Research article

Feasibility of Low Water Level Management in Irrigation Ponds: Focusing on Baseflow and Water Storage Recovery Periods in Oro River Basin, Tottori

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Received 30 December 2024 Accepted 10 June 2025 (*Corresponding Author)

Abstract Japan has about 150,000 irrigation ponds, primarily located in areas with low rainfall and regions lacking nearby rivers. These ponds primarily supply irrigation water for paddy fields and serve as year-round sources of domestic and fire-fighting water. In recent years, Japan has experienced an intensification and increase in the frequency of heavy rainfall events from summer to autumn (July to September), leading to an increase in the number of water-related disasters. These irrigation ponds have also suffered an increase in disasters caused by heavy rainfall. To address this issue, one of the flood control methods for irrigation ponds is "low-water-level management". By maintaining lower water levels, it is expected that the risks of dike breaches due to overtopping will be minimized, and peak flow from the spillway will also be mitigated. However, implementing low-water-level management may lead to the potential risk of not being able to secure a sufficient water supply for irrigation. This study evaluated the feasibility of implementing low-water-level management across 52 irrigation ponds in the Oro River Basin in Tottori City, Tottori Prefecture. We calculated the recovery period for water storage using only baseflow to determine whether it is possible to maintain low water levels without compromising the necessary water supply. The results indicate that low-water-level management can be implemented in many ponds without significant concerns regarding water availability, supporting its potential as a flood control measure.

Keywords low-water level management, baseflow, hydrological observation, flood mitigation

INTRODUCTION

Japan's landscape is dotted with approximately 150,000 irrigation ponds, primarily in areas with low precipitation or lacking large rivers. These ponds are mainly used for irrigating rice paddies in the region. Some ponds also serve other roles, such as irrigating upland crops and fruit trees, providing domestic water supply, and preventing fires in downstream villages.

The increasing intensity of heavy rain, a direct consequence of climate change, has wreaked havoc on Japan's irrigation ponds in recent years. The Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF) reports that from 2013 to 2023 (MAFF 2024), heavy rains have damaged a staggering 6,040 irrigation ponds, with 320 collapsing under the onslaught.

Failures in irrigation ponds caused by heavy rainfall can be broadly classified into three categories: seepage, embankment sliding, and overflow (Hori et al., 2002). Overflow failure occurs when the water level in an irrigation pond rises rapidly during heavy rainfall, causing water to overflow the embankment and leading to erosion. The risk of overflow failure is expected to increase with an increase in heavy rainfall events owing to global warming (Mihara et al., 2023).

As a preventative method to mitigate the risk of overflow failure, the Japanese government has set a design standard requiring irrigation pond spillways to safely pass a 200-year flood event. However, renovating a large number of irrigation ponds is time-consuming and costly. To address this issue, a low-cost emergency discharge device was developed to prevent or mitigate flooding (Shimizu et al., 2016).

In recent years, low-water-level management has attracted attention as a cost-effective and efficient method for mitigating the risk of overflow failure. This approach includes two main strategies: (1) pre-release before rainfall, where water levels are temporarily lowered in anticipation of heavy rainfall, and (2) scheduled water level control, where water levels are managed at specific values according to a predefined plan for different periods of time. Both methods aim to enhance the effectiveness of irrigation ponds in terms of flood mitigation by maintaining an adequate capacity to accommodate heavy rainfall.

However, the primary function of irrigation ponds is to maximize water storage. Implementing low-water-level management would defeat the original purpose of irrigation ponds and may lead to insufficient water availability for irrigation. Additionally, irrigation managers often hesitate to adopt pre-release strategies before rainfall because of uncertainty regarding the time required for water levels to return to their original state after release.

OBJECTIVE

This study aimed to quantify the monthly baseflow from hydrological observations at two irrigation ponds in the Oro River Basin, Tottori, and to estimate the water storage recovery period in 52 irrigation ponds using observed baseflow rates.

METHODOLOGY

Target Area

In this study, we selected irrigation ponds in the Oro River Basin in Tottori City. Various efforts have been made for watershed flood control in the area because flood damage due to heavy rainfall has been frequent in the past. Most of these irrigation ponds are created by filling valleys. Their total storage volume ranges from 200 to 260,000 m^3, catchment area from 0.004 to 1.483 km^2, and full water area from 60 to 40,000 m^2. Data for each irrigation pond were obtained from the irrigation pond registry owned by Tottori Prefecture.

In this region, the irrigation season for paddy fields is from May to September (Harasawa et al., 2023; Shimizu et al.,2015). This season coincides with the season (August and September) when heavy rainfall events such as typhoons are most frequent.

Hydrological Observation

Precipitation: Precipitation was measured at the Tottori Observatory by the Japan Meteorological Agency (JMA). Data were collected from the Internet (JMA, 2024). The collection interval was 1 h, and the period was from August 1, 2023, to December 31, 2023.

Runoff volume: The runoff volume from the catchment area into the irrigation ponds must be determined. However, directly capturing the discharge from irrigation ponds in the catchment area is difficult. Therefore, we selected irrigation ponds with few water withdrawal operations and relatively stable near-full water levels and measured the overflow from the spillways of these irrigation ponds by flow observation in the canal immediately below the irrigation ponds and assumed that this was the discharge from the catchment area into each irrigation pond. Table 1 shows the characteristics of the irrigation ponds where hydrological observations were made.

Table 1 Specifications of the ponds where hydrological observations were conducted

	Storage capacity (m^3)	Catchment area (km^2)	Water area (m^2)
Pond 1	3,100	0.131	2,400
Pond 2	3,200	0.029	800

We conducted water level and flow observations in the downstream canal of two irrigation ponds. Water levels were observed at 15 min intervals using a capacitance water level meter. The observation period was from August 1 to December 31, 2023. The average flow velocity at different water levels was measured five times in both irrigation ponds using a current meter. The values were multiplied by the cross-sectional area of the canal to obtain the flow rate. A water level-flow curve was prepared from the canal water level and flow rate through flow observations.

The lowest stable water level for each month was extracted from the observed water levels. The values were substituted into the water level-flow curve, and the calculated flow rate was used as the base-flow rate. Eq. (1) was used to convert the flow rate into the baseflow height.

$$q_b = \frac{0.0864Q}{CA} \quad (1)$$

Where q_b is baseflow height (mm/d), Q is flow rate (L/s), CA is catchment area (km^2).

Water storage Recovery Period

We selected 52 of the 72 ponds in the Oro River Basin to estimate the water storage recovery period based on the following criteria: (1) irrigation ponds that store water only from runoff from the catchment area without any water supply from the river and (2) irrigation ponds with available data on total storage, basin catchment area, and full-water area.

Here, we estimated water storage recovery periods for two types of water level differences in each pond (Fig. 1). (a)Water level difference from the topmost intake level to the full-water level. (b) Water level difference from the second intake level to the topmost intake level.

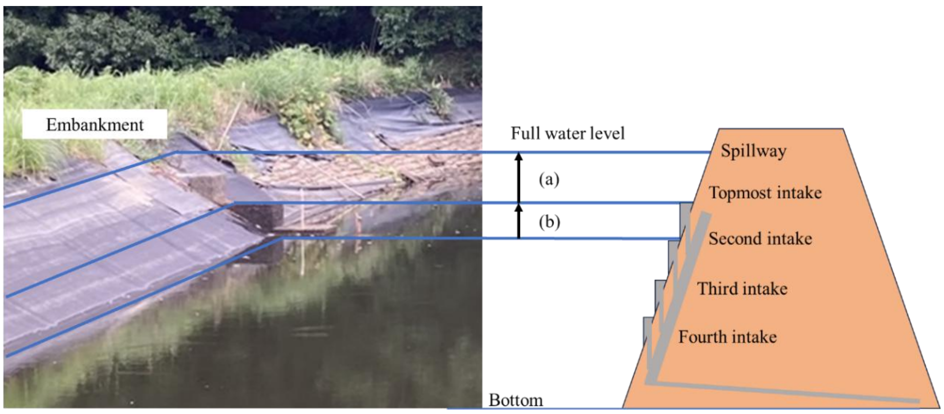

Fig. 1 Water level difference (a) and (b)

Both periods were calculated for the late summer season, when most damage from heavy rainfall or typhoons is expected. However, September is the end of the irrigation season; therefore, water demand is relatively low, and pre-release is unlikely to cause serious problems. Furthermore, by the end of the irrigation period, water levels are usually low, so pre-release is unnecessary. Therefore, this study did not consider the case of September. The respective recovery periods for each irrigation pond were calculated using Eq. (2).

$$T = \frac{V}{1000 \cdot q_b \cdot CA} \quad (2)$$

Where T is water level recovery period (d), V is storage capacity (m^3), q_b is baseflow height (mm/d), and CA is catchment area (km^2).

V was defined as the full-water area multiplied by the measured intake spacing ((a) or (b) in Fig. 1). For irrigation ponds where the intake spacing could not be measured, an average value of 30 cm was used for both (a) and (b).

RESULTS AND DISCUSSION

Monthly Baseflow Height

The monthly baseflow heights of ponds 1 and 2 and the precipitation during the month are shown in Table 2.

Table 2 Monthly basal run-off heights and precipitation in Ponds 1 and 2

	Baseflow height at Pond 1 (mm/d)	Baseflow height at Pond 2 (mm/d)	Precipitation (mm/m)
August	3.03	4.43	266.0
September	0.97	1.66	133.5
October	0.73	1.91	101.5
November	1.03	2.71	166.0
December	2.28	2.71	102.0

The monthly baseflow height for each pond ranged from 0.73 to 3.03 mm/d for Pond 1 and from 1.66 to 4.43 mm/d for Pond 2. The baseflow heights of ponds 1 and 2 in the same month differed by 0.4-1.4 mm/d. In both ponds, baseflow heights were high in August, when rainfall was high, while baseflow heights were low when rainfall was low. In contrast, baseflow heights were higher in December, despite the low precipitation.

We calculated the correlation coefficients between the monthly base runoff height and the total precipitation one month before the day the base runoff was observed. The correlation coefficients were 0.73 for Pond 1 and 0.81 for Pond 2, indicating a strong correlation between the two irrigation ponds. A high correlation between the monthly base runoff height and the total precipitation the month before the day indicates that the previous rainfall greatly affects the baseflow rate in a small catchment area, such as an irrigation pond. In August, the baseflow heights used to estimate the water storage recovery period during the irrigation period were set at a minimum of 3.03 and a maximum of 4.43 m.

Water Storage Recovery Period

Figure 2 shows the top 20 ponds with the longest water storage recovery periods among the 52 ponds. Almost all irrigation ponds (ponds A to M in Fig. 2) recovered the water level to the maximum within a week, regardless of the water storage recovery period of (a) and (b). Among the remaining 32 irrigation ponds not included in Fig. 2, the water storage levels recovered quickly, with recovery periods ranging from 0.1 days to a maximum of 3 days. Therefore, the possibility of a water shortage is low. In this region, rice paddy irrigation is generally completed by mid-August. While some paddies with longer growing periods may continue irrigation into September, they represent a small minority of the total. In light of this situation, by August, which marks the final stage of the irrigation period, if the irrigation pond is at full capacity or reaches the level of the first intake valve, then even if the water level is reduced by one intake valve, the risk of water shortage is considered low, provided that the level can recover within approximately one week without rain. Therefore, the irrigation manager can pre-release water before rainfall during the irrigation season. In addition, these are the water storage recovery periods considering only the baseflow rate, and the actual recovery period is expected to be shorter than this. In addition, because the baseflow heights of ponds 1 and 2 were applied to all irrigation ponds in the Oro River Basin in this study, the actual results may differ from these.

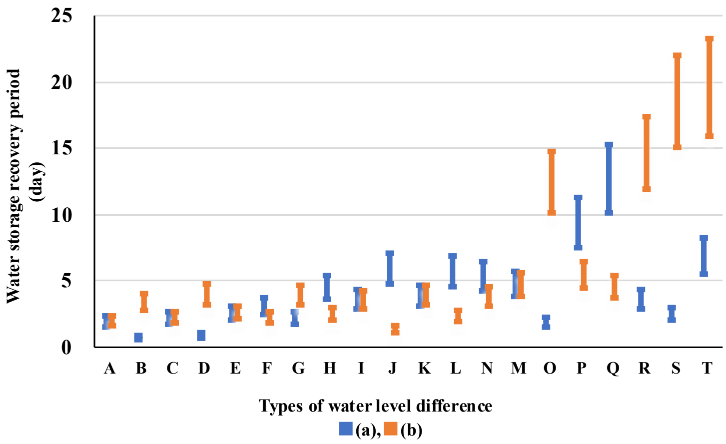

Fig. 2 Water storage recovery period

CONCLUSION

We found that the amount of baseflow into the irrigation ponds varied greatly from period to period, which was strongly influenced by rainfall. The differences in flow rates, despite the irrigation ponds being in the same area, suggest that observations should also be conducted in other irrigation ponds.

Low-water-level management during the irrigation season can also be implemented without worrying about water shortages due to quick recovery. The actual water storage rate recovery period is expected to be shorter than estimated because only the baseflow rate was used as inflow for the calculation.

To accurately calculate the water storage recovery period, the following issues need to be addressed: water level monitoring throughout the year, accurate irrigation pond storage capacity measurement methods, and the development of runoff analysis models that can be adapted to small catchment areas.

In addition, it is necessary to estimate the water requirements of the beneficiary areas and evaluate the flood control function of low-water-level management in irrigation ponds.

ACKNOWLEDGEMENTS

Part of this study was supported by the Tottori Prefecture “2023 Basin Flood Control Study Project.” We would also like to thank the members of the laboratory who assisted with the observations.

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