Impact of Climate Change on the Safety of Dam

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Impact of Climate Change on the Safety of Dam

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Abstract. Dams are built to overcome surface water problems. These problems include excess water in the rainy seasons and scarcity of water in the dry seasons. As the occurrence of climate change has been recognized by people around the world, engineers have to be able to consider its impact on the safety of dams. This study proposes a procedure for studying the impact of climate change on the safety of gated spillway dams. The procedure consists of a statistical consistency test, selection of global climate change variables, modelling of local climate change, calculating flood discharge due to climate change, and evaluation of dam safety. This study was conducted at the Batujai Dam, Central Lombok Regency. Global climate change data from 1998 to 2100 taken from the Intergovernmental Panel on Climate Change (IPCC) and maximum daily rainfall data from 1998 to 2020 from the Pengadang Station were used to demonstrate the application of the proposed procedure. The results show that the proposed procedure can be used to evaluate the impact of climate change on dam safety. It is also known that climate change has a significant effect on the tendency of increasing flood discharge entering the Batujai Reservoir. The four spillway gates: P_1, P_2, P_3, and P_4 have to be opened 1.0 m, 1.2 m, 1.2 m, and 1.0 m, respectively to anticipate the 1000-year return period of a flood event due to climate change, at a rate of 1833.54 m^3/second.

Keywords: Climate change, Maximum daily rainfall, Gated spillway dams, Safety of dam.

1 Introduction

Dams are built for many benefits. However, there are potential dangers if floods overtop the dam embankments. The dam will break and a flash flood will occur downstream. In the Dam Design guidelines, embankment heights should be designed based on at least a 1000-year return period of flooding. Since the consensus on climate change in Kyoto in 1992, engineers must evaluate the impact of climate change on dam safety.

Global climate change predictions have been simulated by agencies around the world under the coordination of the IPCC. The resolution of the global simulation is still very rough, however, and cannot be used directly for local designs. The results of global climate change simulation have to be downscaled following the local historical data to obtain local scaled climate change data that can be used in local designs and evaluations [1].

This study proposes the procedure for dam safety evaluation based on the impact of climate change, to develop a local rainstorm model based on climate change, to calculate the 1000-year return period of flooding due to climate change, and to obtain the opening height of the spillway gates required to secure the dam.

2 Literature review

The problem of the increase in water demand caused by the increase in population in the Tasikmalaya Regency can be solved through the construction of a water reservoir, namely the Manonjaya Dam [2]. The Manonjaya Dam is an earth-fill type dam with a vertical core on the Citanduy River with a catchment area of 590,422 km^2. The purpose of the Manonjaya Dam is to meet the needs for domestic water and irrigation in the Tasikmalaya Regency area.

The problem of flooding in the rainy season and the lack of clean water during the dry season in Ponorogo Regency, East Java, can be overcome through the construction of the Bendo Dam [3]. A 1000-year return period of a flood of 676.37 m^3/sec was used to design the dam height. The design life of the dam is 50 years.

Climate change refers to permanent changes in the statistical characteristics of climate factors such as solar radiation, temperature, wind, humidity, rainfall, air pressure, and so on, over a long period such as tens of years to millions of years [4][5][6]. Currently, the world is experiencing global climate change [7]. The impacts of climate change in Indonesia include an increase in the average air temperature from January 1971 to December 2006 of 0.5 degrees Celsius; an increase in the maximum air temperature of 0.7 degrees Celsius; a decrease in the minimum air temperature of about 1.2 degrees Celsius; change in the maximum rainy season from January–March to October–December; and the occurrence of drought in some areas. In addition, many small islands such as Lombok, Sumbawa, Flores, Sumba, Timor, Solor, and Alor will be more vulnerable to climate change than the large islands [8].

3 Methodology

The study procedure consists of the following five strategic steps: Preparation, Standard Statistical Screenings, Climate Change Modelling, Hydrological Frequency Analysis, and Hydraulic Analysis to check for overtopping. The procedure is shown in Fig. 1.

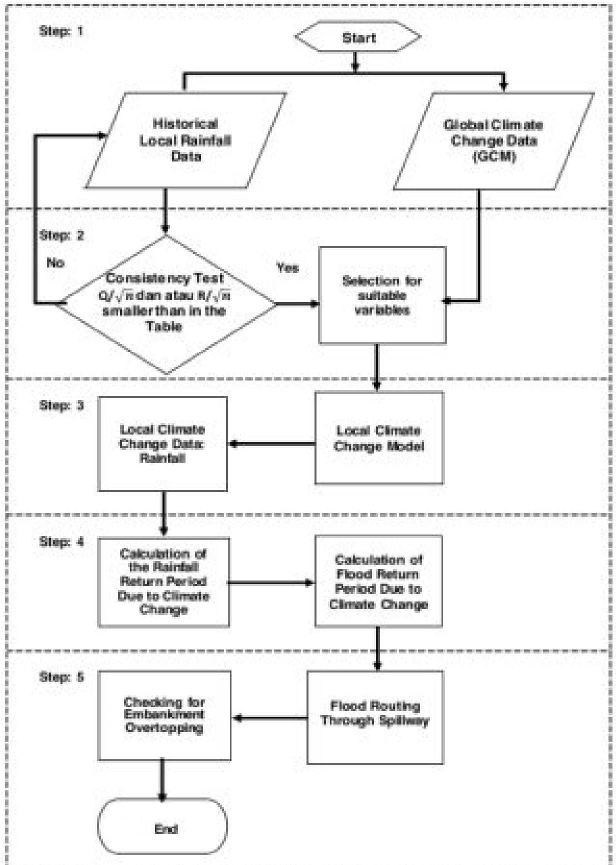

Fig. 1. The procedure of the study

3.1 Step: 1 Preparation

In this step, both historical local rainfall data and global climate change data are collected. The range of historical local rainfall data (HLRD) has to be within the range of the global climate change data (GCCD). The period of HLRD has to be at least 20 years to ensure statistical validity in the calibration and verification processes. HLRD is collected from all rainfall stations around the catchment area of the reservoir.

The GCCD is the result of global climate models (GCM). In the Intergovernmental Panel on Climate Change (IPCC), GCCD of various GCMs from various countries are stored. One has to register before downloading the data. The GCCD cannot be applied directly for local designs because the resolution is very coarse. The GCM variable needs to be downscaled to get better-scaled variables that can be used for local designs. Downscaling models can be grouped into the three following approaches: dynamic models, statistical models, and change factor methods [1] [9]. Regression models are proposed in this study procedure for the climate change downscaling model.

3.2 Step: 2 Standard Statistical Screening

Statistical screening tests are used to ensure all the data are ready. The term 'ready' refers to data that are consistently collected in the expected condition. The Rescaled Adjusted Partial Sums (RAPS) method [10] is applied in this procedure for the standard statistical screening test. As RAPS has been frequently explained in many hydrological references, this method is not described further in this paper.

3.3 Step: 3 Climate Change Modelling

This study applies the three most suitable GCM variables as independent variables to simulate local climate variables. The selection of suitable GCM variables is made using common statistical analysis: correlation coefficients (CC) [11].

In this study, the best multiple linear regression is selected and used to downscale the GCM variable into local rainfall variables.

3.4 Step: 4 Hydrological Frequency Analysis

In this study, the frequency analysis is used to obtain the estimated return period of rainstorms due to climate change. Then, the flood return period is calculated based on the return period of rainstorms. The Nakayasu Synthetic Unit Hydrograph is used to simulate the flood [10]. The Unit Hydrograph as shown in Figure 2 is calculated using Eq. (1) to Eq. (11):

$$Q_P = \frac{AR_0}{3.6(0.3t_P + T_{0.3})} \quad (1)$$

where: Q_p = peak flow (m^3/sec), A = catchment area (km^2), R_o = unit rainfall (mm), t_p = time lag from the initial rain to the peak flow (hours), $T_{0.3}$ = the time it takes for the discharge to decrease, from peak discharge to 30% of peak discharge (hours).

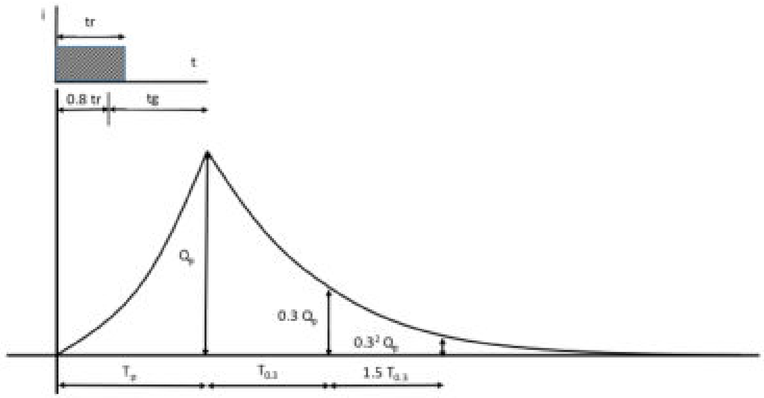

Fig. 2. The illustration of Nakayasu Synthetic Unit Hydrograph

In Fig. 2, T_p and $T_{0.3}$ are calculated using Eq. (2) and Eq. (3):

$$T_p = tg + 0.8\ tr \tag{2}$$

$$T_{0.3} = \alpha\ .\ tg \tag{3}$$

where tg is calculated based on Eq. (4) or Eq. (5), and tr is calculated using Eq. (6):

$$tg = 0.21\ L^{0.7} \qquad \text{for } L < 15\text{ km} \tag{4}$$

$$tg = 0.40 + 0.058\ L \qquad \text{for } L > 15\text{ km} \tag{5}$$

$$tr = (0.5 \sim 1.0)\ tg \tag{6}$$

where tr = the effective duration of rain.

The rising curve for the range of $0 \le t \le T_p$

$$Q_a = Q_P \left[\frac{t}{T_P}\right]^{2.4} \tag{7}$$

The declining curves for the range of

1) $Q_d > 0.3\ Q_P$ or $T_P \le t < T_{0.3}$

$$Q_d = Q_P 0.3 \left[\frac{t - T_P}{T_{0.3}}\right] \tag{8}$$

2) $0.3\ Q_P > Q_d > 0.32\ Q_P$ or $T_{0.3} \le t < 1.5\ T_P$:

$$Q_d = Q_P 0.3 \left[\frac{(t - T_P) + 0.5 T_{0.3}}{1.5 T_{0.3}}\right] \tag{9}$$

3) $0.3^2\ Q_P > Q_d$ or $t \ge 1.5\ T_{0.3}$

$$Q_d = Q_P 0.3\left[\frac{(t-T_P)+1.5T_{0.3}}{2T_{0.3}}\right] \quad (10)$$

The relationship between the shape of the drainage area and $T_{0.3}$ can be stated as a constant of α:

$$\alpha = \frac{0.47(AL)^{0.25}}{tg} \quad (11)$$

where: Q_a = runoff before reaching peak discharge (m^3/sec), Q_d = runoff after reaching peak discharge (m^3/sec), t = time (hours), L = length of river channel (km), tg = concentration time (hours), and α = constant.

3.5 Step 5: Hydraulic Analysis for overtopping

The flood routing through the spillway aims to simulate the capacity of the spillway concerning changes in the inflows of the dam. The eq. (12) and eq. (13) were used in the simulation. The simulation must consider the upstream and downstream water conditions.

$$Q_s = \mu . a_s . b_s . \sqrt{2gh_1} \quad (12)$$

where: Q_s = discharge (m^3/sec), μ = discharge coefficient (given: 0.8), a_s = height of the opening (m), b_s = width of opening (m), g = gravitational acceleration (9.8 m/ sec^2), and h_1 = hydraulic energy at the opening (m).

$$I + \frac{S_1}{\Delta t} - \frac{O_1}{2} = \frac{S_2}{\Delta t} + \frac{O_2}{2}$$

where: I = Inflow (m^3/sec), S_1 = Storage at time 1, S_2 = Storage at time 2, Δt = routing interval (hours), O_1 = Outflow at time 1 (m^3/sec), O_2 = Outflow at time 2 (m^3/sec).

4 Case Study

To demonstrate the procedure, this study was applied in the Batujai Dam in Penujak Village, Central Lombok Regency, West Nusa Tenggara Province, Indonesia, as shown in Fig. 3.

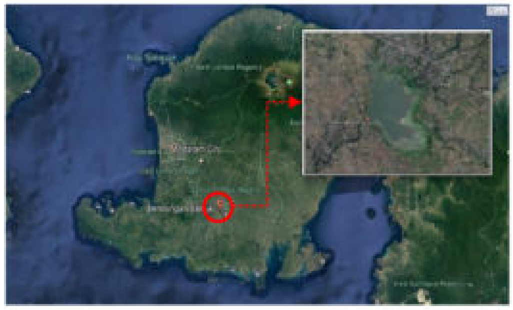

Fig. 3. Study location

4.1 Step: 1 Preparation

In this study, 23 years of maximum daily rainfall data from 1998 to 2020 from Pengadang Rain Stations were used as local historical data and Global Climate Change data from 1998 to 2100 were downloaded from the IPCC website. The data are: X1 = mean 2m wind speed (m/s), X2 = evaporation (mm/day), X3 = precipitation (mm/day), X4 = screen (2m) temperature (°C), X5 = screen spec. humidity (kg/kg), X6 = sea level pressure (hPa), X7 = surface temperature (°C), X8 = solar flux at surface (W/m^2), X9 = surface pressure (hPa).

4.2 Step: 2 Standard Statistical Screening

From the calculations of the RAPS test of the annual rainfall data from the Pengadang station, it is found that these are consistent.

The next step is to select the three most suitable GCM variables, which are air temperature (X4), specific air humidity (X5), and air temperature at the Earth's surface (X7). The three GCM variables are then considered as independent variables in the multiple linear regression model for modelling local rainfall due to climate change.

4.3 Step: 3 Climate Change Modelling

The multiple linear regression model is expressed as Y = 0.453 + 0.44 X4 + 0.253 X5 - 0.81 X7. The proportion of the variance for a dependent variable that can be explained by the variables is quite high, being approximately 80.7%.

The local rainfall data due to climate change are generated using the regression model. The results are shown in Fig. 4.

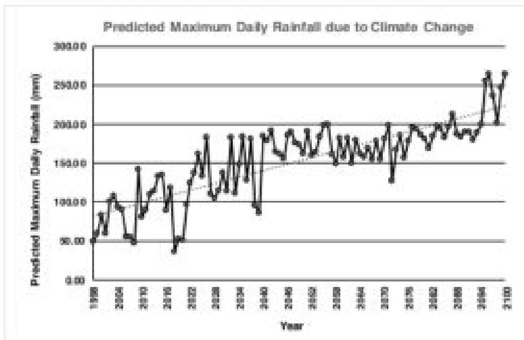

Fig. 4. Predicted local maximum daily rainfall due to climate change

Figure 4 shows that the predicted mean local maximum daily rainfall in the area of study has an increasing trend. The next step is to look for the 1000-year return period of rainfall and the 1000-year return period of flooding.

4.4 Step: 4 Hydrological Frequency Analysis

It is found that the statistical distribution of the data is a 2-parameter exponential. The amount of the 1000-year return period of a rainstorm is 797.2 mm. This amount is used to simulate the inflow of the Batujai Dam using the Nakayasu Hydrograph. From the simulation, it is obtained that the peak of the 1000-year return period of flooding that enters the Batujai reservoir is 1833.538 m^3/s.

4.5 Step 5: Hydraulic Analysis for overtopping

In this step, flood routing simulation through a gated spillway is conducted to obtain whether the 1000-year return period of flooding overtops the dam or not, and how to arrange the gates of the spillway to avoid overtopping. The results of the simulation using eq. (1) to eq. (13) are presented in Table 1.

Table 1. Results of flood routing simulation

Simulation: Routing output for Batujai Reservoir			
Q-inflow	1833.54	m^3/sec	
Q-outflow	875.24	m^3/sec	
Reduction - Q	52.26	%	4 x @ 11 meters
opening (m)			
Gate #1	Gate #2	Gate #3	Gate #4
1.00	1.20	1.20	1.00

Table 1 shows that when the amount of the 1000-year period of flooding of 1833.54 m^3/s comes into the reservoir, the four gates have to be opened by 1.0 m, 1.2 m, 1.2 m, and 1.0 m respectively to avoid overtopping of the dam.

5 Conclusion

Based on the results of the analysis, the following conclusions can be drawn:

1) The proposed procedure can be reasonably applied for the evaluation of dam safety based on the impact of climate change;
2) The study successfully developed a local rainstorm model affected by climate change;
3) The amount of the 1000-year return period of flooding due to climate change is 1833.54 m^3/s; and
4) The opening heights of the four spillway gates required to secure the dam are 1.0 m, 1.2 m, 1.2 m, and 1.0 m respectively.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10