Jurnal
Teknologi

Full Paper

AGRICULTURAL WATER-GATE MANAGEMENT FOR OPERATIONAL FLOOD PROTECTION IN LOW-LYING PADDIES

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Article history
Received
15 July 2015
Received in revised form
2 August 2015
Accepted
26 August 2015

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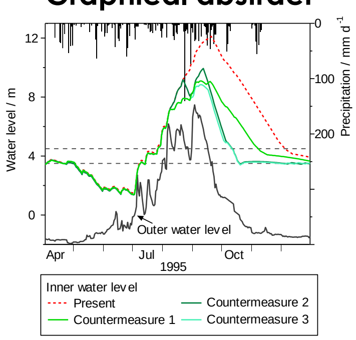
Graphical abstract



Abstract

It is essential to assess in influence of water-gate operations on inundation processes during the wet season to mitigate inundation damage. Here, a numerical analysis method for modelling regional drainage through water gates was developed by integrating the Distributed Water Circulation Model incorporating Agricultural Water Use (DWCM-AgWU). The inundation process was reproduced using an *H-V* curve (flooding water level verses area volume). The developed model was applied to the low-lying paddy areas of the Nam Cheng River basin in the Lao PDR. This study area is a sub-basin of the Nam Ngum River, with which the Nam Cheng River merges downstream of the Nam Ngum 1 dam. Fourteen agricultural water gates of slide-type at the river outlet function as a storage facility for irrigation water for the paddies during the dry season and as a flood protection measures against backwater effects from the main stream of the Nam Ngum River during the wet season. However, current gate operation is based on empirical knowledge without reference to filed observational data. The simulated results revealed that the outer water level did not exceed the inner level, if the difference between the inner and outer water levels was > 4 m on operational days. Several feedback control strategies combined with gate opening heights, the number of open gates, operation intervals, and the threshold inner and outer water level differences were examined focusing on inundation damage within the area and drainage volume through the gates.

Keywords: Inland flooding, Inundation damage, inundation water level, hydrological distributed model, Lao PDR

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1.0 INTRODUCTION

Rice is the most important cereal crop sustaining the population of Asia. Rice cultivation in irrigated and rain-fed paddies in low-lying areas is often affected by floods, and damage caused by submergence in floodwater is a major limiting factor for rice production in such areas. In the Lao PDR, flood hazards have been reported regularly and are a major concern because of adjoining rivers such as the Mekong River and its tributaries. During 1990-2014, 69.6% of natural disasters in Lao PDR were caused by floods [1]. Floods are one of the primary climate-related disasters, and within the context of climate change, the occurrence of extreme floods is likely to increase in both spatial extent and frequency in current flood-prone regions.

Countermeasures and adaptations against flooding must be developed and evaluated to protect rural areas from such natural disasters. The final target of this study to present procedures for determining adaptation measures in rural areas based on the use of agricultural water gates and an Early Warning System (EWS), together with a hydrological observation network. Hydrological analysis is necessary to reveal both the inundation processes and the influencing factors to develop more effective operational management strategies for the use of water gates. In this stage of a larger study, the investigation focused on the management of agricultural water gates for operational flood protection in low-lying paddies based on numerical simulations.

2.0 STUDY AREA

2.1 Nam Cheng River Basin

The study area comprises the low-lying paddy areas of the Nam Cheng River basin in the Lao PDR (Figure 1). The Nam Cheng River basin has a typical tropical monsoon climate with wet and dry seasons. The basin is located the in south of Vientiane province and is it 70 km north from the capital Vientiane. The area encompasses approximately 457 km^2 with X coordinates ranging from 206,300 to 239,000 m and Y coordinates ranging from 2,021,000 to 2,056,000 m in the UTM coordinate system. In the downstream area, the Nam Ping and Nam Chim rivers connect to the Nam Cheng River. The elevation of the basin range ranging from 134 to 770 m (Figure 2).

The Nam Cheng River basin is a sub-basin of the Nam Ngum River, with which the Nam Cheng River, merges downstream of the Nam Ngum 1 dam. The Nam Ngum 1 dam was constructed in 1971 for power generation. With a catchment area of 8,460 km^2 and effective storage capacity of 4.7 billion m^3, the total capacity of power generation is 155 MW. In recent years, other hydropower dams have been completed, e.g., the Nam Ngum 2 and 5 dams on the Nam Ngum River and the Nam Lik 1 and 2 dams on its tributaries. These hydropower dams commenced operations in 2010 or 2011 and they mainly supply electricity to Thailand.

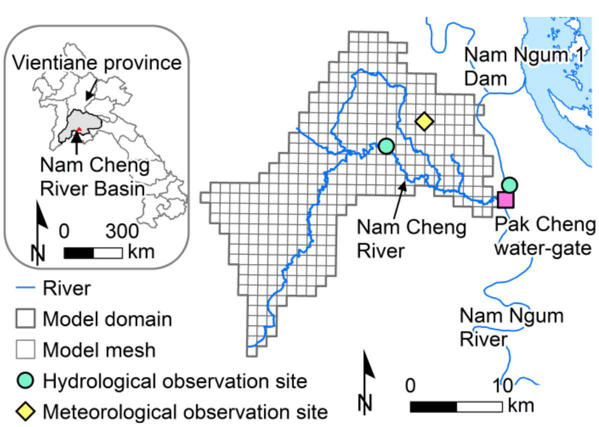

Figure 1 Areal Model of the Nam Cheng River basin

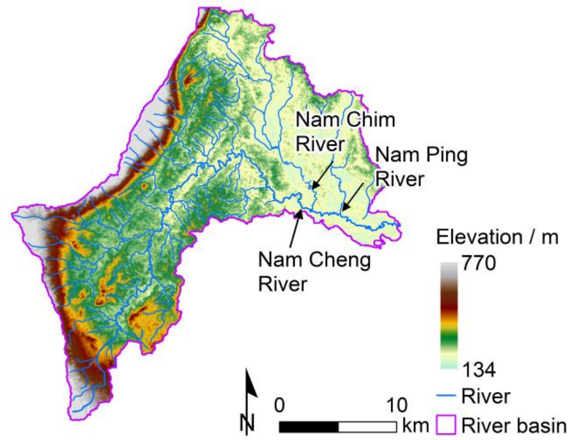

Figure 2 Elevation distribution in the Nam Cheng River basin

Figure 3 Outline of the Pak Cheng Water Gate

2.2 Pak Cheng Water Gates

Fourteen slide-type agricultural water gates were installed at the river outlet, 700 m upstream from its confluence point with the Nam Ngum River. The individual gate width, maximum opening height, and total gate height is 2.8, 2.4, and 9.5 m, respectively (Figure 3). The gates have been used since 2000 (controlled electronically since 2011) and they function as a storage facility for irrigation water for paddy cultivations during the dry season and as a flood protection measures against backwater effects from the main stream of the Nam Ngum River during the wet season (May to mid of October). However, some villages have experience greater inundation since the completion of the water gates because their improper operation can obstruct drainage.

In dry seasons, from the end of October to the end of April, the water gates are generally closed, maintaining the inner water level at 3.5 –4.5 m, so as not to interfere with paddy irrigation practices using river pumps. These figures have a benchmark of 0 m at the bottom of the water gates. In wet seasons, according to current operational procedures, the water gates are generally full open.

The water gates are not equipped with any water-level indicators such as water gauges or automatic water level sensors, i.e., the inner and outer water levels are simply verified visually. Water gate operations, checking the inner/outer water levels and opening/closing the water gates, are conducted only on Monday mornings and Friday evenings. In addition, under status quo, real-time hydrological observational data are not used in the operation of the gates and information on their gate operational status is not available.

2.3 Hydrological Observation

Meteorological observations in the study area, including precipitation, temperature, humidity, wind speed, and sunshine have only been recorded at the only Phon Hong site (Figure 1). During 1994–2008, the average annual precipitation was 2,459 mm and the monthly precipitation in May–November ranged from 340–570 mm.

The water level of the Nam Ngum River has been observed at the Pak Kanhoung hydrological observation site (Figure 1), 2 km north of the water gates, since 1963. In addition, the daily water level of the Nam Cheng River has been observed at a midstream point (Figure 1). In this study, these water levels were converted to water discharges using the conventional Manning equation. The water levels at both sites were measured using staff gauges.

2.4 Land Use

Land use within the study area, based on a simple classification of forest, low-forest, and paddy fields [2], is shown in Figure 4. Paddy fields are dominant in the low-lying region of the study area. Agricultural land use can be classified broadly into paddies and dry fields. The major paddy rice-cropping pattern is double cropping of glutinous rice in both wet and dry season. Land in the downstream areas of the Nam Ping and Nam Chim rivers is vulnerable to flooding and therefore, parts of these areas are subject to restricted cultivation during wet seasons to avoid inundation damage. The maximum inundation water depth recorded was 2–4 m and the longest inundation duration was about 30 days.

3.0 MODEL DEVELOPMENT

3.1 Simulation Outline

A flow chart of the inundation analysis is shown in Figure 5. The first step is to simulate the inner water levels with the water circulation model. The model was employed to calculate the drainage through the agricultural water gates, and the inundation process was reproduced using an *H–V* curve.

The computational time step was set as 1 day. the set as calculation period was 1995—2008, and 1994 was used the pre-calculation period.

3.2 Runoff Model

A numerical simulation Distributed Water Circulation Model incorporating Agricultural Water Use (DWCM-AgWU) was originally developed for the analysis of the water use of the Mekong River basin [3], [4]. The DWCM-AgWU takes into account the land use and agricultural water use in paddy fields through several submodels. Recently, Kudo *et al*. [5] modified the model to reproduce paddy irrigation processes in areas with large dams, such as in Northeast Thailand. Yoshida *et al*. [6] introduced a scheme for coupling inundation processes into a basin-wide hydrological model for low-lying river areas, which has been applied to a basin within the Lao PDR. This model can estimate the volume of irrigation water used for crops and the runoff is routed using a kinematic-wave model. This model has also been adapted to the Chao Pharaya River basin by Vongphet *et al*. [7]. Furthermore, Kudo *et al*. [8] assessed the complex influence of several dams on the flow regime of the Nam Ngum River using the model. The model parameters for our study used values determined by these earlier researches. In this analysis, parameters *K* and *P* for the kinematic wave model applied to the calculation of the river channel flow were estimated using the channel information of the Nam Cheng River and its tributaries.

3.3 Inundation Model

In low-lying areas, inundation can be categorized as a near-flat water surface and flood plain. Furthermore, most sections of the rivers have natural low levees, which means that slope can be considered negligible and the inundation area can be regarded as single retarding basin. Therefore, the inundation process was reproduced using an *H–V* curve, i.e., floodwater level verses areas volume. The *H–V* curve encompassed both the river channels and the conditions of other land surfaces. Storage volumes within the river channels were estimated from river widths and depths on several in site measurements. This study used the second version of the Aster GDEM (GDEM2) with 1 arc-second (30 m) grid of resolution. To assess the inundation damage, the *H–A* curve, was used, i.e., floodwater level verses the area.

3.4 Gate Operation and Discharge Model

Vertical lift gates with underflow are raised vertically between the piers of the structure. The two main flow types for such these gates are free and submerged flows. In this study, the estimated discharges through the water gates were based on three hydraulic formulas that considered the high/low condition of the inner/outer water levels and the opening heights of the water gates. These formulas are schematized in Table 1. Based on the number of opening gates and operation intervals, daily discharges through the water gates were determined. This study assumed that outer water levels were not influenced by drainage through the water gates

Table 1 Outline of calculation for discharge through water gates[a, b, 9]

Flow condition	Formula	Criteria for flow conditions	Discharge coefficient C	Remark
Submerged discharge	$Q = CBH\sqrt{2g(h_1 - h_2)}$	$h_2 \geq H$	0.75	-
Transition discharge	$Q = CBH\sqrt{2gh_1}$	$h_2 < H$ and $h_1 \geq \frac{3}{2}H$	0.51	-
Free discharge	$Q = CBh_2\sqrt{2g(h_1 - h_2)}$	$h_2 < H$ and $h_1 < \frac{3}{2}H$	0.79	When $\frac{h_1}{h_2} \geq \frac{3}{2}$, then $h_2 = \frac{3}{2}h_1$

[a]Where *Q* is discharge through gates, *H* is opening heights of water gates, h_1 is upstream water level (inner level), h_2 is downstream water level (outer level), *g* is gravel, *C* is discharge coefficient for submerged flow, and *B* is gate width.
[b]water levels were converted to water depths above gauge zero level.

4.0 RESULTS AND DISCUSSION

4.1 Estimated Results of River Flow and Inundation Damage

Figure 6 shows the observed and calculated discharges at the midstream of the Nam Cheng River. The relative errors for the daily and decadal average discharge were 47% and 42%, respectively. In this study, meteorological data observed at only one site were used and correction of the precipitation data for elevation was not performed. Thus, these data might have caused the overestimation seen during the dry season. The peak and low discharges are reproduced well and there are few differences between specific discharges of the floodpeaks between the outlet of the Nam Cheng River (at the water gates) and the three hydrological observation sites of the Nam Ngum River. These abridged results indicate that the simulation model could provide reasonable discharge estimations. Moreover, the estimated inundation area corresponded well with that of the 2008 hazard map.

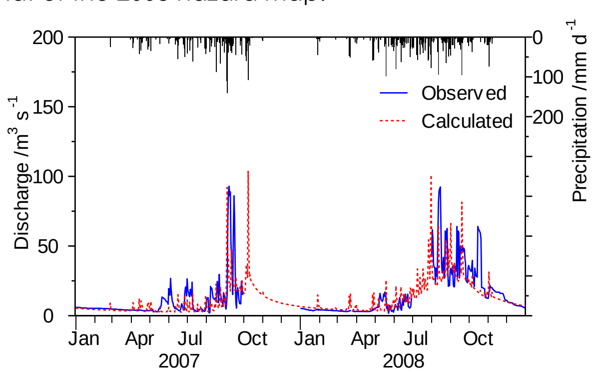

Figure 6 Comparison of observed and calculated hydrographs at a site in the Nam Cheng River

Figure 7 shows estimates of the inundation area and depths. When floodwater depths (in the lowest paddies within the area) are relatively low, up until they reach about 6.5 m, the inundation areas expand around the lagoons in the middle of the Nam Chim River and along downstream areas of the rivers. Increasing the floodwater depth in 2 m increments from 4.5 m shows that the inundation area becomes enlarged by about 10 km^2. Land use condition on the floodplain is dominated by paddy fields (about 80%). Figure 8 shows the inner/outer water levels, precipitation, inundated area of paddy fields and inundation water volume of paddy fields. In this study, inundation damage was taken into consideration when inundation depths were > 0.3 m. For pluvial years in the past, outer water levels are generally >4.0 m throughout August and September. This tendency suggests the long-lasting and relatively high outer water levels, rather than frequent peaks of the inner water level has greater influence on the inundation area under the current system of water gate management. Therefore, greater drainage through the water gates should be adopted even when the inner/outer water level difference is small.

Figure 9 shows the annual changes of maximum inner water level and precipitation, and the maximum inundated area and inundation water volume in the paddy fields, and their accumulation in the paddy fields. Inundation damage corresponds to the amount of precipitation. It can be seen that the maximum damage occurred in 1995. Except for 1995, the ranges of area and water volume are at most two times larger than during years of little precipitation.

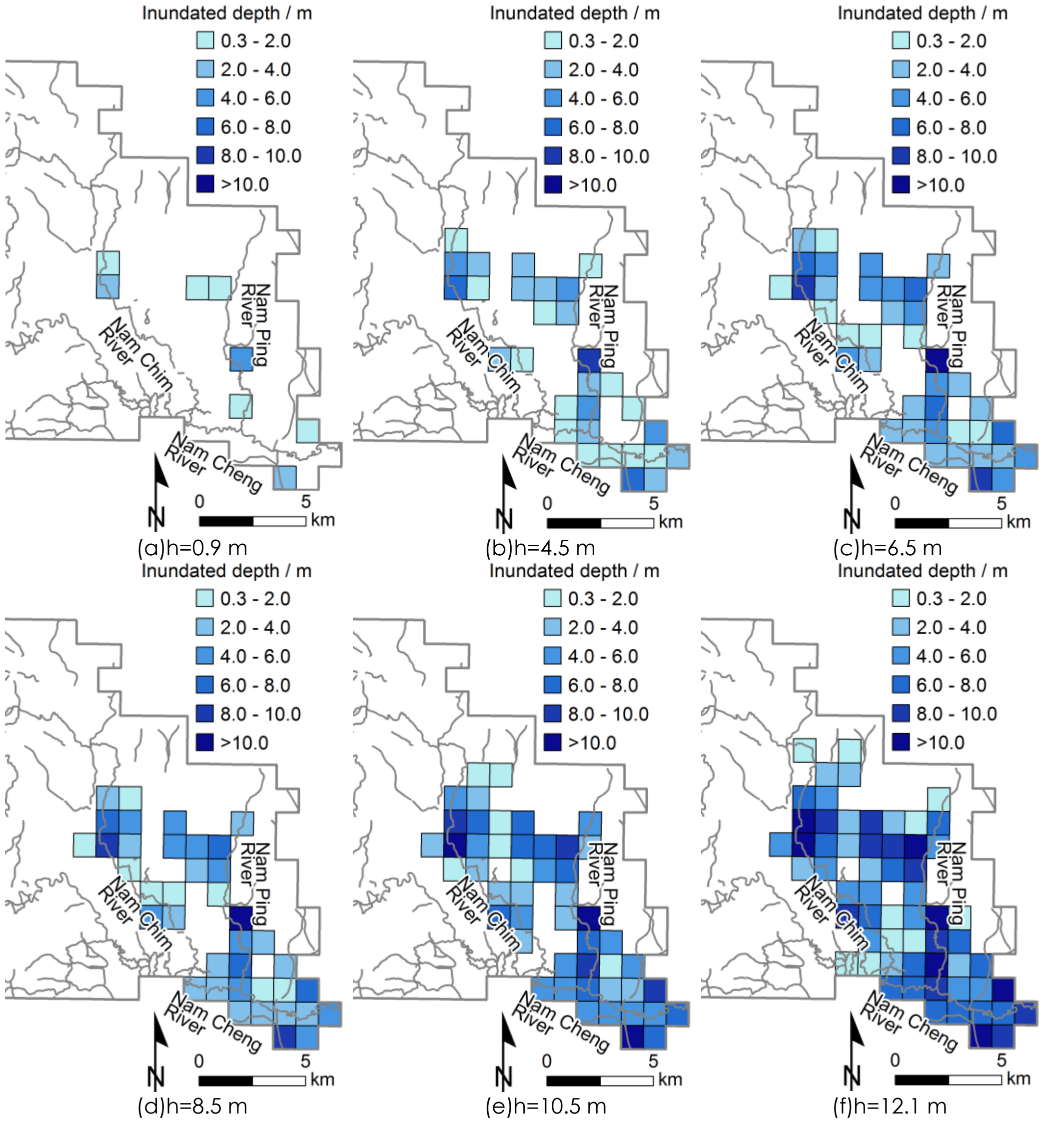

Figure 7 Inundation area and depth within range of flooding water levels[a, b, c, d, e]

[a]h represents inundation water depth (at the lowest paddies in the area).
[b]Target water levels were set in dry season.
[c]When h is 4.5 m, water levels equal to the upper target water level in dry season.
[d]h = 0.9 is the simulated minimum water level during wet seasons.
[e]h =12.1 is the simulated maximum water level during wet seasons.

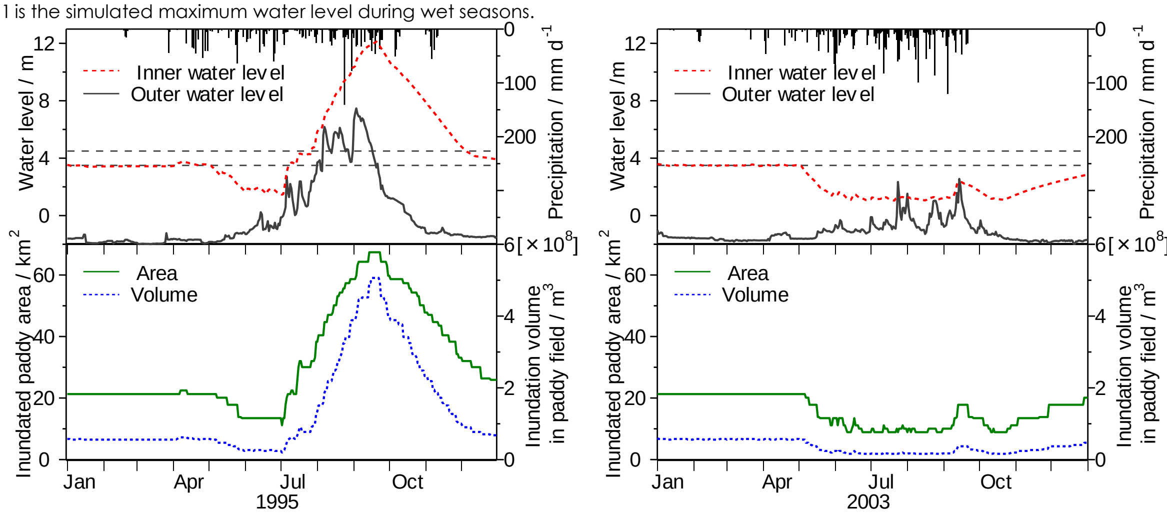

Figure 8 Some examples of transition of daily inner/outer water levels, precipitation, and inundated paddy field area, inundation water volume in paddy fields (1995 and 2003) [a, b]

[a]Dash lines in the upper figures show two target water levels ranging from 3.5 m to 4.5m in dry seasons.
[b]Outer water levels were converted into water levels with a reference point as the river bottom at the water gates.

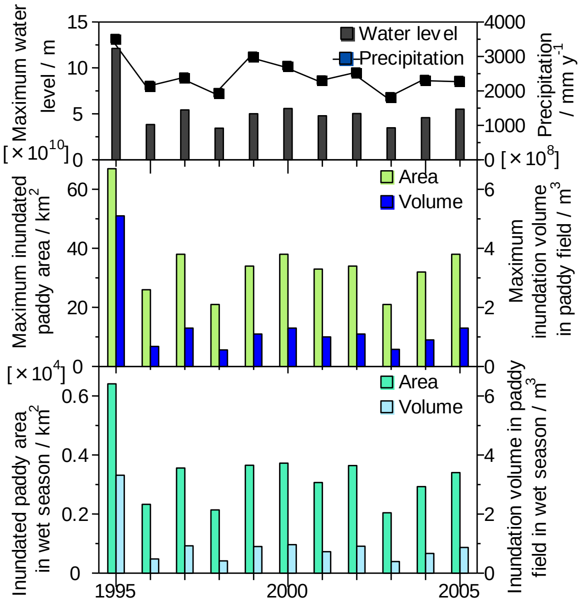

Figure 9 Annual precipitation, maximum inundated paddy filed area in wet seasons, maximum inundation water volume in paddy fields in wet seasons (1993—2008)

4.2 Water Gate Management for Operational Flood Protection

Based on the result of interviews, it was established at the current water gate operation for maximum discharge was to use five gates at 1.2 m height. Moreover, all water gates were closed to avoid backwater flooding when the outer water level was >4.0 m.

By determining the changes in inner/outer water level differences during days with gate operation, it would be possible to drain excess water through the gates, even when the outer water level was relatively high, i.e., when it exceeded the threshold for closing the gates under the current operational scheme. The differences between the inner/outer water levels were compared with the scale of rising outer water level and simulated results for decreasing inner water levels.

Table 2 shows the maximum scale of rising outer water level. The values range from 1.94 m to 4.97 m per two days. In the calculation period (1994—2008), the historical recorded maximum value of rising water level is 3.5 m. The simulated scales of decreasing outer water level are shown in Table 3. The maximum rate of decreasing inner water levels under the current operational scheme was 0.39 m.

Based on the threshold inner/outer water level differences, several feedback control strategies were evaluated (Table 3). The current operational scheme for maximum drainage requires five gates to be opened to 1.2 m height (present operation), which is half the maximum opening height (2.4 m). The limitation on the number of open gates and opening heights was imposed to protect downstream river dikes. Drainage through the gates was also considered for assessing the countermeasure operations. Change in opening heights or the number of open gates were effective for increasing the rate of discharge through the water gates. To reduce the labor involved in gate operations, changing the opening heights is considered reasonable. Therefore, the three countermeasures for gate operations, proposed by this study, considered five open gates and different opening heights. The opening heights used for countermeasure 1 and both countermeasures 2 and 3 were 1.2 and 2.4 m, respectively. Relatively high outer water levels were observed only for the period from August to September. Countermeasure 3 involved operating the water gates three times a week. On operation days, the scale of decreasing inner water level, attributable to the countermeasures, is ranged from 0.1 to 0.5 m (Table 3). The simulations showed that if the difference between the inner and outer water levels was >4.0 m on gate operation days, the outer water level did not exceed the inner level. The configurations of the three countermeasures are as follows. When the outer water level is >4.0 m and the difference between the inner and outer water levels is <4.0 m, all water gates are closed. When the difference is >4.0 m, five water gates are opened irrespective to any the outer water level. When the outer water level is ≦4.0 m, five water gates are also opened (no change from the present operation).

Table 2 Scale of rising outer water level[a]

Period	Maximum scale of rising outer water level /m		
	Within two days	Within three days	Within four days
1963-1970	2.32	3.10	3.85
1971-1993	1.94	2.87	3.24
1994-2008	3.46	3.45	3.20
2009-2013	4.97	3.40	3.82

[a]Outer water levels were converted into water levels with a reference point as the river bottom at the water gates.

Table 3 Number of inundation days, decreasing water level, and discharge through water gates in each water gate operation in wet seasons (1995—2008)[a]

Water gate operation			Number of inundation days /d	Maximum scale of decreasing inner water level /m			Maximum discharge through water gates /$m^3 \cdot s^{-1}$	Remark
Opening heights /m	Number of open gates	Operation intervals /times per week		Within two days	Within three days	Within four days		
1.2	5	2	208	0.13	0.26	0.39	125	Counter-measure 1
1.2	7	2	204	0.26	0.52	0.78	179	
1.2	9	2	179	0.32	0.63	0.94	215	
1.2	11	2	171	0.38	0.76	1.13	242	
1.2	13	2	162	0.41	0.80	1.20	291	
2.4	5	2	182	0.26	0.50	0.72	219	Counter-measure 2
2.4	5	3[b]	162	0.25	0.49	0.71	210	Counter-measure3

[a]Gates are opened when the outer water level is ≦4.0 m or when the outer water level is > 4.0m and the inner/outer water difference is >4.0 m on gate operation days.

[b]Only during August-September.

Table 4 shows the inundation durations of inner water levels relating to the inundation damage under each countermeasure. All proposed countermeasures lead to the reduction to zero days when the inner water level is >10.5 m. Under countermeasure 3, it was possible to reduce the water level rang to 8.5–10.5 m. The maximum discharge from the water gates was 219 m^3 s^{-1} under countermeasure 2 and 210 m^3 s^{-1} under countermeasure 3. These values are 1.5 and 1.4 times that of under the present operational management scheme (Figure 10). Each countermeasure causes the maximum water level to decrease by 1.5 m. With a 2.4 m opening height, the scale of the decrement floodwater level is larger than under the other schemes. The proposed gate operations and acceptable volumes of discharge through the gates should be assessed practically as a demonstration of their efficacy as valid flood prevention practice.

Table 4 Inundation duration at inner water levels (1995—2008)

Inner water levels /m	Present operation	Countermeasure 1	Countermeasure 2	Countermeasure 3
	Number of days /d			
≦4.8[a]	5,206	5,270	5,296	5,316
4.8—6.5[b]	162	137	122	112
6.5—8.5[c]	42	49	35	37
8.5—10.5[d]	39	22	25	13
>10.5[d]	29	0	0	0

[a] h = 4.8 m is upper target water level in dry seasons (4.5 m) + 0.3 m.
[b] h = 6.5 m is upper target water level in dry seasons (4.5 m)＋2m.
[c] h = 8.5 m is upper target water level in dry seasons (4.5 m)＋4m.
[d] h = 10.5 m is upper target water level in dry seasons (4.5 m)＋6m.

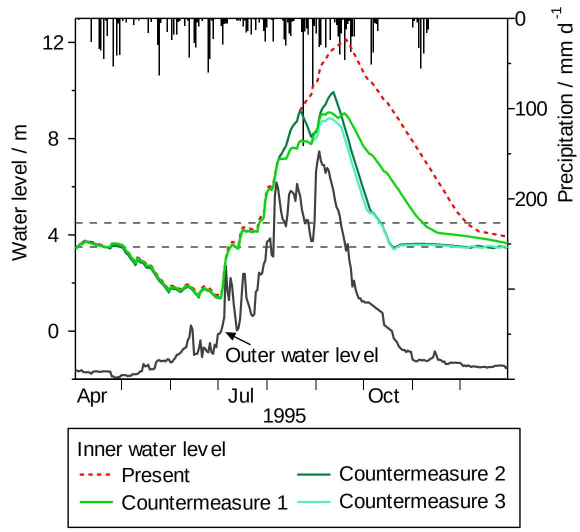

Figure 10 Daily inner/outer water levels at the Pak Cheng Water Gate, and precipitation in each countermeasure (1995)[a, b]

[a]Dash lines in the upper figure show two target water levels ranging from 3.5 m to 4.5m in dry seasons.

[b]Outer water levels were converted into water levels with a reference point as the river bottom at the water gates.

5.0 CONCLUSIONS

This study assessed impacts of agricultural water gate on inundation damage in low-lying paddies in the Lao PDR. The evaluation of the water gates was based on the distributed water circulation model considering agricultural water use, the *H-V* curve, and the hydraulic model for gate operations. Simulation results proposed three effective countermeasures for operational flood protection. The countermeasures accounted for inner/outer water level differences to against back-water affects and drainage through the gates even when outer water levels were relatively high.

Further study, however, for the proposed countermeasures would be carried as flood prevention practices on site.

Acknowledgement

This research was supported by a subsidy from the Japanese Institute of Irrigation and Drainage (JIID) entitled "Study on disaster management planning in rural areas." We acknowledge the Japan International Research Center for Agricultural Sciences (JIRCAS) for providing the hydrological and meteorological data.

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