow or groundwater contribution to streamflow (mm).

Crop-water interaction models model crop responses to water availability. These models typically employ equations representing crop growth, water uptake, and yield generation processes [1, 37, 39, 40].

Agro-hydrological models combine hydrological and crop-water interaction models to mimic water-environment interactions in agricultural settings. Climate data, soil parameters, land use patterns, and crop characteristics are common data sources used in these models [1, 33, 37, 41, 42].

Agro-hydrological modelling offers several advantages, including predicting the impact of climate change on agricultural production, identifying the most efficient methods of irrigation water use, reducing waterlogging and soil salinity, and improving the quality of irrigation and drinking water [17, 33, 37, 43]. However, there are significant drawbacks to agro-hydrological models, which include: the models' intricacy can make them challenging to utilize and interpret; these models often have high data requirements; and frequently, the models are not calibrated or validated for specific locations or situations.

Despite these obstacles, agro-hydrological modelling has the potential to be a valuable tool for optimizing agricultural water management. These models can help ensure that water resources are used more efficiently and sustainably by providing insights into the complex relationships between water, agriculture, and the environment [1, 17, 33, 37].

Numerous agro-hydrological models have been developed to analyze and forecast the effects of climate change on food production and water resources on a global scale. Some well-known global agro-hydrological models that have been developed and used include the Global Agro-Ecological Zones (GAEZ) model. This GAEZ model is a widely used agro-hydrological model created by the United Nations Food and Agriculture Organization (FAO) in collaboration with the International Institute for Applied Systems Analysis (IIASA).

It integrates climate, soil, and topographic data to assess agricultural potential, water availability, and crop suitability across different regions globally [41, 42, 44]; the DSSAT (Decision Support System for Agrotechnology Transfer) model suite can be used to simulate crop growth, yield, water use, and fertilizer management in agricultural systems [45-49]; SWAT (Soil and Water Assessment Tool) is a hydrological model that simulates water transport through soil, groundwater, and surface water [16, 50-54] while SWAT+ (Soil and Water Assessment Tool Plus) is an improved version of SWAT that includes additional modelling capabilities for a broader spectrum of environmental processes. SWAT+ addresses more complex and integrated research questions in water resource management [55, 56]. AquaCrop is a crop model that simulates crop responses to water availability [14, 18, 57, 58]. These are only a few of the several agro-hydrological modelling systems available. The user's requirements determine the model to be used.

3.1 Hydrological Processes and Their Interactions with Agriculture

A variety of hydrological systems interact with agriculture in various ways. Precipitation, for example, may irrigate fields or generate floods, which destroy crops. It is the most significant agricultural water supply. It might come as rain, snow, or hail. Precipitation might be intercepted directly by plants or can reach the soil surface and infiltrate [5, 17]. Infiltration: Water penetrates the soil via infiltration. The type of soil determines the infiltration rate, the quantity of water falling, and the presence of plants [59-61]; Evapotranspiration is the process of transferring water from the soil, plants, and atmosphere. The sun's energy drives evapotranspiration, the primary mechanism for water loss from agricultural systems. It may take water from the soil, causing crop water stress [33, 59, 61-63]. Runoff: Water that runs over the ground surface and into streams, rivers, and lakes is called runoff. Heavy rainfall, snowmelt, and irrigation may all generate runoff.

It may transport silt and contaminants into streams and rivers, thereby harming aquatic habitats [64-67]. Groundwater is the water held under the ground surface in the soil and rocks. Groundwater can be utilized for irrigation, drinking water, and industrial purposes. It can be used to irrigate crops, but it is also prone to contamination by agricultural pesticides [63, 68].

We can better manage our water supplies and safeguard our agricultural systems if we understand the major hydrological processes and their linkages with agriculture.

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In addition to the above, waterlogging, soil salinity, and drought are also ways that hydrological processes may affect agriculture [69-71]. Water resources and agricultural systems are better managed and protected when the consequences of these actions are understood.

3.2 Overview of Agro-Hydrological Modelling Frameworks and Approaches

Agro-hydrological modelling is a scientific technique that integrates agriculture and hydrology to simulate and understand the interactions between water, soil, crops, and the environment in agricultural systems, utilizing computer models to predict agricultural water availability, movement, and management [1, 15, 61].

These models facilitate the optimization of water balance, irrigation scheduling, crop selection, and land management practices. Agro-hydrological models enable informed decisions regarding water resources and sustainable agricultural practices by simulating precipitation, evapotranspiration, soil properties, and crop characteristics. They promote water conservation, increase crop yields, and minimize environmental impacts.

However, a bibliometric network visualization map of the Authors' Keywords was carried out, as depicted in Figure 2. The network visualization of author keywords used in the research of the Agro-Hydrological model was mapped out using VOSviewer. The line in the figure represents the connection between different keywords used by the authors.

Furthermore, Figure 2 shows three distinct keywords for the authors' clusters identified in the Agro-Hydrological model research field. Initially, the first cluster in yellow comprises Agro-Hydrological modelling, climate change, agriculture, runoff and catchments, including other keywords for the author. The author's keywords, the Agro-Hydrological model, have been most frequently used in the first yellow cluster. The second cluster, labelled green, represents irrigation, evapotranspiration, and water management, as well as other authors' keywords. The third cluster, denoted in blue, represents authors' keywords, including crop production, crop yield, and agricultural modelling.

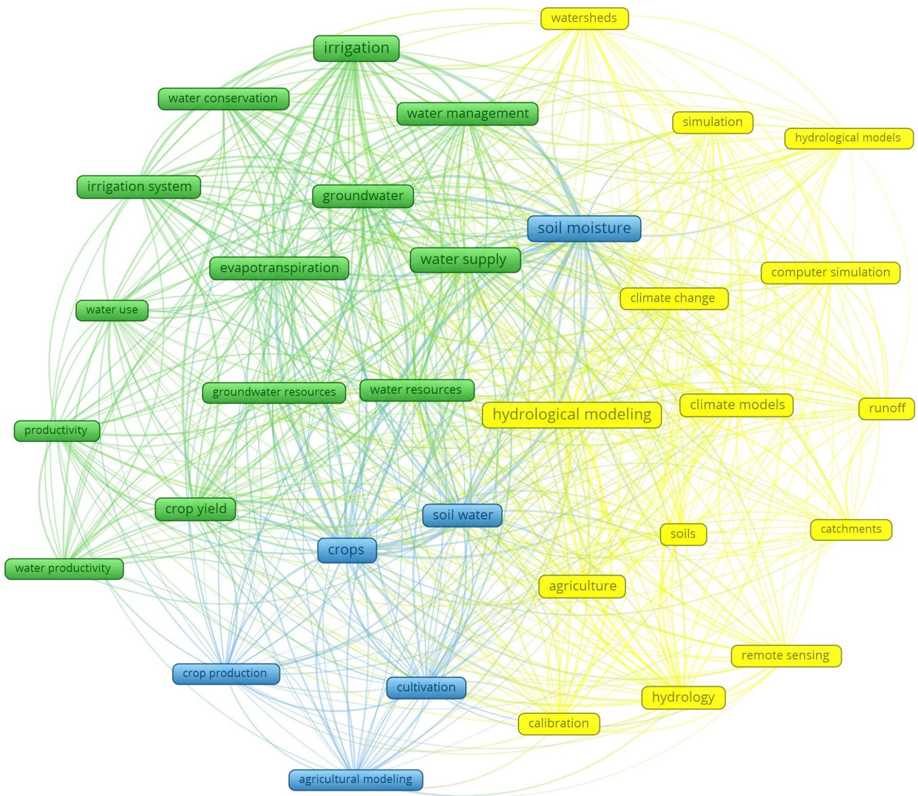

Figure 2: The VOSviewer Network Visualization Map of the Authors' Keywords (Minimum order of the Occurrence=10)

Moreover, few countries have applied agro-hydrological techniques, as shown in Figure 3, which presents publications country-wise. Two hundred sixty-two (262) journal articles were collected from the Scopus database at the time of this report, with the following countries represented for the Agro-Hydrological model application. Their number of publications: China (77), Italy (41), Canada (31), United States (29), France (26), Netherlands (18), Germany (13), India (12), Spain (11), Iran (10), United Kingdom (9), Brazil (8), South Africa (7) and other countries like Belgium, Denmark, Australia, Pakistan, Tanzania have 2 to 6 publications while Malaysia is among countries with just one publication of agro-hydrological models.

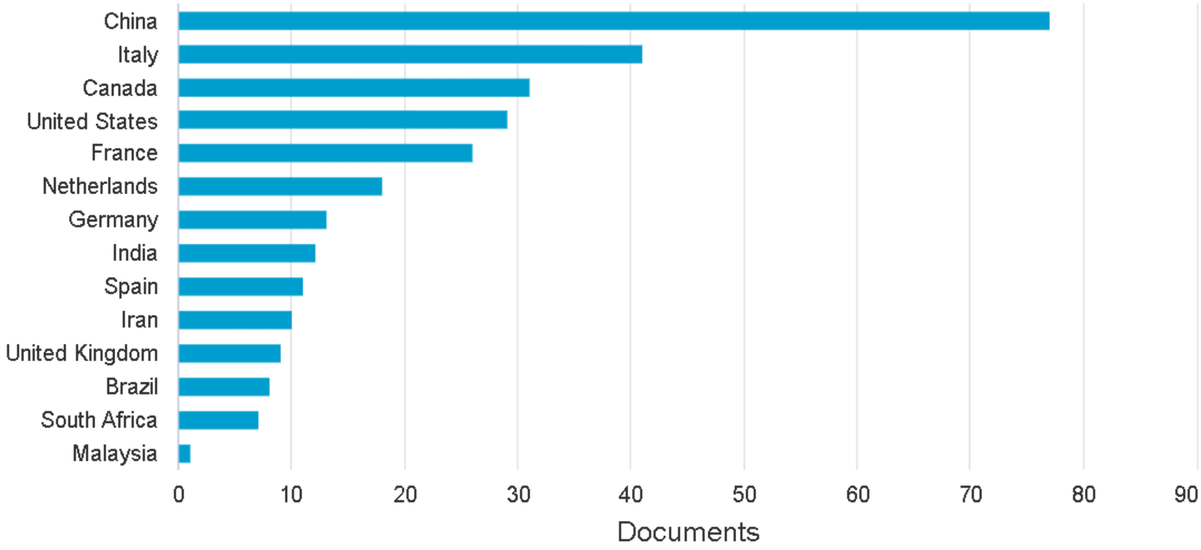

Figure 3: Documents by country-wise

The discipline in which most of the agro-hydrological model research was carried out and their number of publications (Figure 4) are as follows: Environmental Science (157 ~30.3%), Agricultural and Biological Sciences (124 ~ 23.9%), Earth and Planetary Sciences (79 ~ 15.2%), Engineering (40 ~ 7.7%), Computer Science (32 ~ 6.2%), Mathematics (18 ~ 3.5%), Physics and Astronomy (12 ~ 2.3%), Social Sciences (12 ~ 2.3%), Biochemistry, Genetics and Molecular Biology (10 ~ 1.9%), Chemical Engineering (9 ~ 1.7%), and other subjects carry 5%. It was observed that most studies were conducted under the disciplines of Environmental Science, Agricultural and Biological Sciences, and Earth and Planetary Sciences, respectively.

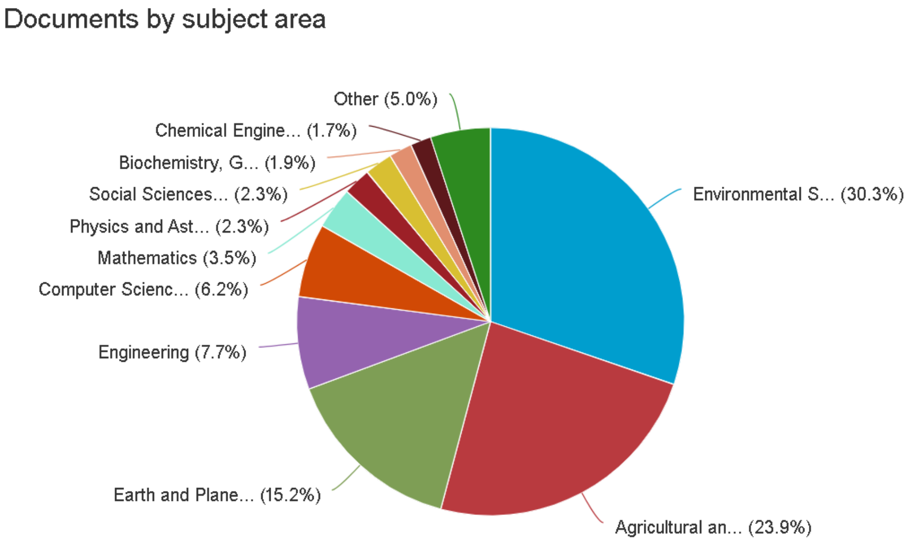

Figure 4: Documents by subject area

The top 10 universities/institutions (Figure 5) that researched the agro-hydrological model include China Agricultural University (44), University of Alberta (23), Università degli Studi di Palermo (17), L'Institut Agro Rennes-Angers (11), Sol Agro et hydrosystème Spatialisation SAS (11), CNRS Centre National de la Recherche Scientifique (10), Università degli Studi di Napoli Federico II (10), Centre INRAE Bretagne-Normandie (10), Zhejiang University (9), Wageningen University & Research (9), while Universiti Putra Malaysia and National Hydraulic Research Institute of Malaysia, NAHRIM which is now National Water Research Institute of Malaysia, NWRIM (1) are among the institutions with the minor publication.

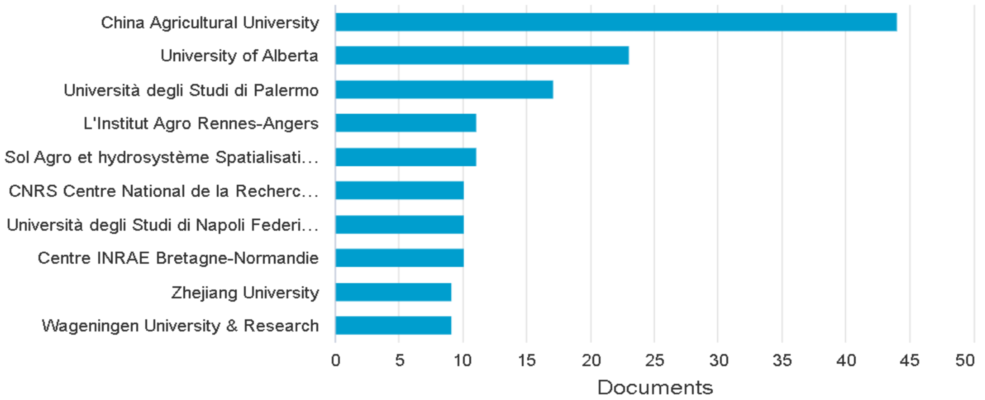

Figure 5: Documents by affiliation

Journal of Agricultural Water Management (37), Journal of Hydrology (15), Science of the Total Environment Journal (11), Computers and Electronics in Agriculture (7), and IFAC Papersonline (6) are among the leading Journals in agro-hydrological models' publications as seen in Figure 6 while Water Resources Research Journal are among the least on publication of the subject matter.

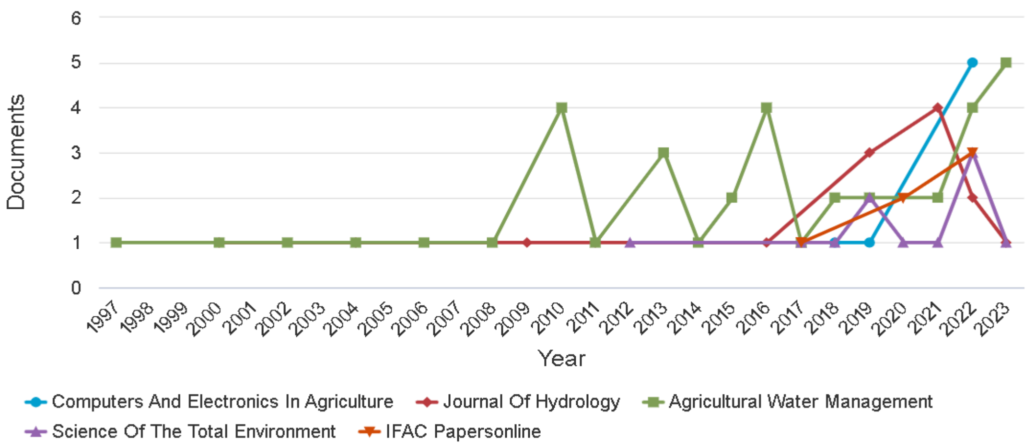

Figure 6: Documents per year by source

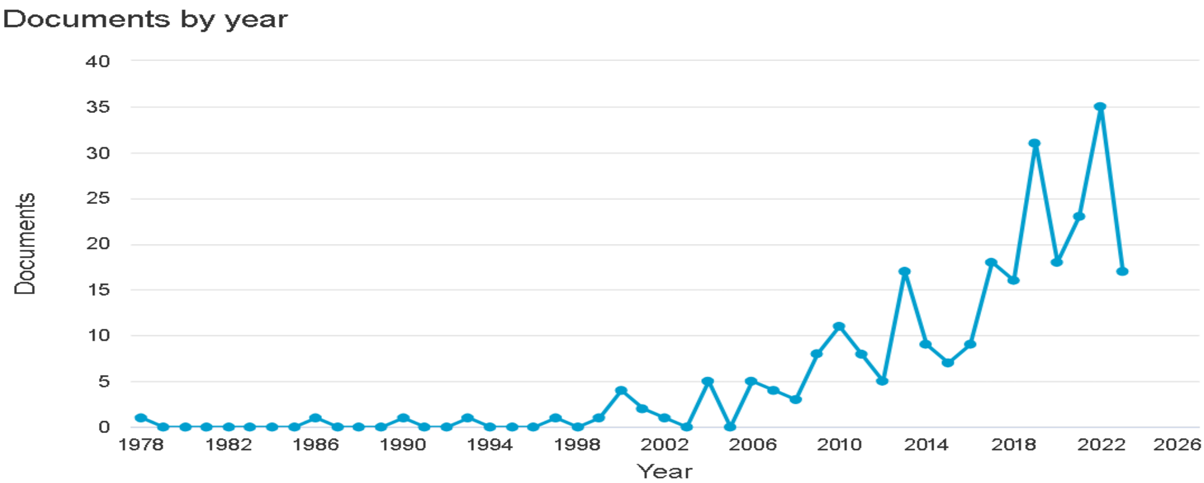

Figure 7: Documents by year

It was observed that the first publication on agro-hydrological models was in 1978, with only one publication listed in the Scopus database (Figure 7), while the highest number of publications was recorded in 2022, with 35 publications. Between 1978 and 1999, one (1) or zero (0) publication was recorded. The number of publications started increasing from the year 2000, with four (4) publications to the year 2022 (35 publications), and the years

2003 and 2005 recorded zero publications, which can be termed as outliers within the range of the years (2000 – 2022). However, the year 2023 has recorded 17 publications and is still counting; this implies that the awareness of agro-hydrological modelling is becoming one of the recent trends in this area (agro-hydrological modelling) of research, which Malaysia should not be left out of due to its dependence on agriculture and its vulnerability to climate change.

3.3 Available Agro-Hydrological Modelling Systems in Peninsula Malaysia

Malaysia, with its diverse agricultural sector, which includes rice cultivation, oil palm plantations, and vegetable farming, heavily relies on water availability. Therefore, agro-hydrological models tailored to the Malaysian context can help in understanding the impacts of changing rainfall patterns, temperature, and land-use practices on water resources and crop productivity. Among other countries, Malaysia applies some global agro-hydrological models, such as SWAT [1, 72-74]. SWAT has been deployed in conjunction with other software to simulate hydro-climatic scenarios for land, environmental, and water resource management in Malaysia [1, 75-77].

However, a summary of Agro-Hydrological models developed for Malaysia is presented in Table 1. In 2011, Ranhill Consulting firm developed the National Water Resource Management Decision Support System (NWRM-DSS), an integrated water resources management decision support system with a centralized databank, a synchronized distributed application for state-level water supply and demand assessment, and updated information on water resources planning [78]. The framework (Figure 8) does not allocate equitable water to irrigation fields/plots.

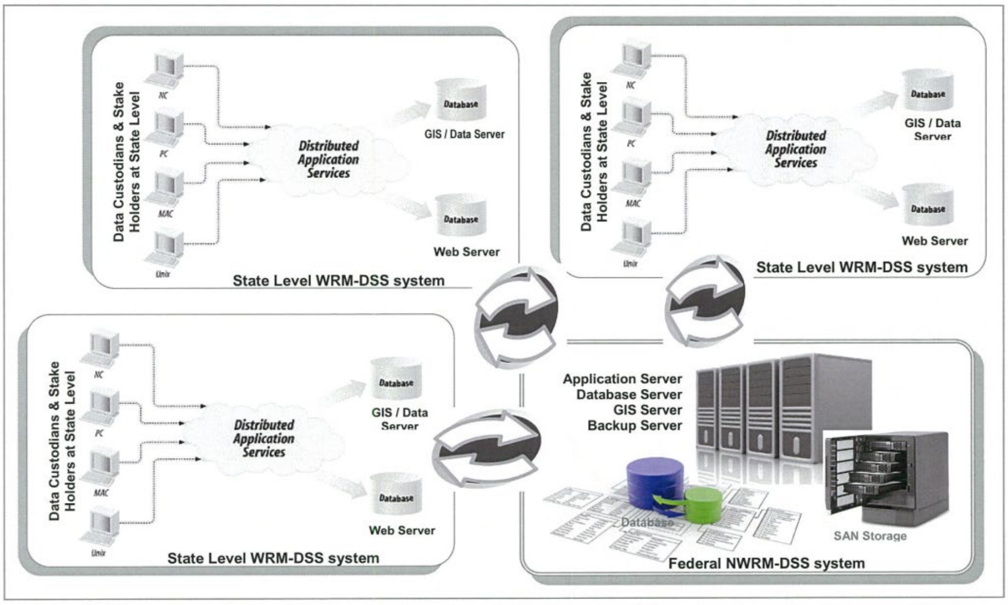

Figure 8: General Schematic of NWRM-DSS Distributed Application Architecture.
Source: DID [78]

Table 1: Summary of Agro-Hydrological models developed for Malaysia

No. Source	Authors	Title	Publication	Year	Category /location	Objectives	Methodology	Findings	Recommend ation/gap	Remark
1	[78]	Review of the National Water Resources Study (2000-2050) and Formulation of National Water Resources Policy	Report on Review of the National Water Resources Study (2000-2050) and Formulation of National Water Resources Policy by Ranhill Consulting Sdn Bhd	2011	Physically-based model/Malaysia	to develop an integrated water resources management decision support system with a centralized data bank for federal-level management, a synchronized distributed application for state-level water supply and demand assessment, and updated water resource planning information.	General Requirements - The first step was to understand the intended DSS objective, scope, limitations, and constraints; identify alternative models or analysis techniques for the DSS component; and determine the data to support such development.	The National Water Resource Management Decision Support System (NWRM-DSS) framework was developed to integrate a water resources management decision support system with a centralized database for federal-level management, along with a synchronized distributed application for state-level water supply and demand assessment.	The framework does not provide equitable water allocation to irrigation fields/plots.	Not specific to the agro-hydrological application
2	[72]	Review of studies on hydrological modelling in Malaysia	Journal of Modelling Earth Systems and Environment (2018) 4: 1577 – 1605 https://doi.org/10.1007/s40808-018-0509-y | Springer database	2018	Physically, Empirical and Conceptual-based model/Malaysia	to review hydrological studies in Malaysia; To evaluate the hydrological models used in Malaysia and determine the coverage of hydrological models in major River basins and to identify the methodologies used (specifically model performance and evaluation).	Data/articles collected from different journal databases	From the review, it It was found that most hydrological studies focused on simulating streamflow in one river basin or another.	All the reviewed hydrological studies focus on simulating streamflow in one river basin or another, with no application of the simulation or projection outcomes for irrigation planning and scheduling.	Not specific to the agro-hydrological application

No. Source	Authors	Title	Publication	Year	Category /location	Objectives	Methodology	Findings	Recommend ation/gap	Remark
3	[11]	Malaysia's National Water Balance Management System: Tool for Water Resources Manager	International Conference on Dam Safety Management and Engineering (ICDSME 2019). Malaysia National Committee on Large Dam (MYCOLD). 19-21 Nov 2019, The Wembley Hotel, Penang, Malaysia.	2019	Physically-based model (MIKE BASIN)/Perak and Penang, Malaysia	to develop the National Water Balance Management System (NAWABS) for Malaysia	It is developed using the MIKE modelling platform.	NAWABS provides a coherent framework to cross-evaluate the information on supply, demand, and impacts on water availability for the river basin	The framework does not provide equitable water allocation to irrigation fields/plots.	Not specific to the agro-hydrological application
4	[1]	Climate-Smart Agro-Hydrological Model for a Large-Scale Rice Irrigation Scheme in Malaysia	Journal of Applied Science: 2020, 10, 3906; doi:10.3390/app10113906 www. mdpi.com/journal/applsci | MDPI database	2020	Physically-based model/Tanjung Karang, Malaysia	to develop a climate-smart agro-hydrological model for adaptive irrigation and wise water resource management Management towards water security under the new realities of climate change	Excel-based Visual Basic For Applications (VBA), the method was adopted	The development of a Climate-Smart Agro-Hydrological Model for a Large-Scale Rice Irrigation Scheme in Malaysia only considers the water requirement for the Tanjung Karang irrigation scheme from the run-of-the-river project of the Bernam catchment.	The model does not make provision for the proportionate distribution of water among The tertiary canals through proper control of the off-take structure gate and scheduling	specific for the agro-hydrological application

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Similarly, [11] also reported the development of Malaysia's National Water Balance Management System (NAWABS). NAWABS aimed to provide a coherent framework (Figure 9) to cross-evaluate the information on supply, demands and impacts on water availability for river basins. Still, the framework does not provide equitable water allocation to irrigation fields/plots.

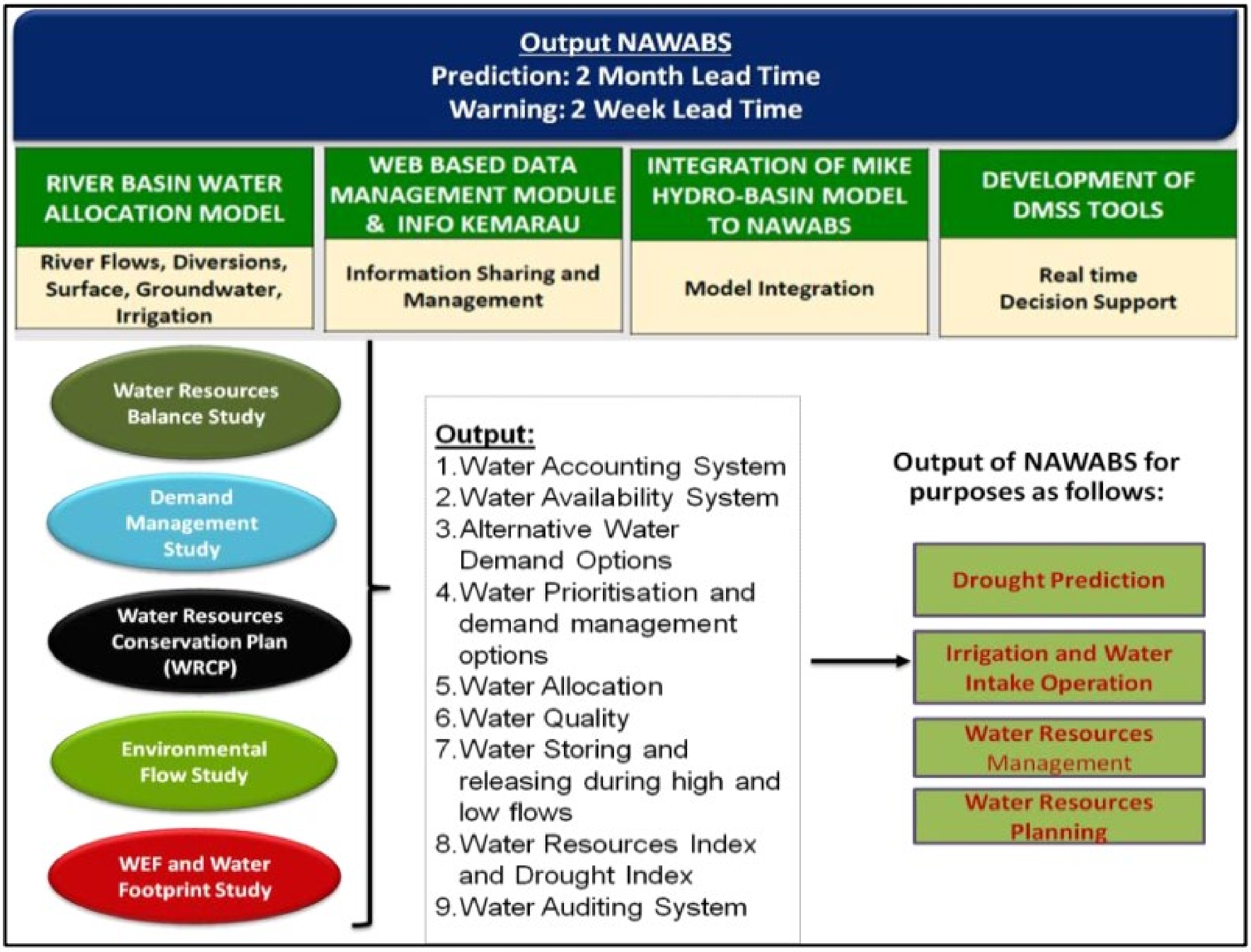

Figure 9: Structure of NAWABS. Source: Ismail, et al. [11]

Consequently, [72] reviewed studies on hydrological modelling in Malaysia (Table 1) by sourcing data from different journal databases. They reported 70 hydrologic modelling studies in Malaysia and found that most hydrological research focused on simulating streamflow in one river basin or another. Of these reported hydrologic modelling studies, none have applied the simulation or projection outcomes for irrigation planning and scheduling.

Nevertheless, [1] reported the development of a "Climate-Smart Agro-Hydrological Model for a Large-Scale Rice Irrigation Scheme in Malaysia," which only considers the water requirement for the Tanjung Karang irrigation scheme from the run-of-the-river project of the Bernam catchment. However, the model does not account for the proportionate delivery of water among the tertiary canals through proper control of the off-take structure gate and scheduling. Still, the model is designed explicitly for agro-hydrological applications. The framework for this model is presented in Figure 10.

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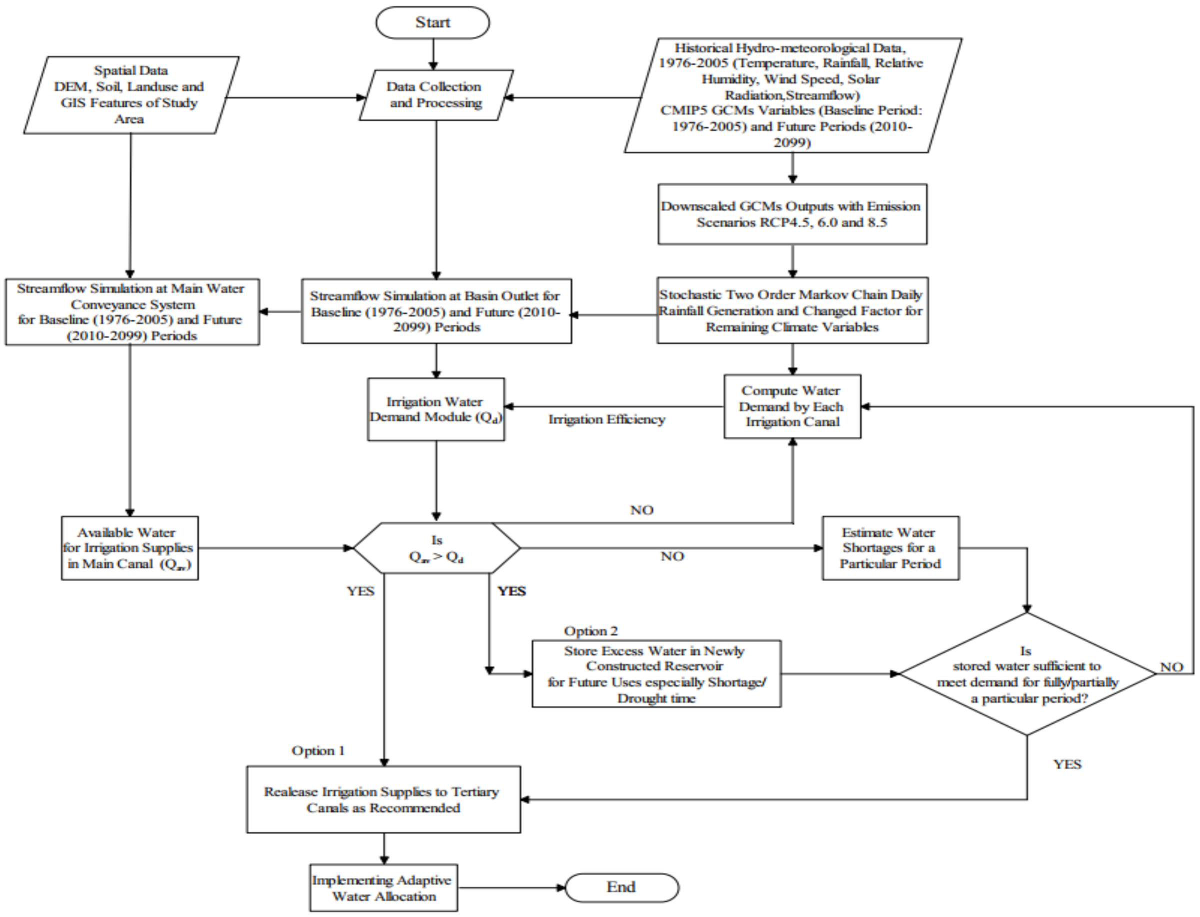

Figure 10. Framework for the climate-smart agro-hydrological model. Source: Ismail, et al. [1].

3.4 Description of Model Structures, Algorithms, and Key Input Parameters

By understanding the model structures, algorithms, and key input parameters of agro-hydrological modelling systems, we can better comprehend how these models operate and how they simulate the interaction between water and the environment in agricultural systems. Model structures, algorithms, and essential input parameters are described as follows for agro-hydrological modelling systems:

Model structures: Agro-hydrological modelling systems have two primary components: hydrological and crop-water interaction models. The hydrological model simulates water movement throughout the environment, whereas the crop-water interaction model simulates the plants' response to water availability [37, 51, 79].

The algorithms used in agro-hydrological modelling systems differ based on the model. Nonetheless, some prevalent algorithms include Richards' equation: This equation is utilized to simulate the flow of water via soil [80-84]; Equation of Penman-Monteith: This equation is used to simulate evapotranspiration; Crop growth models: These models affect the development and growth of plants; including their water needs [85-87].

Principal input variables: Among the most important input parameters for agro-hydrological modelling systems are Climate data, including precipitation, temperature, relative humidity, and solar radiation [37, 51, 79]. Typical climate data used in agro-hydrological modelling systems include daily or hourly measurements of precipitation, temperature, relative humidity, and solar radiation [37, 51]. This data is available from meteorological stations and climate models. Soil properties: This data refers to the soil's nature, texture, and depth. Typical agro-hydrological modelling systems utilize soil type, texture, depth, and hydraulic conductivity as soil properties [88, 89]. This data can be collected through soil surveys or laboratory experiments. Land use patterns: This data describes the nature of land cover, including cropland, forest, and grassland. In agro-hydrological modelling systems, land use patterns typically indicate the type of land cover, such as cropland, forest, or grassland [90-92]. This data is accessible via land use maps or remote sensing data. Characteristics of crops: This data comprises crop type, variety, and date of sowing. In most agro-hydrological modelling systems, crop type, variety, planting date, and growth stage are crop characteristics [93-95]. This data can be obtained from crop database searches or field trials.

The precision of agro-hydrological modelling systems depends on the quality of the input data. Consequently, it is essential to utilize high-quality data when conducting these models.

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3.5 Comparison of Different Modelling Systems Based on Their Applicability and Performance

The agro-hydrological models enumerated in Table 2 can be used to simulate the interaction between water and the environment in agricultural systems. The complexity and applicability of these models differ, but they all have the potential to shed light on the intricate interactions between water, agriculture, and the environment.

Table 2: Comparison of different modelling systems based on their applicability and performance

S/N	Model	Description	Applicability	Performance	Citations	In some of the countries where it has been applied	Some citations for Malaysia
1	CROPWAT	Crop water requirements and irrigation scheduling	Crop water requirements and irrigation scheduling	Good accuracy can be used for a variety of crops and conditions	[96, 97]	China, India, Bangladesh, Ethiopia, Iraq, Nigeria, Malaysia, United States	[98-101]
2	GLEAMs	Groundwater Loading Effects of Agricultural Management Systems	Soil water balance and crop growth	Good accuracy can be used for large areas	[102, 103]	Italy, Finland, United States	-
3	SWAT	Soil and Water Assessment Tool	Watershed hydrology and water quality	Good accuracy can be used for complex systems	[50, 51]	China, Malaysia, United States, Ethiopia, Brazil, Canada, Morocco, India, Iran	[13, 72, 104-107]
4	SEBAL	Surface Energy Balance Algorithm for Land	Evapotranspiration and surface energy balance	Excellent accuracy can be used for complex systems	[108-110]	China, Iraq, Zimbabwe, Egypt, United States	-
5	VIC	Variable Infiltration Capacity	Land surface hydrology and ecosystem dynamics	Excellent accuracy can be used for complex systems	[111-113]	Canada, Sweden, India, China, United States	-
6	DSSAT	Decision Support System for Agrotechnology Transfer	Crop growth, water use, and nutrient management	Good accuracy can be used for a variety of crops and conditions	[48, 114]	China, India, Malaysia, Senegal, United States	[18, 115-119]
7	SWAP	Soil–Water–Atmosphere–Plant	Designed to simulate water flow, solute transport and plant growth in a soil–water–atmosphere–plant environment	Good accuracy can be used for large areas	[120, 121]	China, Italy, India, Israel, United States	-
8	AquaCrop	Crop Water Productivity Model	Response of Crops to Water Availability	Good accuracy can be used for a variety of crops and conditions	[122, 123]	Belgium, China, India, Iran, Egypt, Nigeria, Malaysia, United States	[18, 124]

9	HYDRUS	Soil-Plant-Atmosphere-Water Dynamics	For simulating the movement of water, heat, and solutes in one-, two-, and three-dimensional variably saturated media.	Excellent accuracy can be used for complex systems.	[125, 126]	China, Canada, Iran, India, Jordan, Morocco, Malaysia, South Africa, United States	[127-129]
10	WOFOST	World Food Studies	Crop growth, water use, and nitrogen dynamics	Good accuracy can be used for a variety of crops and conditions	[130, 131]	China, Czech Republic, Israel, Belgium, Netherlands, India, Malaysia, United States	-
11	SWAT+	Soil and Water Assessment Tool+ (SWAT+)	Designed for a more flexible spatial representation of watershed interactions and processes	Good accuracy can be used for complex systems.	[37, 132]	United States, South Africa, Tanzania, Iran, Ethiopia, Kenya, Sweden, Turkey, China, Italy, Germany, Morocco, Malaysia,	[133]

However, it can be observed that some of these global agro-hydrological models have not been tested or utilized in Malaysia's agricultural sector, despite the country's significant investment in this sector and its substantial contributions to the global food supply. Food security has become more critical due to the pandemic impact on agricultural production and prices. Ensuring food supply stability is vital, especially for agricultural products with low self-sufficiency and high import dependency. To mitigate the effects of climate change on agricultural production, the internal food supply gap, import dependence, and the virtual displacement of water used for agricultural production for export must be addressed. This requires equitable access, a good water allocation system, and the development of sustainable water resources.

3.6 Applications of Agro-Hydrological Modelling Systems

Malaysia is a Southeast Asian country with a tropical climate. It is a significant producer of agricultural goods, including rice, rubber, and palm oil [1, 30-32]. The country also faces challenges related to water scarcity and climate change in its agricultural sector [1, 134].

Several models from Table 2 have been applied to Malaysia to address some of these obstacles. CROPWAT has been used to analyze the water requirements of various crops [98-101]. SWAT has been used to simulate the impact of streamflow and climate on some of Malaysia's catchments [13, 72, 104-107], among others.

The application of agro-hydrological models in Malaysia is still in its infancy, but these models have the potential to play a significant role in water management and agricultural planning.

The efficacy of the models specified varies depending on the application. Some models are more pertinent to specific problem types, while others are more accurate. However, each of the models mentioned above can illuminate the intricate interactions between water, agriculture, and the environment.

3.7 Strengths and Limitations of Agro-Hydrological Modelling Systems

Systems for modelling agro-hydrological interactions are effective tools for regulating interactions between agriculture and water resources [14, 17, 20, 135]. They can be applied to model crop growth and water use under various management scenarios, to evaluate how climate change will affect agricultural water demand, to design irrigation systems, and to maximize water allocation. However, these models have the following advantages: They can be used to develop and evaluate water management strategies, explore various management options, identify potential risks and opportunities, and effectively communicate the research results. They can simulate complex interactions between the atmosphere, soil, plants, and water. They can also assess the impact of various factors on agricultural water demand, including climate change, crop selection, and irrigation management [14, 17, 20, 135].

Consequently, these models also have the following setbacks: the models may not be able to capture all of the complexities of the real world, such as the behaviour of individual plants or the effects of pests and diseases; they may be complex and require a large amount of data; the accuracy of the models may be affected by the quality of the data and the assumptions that are made; they may may be expensive to develop and run; they may be challenging to use; and they may be sensitive to the quality of the data [14, 17, 20, 135].

Despite these setbacks, agro-hydrological modelling systems support, comprehend, and regulate the relationships between agriculture and water resources. In addition to improving the efficiency with which water is utilized in agriculture, they can help ensure that there is enough water available to meet the needs of both agricultural and other users.

3.8 Limits, Uncertainties, and Challenges in Model Application

Before applying agro-hydrologic models, it is crucial to comprehend some of their fundamental characteristics. In this regard, a brief outline of the restrictions, uncertainties, and challenges of agro-hydrological modelling is given below:

Agro-hydrological models exhibit a high degree of complexity and necessitate a substantial amount of data. The complexity of these factors may render them difficult to comprehend and apply, while also necessitating careful consideration of the data's reliability and validity [14, 136].

The availability of data frequently limits the application of models. This assertion holds particular validity concerning data on agricultural yields, soil attributes, and meteorological patterns [137].

The parameterization of an agro-hydrological model frequently influences its accuracy. This suggests that the parameter values for the model must be determined using the data. However, doing so may be challenging and complicated [138, 139].

Model calibration and validation are also crucial for ensuring the accuracy of agro-hydrological models. These procedures, nevertheless, may be laborious and iterative [33, 37, 140].

Agro-hydrological models are always subject to some degree of uncertainty. This is so because the models are predicated on assumptions that may not be entirely true about the actual world [141, 142].

Additionally, model coupling may complicate the modelling process and increase uncertainty in the outcomes. Model size can also affect the accuracy of the results, and model maintenance can be complex for organizations that lack the requisite resources or knowledge.

Agro-hydrological modelling is an intricate and challenging field, and applying the models to real-world scenarios can be complex, as it's crucial to understand their limitations [61, 72]. Nevertheless, these models may help determine and regulate the interaction between agricultural and water resources.

3.9 Assessment of Data Requirements and Availability for Accurate Modelling

Assessing data requirements and availability for accurate modelling is vital in any data science project [143-147]. This assessment aims to certify that the data is sufficient to answer the research questions and is highly adequate to produce accurate results.

Different agro-hydrological models have varying data requirements, depending on the specific model and its intended application. However, a few typical data needs are as follows: GIS data (topography, soil type, land use, and sub-catchment ID) plus weather data (precipitation, temperature, wind, and relative humidity). The following details the functions of the input data:

Digital Elevation Model (DEM): The agro-hydrological model, which simulates water flow and other processes in a watershed, is run using a Digital Elevation Model (DEM). The DEM gives elevation data, which aids in representing the land's topography. It maps the landscape, figures outflow directions and accumulation patterns, and draws sub-watershed boundaries. The DEM also enables the calculation of slopes, which is necessary for modelling erosion, sediment transport, and deposition. Furthermore, the DEM aids in model calibration and validation by comparing simulated outputs to field measurements. Overall, the DEM is critical for accurately capturing the topography of the watershed and simulating hydrological processes within the SWAT+ model [148, 149].

Soil Map: Agro-hydrological modelling relies on the soil map for classification, parameterization, runoff estimation, simulation of erosion and sediment transport, and nutrient cycling. Its integration accurately represents hydrological processes, enabling academics and land managers to make informed decisions about watershed management and conservation [89].

Land Use Map: The land use map provides crucial spatial information regarding land cover and land use classes, allowing the models such as SWAT/+ to simulate hydrological processes, soil erosion, sediment transport, nutrient and chemical transport, and assess the effects of land management scenarios on the watershed dynamics [91, 92].

Weather Data: Weather data is vital for accurately modelling agro-hydrological processes. Weather data are primarily required in agro-hydrological modelling (precipitation, temperature (maximum and minimum), solar radiation, wind, and relative humidity). Researchers and hydrologists can improve watershed management by putting precise meteorological data into agro-hydrological models [148].

Data availability: Depending on the region and the time frame, many data types may be available for agro-hydrological modelling. Data may sometimes be easily accessible from governmental organizations or academic institutions. In some situations, gathering data, especially for modelling projects, may be necessary.

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Data reliability: For accurate modelling, data quality is also critical. Data must be precise, comprehensive, and consistent. The model findings might be suspected if the data is of low quality.
The accuracy of the model's findings typically increases with the amount of data supplied. It is crucial to remember that data availability might restrict agro-hydrological modelling.

Cost: Agro-hydrological modelling may be constrained by the costs associated with data collection and processing. A less complex model with less data may be more cost-effective in certain situations.

The availability and need for data for agro-hydrological models might be complicated. However, an accurate and dependable model can be created by carefully considering the unique requirements of the modelling project.

3.10 Integration of Agro-Hydrological Models into Decision Support Systems

Computer-based technologies, known as decision support systems (DSS), help users make informed choices [150-152]. Moreover, integrating the agro-hydrological model with DSS may increase decision-making precision, save time and cost, and enhance stakeholder communication.

There are several instances of how agro-hydrological models have been included in DSS, including a DSS for water management in the Mekong Delta [153] and a DSS for irrigation scheduling in arid farmland [154].
Integrating the agro-hydrological model with DSS may help enhance agricultural decision-making. As these models continue to evolve, more cutting-edge DSS applications in agriculture are expected to emerge.

3.11 Importance of Integrating Modelling Systems with Decision Support Tools

Agro-hydrological model integration with DSS has advantages that extend beyond agriculture [1, 155, 156]. These models may also inform decisions regarding water management in urban areas, forestry, and other land-use sectors [157, 158]. However, successfully integrating agro-hydrological models into DSS requires modelling and development skills. Nevertheless, the potential advantages of this integration are substantial, and the work needed to make it happen is well worth it.

3.12 Future Perspectives and Research Directions

We must deepen our understanding of the agro-hydrological system and develop technologies that enable us to manage agricultural water supplies more sustainably as the climate changes and agricultural needs increase. On this background, a few of the agro-hydrological models in Peninsula Malaysia's future perspective and research areas are highlighted as follows:

Improved data quality and availability: In Peninsula Malaysia, agro-hydrological modelling is somewhat constrained by the quality and availability of data [159]. Data collection and management, including ground-based observations, remote sensing data, and socioeconomic data, could be improved in future studies.

Development of more integrated models: Agro-hydrological models are often compartmentalized, meaning they only represent a single system element, such as crop growth or water flow [1, 160]. Developing more comprehensive models that can replicate the interactions between various system components should be the primary goal of future studies.

Incorporation of climate change and uncertainty: The agricultural productivity of Peninsula Malaysia is seriously threatened by climate change [1, 161]. Future studies should focus on incorporating climate change into agro-hydrological models and assessing its impact on crop yields and agricultural water supplies.

Development of decision support tools: Agro-hydrological models can be utilized to create decision support systems that assist policymakers and farmers in making informed choices regarding agricultural management [156]. Future studies should focus on developing user-friendly decision support systems applicable to specific agricultural issues.

3.13 Incorporation of Climate Change Scenarios in Agro-Hydrological Modelling

Peninsula Climate change threatens Malaysia's agricultural productivity [1, 161]. Future research should focus on incorporating climate change into agro-hydrological models and assessing its impact on crop yields and agricultural water resources. To achieve this goal, the following steps are routinely done to incorporate climate change scenarios into agro-hydrological models:

Choosing a scenario for climate change: Temperatures, precipitation, and other climate-related changes are projected in various climate change scenarios that are now available [1, 162, 163].

Downscale: Downscale the climate change scenario to the spatial scale of the agro-hydrological model [164, 165]. This is accomplished via downscaling, a statistical technique that takes the global climate change scenario and generates a more localized projection of climate change.

Input the downscaled data: Input the agro-hydrological model with the scaled-down climate change scenario [105, 165]. This is achieved by substituting the downscaled climate change scenario for the historical climate data in the model.

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Run model: Start the agricultural hydrology model [105, 165]. This will model how climate change will affect the water needed for agriculture, crop production, and soil erosion. For instance, in the development of an agro-hydrological model, deploying the Soil and Water Assessment Tool plus (SWAT+) and Coupled Model Inter-comparison Project Phase 6 (CMIP6) involves the following steps. Figure 11 presents the flow chart of the SWAT+ model setup, along with a brief description of the procedure.

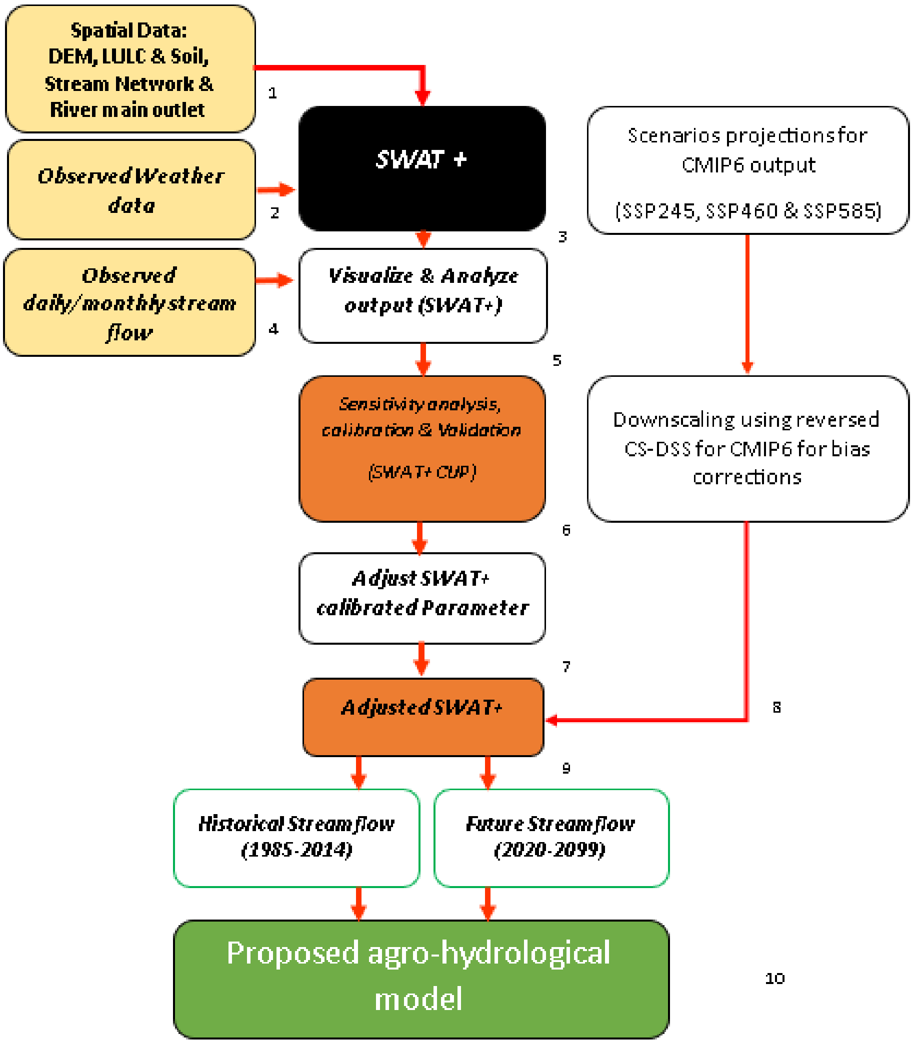

Figure 11: Flow chart for SWAT+ model setup and input data

1. Spatial data collection and input
2. Observed weather data input
3. Running SWAT+ for simulation
4. Observed daily stream flow input for comparison with the simulated flow out
5. Visualize and analyze the SWAT+ output.
6. Sensitivity analysis, calibration, and validation of SWAT+ parameters using SWAT+CUP
7. Adjust the SWAT+ calibrated parameters for daily stream flow simulation
8. Downscaled and bias-corrected CMIP6 data input
9. Simulation of historical (1985-2014) and future (2020-2099) stream flow, respectively.
10. Running the agro-hydrological model for agricultural water needs, crop production, crop yields, etc.

Agro-hydrological model outcomes can guide agricultural systems' adaptation and mitigation efforts. Farmers might need to adopt more effective irrigation techniques if the model predicts that climate change will increase the demand for agricultural water.

However, the following are some difficulties in including climate change scenarios in agro-hydrological modelling:

The reliability of climate change scenarios is unclear; methods for downscaling can be complex and require a substantial amount of data; the selection of input parameters can significantly affect how sensitively agro-

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hydrological models perform. Contrary to the above, the advantages of using climate change scenarios in agro-hydrological modelling include the following: Enable finding the region most susceptible to the effects of climate change can be helpful; Developing techniques for agricultural system adaptability can be beneficial; It may contribute to the development of climate change mitigation plans [1, 166].

Despite these difficulties, agro-hydrological modelling is essential for evaluating how climate change will affect agricultural systems. These models will be even more crucial for informing adaptation and mitigation efforts as our knowledge of climate change deepens and agro-hydrological models advance in sophistication.

3.14 Importance of Agro-Hydrological Modelling Systems in Sustainable Water Management

Agro-hydrological modelling systems are helpful tools for long-term water management. They can assist farmers, water managers, and legislators in making more educated decisions about how to use water productively and sustainably.

Agro-hydrological modelling systems, for example, are utilized in practice in various countries:
The Asian Institute of Technology, Bangkok, Thailand, utilizes agro-hydrological models to determine the required irrigation deliveries and compares these with existing practices [167].

Agro-hydrological models are utilized by the Murray-Darling Basin Authority (MDBA) in Australia to inform water management in the Murray-Darling Basin, one of the country's largest river systems. The models are now being used to investigate how climate change may affect water availability and to create water management strategies that are both ecologically and financially viable [168-170].

Agro-hydrological models have been employed by the United States Geological Survey (USGS) to assist the Central Valley community in California in becoming more water-efficient. The utilization of models is employed to assess the efficacy of management techniques aimed at mitigating the detrimental effects arising from subsidence, while concurrently optimizing the accessibility of water resources [171].

For these reasons, the agricultural sector is essential to the nation's economy and the nutritional security of Peninsula Malaysia, coupled with the impact of climate change, calls for the development of similar agro-hydrological models because they can be used for the following:

Quantify crop water requirements: This data can be used to create irrigation plans that are tailored to the individual demands of each crop, reducing water waste and increasing crop yields; *Simulate the effects of climate change on water availability and crop yields*: Agro-hydrological models can be used to simulate the impact of climate change on water availability and crop yields. The provided data has the potential to aid farmers in adjusting their agricultural practises to accommodate the effects of climate change; By utilising agro-hydrological models, it becomes possible to assess the environmental consequences associated with agricultural water usages, such as impacts on the quality of water, erosion of soil, and other pertinent environmental concerns. This data can be utilized to assist farmers in making more sustainable water management decisions; *Improve the efficiency of water distribution systems*: Agro-hydrological models can assist in identifying locations where water can be saved by analyzing how water is used in different portions of a watershed; *Agro-hydrological models can be used to examine the trade-offs between diverse water uses, such as irrigation, drinking water, and environmental protection, to help with water allocation decisions*; and *Create novel water management strategies*: Agro-hydrological models can be used to evaluate the efficacy of various water management measures, such as rainwater gathering and water conservation.

The utilization of agro-hydrological modelling systems is contributing to the enhancement of water management practices. These models will become increasingly crucial tools for ensuring that water is sustained as the world's population continues to grow and water demand rises.

4.0 Conclusion

In Peninsula Malaysia, agro-hydrological modelling systems are significant instruments for water management. The following conclusions were drawn based on the evaluated publications: When implemented appropriately, agro-hydrological modelling systems can be valuable for water management in Peninsula Malaysia. These systems can forecast the influence of climate change on water supply, optimize irrigation schedules, and assess the sustainability of agricultural practices.

In Peninsula Malaysia, the application of agro-hydrological modelling systems is still in its early phases. However, these techniques can significantly improve water management in the region when adequately explored.

Despite the numerous models and frameworks developed and deployed in Malaysia [1, 11, 72, 78], no equitable water allocation model has been developed for Malaysia to support agro-hydrological management.

5.0 Recommendations for Policymakers and Future Research

Agro-hydrological modelling is an effective technique for improving water management in agricultural systems. There is an increasing need for a better knowledge of the relationships between water, land, and crops in Peninsular Malaysia, where agriculture is a significant economic engine. Based on the findings of this study, the following recommendations for future research in agro-hydrological modelling in Peninsular Malaysia are made:

1. Create more detailed agro-hydrological models: Existing models frequently fail to capture the complexities of agricultural systems. More comprehensive models are needed for soil type, crop type, irrigation practices, and climate change.

2. Increase policymakers' and farmers' access to agro-hydrological models: Agro-hydrological modelling results might be complex and challenging to interpret. These models must be made more accessible to policymakers and farmers so that they can be utilized to inform water management decisions.

3. Support sustainable agriculture practices via agro-hydrological modelling: Agro-hydrological modelling can identify sustainable agriculture practices that preserve water while increasing crop yields. Models, for example, can be used to evaluate the influence of various irrigation strategies on water use and crop productivity.

Some of these fundamental specific research questions, however, may be addressed in future studies:

1. How will climate change affect crop output and water availability in Peninsular Malaysia?
2. How can we increase the efficiency of Peninsular Malaysia's irrigation systems?
3. How can Peninsular Malaysia establish more sustainable farming practices?

By addressing these issues, policymakers and academics can help ensure that Peninsular Malaysia's agricultural sector is resilient to climate change and continues to contribute to the country's economic growth.

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