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REVIEW

Review of Research on Irrigation Pond Damage due to Heavy Rain and Related Disaster Prevention Countermeasures in Japan

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Abstract

There are about 170,000 irrigation ponds in Japan (May 2019) that serve a vital role as agricultural water resources in rural areas. However, these ponds are aging and the number of abandoned irrigation ponds has increased due to more farmland being abandoned and the aging of farmers. Many damaged irrigation ponds have been reported after heavy rains and earthquakes. During the past 10 years (2008-2017), 73% of all damaged irrigation ponds were damaged by heavy rainfall. About 64,000 ponds are specified as disaster-prevention-focused irrigation ponds (May 2019), which could pose a significant risk to downstream assets in case of a break. Thus, there has been rapidly growing social concern regarding disaster prevention and mitigation of the threat of such irrigation pond breaks. The prevention of irrigation pond failure due to heavy rain has consequently become a critical research topic. Accordingly, in this paper we review previous research on the damage to irrigation ponds due to heavy rain and the effects of various disaster prevention countermeasures relative to the following: 1) forms of damage and specific causes due to heavy rain; 2) flood analysis in case of a pond break, and flood control measures; and 3) methods of predicting potential damage due to an irrigation pond break.

Discipline: Agricultural Engineering
Additional key words: causes of irrigation pond damage, flood analysis, flood control, forms of irrigation pond damage, irrigation pond break

Introduction

Rice paddy cultivation requires a great deal of water, so securing sufficient water resources is essential to ensure a stable harvest. This is why many irrigation ponds have been built in Japan. At present (May 2019), there are about 170,000 ponds, 96,000 of which have beneficiary areas of 0.5 hectare or more, and 74,000 of which are small-scale ponds with a beneficiary area of less than 0.5 hectare (March 2018; MAFF 2019a). These ponds serve a vital role as agricultural water resources. In 1997, the beneficiary areas of about 61,000 irrigation ponds (each having a beneficiary area of 2 hectares or more) account for approximately 1.2 million out of the 2.7 million hectares of rice paddy fields in Japan (MAFF 2019b). Many irrigation ponds in Japan are growing old, with about 69% of 96,000 ponds registered in the irrigation pond database having been built before the Edo period (1603-1868) or of unknown origin. Data on about 96,000 ponds (each with a beneficiary area of 0.5 hectare or more) are registered in the database, including location, year of construction, reservoir capacity, and other details (MAFF 2019c). There are concerns about unsafe conditions due to deterioration over the years, as too many ponds need repairs and many are not durable enough to withstand extreme events (e.g., heavy rains, earthquakes). Indeed, damage to many irrigation ponds is reported following each heavy rain event or severe

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earthquake in Japan. Over the past 10 years (2008-2017), 8,808 cases of damaged ponds have been reported, 73% of which were due to heavy rains and 27% of which were due to earthquakes (MAFF 2019a).

Recent years have witnessed a decrease in the most basic farming groups for agricultural production utilization in rural areas, due to a declining and aging farming population. Thus, there are concerns about whether daily pond maintenance can be performed properly. Local communities have grown to consist of not only the original local farmers but also newcomers who have jobs in more urban areas, resulting in the widespread development of rural areas (MAFF 2019c, MAFF 2019d). Many assets including houses, roads, and railroads have been constructed in the immediate downstream vicinity of irrigation ponds. The possible risk to such assets or residents in these downstream areas posed by a pond break has accordingly increased. The Ministry of Agriculture, Forestry and Fisheries (MAFF) ordered a large-scale inspection of irrigation ponds throughout Japan (conducted from 2013 to 2015) that targeted about 96,000 irrigation ponds with a beneficiary area of 0.5 hectare or more, or which posed a significant risk to downstream assets in case of a break. The latter ponds were defined as disaster-prevention-focused irrigation ponds, designated using certain criteria. As a result of this inspection, about 11,000 ponds were specified as disaster-prevention-focused irrigation ponds (MAFF 2019e). However, in the aftermath of the Heavy Rain Event of July 2018, many small-scale irrigation ponds not targeted for the large-scale inspection of irrigation ponds were broken. Specifically, 32 irrigation ponds broke, 29 of which were not targeted for large-scale inspection, and damage to three ponds caused secondary damage in downstream areas (MAFF 2018a). After such small-scale pond disasters due to heavy rain, MAFF ordered the reselection of disaster-prevention-focused irrigation ponds. As of May 2019, there were about 64,000 disaster-prevention-focused irrigation ponds (MAFF 2019f). Social concern regarding disaster prevention and mitigation of the threat posed by such ponds has since increased significantly.

We accordingly reviewed previous research on the damage to irrigation ponds due to heavy rain and appropriate disaster prevention countermeasures, as damage due to heavy rain is more frequent than damage due to earthquakes. And given the possibility of predicting the degree of damage to ponds and downstream assets due to heavy rains in advance on some level, we also reviewed research on this aspect of irrigation pond behavior.

Forms of damage and causes resulting from heavy rain

Ogura & Nemoto (1989) statistically examined the relation between the pond parameters (e.g., location, shape, year of construction, reservoir capacity, dam height) obtained from the register of ponds and the presence/absence of damage. Damage due to heavy rain was classified as dam body damage, waterway damage, revetment damage or sediment inflow, and 200, 40, 83 and 19 instances of each form were observed, respectively. Of the 200 cases of dam body damage, 13 entailed dam breaks. Many of the heavily damaged ponds had a low dam height and damage that occurred around the water intake facilities. This research did not examine the forms and causes of damage during the process of pond collapse.

There has been some research on the forms and causes of damage during the process of pond collapse, however. A pioneering study conducted by Hori (2005) clarified the following points. 1) The forms of damage were classified into three types: overflow failure (a phenomenon whereby the storage level exceeds the crest of the dam body, with failure occurring when water flows over the downstream slope); sliding failure (where the penetration of reservoir water and higher pore water pressure in the dam body due to rainfall infiltration reduce the water retention capability of the dam body, causing its downstream slope to slide); and seepage failure (where local infiltration occurs somewhere in the dam body, washing away soil particles in the running water, and causing progressively greater destruction). Among these three types, seepage failure was observed as being the most frequent. 2) No clear relation was identified between the dam body soil parameters (e.g., sandy, loamy, silty) and the form of damage (described later). 3) The occurrence of damage (pond collapse) was found to be related to the maximum hourly rainfall and accumulated rainfall. 4) Pond breaks were confirmed to be strongly influenced by the stability of the dam body, which is related to the penetration of rainfall and a rise in the reservoir level. There have been other such studies as well, including by Yamamoto et al. (1998), Hori et al. (1998), and Hori et al. (2002).

It has recently been reported that debris flows into irrigation ponds were observed as originating from the upper reaches, thus causing damage. Most of the relevant research on such debris flows is based on specific case reports (Hori et al. 2015a, Mohri et al. 2015, Oda et al. 2015). These reports indicate that some ponds were broken, and then water and sediment in the reservoir flowed downstream. It was also confirmed that some ponds suffered no major damage because an amount of water equivalent to the sediment inflow was able to flow safely from spillways. These reports did not examine the direct impact of debris inflows on the ponds. Kojima et al. (2016) conducted an advanced study and validation of an analysis model that could express the debris flow as the preceding stage, with the aim of developing a method of predicting the behavior of sediments flowing into the pond. They conducted modeling through the particle method and behavioral analysis of a debris flow using channel experiments, and then compared the simulation results with the observed behavior. By adjusting the physical property parameters of the debris flow (including its cohesion and coefficient of viscosity after yield), simulation results similar to those observed in the experiments were obtained. However, there has been little case analysis, and thus this body of research remains insufficient, particularly given the need to clarify such issues as the direct impact of debris flow on the pond and the mechanism leading to dam failure. Once this mechanism is elucidated, such knowledge could be useful in informing the design of repairs or retrofits to such pond facilities as the dam body and spillway.

Research on disaster prevention countermeasures

Disaster prevention countermeasures for irrigation ponds can be classified into structural countermeasures, such as repairing the dam body and spillway, and non-structural countermeasures, such as providing flood control for the pond and drawing hazard maps (showing the predicted area of damage in case of a break). Of course, it is difficult to provide structural countermeasures for all ponds given the limited budget for such expenditures. Moreover, ponds are damaged almost every year. As a result, non-structural countermeasures have become an important focus of research. In this section, we review previous research related to non-structural countermeasures including: 1) utilization of flood control, 2) flood analyses in case of pond breaks, and 3) prediction of the risk of damage.

1. Research on flood control

Flood control reduces the quantity of flood discharge into downstream areas by storing and delaying surface runoff. Utilizing such functionality requires the following preparations: operating ponds at a low water level to store flood discharge, urgently discharging prior to predicted heavy rainfall, and providing vacant storage capacity by adjusting irrigation use among neighboring ponds.

Nakanishi et al. (1999) conducted a representative flood control study for an agricultural dam that was constructed with no flood control capacity by investigating the actual inflow and discharge during several flood events. The flood control worked well for some flood events, but not sufficiently for all; thus, the effect of flood control measures depends on the ability to reduce the peak flow of floods using vacant or temporary storage capacity.

Kato & Satoh (2002) conducted a representative study on the flood control of irrigation ponds by calculating the actual volume required for flood control based on the rainfall and observed water level in an irrigation pond, then constructing a flood runoff model using the parallel tank model, with floods being reproduced by the model using the probable rainfall for 5 to 200-year periods. The effect of flood control on downstream areas was then evaluated. This study clarified the following points: 1) generally, 37%-98% of floodwater could be controlled; 2) the degree of control was strongly influenced by the vacant storage capacity immediately prior to the flood and the pattern of flood inflow; 3) the proposed model controlled 37%-43% of floodwaters for any rainfall pattern evaluated, and flood control was shown to reduce the flood frequency downstream of an irrigation pond from approximately once a year to approximately once every two years.

Takeshita et al. (2006) proposed a method of evaluating the flood control of ponds based on the work by Kato & Satoh (2002) and Nakanishi et al. (1999), who analyzed the prolonged duration of flood concentration and peak reduction of the flood volume. They then proposed an equation for estimating flood control volume based on hydrological data and numerical simulations. Finally, the estimated flood control volume was verified. This method was shown to work sufficiently well when applied to actual flood events, and its most beneficial feature is that it does not require water-level monitoring data, only the specifications of the pond.

Kakudo et al. (2013) conducted representative research on establishing vacant storage capacity by managing the storage water level in every evaluated period. They set the vacant storage capacity for flood control based on the required storage capacity and simulated the degree to which the runoff would be adjusted by the vacant storage capacity. They applied the Operational Curve of Required Storage for Drought (RSDC) method and the tank model. As a result, the simulated storage management method demonstrated excellent flood control capabilities, especially during the irrigation period.

Nakanishi et al. (2002) examined flood control for a group of several ponds, macroscopically evaluating the potential rainwater storage capacity created by and in conjunction with irrigation use. Specifically, they calculated the vacant storage capacity during the flood season based on changes in the storage rate and evaluated the rainwater storage capacity of the ponds compared to that of the paddy fields. The results clarified the following points: 1) the group's rainwater storage capacity was found to be quite small in June (i.e., beginning of the irrigation period), 2) the rainwater storage capacity increased at the end of September (i.e., typhoon season and end of the irrigation period) as the quantity of stored irrigation water decreased, and 3) the potential rainwater storage capacity in early September was about 1.2 to 2.1 times that of the paddy fields in a normal year.

There have also been studies adopting a distributed runoff model to estimate flood control for a group of several ponds. For example, Oyagi et al. (2005) conducted a field survey of 121 ponds in a targeted area to which a distributed runoff model was applied. The effect of flood control was then evaluated by comparing the effects of a dam in the same area. The total flood control capacity of the ponds was equivalent to about 40% of the dam's capacity, and the reduction in peak discharge using the group of ponds was about 80% of that using the dam. Needless to say, using the group of ponds also has the effect of prolonging the duration of flood concentration. A few other studies have been conducted using this proposed function, including those by Yoshisako et al. (2007) and Ogawa et al. (2012).

Accordingly, the creation of flood control capacity by repurposing the irrigation storage capacity of ponds is under active consideration as a disaster countermeasure (MAFF 2018b). Realizing this countermeasure requires common agreement between all water right holders. To obtain this agreement, the objective effect or value of this countermeasure must be demonstrated to the parties concerned. To do this, Yoshisako & Ogawa (2009) conducted an advanced study that provided: 1) continuous observation of the water level of a pond and calculation of its storage rate, 2) analysis of the relation between the storage rate and precipitation, 3) calculation of the reduction in the water storage rate due to water use, 4) simulation of the water storage rate during the irrigation period, 5) calculation of the necessary water use capacity dictated by the storage rate, and 6) examination of the possibility of providing appropriate flood control capacity. It was found that during 86% of the days during the three years of irrigation periods, the storage rate was 70% or greater, indicating that there was room in the water use capacity for flood control due to the decrease in irrigated paddy field area. Thus, sufficient flood control capacity could be provided through the repurposing of some irrigation storage capacity.

Yoshisako et al. (2017) also conducted research on enhancing the flood control of a group of ponds, proposing a method that depends on adjustment of the water supply among the ponds as follows: 1) calculation of the water storage rate in each pond by the water balance formula, 2) evaluation of a pond's water storage rate (where the pond is deemed to have a margin for irrigation water supply, if the water storage rate does not fall below 0% throughout the irrigation period), and 3) adjustment of the distribution of irrigation water among ponds. The applicability of the proposed method was also examined, demonstrating that it was possible to mitigate disasters using flood control without having to expand the capacity of any ponds.

2. Flood analysis of irrigation pond breaks in rural areas

Flood analysis is a method of simulating flow behavior in the area downstream of an irrigation pond after a pond break. Such analysis can be used to obtain the data essential for drawing hazard maps. Kawamoto et al. (2013) improved the "Inundation Analysis System of Small Earth Dams" (Tani & Inoue 2009) developed and operated by the National Agricultural and Food Research Institute (NARO), thereby clarifying the influences of such analysis conditions as elevation and failure position on the results.

There have only been a few studies, however, verifying the predictions of numerical models against actual flood behaviors. Representative research includes that of Shoda et al. (2014), who compared the maximum water depths and flow velocities obtained by flood analysis with survey data from nine broken ponds, so as to verify the overall flood analysis. This analysis used an improved version of the simple flood analysis model proposed by Kawamoto et al. (2013), and the results thereof clarified the following points: 1) the calculated maximum water depth roughly agreed with the actual survey data, while the flow direction and inundation area calculated from the flood analysis tended to differ slightly from those of the observations, 2) the flow velocity tended to be faster near the dam body, and 3) differences were sometimes observed between the simulation results and the actual inundation area, mainly depending on the presence or absence of waterways or road embankments in the digital elevation model (DEM) data. Other research in this vein includes that conducted by Shoda et al. (2012) and Shoda et al. (2015).

3. Computer systems for predicting the risk due to irrigation pond breaks

Several analysis systems have been constructed considering both flood analysis and flood control to determine the risk to downstream areas posed by an irrigation pond break. Studies include those by Tani (2005), Kikusawa (2007), Hori et al. (2015b), and Hori et al. (2019), the latter two of which are discussed in detail in this section.

Hori et al. (2015b) developed a system for forecasting the water level in a pond when subjected to heavy rain. This system was able to easily estimate the rise in water level and the risk of overbank discharge, based on past and predicted rain data from the Japan Meteorological Agency. The user of this system can consider the timing of prior discharge or set low water level management parameters. The accuracy of the proposed system was confirmed through a comparison with field-collected data. However, the runoff characteristics of each pond were observed to vary with their areas. Therefore, various ponds still need to be verified, in order to increase the accuracy and applicability of the proposed system.

Hori et al. (2019) developed the Disaster Prevention Support System for Irrigation Ponds (DPSIP) with the objective of enabling the sharing of pond break or status information in case of a major disaster. The objective of the system is to support early evacuation attempts by immediately informing the parties concerned downstream of a predicted failure upstream.

Such a system for predicting the risk due to irrigation pond breaks requires accurate information about the parameters and status of many irrigation ponds (e.g., reservoir capacity, dam height, management conditions). An emergency inspection of 88,133 ponds was conducted in August 2018, clarifying some issues of irrigation ponds as follows (MAFF 2018a): 1) the maintenance of some ponds (especially small-scale ponds) was inappropriate, 2) many small-scale irrigation ponds were not registered in the database, and 3) there were significant discrepancies between information in the database and the actual parameters of the ponds in the field. As a result, MAFF is promoting the establishment of a system for the accurate management and maintenance of all irrigation ponds. Specifically, MAFF ordered the current reselection of disaster-prevention-focused irrigation ponds, and the “Act on the Management and Conservation of Irrigation Ponds” enacted in April 2019 requires pond owners or managers to report pond information (e.g., reservoir capacity, dam height, management conditions) to their prefectures. Thus, it is now possible to obtain information on small-scale irrigation ponds in prefectures and municipalities (MAFF 2019f, MAFF 2019c). Once pond information is reflected in the system for the prediction of potential damage due to an irrigation pond break, it could be useful for disaster prevention and the maintenance of small-scale irrigation ponds.

Conclusions

We have reviewed previously published research on the damage to irrigation ponds in Japan due to heavy rain, and on associated disaster prevention countermeasures. Most research has been conducted on medium and large-scale ponds, so accurate information describing the parameters and status of many irrigation ponds remains necessary, as there has been little study concerning small-scale ponds. With the occurrence of small-scale pond disasters due to heavy rain, there has been rapidly growing social concern regarding disaster prevention and mitigation of the risk of irrigation pond failures. MAFF is promoting the establishment of a system for the accurate management and maintenance of irrigation ponds, and focusing on effective disaster prevention countermeasures. Specifically, MAFF ordered the current reselection of disaster-prevention-focused irrigation ponds, and the “Act on the Management and Conservation of Irrigation Ponds” was enacted in April 2019.

In many developing Asian countries currently undergoing economic development, urbanization, and population growth, various countermeasures (including the construction of irrigation ponds and development of irrigation facilities) are being promoted to respond to the growing demand for rice, cultivation area, and water resources (MAFF 2019g). In the case of paddy field irrigation in Korea, an irrigation pond is more important than in Japan due to the characteristics of the river flow regime (Lee et al. 2017). However, the deteriorating conditions of such ponds are likely to result in a situation similar to that of the current situation in Japan, where the failure of irrigation ponds represents a threat to assets and human life. The disaster prevention studies discussed in this review are accordingly expected to be a useful reference in addressing the risk posed by aging irrigation ponds in these countries as well as in Japan.

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