Research article

Development of Indexes to Evaluate the Effectiveness of Low Water Level Control in Irrigation Ponds – A Case Study of Irrigation Ponds in Tottori, Japan

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Abstract The spillways of most irrigation ponds in Japan need additional repairs to safely pass the 200-year flood event, which is the design criteria set by the government. At the same time, low water level control (LWLC) in irrigation ponds is currently recognized as one of the countermeasures for mitigating floods and avoiding dam collapse. However, the pond managers do not know to what extent the water level of the pond should be lowered. In this study, the flood mitigation function of LWLC in each pond was quantitatively evaluated, and indexes were proposed to determine whether it is worth practicing LWLC in each pond or whether the spillway needs to be repaired. Seventy-two irrigation ponds in Tottori prefecture were selected for analysis and the water balance of each pond was calculated with 10-, 50-, and 200-year rainfall events. The results showed that half of the ponds cannot safely cope with a 10-year rainfall event even if they are empty prior to the event. The ratio of the catchment area to water surface area at full capacity in such ponds often exceeds 50 to 1. On the other hand, ponds with a catchment to water surface area ratio of less than 50 show a high flood mitigation function due to LWLC. In addition to this, priority for repair work can be evaluated in terms of whether the spillway can pass peak runoff or not, because the size and the type of spillway are different among ponds. The effectiveness of LWLC can be evaluated in terms of the ability of the spillway to pass peak runoff from the catchment when the pond is full. The three indicators, namely, the ratio of catchment area to water surface area at full capacity, difference of peak flood reduction rate, and peak discharge ratio, are simple and useful indexes for LWLC to prevent dam collapse.

Keywords flood mitigation, spillway, water management, water balance

INTRODUCTION

In recent years, unexpected, short, and heavy rain has been increasing in Japan. Especially in 2021 one of the strongest rainfall events occurred at many meteorological observing stations in Japan. Some irrigation ponds have been damaged and broken down due to heavy rainfall. For instance, Hutago Pond in Tottori was broken down because of a heavy rainfall event in July 2021. An irrigation pond is generally constructed to irrigate agricultural water which is mainly used for the paddy rice fields if there is no river near the irrigated district. The number of irrigation ponds in Japan is about 150 thousand and most of them are constructed over 100 years ago (MAFF). The spillways of some irrigation ponds in Japan are too small and require repairs to safely pass the 200-year flood event which means the probability of flood occurrence, is once per 200 years, which is the design criteria set by the Japanese government (MAFF, 2015). However, due to the large number of ponds and the high repair costs, extensive time will be required to repair the spillways of every irrigation pond.

Therefore, the low water level control (LWLC) was suggested as one of the low-cost and non-structural solutions to prevent dam collapse. However, the water control entirely depends on the manager's experience and the municipality doesn't have clear guidelines or indicators on the amount of water that should be released in advance. Moreover, no assessment of the flooding mitigation function of irrigation ponds when LWLC is practiced has been done.

OBJECTIVES

In this study, the flood mitigation function of LWLC in irrigation ponds was quantitatively evaluated, and indexes were proposed to determine whether it is worth practicing LWLC in each pond or whether the spillway needs to be repaired. This study was conducted on the irrigation ponds certified as priority irrigation ponds for disaster prevention in Tottori Prefecture, Japan.

METHODOLOGY

Study Area

In this study, the water levels of the irrigation ponds in Tottori were estimated using a water balance model under the different heavy rainfall events at each rainfall station. The number of irrigation ponds in Tottori is around 950 (Tottori Prefecture, 2022). Of these 72 irrigation ponds were selected for analysis. Figure 1 shows selected 72 irrigation ponds that are indicated as black spots. Most of them were constructed in mountainous areas and store water only from the runoff from the catchment areas. Therefore, when LWLC is practiced, the farmers will take on the risk increase that the storage water would be dried up. They are located near residences which could be damaged if the ponds are flooded. Besides, all of them cannot safely pass the peak runoff with a 200-year rainfall event, which is a design criterion set by the government. Table 1 shows the features of irrigation ponds in the study area. The irrigation ponds are classified by storage capacity.

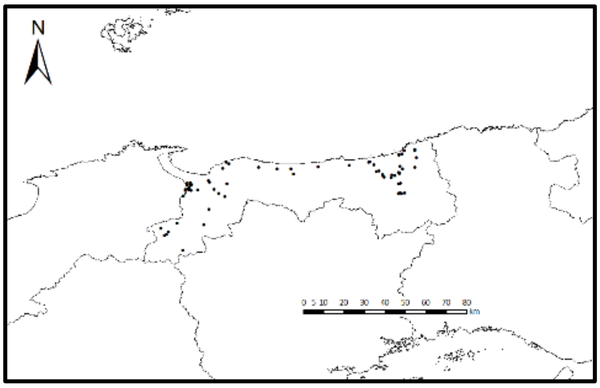

Fig. 1 Selected irrigation ponds in Tottori

Location source: Tottori web map

The distribution of the storage capacities is biased to a small, less than 10,000 m^3. Of the 72 selected irrigation ponds, the number of the small-sized ones is 55. Those with a storage capacity of less than 3,000 m^3 account for 36. The number of beneficiary farmers in these irrigation ponds is quite small, and some of them are often not well maintained. The capacity of medium-sized irrigation ponds ranges from 10,000 m^3 to 100,000 m^3. The number of medium irrigation ponds is 15. The capacity of large-sized irrigation ponds is more than 100,000 m^3 and there are two such irrigation ponds in the study area, with capacities of 101,000 m^3 and 120,000 m^3. The number of beneficiary farmers is large, and downstream damage due to a potential dam collapse on these ponds would be enormous.

Table 1 Features of irrigation ponds in the study area

Irrigation Ponds	Capacity (m^3)	Numbers of ponds
Small	<10,000 m^3	55
Medium	10,000~100,000 m^3	15
Large	> 100,000 m^3	2

Water Balance Analysis

Outline of Irrigation Pond Water Balance Model

The irrigation pond water balance model was developed by referring to the Guidance of flood control function intensify of irrigation ponds (MAFF, 2018). The difference points are estimation formulas of coefficient K for the storage function method, effective rainfall intensity, outflow water estimation from the spillway, and height-volume curve of the irrigation pond (H-V curve).

To determine and compare the effectiveness of LWLC from the aspect of the return period, 10-year, 50-year, and 200-year return period hourly and daily rainfall was estimated by Iwai formula and Talbot formula. The hourly and daily return period was estimated at 9 stations such as Iwai, Tottori, Shikano, Kurayoshi, Shiotsu, Daisen, Ebi, Yonago, and Chaya. The rainfall duration was assumed to be 3 hours, and the rainfall distribution was assumed to have a rainfall intensity peak in the latter half of the rainfall. The inflow of water to the ponds is estimated by the storage function method. It needs to estimate coefficient K, p, and effective rainfall intensity. K is referred from Nagai et al. (1987). p is set to 0.6 as Sugiyama et al. (1988) suggested. Effective rainfall is estimated to multiply rainfall intensity by the theoretical peak outflow rate referred from the internal survey documents of Tottori Prefecture. Only the outflow from the pond is considered for the outflow from the spillway of the pond. In this study, the outflow from intake taps is not considered because it is negligibly small compared to that from the discharge from the spillway. In addition to this, due to the assumption of short and heavy rainfall, evaporation and infiltration from the irrigation pond are also ignored (Shimizu et al, 2016). To estimate the amount of released water, the relationship between the water level and the storage capacity of a pond is required, but these data are not available. Therefore, in this study, a simplified method is employed to make an H-V curve with the assumption that the shape of the irrigation pond is approximated as frustum (Tanakamaru et al., 2015).

Validation

To validate the results of the water balance model, the actual water level fluctuation was observed at 3 irrigation ponds in Tottori using the heavy rainfall data at 2 rainfall stations from 7th July to 9th July 2021.

Indexes Proposal and Classification

In the analysis, the extra height of each irrigation pond was defined as the height of the spillway in case of seepage collapse of the irrigation pond. There are three main reasons for dam collapse following heavy rainfall, namely overflow erosion, sliding, and seepage collapse. In the case of seepage collapse, internal erosion occurs from the upstream slope near the full water level (Hori et al., 2002). Moreover, the interval of intake taps is supposed to be 0.5 m and release water level 0.5 m each, and estimate released water previously that peak water level is less than the height of the spillway at each irrigation pond. To calculate how many meters of water level should be lowered, storage water was released corresponding to 0.5m each from full water level until the peak water level in case the irrigation pond conducts LWLC would not over the height of the spillway. The water level reduction rate (R) can be expressed as a ratio of released water level and water storage depth (the height difference between the bottom and full water level) shown in Eq. 1.

$$R = \frac{D}{H} \tag{1}$$

Where R is the water level reduction rate, D is the depth after the water is released from the full water level, and H is the water storage depth.

As follows, we proposed 3 indicators that are useful to classify the irrigation ponds based on the calculation from the data of irrigation ponds and rainfall data. Catchment to storage ratio (CSR) is one of the indexes that can be calculated to divide the catchment area with the storage area (full surface water area) of each irrigation pond shown in Eq. 2.

$$A_r = \frac{A}{S_1} \tag{2}$$

Where A_r is the catchment to storage ratio, A is the catchment area, and S_1 is the full water surface area.

Design discharge to peak discharge ratio (DPR) is the index that can be calculated to divide the design discharge of the spillway (Q_{out}) by peak discharge (Q_p) when the water level is full of each irrigation pond shown as Eq. 3.

$$D = \frac{Q_{out}}{Q_p} \tag{3}$$

Where D is the design discharge to peak discharge ratio, Q_{out} is the design discharge of the spillway, and Q_p is peak discharge when the water level is full.

In addition to this, to understand how much water discharge could be reduced by conducting LWLC, the flood peak mitigation rate was calculated when the initial water level was 0.5m lower than the full water level. The difference in flood peak reduction ratio (PRR_d) is expressed as the ratio of the difference in peak discharges with and without LWLC implementation to the peak runoff from the catchment area shown in Eq. 4.

$$Q_d = \frac{Q_p - Q_p'}{Q_n} \tag{4}$$

Where Q_d (%) is a difference in flood peak reduction ratio. Q_p is the peak water flow rate when the irrigation pond is full, Q_p' is the peak water flow rate when the irrigation pond conducts LWLC, and Q_n is the peak inflow water flow rate from the catchment area.

RESULTS AND DISCUSSIONS

Validation

The difference between the estimated peak water levels and observed ones of the irrigation ponds are around 10 cm, 1 cm, and 13 cm. Figure 2 shows observed and simulated water level data at the Kanaguri irrigation pond. The irrigation pond is located in the middle of Tottori prefecture. The peak water level difference is 13cm at Kanaguri irrigation pond.

The observed water level until the peak water level seems to be lower than the calculated peak water level. It is considered that because of the degree of soil saturation. If the soil is dried, the outflow rate is affected to be lower inevitably.

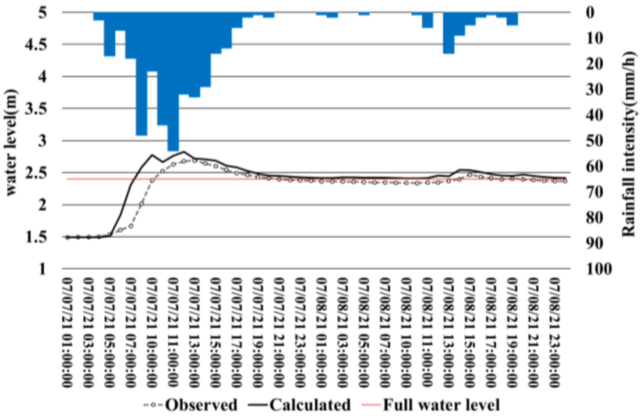

Fig. 2 Comparison with observed water level and calculated water level

Relationship between DPR, CSR, and WLRR

Figure 3 shows the relationship between design discharge to peak discharge ratio (DPR), catchment to storage ratio (CSR), and water level reduction rate (WLRR) in the case of 10-year rainfall. From Fig. 3, half of the irrigation ponds need to release water level until empty because to spillway size is comparatively small to consider their catchment area. Especially under the conditions that the DPR is smaller than 1 and CSR is relatively higher (>50), WLRR gets almost 100 % which means if the water level is released to empty, the theoretical peak water level would exceed the height of the spillway of each irrigation pond. It can be considered that the effectiveness of LWLC has a strong relationship with the inflow of water from the catchment area while it has almost no relationship with the size of the spillway, but the priority of LWLC for preventing dam collapse can be judged by DPR.

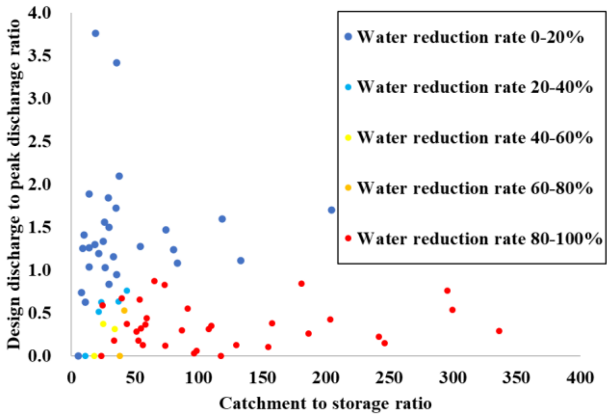

Fig. 3 Relationship between DPR, CSR, and WLRR in case of a 10-year return period

Relationship between CSR and PRR_d

Figure 4 shows the relationship between CSR and the difference in flood peak reduction ratio (PRR_d). The figure shows the difference when the irrigation pond is full and, the irrigation pond has released storage water corresponding to 0.5m from the full water level. If the CSR is under 50, PRR_d tends to be higher. However, in the case of heavy rainfall, PRR_d becomes lower. Therefore, it needs to consider the PRR_d and rainfall intensity carefully when the CSR is under 50. Tanakamaru. et al (2019) selected 1,902 irrigation ponds with a large effect on flood mitigation by water release in advance at Awaji district in Hyogo prefecture, Japan. The effectiveness of LWLC was calculated by the irrigation pond water balance model. After that, the outflow during the flood period was estimated at each irrigation pond. As a result, the study showed that if normalized storage becomes higher, the effectiveness of LWLC will be higher. However, it needs to be careful when calculating the flood control function using normalized storage since the reliability of capacity is low.

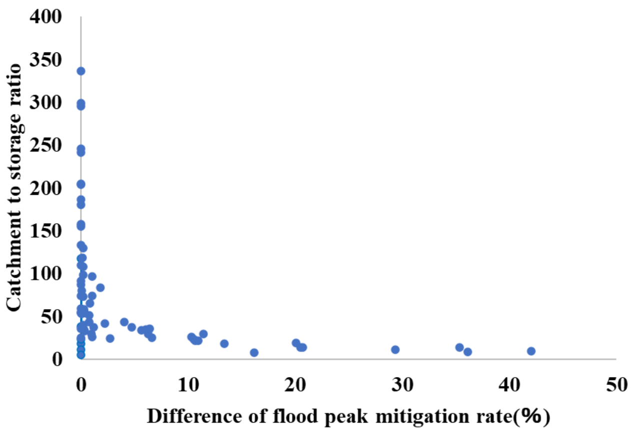

Fig. 4 Relationship between CSR and PRR_d in case of a 10-year return period

Classification of Irrigation Ponds

Based on the above results and discussion, studied irrigation ponds are classified. We proposed 3 classifications as groups A, B, and C. Group A is characterized by lower CSR (<50) and lower DPR (<1). Irrigation ponds categorized in group A are recommended to implement LWLC or rehabilitate the spillway immediately due to the high risk of dam collapse. Group B is characterized by lower CSR (<50) and sufficient DPR (>1). It is recommended to implement LWLC to prevent dam collapse and the overflow of the downstream canal even if the pond is safe. Group C is characterized by higher CSR (>50). It is recommended to rehabilitate the spillway immediately due to the high risk of dam collapse. Thus, it is of no use in implementing LWLC due to its quite small effect ($PRR_d \fallingdotseq 0$). The number of irrigation ponds classified as groups A, B, and C is shown in Table 2.

Table 2 Classification of irrigation ponds

Group	10-year return period rainfall	50-year return period rainfall	200-year return period rainfall
A	20	28	31
B	17	9	6
C	35	35	35

CONCLUSION

There are a lot of irrigation ponds in Japan, and some of these do not have large enough spillways to safely pass the 200-year return period. In this study, we proposed a method to classify irrigation ponds concisely using relatively easy-access data. As a result of calculation, even if low water level control is implemented, some of these have very little effectiveness against flood mitigation. In the case of the ponds with high irrigation use frequency, i.e., high dependence, immediate rehabilitation of spillways should be considered, while in the case of the ponds with very low irrigation use frequency, the abolition of irrigation ponds should be considered to prevent flood damage in case of heavy rainfall events.

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