Assessing the Impact of Groundwater Variability on Dam Safety Based on Flood Situation and Climate Change Scenarios Using Hydrological Model

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Abstract *Monitoring dam behavior during severe storms is a crucial step in assessing dam safety. Utilizing hydrological models is considered an effective approach to studying dam safety by analyzing the relationship among hydrological parameters. The objective of this study is to simulate groundwater conditions associated with runoff into the Lam Khan Chu Reservoir in the northeastern region of Thailand. This is achieved by applying the SWAT hydrologic model to simulate daily runoff conditions from 2018 - 2020 and extending the analysis to the future period from 2021 - 2030 using data from the HadGEM2-AO model in RCP4.5 and RCP8.5 scenarios. The aim is to develop criteria for checking dam safety and predicting the impact of future groundwater changes. The results indicated that the SWAT model exhibited good performance in runoff calculation accuracy, as indicated by R^2, NS, and PBIAS statistical indices. Additionally, the relationship between groundwater level from the SWAT-Check model and those obtained from observation wells was noteworthy. Simulating future dam safety conditions for both RCP4.5 and RCP8.5 forecasts over five years revealed that surveillance measures are necessary for Lam Khan Chu Dam during the rainy season (August - October). This is due to the groundwater showing a trend above normal in the forecasted cases for the specified period. The research methods and findings are anticipated to serve as crucial guidelines for officials overseeing dam safety. These guidelines can be applied to plan preparedness measures, facilitating the timely monitoring and resolution of situations. This applies even to dams or reservoirs lacking a Dam instrument installation.*

Keywords:

dam safety, groundwater, runoff, SWAT, Lam Khan Chu Dam

1. Introduction

Floods are natural disasters that result in damage to life, property, and natural environment. The primary cause of flooding is partly attributed to the influence of various storms, causing damage over a wide area [1]. In 2019 - 2020, during the monsoon seasons from August to October, the northeastern region of Thailand experienced the impact of three consecutive tropical storms and depressions: Podul, Kajiki, and Noul, respectively [2]. Hence, many areas, especially the Lam Khan Chu Watershed in Chaiyaphum Province, were severely affected by flooding. The hydraulic structure impacted by this incident is the Lam Khan Chu Dam, responsible for controlling the direct runoff from the river to prevent flooding in communities in Bamnet Narong District, Chaiyaphum Province.

For this reason, the Royal Irrigation Department, the main agency responsible for water management, has devised special plans to address the situation of water flooding into reservoirs during storms. The safety conditions of the dam are meticulously monitored and assessed to prevent the occurrence of a dam break [3]. Simultaneously, Lam Khan Chu Dam is equipped with a dam instrument designed for measuring the stability of the dam. This instrument is installed in the foundation or other critical areas where it is necessary to monitor the significant behavior of the dam, both during construction and operation periods. It serves as an early warning system for abnormal events. One crucial parameter to measure is groundwater level, as it must be used as a database to indicate the amount of excess pore pressure exposed at the bottom of the capillary zone. This sensitivity to groundwater levels is influenced by various factors, including hydrologic conditions, additional flow from neighboring streams into main streams and reservoirs, and increased water demand [4].

In general, dam safety studies primarily rely on data concerning hydrological conditions, specifically historical precipitation patterns, and the simulation of extreme scenarios [5]. For the examination of dam stability, a hydrological model was employed to analyze the runoff mechanism in watersheds during storms, anticipating an impact on the stability of the dam and reservoir [6]. The study results indicate that the model effectively incorporates the conditions of percolation and water saturation in the soil layer, influenced by varying periods and intensities of precipitation. Additionally, it includes simulating water resource conditions and calculating flood hydrographs to study the dam failure risk [7]. However, there are still very few studies on relationships between hydrological parameters and dam safety utilizing hydrologic models, particularly concerning runoff and groundwater conditions. Moreover, the runoff flowing to reservoir is necessary for supporting a non-construction and cost-saving approach in reservoir operation management [8]-[10].

Over the past two decades, the Soil and Water Assessment Tools (SWAT), a hydrological model has been widely regarded as a tool used by hydrologists and engineers to address water resource engineering challenges globally [11]-[14]. SWAT is a hydrologic model capable of simulating the physical characteristics of a watershed by distributing parameters based on local conditions, facilitating the evaluation of watershed potential. Moreover, SWAT's strength lies in its ability to quantify components of the water balance [15]-[18], such as evapotranspiration, surface flow, and groundwater volume, through a sub-module program called SWAT-Check. For this reason, SWAT and SWAT-Check find extensive application in hydrologic assessment studies and in-depth analyses of water balance components in watersheds [19]-[22].

Consequently, this study has two main objectives: 1) simulating the daily runoff and groundwater volume conditions of Lam Khan Chu Reservoir during 2018 – 2020 by applying SWAT and 2) analyzing the relationship between the simulated groundwater volume from SWAT-Check and the existing water level recorded from the dam instrument during the flood seasons, including studying the impact of changes in groundwater levels due to climate change using GCM model, HadGEM2-AO in case of RCP4.5 and RCP8.5. The research methodology and results of this study are expected to provide another avenue for the application of hydrological models in evaluating and preparing dam safety to address future extreme storm situations. In particular, there are numerous small and medium-sized dams in Thailand that have not yet been equipped with equipment to measure dam behavior.

2. Material and Methods

2.1 Study Area

The Lam Khan Chu Dam is an earthen dam constructed in 1990, situated at Latitude 15.492680 and Longitude 101.544520 in the Lam Khan Chu Watershed (a tributary of the Chi Watershed in northeastern Thailand), as illustrated in Figure 1. Hydrological data comprises the average annual precipitation of 1,123 mm, watershed area of 210 km^2 (square kilometer), the average annual runoff flow into the reservoir of 43.4 MCM (million cubic meter), with a water storage capacity of approximately 42.6 MCM. The physical characteristics of the dam include a height of 26 m and a length of 2,000 m. The dam ridge is 8 m wide, and the dam slope upstream and downstream is 1:3. The primary purpose of the reservoir is to allocate water for consumption and irrigation in a water-scarce area of approximately 70 km^2. Additionally, it serves to mitigate flooding during the flood season.

Fig. **1** Study area.

2.2 SWAT Model

SWAT is a semi-distributed hydrologic model [23]-[25] developed collaboratively by the Blackland Research Center, TAES, and the United States Department of Agriculture–Agricultural Research Service (USDA-ARS). The model was developed with the objective of assessing the impact of changes in runoff resulting from alterations in land use, sediment generation, and agricultural chemical runoff in large-complex watershed due to variations in soil conditions and land use [26]-[28]. The structure of SWAT comprises hydrological analysis divided into two main parts: 1) land phase, which studies the hydrologic cycle to evaluate the quantity of runoff, sediment, nitrogen, and agricultural chemicals flowing into the main streams of each watershed and 2) water routing phase, which calculates the movement of water, sediment, nitrogen, and other components. The water balance equation, as presented in Equation (1), is employed to consider hydrological processes.

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

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is time (day), R_{day} is the volume of rainfall on day i (mm), Q_{surf} is the volume of surface water on day i (mm), E_a is the volume of evapotranspiration on day i (mm), W_{seep} is the volume of water seeping into the groundwater on day i (mm), and Q_{gw} is the volume of groundwater returning to the stream on day i (mm).

2.3 Data Sources

SWAT is a GIS-based model that prepares and imports spatial and hydrological data relevant to the area, featuring the following details (summary data is presented in Table 1).

Table 1 Spatial data used in SWAT operations

Data Types	Year	Resolution	Sources
Digital Elevation Model (DEM)	2015	30 x 30 sqm	LDD
Soil type map	2018	1:50,000	
Land use map	2019	1:50,000	
Climate data	2018 – 2020	Daily	TMD
Rainfall data from 3 stations	2018 – 2020	Daily	
Reservoir boundary map	2022	1:50,000	RID
Streamline map	2015	1:50,000	
Recorded runoff of Lam Khan Chu Reservoir	2018 – 2020	Daily	

Abbreviation descriptions:
LDD - Land Development Department
TMD - Thailand Meteorological Department
RID - Royal Irrigation Department

2.4 Dam Instrument

The Lam Khan Chu Dam has installed a Dam instrument with five types of accessories. 1) Inclinometer was installed at 2 points and used to measure horizontal soil movement by recording data on daily basis. 2) Piezometer was installed at 2 points and used for measuring pore water pressure in the soil layer at various depths and recording data on daily basis. 3) Seepage flow meter was installed at 1 point and used for measuring the rate of water seepage through the dam and recording data on daily basis. 4) Water level sensor was installed at 1 point and used to measure the water level in the reservoir and record the results in analog form on daily basis. 5) Observation wells were installed at 5 points and used for measuring groundwater levels in wells installed on the dam ridge and recording groundwater level data on daily basis. For this study, data were selected from the observation well at the deepest level at +237.64 meters above MSL.

2.5 Model Performance Assessment

To assess the effectiveness of the runoff simulation results obtained from SWAT, they were compared with recorded runoff data from reservoirs using statistical index criteria. In this study, three statistical indices were employed to evaluate hydrological models:

2.5.1 Coefficient of Determination (R^2), with values ranging from 0 to 1: A value greater than 0.5 indicates a reliable level of correlation between the two sets of data (see Equation (2)).

$$R^2 = \frac{[(Q_{obs}-Q_{avr})\times(S_{sim}-S_{avr})]^2}{\sum(Q_{obs}-Q_{avr})^2\times\sum(S_{sim}-s_{avr})^2} \quad (2)$$

2.5.2 Nash-Suttclife efficiency (NS), ranging from -∞ to 1: NS value of 1 signifies a perfect match between the model and measured values. When NS equals 0, the model's value matches the mean value of the measured data, and NS < 0 indicates that the mean value of the measured data is superior to the model's value (see Equation (3)).

$$NS = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}-S_{sim})^2}{\sum_{i=1}^{n}(Q_{obs}-Q_{avr})^2} \quad (3)$$

2.5.3 Percentage Bias (PBIAS), with a minimum acceptable bias threshold value of not more than 25 percent (see Equation (4))

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{obs}-S_{sim})^2}{Q_{obs}} \times 100 \quad (4)$$

From Equations (2) – (4), Q_{obs} is recorded runoff from observed station, Q_{avr} is average recorded runoff from observed station, S_{sim} is runoff calculated by model, S_{avr} is average runoff calculated by model, and *i* is data order.

3. Results and Discussion

3.1 Model Calibration and Validation

When the data utilized in the study was imported into SWAT, the analysis results were related to the watershed components. This study utilizes daily runoff data from 2018 - 2020, reflecting various hydrological variables within the model influencing the runoff flow into the reservoir. Each variable impacts the hydrologic process, leading to distinct changes in runoff. A sensitivity analysis of parameters was conducted using the SWAT Calibration and Uncertainty Programs (SWAT-CUP) with the SUFI-2 [29]-[30] solution search technique, involving 300 iterations. In the process, eight parameters were identified for adjustment, influencing the runoff, as outlined in Table 2. The results of calibrating the runoff calculation from SWAT, which closely align with the observed data, are depicted in Figure 2.

3.2 Relationship of Monthly Groundwater Dataset

The daily runoff calculation results generated by SWAT were analyzed into distinct components using the SWAT-Check model to summarize the monthly groundwater volume, abbreviated as 'Lat_Q,' with depth units in millimeters. Subsequently, the monthly Lat_Q value was compared with the readings from the observation well to conduct a regression analysis, examining the relationship between the Lat_Q value as the primary variable and the underground level from the observation well device as the dependent variable. Upon reviewing the scatter plot graph depicted in Figure 3, it was observed that the R^2 value equaled 0.81, indicating that the model's effectiveness falls within a good range. The findings of this section suggest that monthly groundwater level from Lat_Q, obtained from SWAT-Check, is correlated in the same direction as the groundwater level increase from the observation well during 2018 - 2020.

Table 2 Stativity parameters in SWAT-CUP processes

No.	Parameters	Description	Adjust rang	Optimal value
1	CN2	Initial SCS runoff curve number for moisture condition II	0 - 0.30	-0.186
2	ALPHA_BF	Base flow alpha factor	0 - 2	1.545
3	GW_DELAY	Groundwater delay	0 - 500	309.299
4	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0 - 5,000	1095.000
5	SOL_AWC	Available water capacity of the soil layer	0 - 1	0.131
6	ESCO	Soil evaporation compensation factor	0 - 1	0.935
7	CH_N2	Manning's N value for the main channel	0.01 - 0.3	0.090
8	SLSUBBSN	Average slope length	10 - 150	11.260

3.3 Groundwater Variation from Climate Change

To simulate future climate change in this study, precipitation data from 2021 - 2030 generated by the General Circulation Model (GCM) named HadGEM2-AO [31] was applied in two forecast scenarios: RCP4.5 and RCP8.5 (RCP is an abbreviation for Representative Concentration Pathway). The HadGEM2-AO can provide climate data covering the Lam Khan Chu Reservoir's watershed area based on latitude and longitude grid coordinates with a spatial resolution of approximately 5 × 5 km^2. The accuracy performance of the GCM was assessed as moderately acceptable when compared with 40 Climate Model Intercomparison Project 5 (CMIP5) GCMs based on a validation process with precipitation data from observed stations in Thailand and Southeast Asia during 1900 - 2017 [32]. For reducing the discrepancy in precipitation data from the HadGEM2-AO model, the Gamma-Gamma (GG) Transformation technique has been applied [33]-[34]. Then, the precipitation data from the model were imported into SWAT to calculate daily runoff and Lat_Q values in future conditions between 2021 and 2030. The results of future monthly Lat_Q calculations under the RCP4.5 and RCP8.5 scenarios [35]-[36] for the period 2021 - 2030 can be presented in Figures 4 and 5, respectively.

When comparing the monthly average Lat_Q from the two scenarios, a similar pattern was observed. It was found that the highest volume of groundwater occurred between 10.27 - 16.01 mm during September - October. In the case of RCP4.5, its volume was slightly higher than RCP8.5. Moreover, when comparing the average annual Lat_Q volume in the future between 2021 and 2030, as illustrated in Figure 6, it can be noted that RCP4.5 case yields an annual average of 80.03 mm while RCP8.5 case has an average of 75.84 mm.

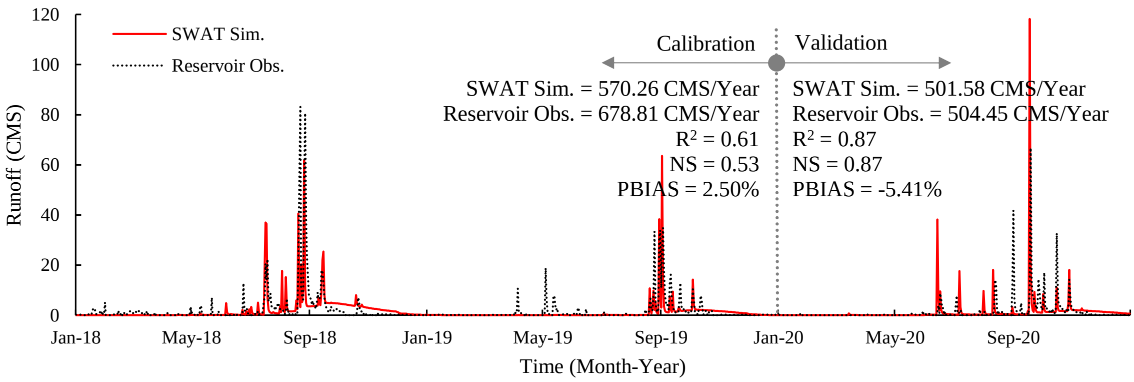

Fig. 2 Comparison on daily runoff during 2018 - 2020 between observed reservoir data and SWAT simulations.

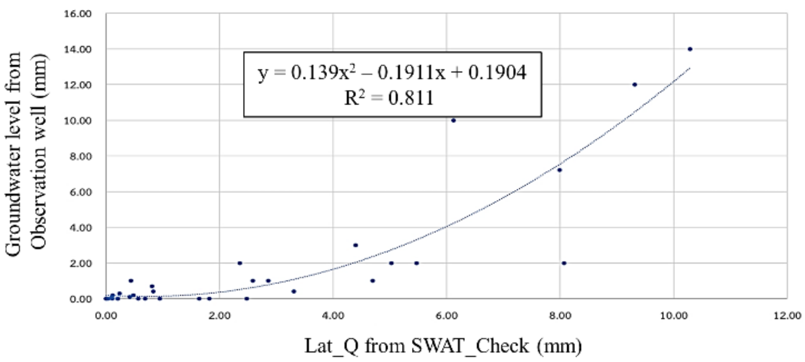

Fig. 3 Relationship between monthly Lat_Q from SWAT_Check and monthly groundwater level from observation well.

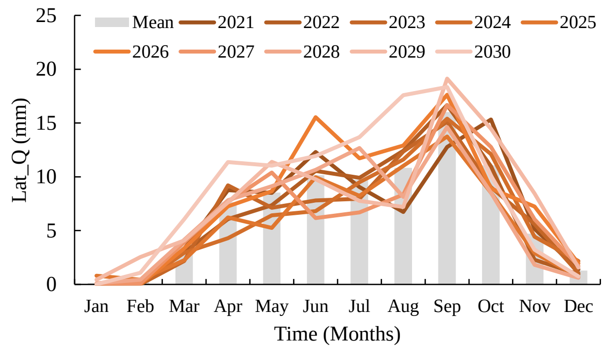

Fig. 4 Monthly Lat_Q from HadGEM2-AO for RCP4.5 scenario.

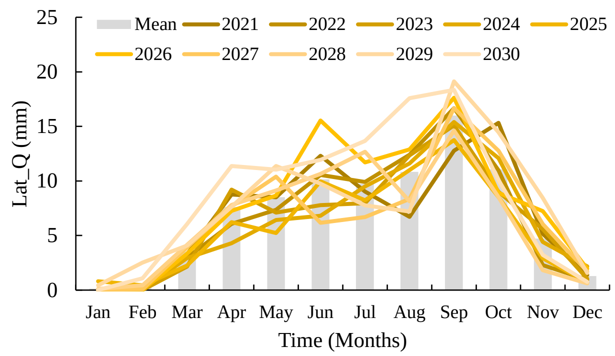

Fig. 5 Monthly Lat_Q from HadGEM2-AO for RCP8.5 scenario.

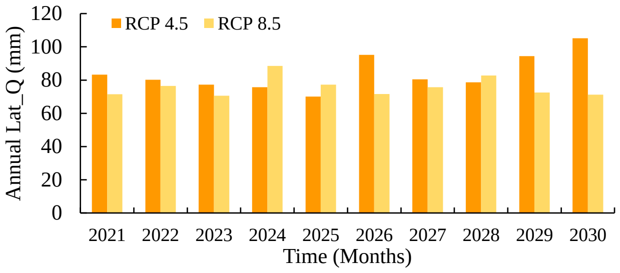

Fig. 6 Average annual Lat_Q during 2021 – 2030.

3.4 Dam Safety Criteria Development

In this study, the development of dam safety criteria is based on the results of studies conducted under the project 'The Study of Safety Criteria from Dam Instruments for the Improvement of the Lampao Dam in Kalasin Province' by the Dam Safety Research Unit, Geotechnical and Foundation Engineering Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Thailand, which was completed in 2016 [37]. The approach for applying the results from the study to the Lam Pao Dam case is to create an equation for predicting groundwater levels based on relationships with water levels in reservoirs and groundwater level within the Lam Khan Chu Reservoir, as shown in Equation 5.

$$y = -0.0025x + 252.82 \qquad (5)$$

where y is the groundwater level from the observation well (metre above mean sea level, m.MSL) and x is the water level recorded from Lam Khan Chu Reservoir (m.MSL).

The recorded data indicated the highest and lowest numerical statistics, representing the behavior of the dam. The volume of groundwater detected by the measuring instrument was recorded, and there was no water leakage on the downstream slope of the dam ridge, as shown in Table 3. This criterion is based on the period when Lam Khan Chu Dam is considered safe during severe storm situations as illustrated in Figure 7.

Table 3 Monthly groundwater level and groundwater volume calculated from Equation 5 of Lam Khan Chu Dam

Months / Years	2018		2019		2020	
	GWL (m.MSL)	GWV (mm)	GWL (m.MSL)	GWV (mm)	GWL (m.MSL)	GWV (mm)
Jan	252.15	0	252.15	0	252.15	0
Feb	252.25	0.1	252.15	0	252.15	0
Mar	252.15	0	252.15	0	252.15	0
Apr	252.55	0.4	252.25	0.1	252.45	0.3
May	252.15	0	252.85	0.7	252.35	0.2
Jun	252.55	0.4	252.15	0	254.15	2
Jul	259.35	7.2	252.15	0	253.15	1
Aug	264.15	12	253.15	1	255.15	3
Sep	254.15	2	266.15	14	262.15	10
Oct	253.15	1	254.15	2	254.15	2
Nov	252.15	0	253.15	1	252.15	0
Dec	252.15	0	252.35	0.2	252.15	0

Abbreviation descriptions:
GWL - Groundwater level
GWV - Groundwater volume

3.5 Dam Safety Assessment under Climate Change Scenarios

The results of groundwater level calculations in the RCP4.5 and RCP8.5 scenarios between 2021 and 2030 revealed that future groundwater levels exceeded the established dam safety criteria. In this context, referring to the findings from the Lam Pao Dam study, the criteria have been categorized into three states: Normal, Monitoring, and Warning. The results highlighted periods when the water level surpassed the dam's safety threshold, primarily during August – October characterized by high precipitation and increased runoff. For RCP4.5, the analysis results indicated that in September 2018, 2022, 2026, 2027, and 2029, as well as August and September 2030, the results exceeded the established dam safety criteria. Meanwhile, in the case of RCP8.5, results exceeding the criteria were observed in September 2024, 2026, 2029, October 2025, and 2030, corresponding to periods with substantial precipitation. This underscores the need for close monitoring and planning of dam safety measures. The analysis results from both forecast cases are presented in Figures 8 - 9 and summarized in Table 4.

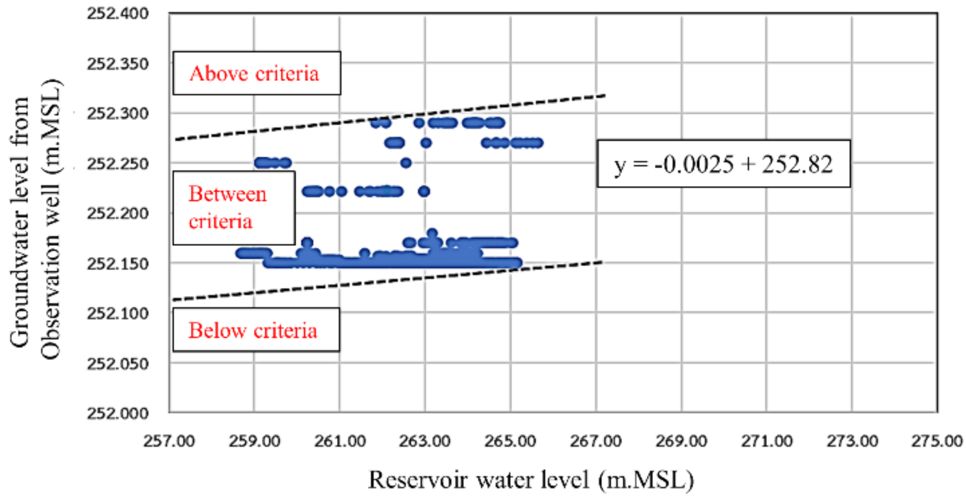

Fig. 7 Safety criteria of Lam Khan Chu Dam developed from Equation 5.

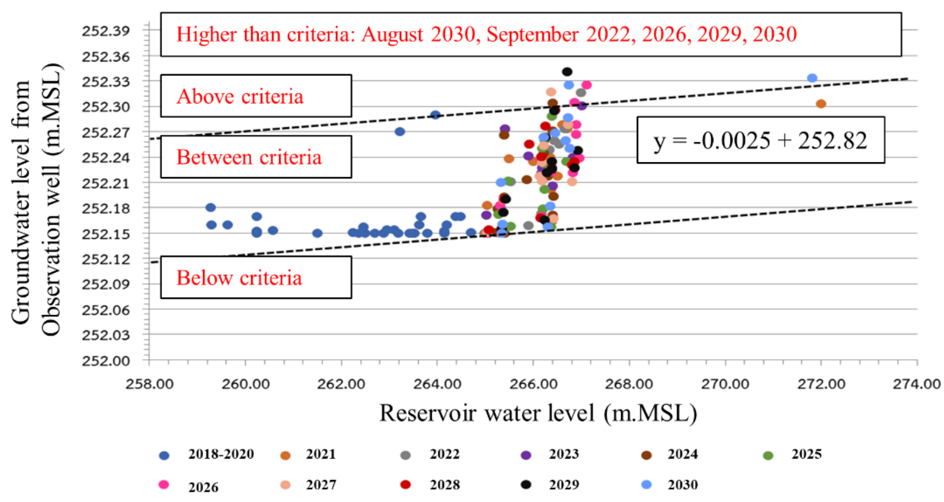

Fig. 8 Dam safety from groundwater levels in RCP4.5 scenario.

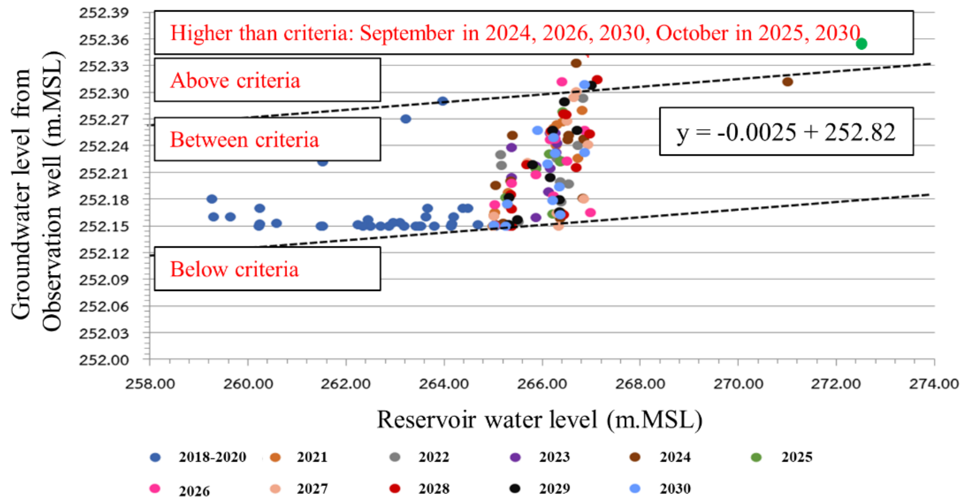

Fig. 9 Dam safety from groundwater levels in RCP8.5 scenario.

Table 4 Dam safety criteria due to groundwater level in RCP4.5 and RCP8.5 scenarios

Ranks	Above criteria due to the groundwater level in RCP4.5 scenario	Above criteria due to the groundwater level in RCP8.5 scenario	Status
1	September 2022	September 2024	monitoring
2	September 2026	October 2025	monitoring
3	September 2027	September 2026	monitoring
4	September 2029	September 2026	monitoring
5	August and September 2030	October 2030	monitoring

4. Conclusion

This study introduces a methodology for evaluating dam safety in response to groundwater variations influenced by climate change in the Lam Khan Chu Dam, located in the Lam Khan Chu Watershed, Chaiyaphum Province. The primary focus is on investigating the impact of future climate change on runoff and groundwater, guiding the formulation of future dam safety criteria. The study commences with the application of the SWAT hydrologic model to estimate runoff. Additionally, the SWAT-Check model is employed to calculate groundwater volume, represented as Lat_Q. Subsequently, the obtained results will be correlated with measurement data collected from the observation well—a crucial component of the dam instrument recording information pertinent to the dam's safety status. Furthermore, the methodology outlined in this study has the potential to evolve into a practical tool for predicting the safety status of dams. This would be accomplished by analyzing daily measured and recorded data within the reservoir.

The study's findings indicate that the simulation of runoff conditions entering the Lam Khan Chu Reservoir, conducted through the SWAT model, meets satisfactory criteria when assessed by R^2, NSE, and PBIAS statistical values. The relationship between monthly groundwater volume, calculated from SWAT-Check (Lat_Q), and the observation well data from 2018 – 2020 (3 years) is deemed satisfactory, with R^2 of 0.81. This suggests a significant correlation between changes in subterranean water quantity and groundwater levels. To align with the development of dam safety assessment criteria, groundwater level data from observation wells were employed to establish safety criteria for Lam Khan Chu Dam following the guidelines developed for Lam Pao Dam in Kalasin Province in 2016. Consequently, equations were formulated to explore the impact of water levels on groundwater. Furthermore, future predictions of groundwater conditions were derived from climate change simulations conducted with the HadGEM2-AO GCM models, specifically under the scenarios of RCP4.5 and RCP8.5 for the years 2021 - 2030, utilizing the developed equations. The findings unveiled elevated groundwater levels, particularly during the rainy season (August - October). This situation necessitates continuous monitoring of dam safety, particularly concerning water leakage in the downstream slope of the dam due to the intensification of storms resulting from climate change events, which are more severe more than in the past. The research methods and findings from this study are expected to serve as crucial guidelines for officials responsible for dam safety. They can be applied in planning preparedness efforts to monitor and address situations promptly. This is especially relevant for dams or reservoirs lacking a Dam instrument installation. The research methods and findings presented in this paper offer an alternative approach that agencies responsible for maintaining small and medium-sized reservoirs throughout Thailand may consider (such as the Royal Irrigation Department). This is particularly relevant as most of these reservoirs currently lack dam instruments. Therefore, they can be appropriately considered and applied in a cost-effective manner.

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