Research article

Development of a Simplified Water Storage Operation Curve at Irrigation Ponds for Flood Mitigation -A Case from Tamatsu District in Tottori, Japan-

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Abstract In recent years, Japan has been receiving heavy rainfall, and the flooding of irrigation ponds is a major concern. The irrigation ponds in the Tamatsu district in Tottori, Japan, are small and overflow easily during heavy rainfall. Pre-releasing water from these ponds was suggested as a simple, safe, and low-cost solution. However, local governments have prepared no clear guidelines or instructions on the amount of water that should be pre-released or regarding the desired water level after pre-release. Currently, the water volume that is pre-released from the ponds depends entirely on the pond manager's experience. To mitigate this situation, we first observed the water level and discharge of the irrigation ponds and collected rainfall data from the nearest meteorological station. We then assessed the water storage operations of pond managers at three irrigation ponds in the Tamatsu district in 2018. Subsequently, we prepared the height-volume curve (H-V curve) of each pond by level survey and 3D image analysis, and a cumulative water demand curve based on the volume of water released from each pond during no rainfall periods. Considering the cumulative water demand curve and the height of the intake tap of each pond, we prepared water storage operation curves for the irrigation ponds. This will assist pond managers to determine the appropriate water level reduction during heavy rainfall events without causing an irrigation water shortage. We confirmed the extent to which the pond management curve could cope with rainfall. Using the developed water storage operation curve, managers can easily understand the drop of the water level in the pond. Moreover, the curves are easily constructed from the information on the beneficial area, precipitation, water level fluctuations of the irrigation pond during dry days, and the H-V curves of ponds. Finally, the effectiveness of the water storage operation curve is evaluated for different rainfall events.

Keywords flood mitigation, disaster prevention, irrigation pond, pre-release of water

INTRODUCTION

In recent years, disasters caused by heavy rain have increased throughout Japan. The heavy rains in July 2018 caused heavy damage in western Japan, and in Hiroshima Prefecture, the pond broke down. The pond is small and is in the study area, Tamatsu district, and the possibility of flooding during heavy rain increases. Disaster prevention and mitigation measures for ponds, therefore, are urgently needed. The government, after conducting an emergency inspection of ponds nationwide, took measures such as selecting ponds for disaster prevention, preparing pond maps, developing an emergency communication system, creating inundation potential area maps, and creating hazard maps (MAFF, 2018). The government also suggested pre-release in preparation for heavy rainfall by lowering the water level of the pond in advance and providing sufficient storage capacity. The spillways of most irrigation ponds in Japan require repairs to safely pass the probability of flood occurrence, once every 200 years, which is the design criteria set by the Japanese government (MAFF, 2015). Because of the large number of ponds and the high repair costs, extensive time, however, will be required to repair the spillways of every irrigation pond. We, therefore, developed a low-cost pre-release of water. The advantage is that there is no need to build a special facility and no funding is required, but there is no specific guideline for the pre-release amount, which depends on the experience of the manager.

OBJECTIVE

In this study, we evaluated water storage management during heavy rains in July and September 2018 and created a water storage operation curve to guide the pre-discharge at three ponds in Tamatsu district of Tottori City in 2018. Furthermore, we investigated how much rainfall the ponds could withstand without flooding when the water level was controlled by the water storage operation curve.

METHODOLOGY

Study Area

Figure 1 shows an overview of the study area. There are six irrigation ponds in the study area, Tamatsu District, Tottori City, Tottori prefecture, Japan. There are three ponds currently functioning for water intake management, namely the Yutani, Shinjoji, and Daigo irrigation ponds. These ponds are stored only by runoff from their basins. A canal connects the Yutani and Shinjoji ponds to the Daigo pond and can be switched between flowing into the Daigo pond and flowing into the river by operating the weir. Table 1 shows the specification of each pond. The main crop is paddy, and the total paddy area is about 6 ha. In this area, there is a rule that water is drawn during the daytime, and each farmer freely takes water from the ponds. The pond manager performs water pond maintenance and the pre-release of water except for water intake.

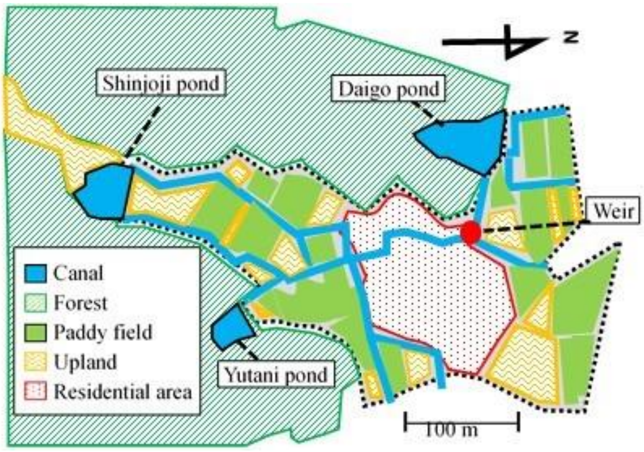

Fig. 1 Study area

Table 1 Information of irrigation ponds

	Yutani	Shinjoji	Daigo
Height of dike（m）	4	6	4
Length of dike（m）	50	88	123
Storage（10^3 m^3）	3.8	19.0	18.0
Catchment area（km^2）	0.08	0.44	0.05
Width of spillway（m）	0.8	5.8	0.5
Height of spillway（m）	0.5	1.2	0.5

Hydrological Observation

To clarify the water level fluctuation of the pond, a pressure-type self-recording water level gauge was installed at the bottom and water surface of the pond, and observations were made hourly. Using a small UAV, the aerial view of the pond was created and a three-dimensional image was created based on the image. The water area for each pond's water level was calculated to create a water level-volume curve. From the water level of the pond and the water level-volume curve, the capacity of the pond was calculated. To clarify the intake status and the operation status of the weir, a capacitance-type self-recording water level gauge was installed in the canal, and the water level was observed at 5-minute intervals. The observation period was from late May to late September 2018, and the mid-drainage period for paddy rice fields is from late June to mid-July. Precipitation data were obtained from the Japan Meteorological Agency (Tottori Observatory).

Estimation of Pre-release of Water

As a method of quantitatively indicating the pre-release rate, we estimated the average daily water requirement during the irrigation period. This was based on the amount of storage change of each pond during the continuous drought period (14 days from August 1 to 14) with precipitation of less than 5 mm/d. Using the average daily requirement, the cumulative required water volume was calculated retrospectively to create a pond management curve. The two types of management curves for each pond are shown based on the land-use status of the target area in 2018 and the assumption that all the farmland in the area is paddy rice, that is, with maximum water demand.

Estimation of Water Storage Operation Curve

Flood arrival times in 60-minute rainfall events were calculated for different probability year using the formula of Talbot, Kadoya–Fukushima, as shown in Eqs. (1) ~ (3), and the water level rise from full and from each intake tap position was calculated. From the result, if the water level is maintained according to the water storage operation curve, it is determined at which probability year the rainfall will not exceed the top of the embankment until 60 minutes of rainfall.

To simulate the water balance and water level of the pond under heavy rainfall, 60-minute rainfall events at return periods of 10, 20, 30, 40, 50, 60, 70, 100, and 200 years were estimated using the Iwai method.

$$I = \frac{a}{t+b} \tag{1}$$

$$t_p = C \cdot A^{0.22} \cdot r_e^{-0.35} \tag{2}$$

$$r_e = f_p \cdot I \tag{3}$$

where I is the rainfall intensity (mm/h), t is the duration of rainfall (min), a and b are the constant parameters related to the meteorological conditions, t_p is the peak flow arrival time (min), C is the parameter related to the land-use conditions, A is the catchment area (km^2), r_e is the average effective rainfall intensity (mm/h), and f_p is the peak runoff coefficient.

The rational equation to determine the peak discharge from the catchment area and average effective rainfall intensity are expressed in Eq. (4).

$$Q = \frac{1}{3.6} \cdot r_e \cdot A \tag{4}$$

The discharge from the spillway was calculated using rectangular weir formulas according to the water level. The formulas used in the calculation are expressed in Eq. (5).

$$Q_s = C_s \cdot b \cdot H^{\frac{3}{2}} \tag{5}$$

where Q_s is the discharge from the spillway, C_s is the discharge coefficient for the rectangular weir, b is the width of the spillway (m), H is the water level of the spillway (m). Calculations continued until the water level reached the top of the spillway.

The water balance and increase rate of the water level of the pond were calculated using the peak runoff as the inflow element and the discharges from the spillway. Due to the assumption of short and heavy rainfall, evaporation and infiltration from the pond were ignored (Shimizu et al., 2016).

The created water storage operation curve of each pond is evaluated for the different rainfall events. In our analysis, the extra height of each pond was defined as the height of the spillway in case of seepage collapse of the dike. There are three main reasons for damage to irrigation ponds by heavy rainfall, namely overflow erosion, sliding, and seepage failure. In the case of seepage failure, internal erosion occurs from the upstream slope near the full water level. In the case of sliding, a failure starts at the toe of an embankment. Overflow failure occurs at the crest above the gut of the foundation (Hori et al., 2002). We, therefore, set the upper limit to the height of the spillway.

RESULTS AND DISCUSSION

Evaluation of Water Storage Management during Heavy Rain

Figure 2 shows the water level fluctuation and precipitation of each pond. It is probable that pre-discharge was not performed at Shinjoji and Daigo ponds because the water level did not drop before the heavy rain. Pre-discharge was not performed at the Shinjoji pond because the manager judged there was no necessity to perform pre-discharge because the spillway of the Shinjoji pond was large enough, as shown in Table 1. Pre-discharge was not performed in the Daigo pond because the water storage rate of the pond was low, about 60%, and the weir was operated so that water from the Yutani and Shinjoji Ponds did not enter the pond. Furthermore, the Daigo pond has a larger water storage capacity for the catchment area than the Yutani and Shinjoji ponds. For a detailed description, Fig. 3 shows the water level fluctuation of the Yutani pond during heavy rains in July (308 mm) and September (180 mm). Since the water level dropped before the heavy rainfall, it was confirmed that the pre-discharge was performed. The water level of the Yutani pond did not rise more than 30 cm from the full water level, the peak of the water level was reduced, and the effectiveness of the pre-discharge was reduced.

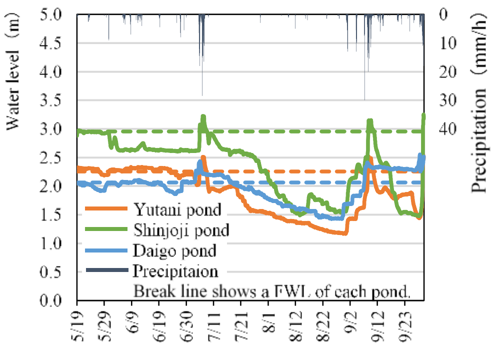

Fig. 2 Water level fluctuation at 3 ponds

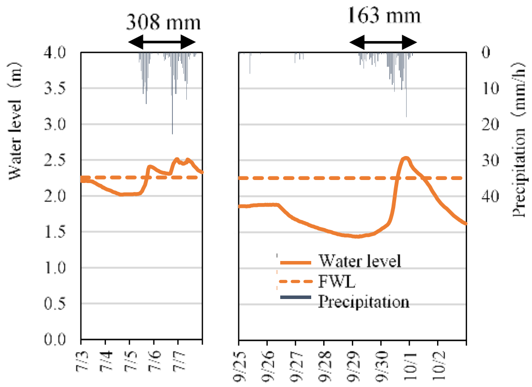

Fig. 3 Water level fluctuation at Yutani pond

Creating Water Storage Operation Curve

Table 2 shows the daily irrigation requirement based on the paddy rice area in 2018 and the daily irrigation requirement assuming that paddy rice is grown in all the fields. Figure 4 (a) ~ (c) shows the water storage operation curves of each pond. The break-line indicates the amount of water stored with a full water level in each pond. When the water storage operation curve falls below the dotted line, pre-release is possible. The dotted line indicates the amount of water storage corresponding to the position of the intake tap in each pond, and the water level can be lowered to the position of the intake tap by opening the intake tap immediately above the water storage operation curve at the time of pre-release. Water storage operation curves created from the land-use situation in 2018 show that the water storage capacity of the Yutani and Daigo ponds is always lower than the water storage capacity of the irrigation pond during the irrigation period. It was shown that pre-release was possible. Regarding the water storage operation curve, assuming the maximum water demand in the area, the management curve of the Daigo pond (Fig. 4 (c)) has fallen below the full storage volume of the pond since June 13th. It was shown that there was room for pre-release from the stage. However, in the management curves of the Yutani (Fig. 4 (a)) and Shinjoji ponds (Fig. 4 (b)), there is no room for water storage until the end of the irrigation season because of the higher ratio of upland fields and fallow land in the beneficiary areas at the Yutani and Shinjoji ponds. Because paddy rice fields are usually irrigated, but upland crop fields are rain-fed, if the ratio of the paddy rice fields increased, the irrigation water requirement also increased accordingly. The reservoir manager can open the intake tap based on this curve to keep the water level in the vicinity of the opened intake tap position and prepare for heavy rainfall.

Table 2 Beneficial area

Name of pond		Yutani	Shinjoji	Daigo
Paddy rice area (ha)	2018	0.15	2.64	2.50
	Maximum paddy rice area	1.84	3.95	2.90
Average water demand per day (m^3/d)	2018	15.56	391.95	206.74
	Maximum water demand	187.15	586.30	324.04

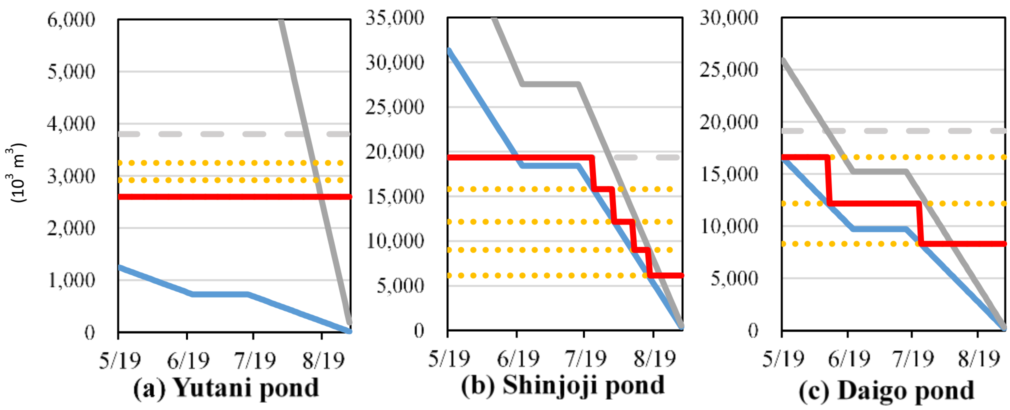

Fig. 4 Water-storage operation curve (red line)

Evaluation of the Effectiveness of the Water Storage Operation Curve

We investigated how much rainfall each pond could withstand without flooding when the water level was controlled by the water storage operation curve. Table 3 summarizes the simulation results. In the Shinjoji pond, the water level did not exceed the upper limit in any rainfall events because the spillway is large enough to pass the flood. In the Yutani pond, the rainfall over the 10-year probability 60-minute rainfall at the full water level exceeds the upper limit. When the water level, however, is lowered to the height of the intake tap No.1, the pond withstands flooding with a 50-year probability 60-minute rainfall. The Daigo pond cannot withstand any rainfall at the full water level or when the water level is at the height of water intake tap No.1. The pond can withstand a 40-year probability 60-minute rainfall if the water level is lowered to the height of water intake tap No.2. Since the water level in the ponds cannot be lowered in a short period of time by opening the intake tap with a small diameter, it is necessary to constantly lower the water level of the ponds or install an emergency discharge device to increase the ability to lower the water level.

Table 3 Effectiveness of water storage operation curve

Yutani pond				
Return period (y)	Full water level	Intake tap No.1	Intake tap No.2	Intake tap No.3
10	○	○	○	○
20	×	○	○	○
30	×	○	○	○
40	×	○	○	○
50	×	○	○	○
60	×	×	○	○
70	×	×	○	○
100	×	×	○	○
200	×	×	×	×
Daigo pond				
Return period (y)	Full water level	Intake tap No.1	Intake tap No.2	Intake tap No.3
10	×	×	○	○
20	×	×	○	○
30	×	×	○	○
40	×	×	○	○
50	×	×	×	○
60	×	×	×	○
70	×	×	×	○
100	×	×	×	○
200	×	×	×	×

○: *water level does not exceed the upper limit*
×: *water level exceeds the upper limit*

CONCLUSION

The pre-discharge of ponds is a simple, safe, and cost-effective method against heavy rainfall in case the spillway is not constructed, but the pond manager uncertain to what extent the water level of the pond can be lowered. Given this, a water storage operation curve was developed by considering paddy rice irrigation, and its effectiveness was evaluated based on the probability of rainfall for different years. The developed method is applicable to any ponds and the created curve makes it easy for pond managers to visually understand how much to lower the water level at what time of irrigation period. Further refinement of the curve is required by more accurate hydrological observation. Also, not only short rainfall events but longer rainfall events such as one to two days long should be considered.

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