Environmental Science and Pollution Research (2023) 30:121865–121880
https://doi.org/10.1007/s11356-023-30967-x

RESEARCH ARTICLE

A review of the management of water resources in Malaysia facing climate change

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Received: 26 December 2022 / Accepted: 5 November 2023 / Published online: 14 November 2023

Abstract

This paper reviewed the impacts of climate change on the management of the water sector in Malaysia discussing the current status of water resources, water service, and water-related disasters. The implementation of engineering practices was discussed to provide the detailed assessment of climate change impacts, risks, and adaptation for sustainable development. The narrative methods of reviewing the literatures were used to get an understanding on the engineering practices of water infrastructures, implication of the government policies, and several models as the main motivation behind the concept of integrated water resource management to contribute as part of the sustainable development goals to achieve a better and more sustainable future for all. The findings of this review highlighted the impacts of climate change on the rivers, sea, lakes, dams, and groundwater affecting the availability of water for domestic and industrial water supplies, irrigation, hydropower, and fisheries. The impacts of climate change on the water-related disasters have been indicated affecting drought-flood abrupt alternation and water pollution. Challenges of water management practices facing climate change should be aware of the updated intensity–duration–frequency curves, alternative sources of water, effective water demand management, efficiency of irrigation water, inter-basin water transfer, and nonrevenue water. The transferability of this review findings contribute to an engagement with the society and policy makers to mobilize for climate change adaptation in the water sector.

Keywords Climate change impact · Comprehensive water resource assessment · Integrated adaptation strategy · Water-related disaster · Water service evaluation

Introduction

Recently, a considerable amount of the literatures has grown up around the theme of climate change and its impact on water resources. The global mean temperature as reported by the Intergovernmental Panel on Climate Change (IPCC) is predicted to increase by 4 °C in 2100 and is facing the major global challenges of water resource management (Mimura 2013). The challenges of supply-side water management affected by climate change can alter the natural patterns of drought, flood, melting glacier, sea level, and storm intensify often with severe consequences. The challenges of demand-side water management affected by population growth and economic development are related to an increased demand of water for domestic, industrial, and agricultural sectors. The widespread problems of water pollution caused by domestic, industrial, and agricultural activities face an increased pressure on the management of water resources and can jeopardize human health and the environment.

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Malaysia as one of the highly vulnerable countries facing climatic change could be because the coastal zone of Malaysia with around 60% of its population living near the coast has a special socio-economic significance (Ehsan et al. 2022). The management of water resources lies at the epicenter of any viable solution projected into the climate change risk management matrix. It is very difficult to maintain the integrity of balanced ecosystem caused by the pattern alterations of drought and flood without coherent overall policies and strategies on the management of water resources. The direct consequences of climate change include an increase in the maximum and minimum temperatures, sea level rise, higher ocean temperature, and an increased frequency of heavy precipitation events. The indirect consequences of climate change may directly affect humans and the environment. These consequences are related to an increase in the hunger and water crises, an increased spread of the pests and pathogens, a number of different health risks caused by rising air temperatures and heat waves, an excessive loss of biodiversity caused by a limited adaptability, and adaptability speed of flora and fauna. The consequences are also related to a new adaptation in the areas of agriculture; acidification of ocean caused by an increased HCO_3 concentration in the water as a consequence of increased CO_2 concentration, forestry, energy, infrastructure, tourism, etc.; and economic implications of dealing with secondary damage related to climate change (Myers et al. 2013).

An integrated adaptation strategy of the Malaysia country facing climate change challenges requires the implementation of structural and nonstructural measures in the management of water resources. Structural measures to deal with the challenges of climate change can be taken in implementing an integrated water resource management (IWRM) at all levels operating in the contexts of design, construction, operation, and maintenance of the public water infrastructures. Land acquisition of public interest for construction of water infrastructures facilitated by an appropriate land supply model allows achieving sustainable development, social justice, and prosperity of society (Roestamy et al. 2022). The implementation of nonstructural measures included the government policies; numerous types of public awareness campaigns regarding the IWRM and river care programs can positively contribute to social, economic, and environmental sustainability. Even though the ways of adapting to climate change for the future management of water resources have been identified to induce a change of opinion into the decision-making process, the necessary basic conditions for implementing an IWRM that has long been considered essential for sustainable development are not fully understood. This paper aims to review the current status of water resources, water services, and water-related disasters to get better understanding of the implementation of IWRM in Malaysia. Reviewing the implementation of structural and nonstructural measures will be important to point out that the concern of water resources management would be taken into account facing the challenges of climate change.

Methods

The narrative methods of reviewing the management of water resources affected by climate change involve analyzing a series from literature, policy, and standard documents. This helps in identifying the reason of urgency to upgrade the existing hydraulic infrastructures, to provide an appropriate design (or redesign) of the proposed new hydraulic infrastructures, and to update the regulations, standards, and other instruments associated with a particular change in a variable causing by different patterns of water cycling and rainfall. The target subjects of reviewing the management of the Malaysian water sector include the policy, institutional framework, structural and nonstructural aspects of water resources, water services, and water-related disasters. Figure 1 shows the conceptual diagram of logically describing the adaptation needs for anticipating the risks and impacts of climate change on the future management of water resources.

Reviewing the management of water affected by climate change

Water resources

Water resources as the natural resources of surface water and groundwater are the important sources for humans used as the sources of water for drinking water supply, industrial water, and irrigation. This subsection aims to briefly review the impacts of climate change on the management of rivers, coastal areas, reservoirs, and groundwater distributed crossing Peninsula Malaysia and East Malaysia to learn about considerations for the future management of water resource sector. The discussion of climate change impacts and structural and nonstructural measures is required to understand the current management of rivers, coastal areas, reservoirs, and groundwater for the targets of better future water resource management options that encourage the most sustainable sources of water supply to have an optimization approach for multisectoral water supply.

Rivers

The variation changes of annual and seasonal runoff of catchment area monitored at the outlet station are commonly used as indicator to assess the impact of climate

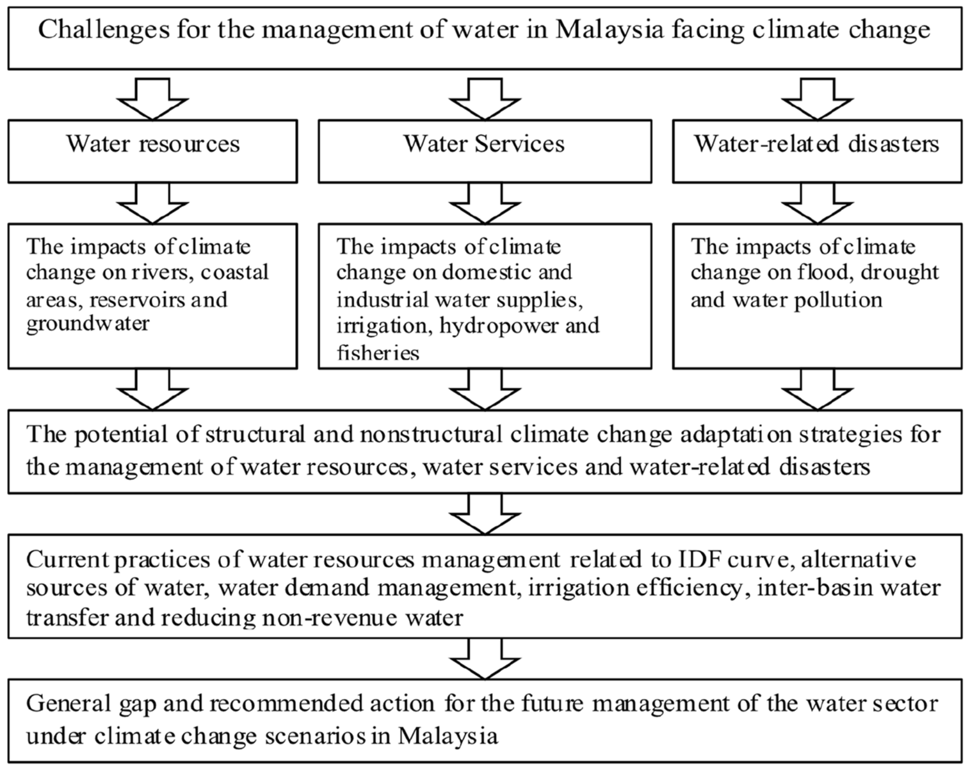

Fig. 1 Conceptual diagram of the future management of water resources facing climate change

change on water resources. Effects of climate change on river runoff patterns at the Klang River watershed of Selangor state have been predicted using the Hadley Centre Third Generation — GCM model with the emission scenarios A2 and B2 for the period 2001–2100. The scenarios A2 and B2 are referred to the storylines to describe the development of different dimensions of social, economic, environmental, and technological policy. The aim of scenario A2 is to predict the future of differentiated world with emphasis on human wealth including the major underlying themes to strengthening the regional cultural identities with an emphasis on high population growth, family values, and local traditions, but less concerned about fitting into a rapid economic development. The scenario B2 emphasized on sustainability and equity can help predict the local solutions facing the development of economic, social, and environmental sustainability in the world (IPCC, 2000). The results show that the mean annual runoff over the whole of Klang River basin decreases by 9.4% and 4.9% and increases by 4.5% according to the scenario A2 and decreases by 2.1%, 2.7%, and 3.3% according to the scenario B2 for the periods of 2020s, 2050s, and 2080s, respectively (Kabiri et al. 2015). The impact of climate change on water resources in the north-eastern Peninsular Malaysia has been predicted for the watershed of Kelantan River using the Soil and Water Assessment Tool (SWAT) model under three representative concentration pathways of 2.6, 4.5, and 8.5 scenarios for the periods of 2015–2044 and 2045–2074 to show an increase in the annual rainfall from 1.2 to 8.7%, an increase in the maximum temperature from 0.6 to 2.1 °C, an increase in the annual stream-flow from 14.6 to 27.2%, and evapotranspiration of Kelantan River basin increased from 0.3 to 2.7% (Tan et al. 2017), as shown in Table 1. The separate and combined impacts of the land-use and climate variability on hydrological components were investigated using the Mann–Kendall and Sen's slope tests and SWAT at the Johor River basin to show that a combined impact of the climate and land-use changes leads to increase the annual stream-flow by 4.4% and the rate of evaporation by 1.2% (Tan et al. 2015). The impact of climate change on water resources leading to an increased air temperature can affect the variability of rainfall and the pattern of extreme high and low precipitation at certain months of the year. The engineering practices of constructing the

Table 1 The impact of climate change on water resources in the north-eastern Peninsular Malaysia predicted by SWAT

Indicator	Unit	Time period	
		2015–2044	2045–2074
Maximum temperature	°C	0.6	2.1
Annual rainfall	%	1.2	8.7
Annual stream-flow	%	14.6	27.2
Evapotranspiration	%	0.3	2.7

new dams, upgrading capacity of the existing reservoirs, adopting the water conservation techniques in agriculture, and encouraging the wastewater treatment and reuse can contribute to mitigating the impact of climate change on water resource management.

The purposes of Love Our Rivers Campaign launched in 1993 by Department of Irrigation and Drainage (DID) are to educate and inform the public on the importance of community networking to preserve local rivers, to promote water conservation measures, and to increase knowledge of implementing an effective river management. An initiative of the Water Resource Council of Negeri Sembilan seeks to introduce the water resource inventory and assessment at state level of the Malaysia country. The Minister of Water, Land and Natural Resources (MWLNR) has promoted the program of off-river water storage as one option to increase the reliable water supply from rivers, to overcome the problem of water scarcity during drought event, and to reduce the risk of flooding during monsoon season. The implementation of the integrated river basin management included an IWRM, land resource management, ecosystems, and socio-economic systems that have been formulated in Tenth Malaysia Plan (TMP) 2011–2015 and National Physical Plan must adopt a more comprehensive approach towards the formal framework of vulnerability to climate change. The national water resource policy has been launched in 2012 as a result of the 2011 National Water Resources Study and is one of the key milestones towards a more sustainable and integrated management of water resources in the country.

Coastal areas

Sea level rise represents potentially one of the costliest impacts of climate change on the sustainable development of coastal areas. The rate of sea level rise at an average of 1.3 mm/yr to represent the coastal areas of Peninsular Malaysia has been recorded at Tanjung Piai in Johor state of Malaysia from 1986 to 2006 (Ainee et al. 2014). The increased rate of sea level rise for all coastal areas of Malaysia has been predicted in 2017 ranging from 0.67 to 0.74 mm/yr (Rashidi et al. 2021). Rising sea levels have the potential to increase coastal flooding, shoreline erosion, and saline intrusion caused by storm surges leading to the damage of fishery resources, land loss, and an increase in the salinity of groundwater. Sea level rise for the coastal areas of Peninsular Malaysia, Sarawak, and Sabah predicted using the tidal data collected from the gauge stations along the Malaysian coastlines from 1984 to 2013 has increased at a rate of 3.67 mm/yr (Hamid et al. 2018). The projection of sea level change along the coastlines of Malaysian country using the Atmosphere–Ocean coupled Global Climate Model/General Circulation Model simulations as shown in

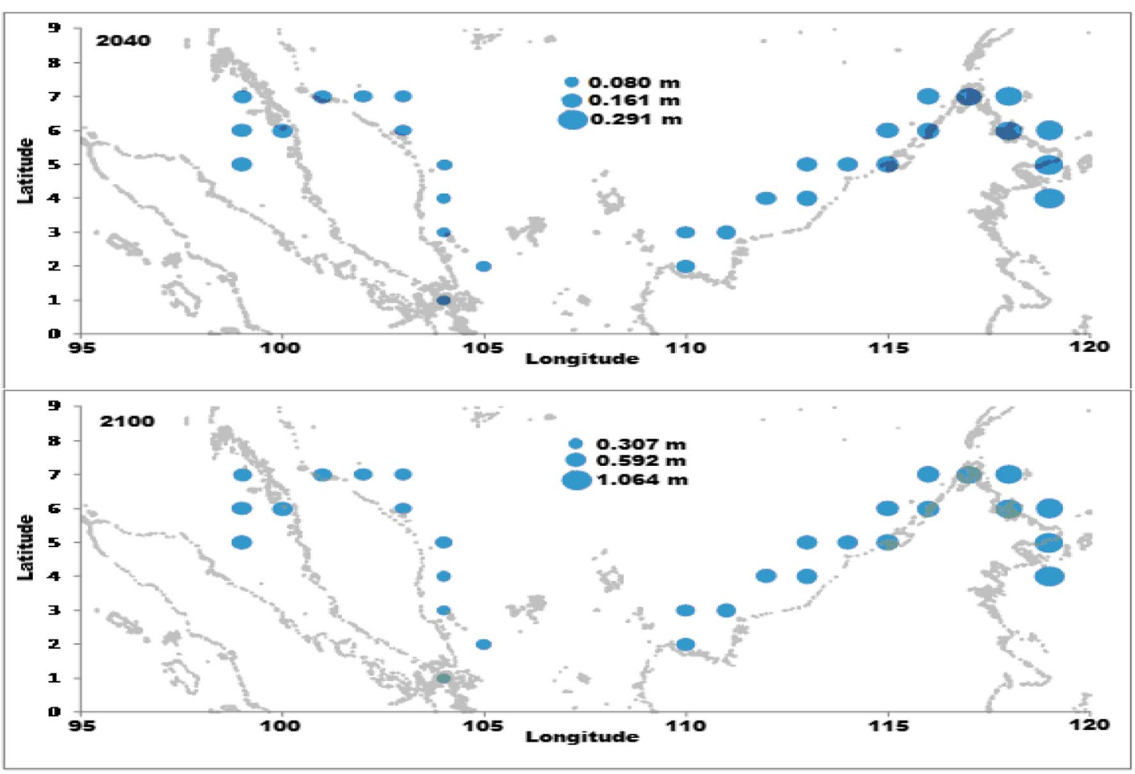

Fig. 2 Projected sea level rise by 2040 and 2100 for Malaysia coastlines (Ercan et al. 2013)

Fig. 2 has been predicted the range of sea level rise from 0.066 to 0.141 m in 2040 and from 0.253 to 0.517 m in 2100 for the coastal areas of Malay Peninsula and from 0.115 to 0.291 m in 2040 and from 0.432 to 1.064 m in 2100 for the coastal areas of Sarawak and Sabah (Ercan et al. 2013).

There are many questions associated with sea level rise regarding the socioeconomic and environmental impacts of climate change on the country of Malaysia which science needs to answer. Malaysia as one country of Southeast Asia that represents the 29th longest coastline in the world has the total coastline of 4675 km with West Malaysia surrounded by 2068 km and East Malaysia surrounded by 2607 km of coastline. The coastline conditions of Peninsular Malaysia can be classified on the basis of erodible range of the soils without regard to any other variables into 55.4 km of critical erosion, 376.1 km of significant erosion, 916.5 km of acceptable erosion, and 720 km of no erosion (Hashim et al. 2017). It seems that the rise of sea level is the major effect of climate change on the coastal areas of Peninsular Malaysia. This study suggests that short-, mid-, and long-term strategies to anticipate the effects of climate change on the management of coastal areas should be implemented through a proper legal and management framework for the effective protection of coastlines, infrastructure, and properties from the erosive force of waves and tidal actions (Bakun et al. 2015). Integrated coastal zone management has been highlighted in the Seventh Malaysia Plan as an integrated approach regarding all aspects of coastal zone management to emphasize the concept of sustained economic growth and social equity shared among the people. The various structural features of 208 selected coastal engineering projects have been implemented from 1985 to 2015 to protect from beach erosion over 212 km of coastline (Rashidi et al. 2021). The most important financial benefits of these engineering projects are to avoid the disastrous effects of climate change on the society and to protect the coastal environment and buildings from damage. By maintaining the existing shoreline of allowing the significant land use, infrastructures, and socioeconomic activities within the coastal zone can be focused on coastal erosion defense and sea level rise adaptation in the management of coastal areas affected by climate change. The reclamation of coastal land critically required to move seaward as a strategy can cause the various adverse impacts on the environment where the adjacent ecosystems of wetlands, salt marshes, and mangroves are becoming more vulnerable caused by the coastal squeeze effects. A number of the coastal adaptation measures recommended by experts for handling the critical erosion coastal areas have been accommodated in the National Coastal Erosion Study revised in 2016. An integrated shoreline management plan conducted by DID for the states of Pahang, Melaka, Negeri Sembilan, Pulau Pinang, Labuan, Sarawak (Miri), Sabah, and Johor in 2017 taking into account the resource exploitation and conservation of sensitive habitats could be an important achievement in the synchronization and harmonization of coastal development programs in the country.

Reservoirs

Malaysia as a Southeast Asian country has 46 dams located in Peninsular Malaysia and 9 dams located in East Malaysia under the management of DID (see Table 2) with the total

Table 2 List of dams in Malaysia

West (Peninsular) Malaysia		East Malaysia	
State	Name of dam	State	Name of dam
Johor	Bekok Dam, Juaseh Dam, Linggiu Dam, Machap Dam, Semberong Dam, Layang Dam, Lebam Dam, Labong Dam, Sultan Iskandar Reservoir	Sabah	Babagon Dam, Kaiduan Dam, Tenom Pangi Dam
Kedah	Beris Dam, Pedu Dam, Muda Dam, Ahning Dam	Sarawak	Bakun Dam, Baram Dam, Batang Ai Dam, Bengoh Dam, Gerugu Dam, Murum Dam
Kelantan	Pergau Dam		
Kuala Lumpur	Klang Gates Dam		
Malacca	Jus Dam, Durian Tunggal Reservoir		
Negeri Sembilan	Gemencheh Dam, Kelinchi Dam, Sungai Terip Dam		
Pahang	Anak Endau Dam, Chematu Dam, Chereh Dam, Chini Dam, Kelau Dam, Pontian Dam, Sultan Abu Bakar Dam		
Penang	Air Itam Dam, Mengkuang Dam, Teluk Bahang Dam		
Perak	Bersia Dam, Chenderoh Dam, Kenering Dam, Piah Dam, Temenggor Dam, Gopeng Dam, Mahang Dam, Jor Dam		
Perlis	Timah Tasoh Dam		
Selangor	Batu Dam, Langat Dam, Selangor Dam, Semenyih Dam, Tasik Subang Dam, Tinggi Dam		
Terengganu	Kenyir Dam		

surface area of 695 km^2 and total storage of 43,800 million m^3 of water. Among 15 hydropower dams, 12 are located in Peninsular Malaysia and 3 in Sarawak. Total storage of water for hydropower dams is 79,142 million m^3 with the largest hydropower dam is Bakun Dam in Sarawak. Reservoirs are greatly affected by climate change especially during the extreme wet and dry seasons (Ehsani et al. 2017). An increase in the intensity of extreme rainfall during wet season resulting in the large amount of runoff volume cannot be stored outside of the capacity of the reservoirs. An increased temperature of air during dry season resulting in higher evaporation rate can increase the loss of water stored in the reservoirs. The coupling between agricultural land expansion and high rainfall intensity can cause the increasing of soil erosion rate and sediment yield of the watersheds leading to the reduction of storage capacity of the reservoirs. An analysis of drought and reservoir storage based on the 15 climate change scenarios conducted under the supervision of the National Hydraulic Research Institute of Malaysia (NAHRIM) predicted that the Bekok Dam in Johor state will experience facing several critical periods from 2010 to 2100 leading to a decrease in the production of oil palm (Sarkar et al. 2020). The critical levels of water stored in the dams of Padang Saga, Bukit Merah, Timah Tasoh, Labong, Bukit Kwong, Gemencheh, Beris, Muda, and Pedu have been experienced during the events of El Niño from 2015 to 2016. The water shortage of the reservoirs has been experienced at least three consecutive months for Labong Dam and eight consecutive months for Bukit Kwong Dam in 2016. Water shortages in the dams of Langat River, Selangor River, and Tinggi River have been experienced at least three consecutive months with the storage capacity of these dams dropped below 50% and predicted will face the experience of dry spells with a return period of more than 10 years by 2040 (Hasan et al. 2021). The water levels of Lebam and Layang dams in the South Johor have been experienced lowering to 9.57 m and 19.19 m, which are far below the critical levels of 12.27 m and 23.5 m, respectively, during severe drought of the El Niño years (Salimun et al. 2014). The Johor states of Malaysia and Singapore have suffered the worst drought event according to the dataset of Palmer Drought Severity Index recorded from the rainfall data of more than 60 years. The analysis of reservoir storage state using the 15 climate change scenarios can predict several critical drought episodes occurred in Bekok Dam of Johor state from 2010 to 2100 (Yaacob et al. 2022). The impact of climate change on the availability of domestic and industrial water supplies can affect changeability in the occurrence of dry and wet periods, leading to pollute water supply and to increase the water exploitation index. Most of 93 dams built until 2013 in Malaysia are old structures serving various purposes of domestic and industrial water supplies, irrigation, flood mitigation, hydroelectric power, sediment control, and recreation. The primary purpose of 57 dams served as a vital water supply is for storage and safe retention of water with sufficient quantity to meet the needs of water for several states and federal territories of Malaysia in support of socioeconomic resilience by providing the raw water sources of domestic and industrial water purposes. Constructing the additional 40 water supply dams to meet the future water demands has been planned by the government facing combined effects of population growth and climate change. The construction of 30, 7, and 3 dams in Peninsular Malaysia, Sabah, and Sarawak, respectively, has been planned to support the future needs of domestic and industrial water supplies.

Because the frequency of water shortages is predicted to increase under future climate change, the current practice in the design of dam stored capacity of 3 months needs to be reviewed to provide a balance between the flow brought by a river and the volume of water required for different usage purposes of the flow to more than 4 months of dry season. The spillway capacity and maximum elevation of the dam need to be redesigned to avert future flood chaos across an area of the watershed. The Emergency Response Plan (ERP) must be developed by every operator of dam to reduce the probability of flooding and to minimize the risk of dam failure. The ERP should include an integrated public alert and warning system for local alerting that provides authenticated emergency and life-saving information to the public when the water level at the elevation of spillway crest has reached the flood danger level. The vulnerability of water resource systems affected by climate change to the extreme hydrological events must be studied particularly for case of the old dams. The experimental studies of the dam-break flow of old reservoirs impacted by climate change are still a few at the present. The government of Malaysia has taken anticipation by preparing the National Dam Safety Management (NDSM) Guidelines and Draft of NDSM Act while the Dam Technical Centre must be established according to as the Act.

Groundwater

The use of groundwater in Malaysia is predicted to increase over time because the abstraction of surface water to meet the demands of water for domestic, industrial, and agricultural uses has been progressively increased with increasing of the population growth and economic development. The principal reason of groundwater use increased could be due to an increased population growth while the polluted rivers, lakes, and springs caused by the urbanization and human activities are no longer viable sources of surface water contributed to increase the use of groundwater. The investigation of underground formations to understand the hydrologic cycle and groundwater quality is required to identify the nature, number, and type of aquifers. It is timely for Malaysia to explore the groundwater potentials to avoid a possibility of water crisis during the prolonged dry period. The effect of climate change reduced approximately 1% of groundwater recharge potential during the period of the 2020s in Malay Peninsula could be due to the prediction of decreased precipitation and increased evapotranspiration (Mogaji et al. 2013). Comprehensive study of spatial analysis required to investigate the impact of climate change on groundwater is due the space–time variability of evapotranspiration and precipitation may be natural and inevitable disasters hitting different regions of the Malaysia country. The management of groundwater resources requires the responsible actions of the related institutions for conjunctive use of groundwater and surface water as a strategy for climate change adaptation (Moraes-Santos et al. 2021).

It has become imperative that the innovative strategies proposed by Department of Mineral and Geoscience for developing and evaluating the interventions to increase the use of evidence from research and for providing the monitoring services of groundwater quality have been put in place to ensure the exploration and development of the groundwater resources (van Rooyen et al. 2021). Providing the design information of extraction safe rate of the groundwater by the Minerals and Geoscience Department to every state government is required as the technical guidelines for issuing the groundwater extraction licenses at the coastal areas to avoid an intrusion of saltwater. Modeling studies focused on the groundwater reserve determination and risk analysis of saltwater intrusion have been accomplished for five major basins of the Malaysia country. The use of the multivariate statistical analysis techniques and analysis of variance to evaluate the pollution of groundwater caused by the major ions and heavy metals could be useful to provide policymakers and managers the current situation of groundwater in the specific areas (Kura et al. 2018). By analyzing the effects of the industrial, agricultural, and weathering activities contributed to groundwater contamination can help technically identify the priorities for sustainable groundwater management to design a more efficient land development (Zainol et al. 2021). The usage of groundwater in Malaysia except the state of Kelantan which has approximately 50% of water used coming from groundwater is still low (Hussin et al. 2020). Nearly all groundwater withdrawals are extracted by the individual users, predominantly used for domestic, industrial, and commercial purposes. The policy initiated to improve groundwater management in the Notification of Development of Wells and Excavations 2013 has been enforced to ensure no excessive extraction occurs. A case–control study to determine the risk factors of saltwater intrusion zones (Trabelsi et al. 2016) for the selected basins has also been conducted under the Eleventh Malaysia Plan (EMP) 2016–2020.

Water services

Domestic and industrial water supplies

The abundant water resources of Malaysia estimated at around 580 km^3/yr can provide the available water of more than 3000 m^3 per capita per year. The use of water in Malaysia are around 76% for agriculture, 11% for municipal water supply, and 13% for industries, whereas the use of domestic water is significantly less compared to the agricultural and industrial uses. There is only less than 1% of the available water resources used for drinking water supply (Rahman 2021). The main reason for the lack of groundwater use in Malaysia could be due to easy availability of surface water resources. Approximately 97% of water demand is extracted from surface water, predominantly from river systems. Clean and sufficient water supply becoming a problem in the management of water resources during the flood event could be because the deterioration of surface water quality associated with accelerated soil erosion, landslide, and river bank erosion in the form of nonpoint source pollution can interfere with the drinking water treatment process (See et al. 2017). Other forms of nonpoint source pollution transported by overland flow could be due to the overflow of wastewater treatment ponds and the wash off of agricultural lands (Shields et al. 2008). An increase in the demand of freshwater as a consequence of population growth and a decrease in the supply of water as a consequence of pollution can cause the disruption of water supply leading to have a potential to stress the existing water infrastructures (Raihan et al. 2023).

The government of Malaysia has shown a commitment in the distribution of water to respond the demands of water for multisectors by creating a sustainable funding mechanism and to improve the customer orientation of service providers by creating a modern institutional structure (Gomez et al. 2019). Role of the local, state, and federal governments to ensure the sustainability of water supply affected by population growth and climate change has been initiated by issuing the appropriate water policies in the implementation of TMP 2011–2015. The endorsement of National Water Resources Policy aimed to ensure the quantity and quality of water supply for domestic and industrial purposes approved by the Cabinet in 2012 provides the strategic directions of water security, water resource sustainability, partnership, capacity building, and awareness raising. Several states of Malaysia such as Sabah, Penang, Kuala Lumpur, Kedah, Kelantan, and Negeri Sembilan have embarked on the policy of private sector participation in water and sanitation since 1990s (Annual et al. 2020). The responsibility of sewerage management in several states of Peninsular Malaysia has been transferred from the local governments to Indah Water Konsortium Sdn Bhd (IWK) since 1994 because an investment in the management of sewerage does not keep pace with an investment in the management of water supply.

Irrigation

Climate change has created challenges for the agricultural sector leading to disrupt food availability, reducing access to food and affect food quality. Adapting the irrigation systems to climate change is the priority for future planning of agricultural water uses. An analysis of the agricultural water using the RegHCM-PM model has been performed in 2009 by NAHRIM to identify the vulnerability in three granary areas of Muda Agriculture Development Authority (MADA), Kemubu Agriculture Development Authority (KADA), and Barat Laut Selangor. The areas of Barat Laut Selangor and KADA projected to experience a water deficit can potentially affect the sustainability of rice farming while the area of MADA was predicted to experience an excessive water up to 76%. It is noted that the most important aspect of reservoir management is to ensure an appropriate quantity of water released to agricultural uses at appropriate times. The effects of agricultural subsidies on cotton production can influence the amount of irrigation water used to irrigate the cultivation area in Harran Plains of Turkey (Çullu et al. 2022).

The development of Climate-Smart Rice Irrigation Management Information System (CSRIMIS) has been proposed as a nonstructural measure to provide better understanding of the government's roles involved in instituting the water policy and implementing the allocation framework of water irrigation (Rowshon et al. 2019). The implementation of nonstructural measures is committed to ensure the knowledge-based decision-making supported by an intensive climate-related research and development, capacity building of adaptation, and mitigation measures. Development of the new strategies adapted to the predicted impacts of climate change as one of the nonstructural approaches to cope with the crop water stress index is the application of CSRIMIS. An appropriate regulation of such as the Sabah Second Agriculture Policy for the new major rice granary areas and agriculture zoning in Sabah state is necessary to support the implementation of nonstructural measures. It is encouraged to include the needs for the improvement of irrigation area in the policy by considering two major rice-cropping seasons of dry and wet seasons in Malaysia.

Hydropower

Hydropower is sensitive to climate change because the sources of energy available to operate the existing hydroelectric power plants depend on the volume of water flow. Five main hydropower dams of Kenyir (Sultan Mahmud) hydroelectric power station with an installed capacity of 400 MW, Pergau hydroelectric power station of 600 MW, Temenggor hydroelectric power station of 348 MW, Bakun hydroelectric power station of 2400 MW, and Murum hydroelectric power station of 944 MW have been operated to generate approximately 11% of the total Malaysian electricity generation. The analysis of dry spell trend in Malaysia predicts that the future of local water stress affected the operation of four hydropower plants caused by climate change (Adib et al. 2022; Payus et al. 2020). The operation of Kenyir and Pergau hydropower dams in Terengganu state and Kelantan state, respectively, is concerned there would be a risk of the high possibility of the limiting water flow. The preliminary analysis of long-term model projection indicated that the operation of hydropower dams in Sarawak state would not be affected by climate change due to the large reservoir capacities of Bakun and Murum hydroelectric power stations. The change of river runoff caused by climate change affects the production of hydroelectric power. High intensity of rainfall resulted in an increased rate of soil erosion flowing into the river and reservoir can lead to reduce the storage capacity of dam.

The development of dam failure concept and modeling as a nonstructural measure aimed to predict outflow hydrograph of the reservoirs can even help improve the performance of hydropower under climate uncertainty. Numerous simulation models of dam failure caused by flow overtopping have been recommended to build community resilience to disasters, which can be used to ensure the proper disaster preparedness, disaster risk reduction, and the formulation of disaster management policy and procedure. Using the simulation model of Malaysia Dams Safety Management Guideline (MyDAMS) can help ensuring the protection of dam and the community in the areas of surrounding a dam (Toh et al. 2020). The development of ERP has been proposed to inform when once the dam safety threshold is in force, an alert of dam safety message can trigger an immediate inspection of the dam, and its surrounding during a flood event to detect early signs of potential dam failure. One of the objectives for energy policy of Malaysia aimed to ensure adequate, secure, and cost-effective energy supply by developing and utilizing alternative sources of the nonrenewable and renewable energy resources using the latest cost options and diversification of supply sources from both inside and outside the country (Sharvini et al. 2018). The promotion of renewable energy detailed in the National Renewable Energy Policy and Action Plan has been approved in June 2010 by the Cabinet with the vision of enhancing the utilization of indigenous renewable energy resources to contribute towards national electricity supply security and sustainable socioeconomic development. The adoption of renewable energy technology supported by the National Green Technology Policy 2009 and the Renewable Energy Act 2011 provides the schemes of enhancing the use of sustainable energy resources.

Fisheries

The impacts of rising atmospheric CO_2 and climate change on the marine ecosystems are associated with concurrent shifts in temperature, oxygen content, nutrient input, stratification, circulation, and ocean acidification with potentially wide-ranging biological effects (Rose 2005). An increase in the water temperature may lead to a decreased maximum body size of the marine fishes (Cheung et al. 2013). The change of species composition caused by climate change may lead to extend the large-scale redistribution of maximum fisheries catch potential with increasing in the high latitudinal regions but decreasing in the tropic regions (Cheung et al. 2010). The effect of climate change on fish landings in the west and east coasts of Sabah state was investigated from the raw annual data of local fish landings affected by climatic parameters with highly correlation of rainfall, temperature, wind, and the Southern Oscillation Index with 20% fish catch dropped during the northeast monsoon (Jafar-Sidik et al. 2010). The impacts of climate change on fisheries communities include (1) the direct effects of change in reproduction, distribution, and population dynamics of fisheries stock and (2) the indirect effects of change in productivity and composition of ecosystems on which fishes depend for food, shelter, and reproduction (Pörtner and Peck 2010).

At the present, one of the adaptation measures developed capacity building for fishermen is to utilize the Fishing Site Identification System (FSIS). The ability of FSIS provided information on fishing ground location is based on the satellite image analysis of sea surface temperature and chlorophyll-*a* concentration and helps fishermen to identify the fishing areas with a high catch potential within a short time. The use of FSIS could be useful to enhance the fishery resource potentials of rising sea temperature that caused high fish mobility. The Malaysian Department of Fisheries has implemented the conservation zone of 0–1 nm from coastline while the use of trawlers in Zone B has been banned for the west coast of Peninsular Malaysia. The implementation of high-impact projects in the Aquaculture Industrial Zone has been carried out as an effort to reinforce the sustainability of aquaculture practices by launching the Malaysian Good Agricultural Practices (MyGAP) in 2013.

Water-related disasters

Flood

In spite of the high rainfall during the Northeast Monsoon season can be seen as the cause of repeated flooding in Peninsular Malaysia, the impact of climate change predicted would be the major cause of flooding in the future. The Climate Change Factor (CCF) developed based on the selected models of statistical downscaling for Segamat River basin in Johor state showing the CCF value of 1.47 predicted for 2060 under the scenario of 270-year average recurrent interval (ARI) is more extended than under the scenario of 200-year ARI with its CCF value of 1.42 and then is more extended than under the scenario of 100-year ARI with its CCF value of 1.33 (Liew and Teo 2013). An increase in the CCF value of the location affected by climate change can cause an increased depth of flood (Holguin et al. 2021). Severe flooding occurred in Kota Tinggi of Johor state affected by the rainfall of 366 mm during the first wave of December 2006 and by the rainfall of 416 mm during the second wave of January 2007 filling all natural hydrologic storage has caused the majority of precipitation becoming runoff (Abdullah et al. 2018). The extraordinary amount of continuous rainfall in Penang state and parts of Kedah state occurred on 4 and 5 November 2017 has caused massive floods in many areas — the worst in the history of Penang — where the rise of water surface level reached 2.7 m (Safizadeh et al. 2022). The drainage capacity of Penang state designed without considering the impacts of climate change did not work optimally and required to open 46 evacuation centers to house 1731 families and around 5000 victims.

The publicinfobanjir website created in 2011 by DID as an extension to website of infobanjir focused on flood early warning dissemination (Acosta-Coll et al. 2018) to public is a simplified method for providing detailed information on the website that interactively displays the evacuation centers, flood status, current rainfall, and real-time water level as well as discharge data recorded from approximately 500 hydrological stations (Tam et al. 2019). The role of National Flood Forecast and Warning Centre under the DID administration is to provide accurate and timely warning of impending floods for reducing public safety risks and property damage. The structural measure of Stormwater Management and Road Tunnel (SMART) as an innovative project of comprehensive flood prevention strategy in place has been made to prevent flooding in the City Centre of Kuala Lumpur and around the vicinity of Masjid Jamek caused by Klang River overflowing. SMART with its diameter of 13.2 m has a distance of 9.7 km from near the Kampung Pandan to Kuala Lumpur-Seremban highway and has a double-deck motorway of 3 km in the middle section of the 9.7-km stormwater tunnel. The structural measure of Flood Barrier Design constructed floodwall and levee for both sides of Golok River in 2018 by MWLNR aims to prevent major flooding in the Kelantan state of Malaysia. The practice of rainwater harvesting that has been included in the Street, Drainage and Building Act 1974 Uniform Building By-Laws (Amendment 2012) is mandatory to reduce flood peak during a heavy rain as part of supplemental nonpotable water supply in the states of Johor, Kelantan, Malacca, Perak, Perlis, Pahang, Negeri Sembilan, and Selangor. Strategic directions and actions established in the National Physical Plan-3 (NPP-3) containing of 15 strategies and 44 actions can identify the roles of the implementing and monitoring agencies for managing a vulnerable area characterized according to the natural hazards by implementing an integrated water cycle management strategy whether directly or in a supporting role (Yamashita 2022).

Drought

Several records of hydrological drought occurred across the Malay Peninsula have been analyzed using statistical downscaling procedure to estimate dry conditions persist amid the predictions of increased future drought driven by climate change (Hazir et al. 2020). The length of dry period increased by 2.5% from 2018 to 2039 and by 3.3% from 2040 to 2069 was predicted for the Pahang state of Malaysia (Tukimat et al. 2017). The occurrence of drought in Selangor as one of the states with fast-growing economies in Malaysia has been identified for the future to show that rainfall in Langat River basin falls highly during December but lowly during October (Hasan et al. 2021). Approximately 49.5% of the 2016 Malaysia's water supply issues was reported in the Selangor state and the number rose to 62.4% in 2017 (Rahman 2021). An implication of climate change related to the availability of water in the northern Malay Peninsula (Kedah) during the period of 30 years analyzed by comparing the data of water level collected for the period of 3 years from 1978 to 1980 to those collected from 2011 to 2013 can decrease the maximum water table by 2.1% from 31.02 to 30.37 m (Suri et al. 2014). A decrease in the water table will contribute to a water crisis in the near future and is predicted to decrease the flow of water in a river during the prolonged dry weather and to increase drought risk in Malaysia.

The establishment of Drought Information Website (InfoKemarau) in early 2001 initiated by DID following an incident of the 1998 drought that affected a large number of residents in the Klang Valley of Malaysia was based on the nonstructural approaches of drought risk area mapping, adaptation and resilience to drought, awareness raising/capacity building, and drought warning system. The objectives of establishing the InfoKemarau system are to disseminate the status of water resources via online, to provide early warning on potential drought, and to treat as technical advisory on drought status. The operation of InfoKemarau used the Standardized Precipitation Index to characterize the meteorological drought on the range of timescales can provide the monthly report of drought conditions over the Peninsular and East Malaysia. The structural measures of 57 water supply dams, bunded storages of water in Melaka, Sungai Labu Off River Storage located in Sepang of Selangor state, and Pahang Selangor Raw Water Transfer Tunnel have been built with orders hoped to ensure continuous water supply during dry season. Collection of field data regarding rainfall, water levels of gauge sites supported by 21 water level stations at dams, 22 water level stations at rivers, and 48 rainfall stations is aimed to the delivery of continuously updated information with real-time streaming. The role of DID is to disseminate information about the space–time relationships of water resource availability and provides accurate, timely, and integrated information on drought conditions at the relevant spatial scale via the web portal liaising with relevant agencies and the public for facilitating public involvement for making early preparation facing a drought event. Standard operating procedure of drought disaster management formulated by all relevant agencies leading by the Malaysian National Security Council as federal agency under the Department of the Prime Minister provides guideline related to classification of drought, agencies responsible for drought monitoring, severity of drought, lines of communication in drought disaster management, and relevant agencies with drought responsibilities.

Water pollution

The application of water quality evaluation system based on the assessment of water quality index and water quality aptitude has been recognized for the Selangor River (Fulazzaky et al. 2010; Fulazzaky 2013) to anticipate the effect of climate change on the quality of stream water demanded serious preventive and corrective measures (Nazari-Sharabian and Taheriyoun 2022). Part of Selangor River highly polluted could be due to the high concentrations of microorganisms and suspended particles (Fulazzaky et al. 2010). Aptitude of the Selangor River water is still suitable for aquatic biota, aquaculture use, drinking water production, irrigation use, leisure and aquatic sport, and livestock watering (Fulazzaky 2013). The pollution of Langat River in the Selangor state caused by the floods has yielded an increased organic pollutant content in the values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Chan 2015). The pollution of Kuala Krai River water affected by severe flooding in 2014 has caused the increased values of suspended solids (SS) affecting an unpleasant odor in the river water and a decreased dissolved oxygen (DO) level lowering growth rate of aerobic microorganisms within deoxygenated waters (Kamarudin et al. 2019). The event of flood eroded the terrain alongside the banks of river causing an increase in the value of SS with its highest value of 74.5 mg/L and its lowest value of 3 mg/L and resulting a change in the pH value has been reported for the Kuala Krai River (Kamarudin et al. 2019). The level of pollution affected by flood event has been indicated by a decreased value of DO from 5.46 mg/L in November 2006 to 5.24 mg/L in December 2006 and then to 5.03 mg/L in January 2007 caused by the loading of nutrients and organic matter charged the Muar River water during the floods (Ching et al. 2015). The value of SS decreased from

84.2 mg/L in December 2006 to 130 mg/L in January 2007 with pH 3.2 has been observed for Muar River water (Ching et al. 2015). The pollution of water in the Chini Lake of Pahang state caused by the October 2004 floods has yielded an increase in the concentrations of sulfate and nitrate and an increased turbidity of higher than 30 NTU (Shuhaimi-Othman et al. 2007). The condition of several river waters in Malaysia affected by climate change of making flooding worse containing mud can lead to decrease the physical, chemical, and biological qualities of the aquatic ecosystems (Jury and Vaux Jr., 2005).

The implementation of River of Life by the government to transform the Klang River that has high economic value into a vibrant and livable water front was divided into three main components of river cleaning, river master planning and beautification, and river development to bring this river from its current status of water quality aptitude (WQA) not suitable for body contact activities to a new WQA status suitable for full water-body contact recreation (Fulazzaky 2013). The initiation and propagation of the integrated lake basin management in 2005 aimed to maintain and restore the environmental integrity of the lake and reservoir ecosystems have been divided into three phases of implementation from 2005 to 2010, from 2011 to 2015, and from 2016 to 2018 to prepare the action plan and policy instruments and to implement strategic planning focusing on the management of lake and reservoir basins for sustainable use. The national standard of lake water quality was developed in 2015 and then approved in August 2017 by NWRC for prospecting the implementation of assessment for the status of lake water quality in Malaysia. The design of the wastewater treatment plants aimed to eliminate the excessive amounts of BOD, COD, SS, and floatable materials has been operated to meet regulatory requirements before discharging into the environment. The different legal frameworks of achieving universal access to water and sanitation for all between West (or Peninsular) and East Malaysia could be because the water reform of Malay Peninsula has been enacted since 2006 while East Malaysia maintains the previous legal and institutional frameworks. The enactment of Water Services Industry Act 2006 (Act 655) was followed by establishing the national water asset holding company as a wholly owned company under the Ministry of Finance and by creating a water forum to give voice to hitherto under-represented stakeholders of such as consumers. The separate functions of policymaker (Government), regulator (National Water Services Commission abbreviated by NWSC), asset ownership (Water Asset Management Company), and water service provision (State Water Companies) from each other has been regulated by the enactment of Act 655 after 2 years of extensive consultations.

Current practices of water resource management

Intensity–duration–frequency curve

The impacts of climate change on the hydrological systems leading to increase the intensity and frequency of extreme rainfall can further increase flood disasters, human casualties, and economic losses. The application of intensity–duration–frequency (IDF) curve derived from long-term observation of good quality rainfall data needs to be updated to possibly select the optimal mitigation strategies for flood disaster hazards. The IDF curves play an essential role in designing, operating, and maintaining hydraulic infrastructures such as urban drainage systems, culverts, and bridges and in managing hydraulic structures to deal with droughts and floods. Flash floods driven by extreme rainfall have been projected to increase under climate change scenarios. Designed storm events for urban drainage based on the historical rainfall data are no longer valid today without considering uncertainty of climate change for designing hydraulic infrastructures especially for estimation of the return periods of maximum rainfall and floods. A change in the intensity of rainfall caused by climate change making severe flooding events is expected to alter the level of protection currently afforded within the management of hydraulic infrastructures. The possible failure of the hydraulic infrastructures caused by an inadequate capacity to cope with the future extreme rainfall is a consequence of climate change. Changing climate by global warming causing an alteration of the rainfall patterns is likely to have a vulnerability of current urban stormwater infrastructure management. Design of the existing urban infrastructures that fully take the effects of climate change into account needs to be revised and updated to reduce the risks of extreme weather events and disasters. A strategic initiative for updating the current IDF curves has been performed to evaluate an uncertainty of climate change impact on the hydrological systems in accordance with the climate change projections. The Hydrological Procedure No. 1 of 2020 has been updated and revised in 2015 by DID in cooperation with NAHRIM to design the IDF curves for the return periods of 2 to 200 years.

Alternative sources of water

The consumption of water in Malaysia was estimated to be around 13,200 million liters per day (MLD) in 2010 and to be around 16,500 MLD in 2020. The alternative water sources of groundwater and rainwater harvesting need to be explored to help solve the problems of future water shortage during the prolonged dry period of uncertain rainfall patterns caused by climate change. The estimation of groundwater used for domestic (60%), industry (35%), and agriculture (5%) is approximately 450 MLD (3.4%) of the total water use. The estimation of groundwater stored approximately 5000 billion cubic meters (BCM) with annual recharge of 64–120 BCM is of important consideration for an integrated water resource management (Karim et al. 2014). Groundwater as a source of drinking water in the Kelantan state of Malaysia has been used at around 40% of total water supply for domestic and nondomestic purposes (Samad et al. 2017). The groundwater project of Sime Darby Water Resources Perak Sdn Bhd in the Batang Padang of Perak state has drilled 136 tube wells that have an average discharge rate of 343 m^3 per well per day for industrial water supply purposes (Sapari et al. 2012). Alternative source of water promoted rainwater with an average annual rainfall of 2400 mm for potable and nonpotable purposes (Lee et al. 2016). An uncertainty with uneven distribution of the rainfall over time and space causing by climate change has led to some areas suffering from dry spells while others affected by major flooding. The use of rainwater as an alternative water source is crucial in the era of climate crisis. The experience of severe drought affected several states in 1998 has triggered the government of Malaysia to propose rainwater harvesting as an alternative source of water for domestic and industrial water uses. The Ministry of Housing and Local Government have encouraged houses since 1999 to install a rainwater collector by issuing guideline on the installation of the rainwater collection and utilization systems. The various forms of initiatives in policies and guidelines have been formulated by the federal and state governments to facilitate the implementation of RWHS for residential and public buildings. IWK playing a significant role for the recovery of wastewater has explored several dedicated models for selling the product of recycled water for industrial applications as one of the effective ways to save water while providing a new revenue stream (Bauer and Wagner 2022).

Water demand management

The majority of Malaysian used more than 210 L per capita per day (LCD) could be related to the social consequences of tariffs for water supply (Rahman 2021). The effect of tariff on water demand management needs to be analyzed by the national and regional tariff systems as a tool to recover water supply costs and to secure equity and affordability for all people. The consumption of water per capita promoted by the World Health Organization as high as 165 LCD should be considered as the long-term water demand management plans for Malaysia (Hussien et al. 2016). The water consumption of 180 LCD over a short-term measure for 2020 targeted by NWSC could be one of the most effective measures to save the water consumptions of 2337 million liters per day (MLD) for Malay Peninsula and 267 MLD for Sarawak and 208 MLD for Sabah. Challenges of managing the optimal future demand of water need to implement an integrated approach of water resource management related to technical issues, institutional frameworks, and regulatory instruments and to involve the participation of stakeholders (Roestamy and Fulazzaky 2022).

Irrigation efficiency

The water demands of domestic and industrial uses expected to continue increasing at certain rates have put the demand of irrigation water under greater scrutiny that probably causing a threatened food security (Hanjra and Qureshi 2010). Strategies for ensuring sustainable use of the limited water resources are of absolute necessity for supporting the safety and health of the environment to provide sufficient agricultural production to feed a growing Malaysian population sustainably. The traditional system of ditch irrigation is popular for small-scale paddy farmers. The ditch irrigation systems of Malaysia have been improved by the responsible agencies such as Muda Irrigation Scheme in Kedah and Perlis, Kemubu Irrigation Scheme in Kelantan, and Trans Perak Irrigation Scheme in Perak. Major sources of water are gathered from the major rivers by managing the river diversion schemes and by regulating the reservoirs located in the upstream part of river basin. Currently, agriculture accounting for approximately 68% of all freshwater withdrawals has the irrigation water use efficiencies of 50% at the large-scale irrigation schemes and less than 40% at the small-scale ones mainly caused by the current agricultural practices of no recycling irrigation water (Ungureanu et al. 2020). Challenges facing sustainable irrigation water management are technical, socioeconomic, and institutional (Fulazzaky 2014, 2017; Young and Lipton 2006). Using the irrigation water saving control systems of both drip irrigation and sprinkler irrigation can help increase the efficiency of agricultural water use reflecting the ratio of optimal input water quantity to the actual one in the process of producing food. The implementation of water-saving irrigation technologies in Zambia has been suggested to mitigate the negative impact of climate change on the availability of water resources to agriculture (Hamududu and Ngoma 2020).

Inter-basin water transfer

The inter-basin water transfer aimed to increase water supply is carried out by transferring an excess water of 1890 MLD from the Kelau Dam located in the Bentong and Raub districts of Pahang state to Kampung Kuala Pangsun located in Hulu Langat district of Selangor passing approximately 44.6 km of Pahang-Selangor raw water delivery tunnel. The fact that the water supply system of Seremban is failing to cope with the increasing demands of portable water even supported by the intra- and inter-basin water transfers and faces an uncomfortable future of the water demand management. The volumetric flow rate of surface water transferred from Tiram River to the Layang River Dam ranged from 10 to 12 MLD passing through 15.3-km total network length of pipes can help meet growing demand for water in the Johor state of Malaysia. The water levels of Layang River and Lebam River dams remain critically low even when water transfers from Tiram River and Papan River, respectively, which are the temporary measures to increase the water levels of these two dams, provide flexibility in the allocation and use of water in the Johor state. Another 15 MLD of surface water transferred through 5-km total network length of pipes from Tiram River to the Layang River Dam aims to increase supply of fresh water for 580,000 consumers in Pasir Gudang, Masai, and several parts of Johor Baru city including industrial water users.

Table 3 General gap and recommended action for the management of the water sector under climate change scenarios

Domain	Topic	Gap	Recommended action
Water resources	Groundwater use and rainwater harvesting	Lack of technical and economic studies for getting better understanding on the groundwater use and rainwater harvesting	The reliability and economic analysis of groundwater use and rainwater harvesting especially for regions of having a water shortage
	Inter-basin water transfer	Lack of studies focused on the environmental and economic impacts attributed to river basin that is supplying water	Assessing the potential impacts of water transfer associated with the financial loss and damage suffered by donor river basin
Water services	Reducing household water consumption	Lack of nonstructural and structural reduction strategies attributed to long-term goals of household water consumption	Creating and executing the long-term strategies for reducing household water consumption
	Promoting modern irrigation system	Lack of studies focused on the application of modern irrigation system affecting the availability of water resources and the amount of agriculture production	Evaluating the implementation of modern irrigation system in Malaysia to the act of timing and regulating irrigation water application
	Reducing nonrevenue water	Lack of comprehensive studies focused on the implementation of the existing water service industry strategies for reducing nonrevenue water	Evaluating the impact of implementing the existing water service industry strategies on the reduction of nonrevenue water
Water-related disasters	Intensity–duration–frequency curve	Lack of studies examined the acceptance of intensity–duration–frequency curve by water professionals	More extension work of intensity–duration–frequency curve needed to gain wide acceptance among the water professionals

Reducing nonrevenue water

One of the major challenges for reducing nonrevenue water (NRW) facing climate change is the high level of water loss in Malaysia. The rate of NRW ranged from 18.2 to 62.4% with an average rate of 36.6% is mainly caused by the old fragile and leaky asbestos cement pipes of distribution networks, which are still available at distribution network length of 41,560 km (27%) across the country (Lai et al. 2017). The government of Malaysia fully committed to reduce the NRW rate from 36.2% in 2008 to 33.4% in 2017 has planned to reach the target approximately 25% of the NRW rate by 2025. NWSC plays a role to monitor the progress of national water pipeline and provides an overview of Key Performance Indicators related to the implementation of the National NRW Reduction Program. Future directions for the essentials of action research adapted to climate change supporting the right policy design and best management practices of the water sector require the review of current practices of water resource management. Table 3 summarizes the general gaps and recommended actions based on the assessment of three domains of learning under six broadly defined discussion topics for the management of the water sector under climate change scenarios in Malaysia.

Conclusions

This paper reviewed the current status of water resources, water services, and water-related disasters showing that the government of Malaysia represented by DID in cooperation with NAHRIM has performed the update of IDF curves considering climate change to possibly select the optimal mitigation strategies for flood disaster hazards. The alternative water resources of groundwater and rainwater harvesting have been promoted to anticipate the impacts of population growth and climate change on the management of the water sector. The long-term management programs of water demand are expected to reach the average rate of water consumption at 165 LCD for domestic and public purposes. Applying the water-saving control systems of both drip irrigation and sprinkler irrigation can increase the efficiency of agricultural water use in the future. The inter-basin water transfer program designed to secure access by conveying water to locations where people need it is required to anticipating water shortage by linking two related river basins. The government of Malaysia has successfully reduced the NRW rate from 36.2% in 2008 to 33.4% in 2017 and has targeted the NRW rate of 25% in 2025. The findings of this review will provide a greater understanding of drivers of public confidence in the government programs for ensuring the sustainability of water resource management affected by the population growth and climate change.

Author contribution All authors contributed extensively to the work presented in this paper. A. S. and M. A. F. conceived and designed the study and are the principal investigators. K. M., M. A. F., A. Y. M., and N. H. A. G. compiled and analyzed the data and wrote the manuscript. Z. Y., M. A. F., K. M., A. Y. M., and N. H. A. B. analyzed the data and contributed to discussion and made interpretation of mechanistic study data. M. A. F. edited and finalized the manuscript. All authors critically reviewed and revised the manuscript, and they have read and approved the final version.

Funding This work was supported by Universitas Djuanda and Universiti Teknologi Malaysia and received no specific grant from any funding agency.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethical approval All research participants did not collect data from minors without parental or guardian permission and did not collect data from animals for the purpose of this study.

Consent to participate All research participants must give their permission to be part of this study and they must be given pertinent information to make an informed consent to participate.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abdullah J, Muhammad NS, Julien PY, Ariffin J, Shafie A (2018) Flood flow simulations and return period calculation for the Kota Tinggi watershed, Malaysia. J Flood Risk Manag 11:S766–S782. https://doi.org/10.1111/jfr3.12256

Acosta-Coll M, Ballester-Merelo F, Martinez-Peiró M, De la Hoz-Franco E (2018) Real-time early warning system design for pluvial flash floods — a review. Sensors 18:2255. https://doi.org/10.3390/s18072255

Adib MNM, Harun S, Rowshon MK (2022) Long-term rainfall projection based on CMIP6 scenarios for Kurau River Basin of rice-growing irrigation scheme. Malaysia SN Appl Sci 4:70. https://doi.org/10.1007/s42452-022-04952-x

Ainee JG, Anwar AM, Omar KS (2014) Towards the implementation of continuous coastal vulnerability index in Malaysia: a review. J Teknol 71:4. https://doi.org/10.11113/jt.v71.3819

Annual ZF, Wan Azmi WNF, Ahmad NI, Sham NM, Wan Mahiyuddin WR, Veloo Y, Abdullah NA (2020) Drinking water quality in Malaysia: a review on its current status. Int J Environ Sci Nat Res 24(2):556132. https://doi.org/10.19080/IJESNR.2020.24.556132

Bakun A, Black BA, Bograd SJ, García-Reyes M, Miller AJ, Rykaczewski RR, Sydeman WJ (2015) Anticipated effects of climate change on coastal upwelling ecosystems. Curr Clim Change Rep 1:85–93. https://doi.org/10.1007/s40641-015-0008-4

Bauer S, Wagner M (2022) Possibilities and challenges of wastewater reuse — planning aspects and realized examples. Water 14:1619. https://doi.org/10.3390/w14101619

Chan NW (2015) Impacts of disasters and disaster risk management in Malaysia: the case of floods. In: Aldrich D, Oum S, Sawada Y (eds) Resilience and Recovery in Asian Disasters. Risk, Governance and Society, vol 18. Springer, Tokyo. https://doi.org/10.1007/978-4-431-55022-8_12

Cheung WW, Lam VW, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob Chang Biol 16:24–35. https://doi.org/10.1111/j.1365-2486.2009.01995.x

Cheung WW, Sarmiento JL, Dunne J, Frölicher TL, Lam VW, Palomares MD, Watson R, Pauly D (2013) Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat Clim Chang 3:254. https://doi.org/10.1038/nclimate1691

Ching YC, Lee YH, Toriman ME, Abdullah M, Yatim BB (2015) Effect of the big flood events on the water quality of the Muar River, Malaysia. Sustain Water Resour Manag 1:97–110. https://doi.org/10.1007/s40899-015-0009-4

Çullu MA, Teke M, Aydoğdu MH, Günal H (2022) Effects of subsidy and regulation policy on soil and water resources of cotton planted lands in Harran Plain. Turkey Land Use Policy 120:106288. https://doi.org/10.1016/j.landusepol.2022.106288

Ehsan S, Begum RA, Abdul Maulud KN (2022) Household external vulnerability due to climate change in Selangor coast of Malaysia. Clim Risk Manag 35:100408. https://doi.org/10.1016/j.crm.2022.100408

Ehsani N, Vörösmarty CJ, Fekete BM, Stakhiv EZ (2017) Reservoir operations under climate change: storage capacity options to mitigate risk. J Hydrol 555:435–446. https://doi.org/10.1016/j.jhydrol.2017.09.008

Ercan A, Bin Mohamad MF, Kavvas ML (2013) The impact of climate change on sea level rise at Peninsular Malaysia and Sabah-Sarawak. Hydrol Process 27:367–377. https://doi.org/10.1002/hyp.9232

Fulazzaky MA (2013) Assessing the suitability of stream water for five different uses and its aquatic environment. Environ Monit Assess 185:523–535. https://doi.org/10.1007/s10661-012-2572-6

Fulazzaky MA (2014) Challenges of integrated water resources management in Indonesia. Water 6:2000–2020. https://doi.org/10.3390/w6072000

Fulazzaky MA (2017) Participation of farmers in irrigation water management in Indonesia: a review. Irrig Drainag 66:182–191. https://doi.org/10.1002/ird.2085

Fulazzaky MA, Seong TW, Masirin MIM (2010) Assessment of water quality status for the Selangor River in Malaysia. Water Air Soil Pollut 205:63. https://doi.org/10.1007/s11270-009-0056-2

Gomez M, Perdiguero J, Sanz A (2019) Socioeconomic factors affecting water access in rural areas of low and middle income countries. Water 11:202. https://doi.org/10.3390/w11020202

Hamid AIA, Din AHM, Hwang C, Khalid NF, Tugi A, Omar KM (2018) Contemporary sea level rise rates around Malaysia: altimeter data optimization for assessing coastal impact. J Asian Earth Sci 166:247–259. https://doi.org/10.1016/j.jseaes.2018.07.034

Hamududu BH, Ngoma H (2020) Impacts of climate change on water resources availability in Zambia: implications for irrigation development. Environ Dev Sustain 22:2817–2838. https://doi.org/10.1007/s10668-019-00320-9

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

Hasan HH, Razali SFM, Muhammad NS, Hamzah FM (2021) Assessment of probability distributions and analysis of the minimum storage draft rate in the equatorial region. Natur Hazard Earth System Sci 21:1–19. https://doi.org/10.5194/nhess-21-1-2021

Hashim H, Suhatril M, Hashim R (2017) Assessment of liquefaction hazard along shoreline areas of Peninsular Malaysia. Geomat Natur Hazard Risk 8(2):1853–1868. https://doi.org/10.1080/19475705.2017.1391882

Hazir MHM, Kadir RA, Gloor E, Galbraith D (2020) Effect of agroclimatic variability on land suitability for cultivating rubber (*Hevea brasiliensis*) and growth performance assessment in the tropical rainforest climate of Peninsular Malaysia. Clim Risk Manag 27:100203. https://doi.org/10.1016/j.crm.2019.100203

Holguin N, Mugica A, Ukar O (2021) How is climate change included in the implementation of the European Flood Directive? Analysis of the methodological approaches of different countries. Water 13:1490. https://doi.org/10.3390/w13111490

Hussien WA, Memon FA, Savic DA (2016) Assessing and modelling the influence of household characteristics on per capita water consumption. Water Resour Manag 30:2931–2955. https://doi.org/10.1007/s11269-016-1314-x

Hussin NH, Yusoff I, Raksmey M (2020) Comparison of applications to evaluate groundwater recharge at Lower Kelantan River Basin. Malaysia Geosci 10:289. https://doi.org/10.3390/geosciences10080289

Intergovernmental Panel on Climate Change (IPCC) (2000) Special report on emissions scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Jafar-Sidik M, Aung TH, Singh AM (2010) Sensitivity of fish landings to some meteorological parameters: a case study. Am J Environ Sci 6:177–183. https://doi.org/10.3844/ajessp.2010.177.183

Jury WA, Vaux H Jr (2005) The role of science in solving the world's emerging water problems. Proc Natl Acad Sci USA 102:15715–15720. https://doi.org/10.1073/pnas.05064671

Kabiri R, Bai VR, Chan A (2015) Assessment of hydrologic impacts of climate change on the runoff trend in Klang Watershed. Malaysia Environ Earth Sci 73:27–37. https://doi.org/10.1007/s12665-014-3392-5

Kamarudin MKA, Sulaiman NH, Wahab NA, Toriman ME, Hanafiah MM, Umar R, Hassan AR, Rosli MH, Samah MAA, Harith H (2019) Impact of Malaysia major flood to river geomorphology changes and total suspended solid using GIS technique. Desalin Water Treat 149:242–257. https://doi.org/10.5004/dwt.2019.23837

Karim MHA, Juahir H, Aris AZ (2014) A comparative study of groundwater quality of various aquifer systems in Malaysia. In: Aris A, Tengku Ismail T, Harun R, Abdullah A, Ishak M (eds) From Sources to Solution. Springer, Singapore. https://doi.org/10.1007/978-981-4560-70-2_57

Kura NU, Ramli MF, Sulaiman WNA, Ibrahim S, Aris AZ (2018) An overview of groundwater chemistry studies in Malaysia. Environ Sci Pollut Res 25:7231–7249. https://doi.org/10.1007/s11356-015-5957-6

Lai CH, Chan NW, Roy R (2017) Understanding public perception of and participation in non-revenue water management in Malaysia to support urban water policy. Water 9:26. https://doi.org/10.3390/w9010026

Lee KE, Mokhtar M, Hanafiah MM, Halim AA, Badusah J (2016) Rainwater harvesting as an alternative water resource in Malaysia: potential, policies and development. J Clean Prod 126:218–222. https://doi.org/10.1016/j.jclepro.2016.03.060

Liew YS, Teo FY (2013) Impacts of climate change on flooding scenario in Segamat River Basin, Malaysia. Proceeding of the World Engineers Summit (WES 2013) - Innovative and Sustainable Solutions to Climate Change. WES 2013 Organisers, Singapore

Mimura N (2013) Sea-level rise caused by climate change and its implications for society. Proc Jpn Acad Ser B Phys Biol Sci 89:281–301. https://doi.org/10.2183/pjab.89.281

Mogaji K, Lim H, Abdullah K (2013) Regional modeling of climate change impacts on groundwater resources sustainability in peninsular Malaysia. Modern Appl Sci 7:72–97. https://doi.org/10.5539/mas.v7n5p72

Moraes-Santos EC, Dias RA, Balestieri JAP (2021) Groundwater and the water-food-energy nexus: the grants for water resources use and its importance and necessity of integrated management. Land Use Policy 109:105585. https://doi.org/10.1016/j.landusepol.2021.105585

Myers SS, Gaffikin L, Golden CD, Ostfeld RS, Redford KH, Ricketts TH, Turner WR, Osofsky SA (2013) Human health impacts of ecosystem alteration. Proc Natl Acad Sci USA 110:18753–18760. https://doi.org/10.1073/pnas.1218656110

Nazari-Sharabian M, Taheriyoun M (2022) Climate change impact on water quality in the integrated Mahabad Dam watershed-reservoir system. J Hydro-Environ Res 40:28–37. https://doi.org/10.1016/j.jher.2021.12.001

Payus C, Huey LA, Adnan F, Rimba AB, Mohan G, Chapagain SK, Roder G, Gasparatos A, Fukushi K (2020) Impact of extreme drought climate on water security in North Borneo: case study of Sabah. Water 12:1135. https://doi.org/10.3390/w12041135

Pörtner HO, Peck MA (2010) Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J Fish Biol 77:1745–1779. https://doi.org/10.1111/j.1095-8649.2010.02783

Rahman HA (2021) A review on water issues in Malaysia. Int J Res Bus Soc Sci 11:860–875. https://doi.org/10.6007/IJARBSS/v11-i8/10783

Raihan A, Pereira JJ, Begum RA, Rasiah R (2023) The economic impact of water supply disruption from the Selangor River. Malaysia Blue-Green Syst 5(2):102–120. https://doi.org/10.2166/bgs.2023.031

Rashidi AHM, Jamal MH, Hassan M, Sendek SSM, Sopie SLM, Hamid MRA (2021) Coastal structures as beach erosion control and sea level rise adaptation in Malaysia: a review. Water 13:1741. https://doi.org/10.3390/w13131741

Roestamy M, Fulazzaky MA (2022) A review of the water resources management for the Brantas River basin: challenges in the transition to an integrated water resources management. Environ Dev Sustain 24:11514–11529. https://doi.org/10.1007/s10668-021-01933-9

Roestamy M, Martin AY, Rusli RK, Fulazzaky MA (2022) A review of the reliability of land bank institution in Indonesia for effective land management of public interest. Land Use Policy 120:106275. https://doi.org/10.1016/j.landusepol.2022.106275

Rose G (2005) On distributional responses of North Atlantic fish to climate change. ICES J Marine Sci 62:1360–1374. https://doi.org/10.1016/j.icesjms.2005.05.007

Rowshon MK, Dlamini NS, Mojid MA, Adib MNM, Amin MSM, Laid SH (2019) Modeling climate-smart decision support system (CSDSS) for analyzing water demand of a large-scale rice irrigation scheme. Agric Water Manag 216:138–152. https://doi.org/10.1016/j.agwat.2019.01.002

Safizadeh M, Marzbali MH, Abdullah A, Maliki NZ (2022) Proposed flood evacuation routes for heritage areas based on spatial configuration analysis: a case study of Penang. J Facilit Manage, Malaysia. https://doi.org/10.1108/JFM-11-2021-0137

Salimun E, Tangang F, Juneng L, Behera SK, Yu W (2014) Differential impacts of conventional El Niño versus El Niño Modoki on Malaysian rainfall anomaly during winter monsoon. Int J Climatol 34:2763–2774. https://doi.org/10.1002/joc.3873

Samad MNSA, Hanafiah MM, Hasan MJA, Ghazali NF, Harun SN (2017) Ratio of water withdrawal to availability in Kelantan watersheds, Malaysia. J Clean WAS 1:39–42. https://doi.org/10.26480/jcleanwas.01.2017.39.42

Sapari N, Azie RZR, Jusoh H (2012) Groundwater from fractured granite and metasedimentary rocks in the West Coast of Peninsular Malaysia. Pertanika J Sci Technol 20:371–379

Sarkar MSK, Begum RA, Pereira JJ (2020) Impacts of climate change on oil palm production in Malaysia. Environ Sci Pollut Res 27:9760–9770. https://doi.org/10.1007/s11356-020-07601-1

See KL, Nayan N, Rahaman ZA (2017) Flood disaster water supply: a review of issues and challenges in Malaysia. Int J Acad Res Bus Soc Sci 7:525–532. https://doi.org/10.6007/IJARBSS/v7-i10/3406

Sharvini SR, Noor ZZ, Chong CS, Stringer LC, Yusuf RO (2018) Energy consumption trends and their linkages with renewable energy policies in East and Southeast Asian countries: challenges and opportunities. Sustain Environ Res 28:257–266. https://doi.org/10.1016/j.serj.2018.08.006

Shields CA, Band LE, Law N, Groffman PM, Kaushal SS, Savvas K, Fisher GT, Belt KT (2008) Streamflow distribution of non-point source nitrogen export from urban-rural catchments in the Chesapeake Bay watershed. Water Resour Res 44:9. https://doi.org/10.1029/2007WR006360

Shuhaimi-Othman M, Lim EC, Mushrifah I (2007) Water quality changes in Chini Lake, Pahang, West Malaysia. Environ Monit Assess 131:279–292. https://doi.org/10.1007/s10661-006-9475-3

Suri S, Ahmad F, Yahaya AS, Mokhtar ZA, Halim MH (2014) Climate change impact on water level in Peninsular Malaysia. J Civil Eng Res 4:228–232. https://doi.org/10.5923/c.jce.201402.39

Tam TH, Rahman MZA, Harun S, Hanapi MN, Kaoje IU (2019) Application of satellite rainfall products for flood inundation modelling in Kelantan River Basin. Malaysia Hydrol 6:95. https://doi.org/10.3390/hydrology6040095

Tan ML, Ibrahim AL, Yusop Z, Chua VP, Chan NW (2017) Climate change impacts under CMIP5 RCP scenarios on water resources of the Kelantan River Basin, Malaysia. Atmospher Res 189:1–10. https://doi.org/10.1016/j.atmosres.2017.01.008

Tan ML, Ibrahim AL, Yusop Z, Duan Z, Ling L (2015) Impacts of land-use and climate variability on hydrological components in the Johor River basin. Malaysia Hydrol Sci J 60(5):873–889. https://doi.org/10.1080/02626667.2014.967246

Trabelsi N, Triki I, Hentati I, Zairi M (2016) Aquifer vulnerability and seawater intrusion risk using GALDIT, GQISWI and GIS: case of a coastal aquifer in Tunisia. Environ Earth Sci 75:669. https://doi.org/10.1007/s12665-016-5459-y

Toh CK, Zakiyyah M, Khor CH, Karuppiah R (2020) Malaysia Dam Safety Management Guidelines (MyDAMS) — from best management practices to capacity building in dam engineering in Malaysia. In: Mohd Sidek, L., Salih, G., Boosroh, M. (eds) ICDSME 2019. ICDSME 2019. Water Resources Development and Management. Springer, Singapore. https://doi.org/10.1007/978-981-15-1971-0_33

Tukimat NNA, Harun S, Shahid S (2017) Modeling irrigation water demand in a tropical paddy cultivated area in the context of climate change. J Water Resour Plan Manag 143:0501700. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000753

Ungureanu N, Vlăduț V, Voicu G (2020) Water scarcity and wastewater reuse in crop irrigation. Sustainability 12:9055. https://doi.org/10.3390/su12219055

van Rooyen JM, Veltman S, Botha F, Matthee J (2021) Groundwater resource exploration & development — focus on groundwater to support surface water supply in the Lower Olifants River. South Africa J Afr Earth Sci 180:104179. https://doi.org/10.1016/j.jafrearsci.2021.104179

Yaacob M, So WW-M, Iizuka N (2022) Exploring community perceptions of climate change issues in Peninsular Malaysia. Sustainability 14:7756. https://doi.org/10.3390/su14137756

Yamashita R (2022) Disaster risk and migration in the west bank of the Malay Peninsula: will the urban-rural divide improve or widen? Int J Disaster Risk Reduc 78:103150. https://doi.org/10.1016/j.ijdrr.2022.103150

Young KR, Lipton JK (2006) Adaptive governance and climate change in the tropical highlands of Western South America. Clim Chang 78:63–102. https://doi.org/10.1007/s10584-006-9091-9

Zainol NFM, Zainuddin AH, Looi LJ, Aris AZ, Isa NM, Sefie A, Ku Yusof KMK (2021) Spatial analysis of groundwater hydrochemistry through integrated multivariate analysis: a case study in the urbanized Langat basin, Malaysia. Int J Environ Res Public Health 18(11):5733. https://doi.org/10.3390/ijerph18115733

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