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Applicability of Water Level Monitoring System and Water Level Estimation System to Tank Cascade in Sri Lanka

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Abstract

A tank cascade system consisting of several small earth dams has been developed for the irrigation system in Sri Lanka. The frequent flooding in recent years has led to the collapse of small earth dams or their spillways (Oka et al. 2013). Such collapse poses a danger to people living downstream. Therefore, disaster prevention measures including water management must be improved to prevent overflow of the embankments and the flooding of populated areas. Small earth dams and spillways frequently collapse in Japan as well. Systems have been developed for monitoring and predicting water levels in reservoirs to reduce the damage from flooding. This paper introduces the water level monitoring system and water level estimation system in tank cascades in Sri Lanka to improve disaster prevention measures. We successfully monitored the water level of small earth dams from a remote location, and the water level estimation system in Sri Lanka was used to calculate the water level of small earth dams.

Discipline: Agricultural Engineering
Additional key words: disaster prevention, heavy rainfall, small earth dam, storage function method, flood

Introduction

In Sri Lanka, the dry zone accounts for approximately 70% of the country's landmass from the northern to central regions (Chandana 2012). The climate of the dry zone is strongly influenced by the monsoon, and clearly classified into a rainy season extending from October to March and a dry season from April to September. The average annual rainfall in the dry zone is less than 1,750 mm, of which the rainy season accounts for 80%. Agricultural production activities are particularly low during the dry season (Geekiyange & Pushpakumara 2013).

Water from rainfall has been stored in small earth dams for irrigation purposes since ancient times. There are about 15,000 small earth dams throughout the entire region, with about 12,000 small earth dams in the northern, north-central, and northwestern regions that constitute the dry zone (Panabokke et al. 2002). A unique system was developed in the dry zone for the efficient utilization of stored water. Some of the water in an upstream small earth dam is stored in a downstream tank and used for irrigation. In the rainy season, water exceeding the bottom of a spillway (called normal water level) is discharged from the spillway and stored in a downstream dam. Madduma (1995) defined this system as a tank cascade system. The tank cascade system consists of several small earth dams. Figure 1 shows a schematic representation of the tank cascade system. The tank cascade system is an important water storage facility managed by villagers (Bebermeier et al. 2017). However, more irrigation water is required due to low reservoir capacity and meager rainfall in the dry season (Asian Development Bank). In this paper, a reservoir refers to storing water in a small earth dam, which is often called a tank in Sri Lanka.

Regular floods in the rainy season have occurred in recent years (Ministry of Disaster Management 2018). Flooding leads to the collapse of embankments or damage to their spillways. Upon surveying dams in Anuradhapura

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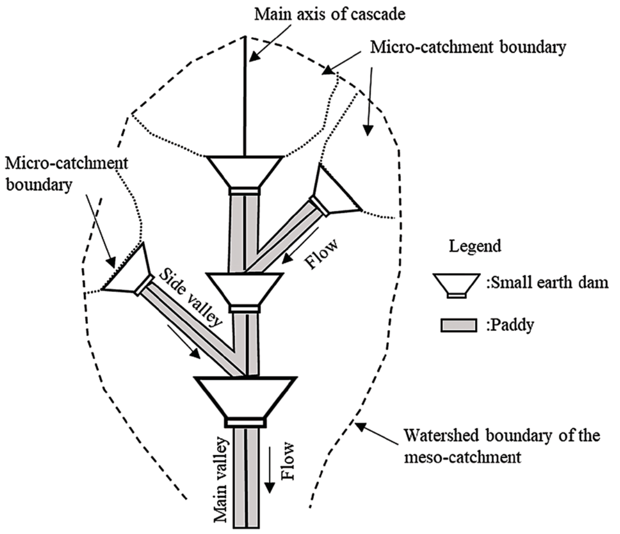

Fig. 1. Conceptual diagram of a tank cascade system (adapted from Panabokke 2013)

District in 2017, we found that 67 small earth dams had collapsed. It is thus necessary to renovate embankments and spillways, and improve disaster prevention measures including better water management. The Sri Lanka government has formulated the North Central Province Canal Program to supply irrigation water to the dry zone in the northern central region. One goal is to reduce the damage due to heavy rainfall (Asian Development Bank).

In recent years, embankments and spillways have also collapsed in Japan due to frequent heavy rainfall (Izumi et al. 2018). There are about 170,000 small earth dams in Japan. In 2019, a total of 63,722 dams were deemed to pose a risk of damage to residents in the event of a collapse (Ministry of Agriculture, Forestry and Fisheries). Among these dams, 3,634 were investigated for safety against heavy rainfall, and 1,399 require construction countermeasures against heavy rainfall. These efforts entail a significant cost and lengthy construction period, as countermeasures against heavy rain are insufficient. The water levels of small earth dams must also be lowered before heavy rainfall events to prevent the collapse of small earth dams. And dam administrators must instruct residents to seek refuge before the potential overflow of small earth dams.

To implement the above measures easily, we developed a water level estimation system for small earth dams during heavy rainfall (Hori et al. 2015) and a water level monitoring system. The water level monitoring system can accurately monitor water levels from a remote location. The water level estimation system can predict water level from a rainfall forecast and calculate it based on the assumed heavy rainfall. By using the estimation system in Sri Lanka, it is possible to clarify the amount of heavy rainfall that could cause embankment overflow, thus allowing evacuation instructions to be promptly issued to residents living near small earth dams.

This paper introduces the water level monitoring system in order to confirm its applicability. The monitoring system was installed in a small earth dam and used for real-time water level monitoring at the Provincial Irrigation Department Office (PIDO) in Anuradhapura. The water levels calculated from rainfall data by the water level estimation system are compared with measured values in Kiulekada near Anuradhapura, located in the North Central Province.

Study site

The study site in the North Central Province is Kiulekada, located 50 km northeast of Anuradhapura (Fig. 2). Most of Anuradhapura is in the dry zone. Ten small earth dams in the tank cascade system are applied for the two systems (Fig. 3).

Given the high cost of the system equipment, the water level monitoring system was only introduced at the most upstream Tank 1 in September 2017. A monitoring PC was set up at the PIDO in Anuradhapura (hosting the server). The water level estimation system calculated the water levels of nine dams (except for Tank 2) from the rainfall data. The water levels in these dams have been measured since October 2016 as shown in Figure 3.

These water gauges were set beside the sluices of dams. The sluice is a gate to discharge water from a reservoir for irrigation. To avoid the effects of water flow and dust, PVC pipes with multiple small holes are fixed beside the sluice of each dam. Water gauges were installed in the PVC pipes. In Kiulekada, water levels were calculated from January 26 to 29 during the rainy season in 2017. Figure 4 shows the time history of hourly rainfall for the period.

Water level monitoring system

The water level monitoring system measures the water level in a dam in real time from a remote location via the Internet. Figure 5 shows a conceptual diagram of the system. The system consists of a water gauge (OSASI Technos Inc.), communication equipment (OSASI Technos Inc.), a water level data logger (OSASI Technos Inc.), battery, three solar panels, and a monitoring PC. The water level measured every hour is displayed on the monitoring PC.

A stable and reliable communication state of the Internet, and a sufficient duration of sunshine for solar energy are necessary for introducing the system.

The field intensity of mobile communication must be higher than −95 dBm to obtain measurement values on the monitoring PC. At least 1.5 hours of sunshine are required to operate the communication equipment and data logger for one day. The charged battery can last for seven days when fully charged without sunshine.

Water level estimation system

1. Storage function method

The water level estimation system utilizes outflow analysis for small earth dams to calculate the time history of water levels by using the storage function method (Nagai et al. 2003). When assuming a watershed to be a reservoir, the method uses the following basic equations:

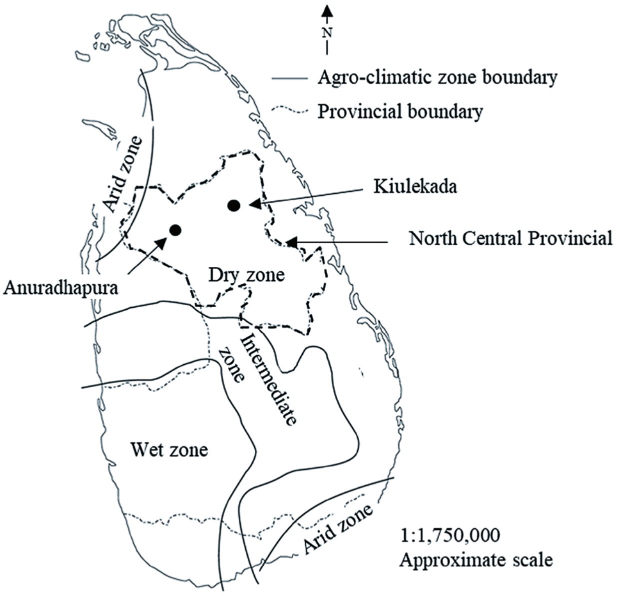

Fig. 2. Climate map of Sri Lanka (adapted from Panabokke 2013)

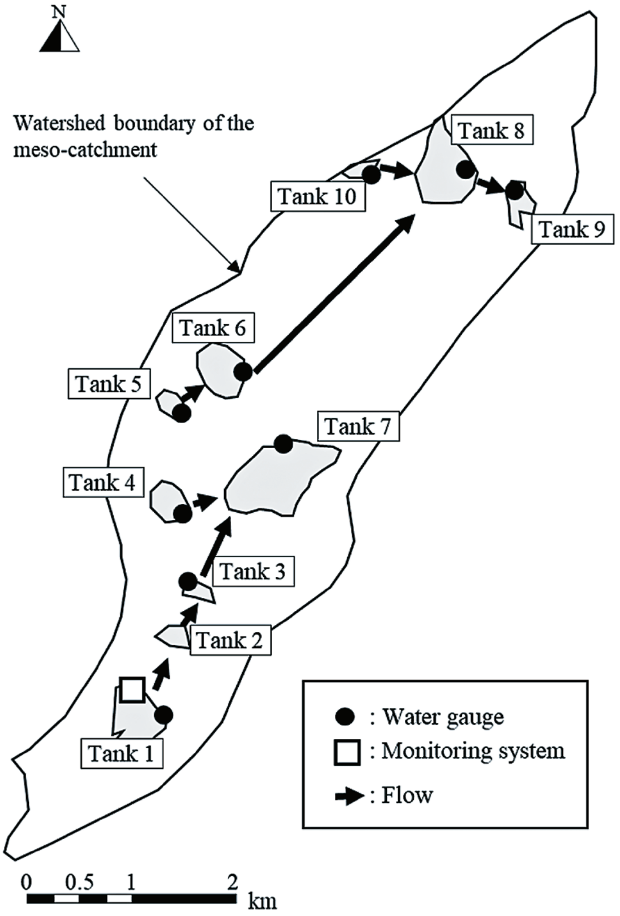

Fig. 3. Location of the ten small earth dams

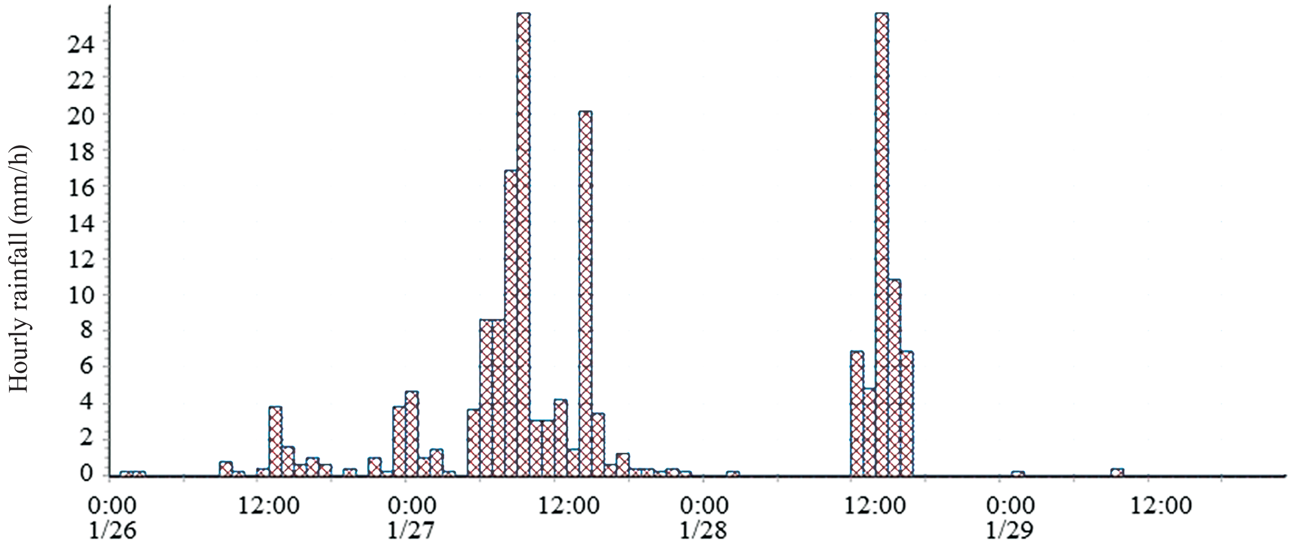

Fig. 4. Time history of hourly rainfall in Kiulekada

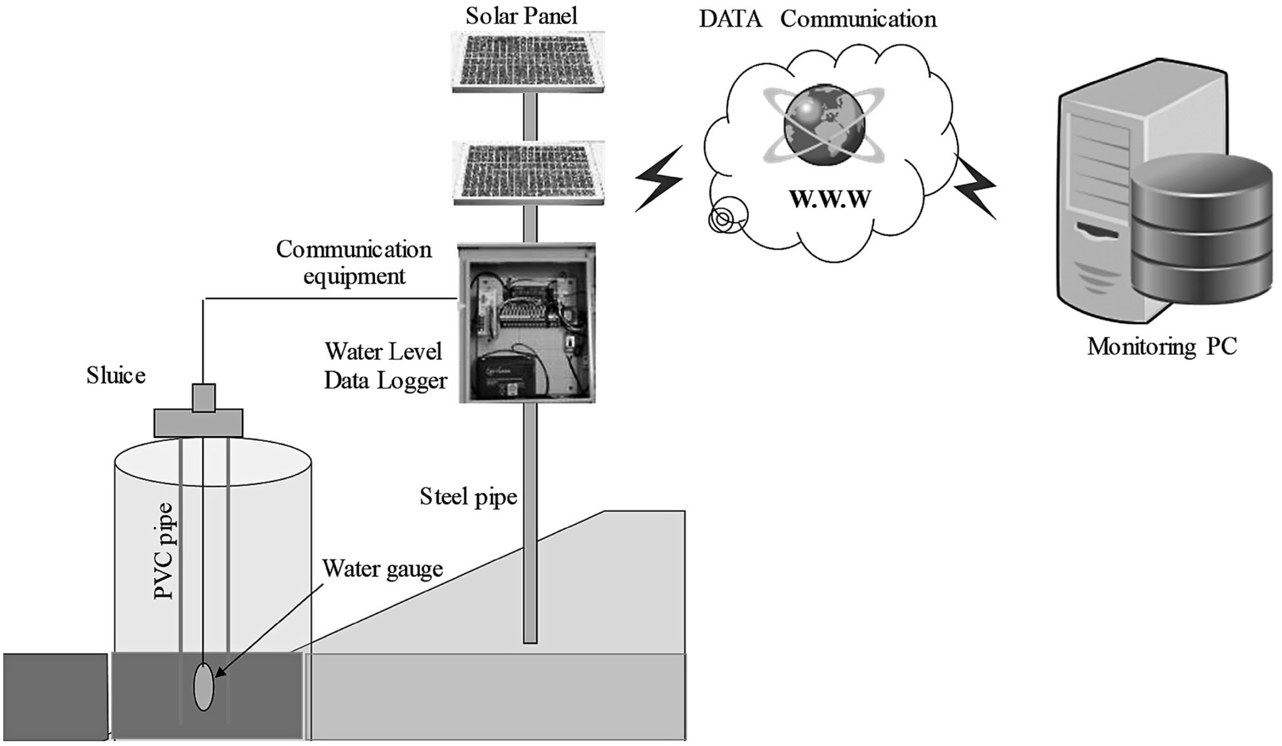

Fig. 5. Conceptual diagram of the monitoring system

$$\frac{dS}{dt} = r_e - q_{in} \tag{1}$$

$$S = Kq_{in}{}^{P} \tag{2}$$

where S is the apparent storage of the reservoir (m), t is the time, r_e is the intensity of effective rainfall (m/h), and K and P are constants. q_{in} is the direct runoff from the reservoir (m/h) and the following equation is established.

$$q_{in}(t) = q_d(t+T) \tag{3}$$

where T is the time delay and q_d is the direct runoff from the reservoir considering the time delay. K is calculated from a simplified estimation formula based on the kinematic wave model as follows (Sugiyama et al. 1988):

$$K = \beta Ar_1^{0.14} \tag{4}$$

where β is determined by the land use (5 in a forest area, 1 in an intermediate area between a forest and an urban area, or 0.5 in an urban area), and $Ar_1$is the catchment area (km^2). P is 0.6.

2. Water level prediction using the storage function method

The water level of a small earth dam is calculated from the relation between rainfall in the catchment area and discharge from the spillway and outlet conduits as follows (Hori et al. 2010):

$$A(H)\frac{dH}{dt} = MAr_2 q_{in} - q_{sp} - q_{ol} \tag{5}$$

where H is the water level in the small earth dam (m), and $A(H)$ is the reservoir area as a function of the water level (m^2). M is the correction coefficient of the catchment area, Ar_2 is the catchment area (m^2), q_{sp} is discharge from the spillway (m^3/h) (U.S. Department of the Interior 1987) and q_{ol} is discharge from the intake facility (m^3/h) (Ministry of Agriculture, Forestry and Fisheries 2015). The discharge from the spillway (q_{sp}) and that from the intake facility (q_{ol}) are obtained as follows:

$$q_{sp} = BC_{sp}H_{sp}^{\frac{3}{2}} \tag{6}$$

$$q_{ol} = aC_{ol}\sqrt{2gH_{ol}} \tag{7}$$

where B is the width of the spillway, C_{sp} is the flow coefficient of the spillway, and H_{sp} is the overflow depth of the spillway. C_{sp} is determined for the cross-sectional shape of the spillway (Ministry of Agriculture, Forestry and Fisheries 2015). a is the cross-sectional area of the outlet conduit, C_{ol} is the flow coefficient of the intake facility, and C_{ol} is 0.62 (Ministry of Agriculture, Forestry and Fisheries 2015). g is the gravitation acceleration, and H_{ol} is the water level from the center of the sluice.

It is difficult to accurately calculate the catchment area from topographic information. In this system, correction coefficient *M* is introduced to correct the water catchment area. *M* is determined by fitting the maximum analysis value and the measured water level.

3. Analysis condition

In the cascade, water discharged from the spillways flows into the downstream dams. The water level is calculated by adding the inflow from upstream (q_{spu}) to Eq. 5 as follows:

$$A(H)\frac{dH}{dt} = M\,Arq_{in} - q_{sp} - q_{ol} + q_{spu} \tag{8}$$

Ar is not the entire cachement, but the area excluding the catchments of the upper dams. The time delay on q_{spu} is assumed to be 10 min. for a distance of 200 m between the upstream and downstream dams, because detailed data on the canal between the upstream and downstream dams could not be obtained. Judging from the field survey results, the amount of inflow from the upstream spillway to the downstream dam should be 80% of the amount of discharge from the upstream dam, because the path from the upstream dam to the downstream dam passes through the channel and the field. The relation between the reservoir area and water levels for both dams was surveyed, and thus *A*(*H*) is modeled as follows:

$$A(H) = \left\{ 0.993 \cdot \left(\frac{H}{H_n} \right)^{1.59} \right\} \cdot A_n \tag{9}$$

where H_n is the normal water level and A_n is the area at the normal water level. Normal water level means the highest water level that can be stored in the reservoir.

In the cascade consisting of 10 small earth dams in Kiulekada near Anuradhapura located in the north-central region, we used this system to calculate the water level of each dam. Table 1 lists the analysis conditions. The heights of the dams are approximate values that do not affect the analysis results. For all dams, the amount of discharge from the intake facility is assumed to be zero as the runoff from the intake facility hardly affects the calculated water level during heavy rainfall. *M* for each dam is determined by fitting the maximum analysis value and the measured water level to the rainfall from January 26 to 29, as shown in Figure. 4.

Results and discussion

1. Applicability of the water level monitoring system

Measuring the field intensity of mobile communication in the tank cascade in Kiulekada revealed that the field intensities of Tank 1, Tank 7, and Tank 8 were −81 dBm, −59 dBm, and −69 dBm, respectively. As the required field intensity of mobile communication in the monitoring system is higher than −95 dBm, data communication is possible in this area. The necessary duration of sunshine was satisfied for solar panels and other equipment installed on the sluice (Fig. 6).

The water level in Tank 1 was displayed on the monitoring PC at the PIDO (Fig. 7). The graph shows the time history of the water level, with the bottom of the sluice at 0 m. The water level was continuously acquired except at 2 p.m. on 9/11 when we checked the data logger and the communication equipment. This result showed that the field intensity of mobile communication in Tank 1 was stable. After completing system installation, we trained the PIDO staff in terms of a system overview and the method of operation.

Based on the above results, the system has applicability in Sri Lanka. It is easy to monitor water levels of the dams by using the system. Moreover, the system can predict embankment overflow before it occurs, making it possible to issue an evacuation order to downstream residents.

2. Applicability of the water level estimation system

(1) Analysis results

Figure 8 shows the hydrographs of measurement and analysis values for Tanks 1, 3, 4, 5, 6, 7, 8, 9 and 10, respectively. The water level is zero at the bottom of the spillway in Figure 8. The hydrographs of analysis values correspond to the hydrographs of measurement values for Tanks 1 and 5. The times at which the analysis and measurement values increase are equivalent, and the analysis values roughly match the measurement values for Tanks 6, 7, 8, and 9. For Tank 9, the analysis value is larger than the measurement value from 06:00 on January 27th to 18:00 on January 28th. For Tank 10, the analysis value increases earlier than the measurement value, but the difference in water level between the analysis and measurement values is small in the other parts. This is because the relation between the reservoir area and water level shown in Eq. (9) does not partially match. In order to completely predict the water level, the relation between reservoir area and water level must be measured for each dam. For Tank 3, the analysis value increases from 12:00 on January 26th. On the other hand, the measurement value increases from 00:00 on January 27th. This result indicates that *A*(*H*) does not fit the actual reservoir area. Under the analysis conditions, a time lag does not occur for the other small earth dams. Therefore, *A*(*H*) and *T* obtained from the detailed field survey must be modified for Tank 3. For Tank 4, the analysis value draws a hydrograph similar to those of other dams, but the

Table 1. Analysis conditions

Small earth dam		Puliyankulam	Halmillawatya	Ikirigollawa	Nawagha wewa
Tank No.		Tank 1	Tank 3	Tank 4	Tank 5
Dam	Height (m)	5	5	5	5
	Catchment area (km^2)	2.6	0.9	0.3	0.9
	Reservoir area (km^2)	0.02	0.07	0.03	0.07
Spillway	Width (m)	15	17	10	17
	Flow coefficient	1.2	1.2	1.2	1.2
Sub spillway	Width (m)	18	-	-	-
	Flow coefficient	1.2	-	-	-
Parameter, *K*		5.209	5.709	4.903	4.204
Parameter, *P*		0.6	0.6	0.6	0.6
Land use		Forest area	Forest area	Forest area	Forest area
Correction coefficient, *M*		1.35	0.45	0.50	1.25
Downstream Tank 1	Tank No.	Tank 7	Tank 7	Tank 6	Tank 7
	Delay time (min.)	50	30	20	30
	Distance (m)	957	574	365	574
Downstream Tank 2	Tank No.	Tank 7	-	-	-
	Delay time (min.)	50	-	-	-
	Distance (m)	957	-	-	-

Small earth dam		Kudagama	Gonahathdenawa	Kiulekada	Kulakada Ihal wewa	Galkadawala
Tank No.		Tank 6	Tank 7	Tank 8	Tank 9	Tank 10
Dam	Height (m)	5	5	5	5	5
	Catchment area (km^2)	1.1	5.5	11.1	0.84	0.32
	Reservoir area (km^2)	0.14	0.47	0.25	0.05	0.04
Spillway	Width	30	23	26	38	10
	Flow coefficient	1.2	1.2	1.2	1.2	1.2
Sub spillway	Width	-	-	-	-	-
	Flow coefficient	-	-	-	-	-
Parameter, *K*		5.067	6.353	7.002	4.879	4.263
Parameter, *P*		0.6	0.6	0.6	0.6	0.6
Land use		Forest area	Forest area	Forest area	Forest area	Forest area
Correction coefficient, *M*		1.00	0.75	0.40	0.45	1.40
Downstream Tank 1	Tank No.	Tank 8	-	Tank 9	-	Tank 8
	Delay time (min.)	120	-	10	-	20
	Distance (m)	2324	-	272	-	435
Downstream Tank 2	Tank No.	-	-	-	-	-
	Delay time (min.)	-	-	-	-	-
	Distance (m)	-	-	-	-	-

measured value decreases to −1.5 m regardless of the increase in rainfall as shown in Figure 4. After the measured value increased to −1.35 m due to rainfall from 12:00 to 17:00 on January 28th, the measured value decreased again to −1.5 m. Regardless of the values substituted for M, the hydrograph of analysis does not match the hydrograph of measurement. This suggests that someone opened the intake facility gate or there was leakage in the embankment at −1.5 m, because the water gauge was not broken.

(2) Suitability of parameters *P* and *K*

These results show that the designed system is compatible with tank cascades in Sri Lanka. As mentioned above, *P* is fixed at 0.6 and *K* depends on the land use in Japan in the estimation formula.

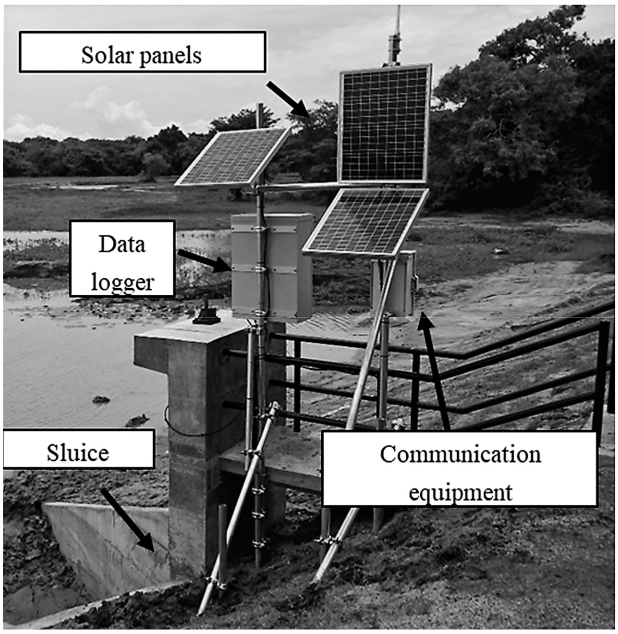

Fig. 6. Installation of solar panels, data logger, and communication equipment

Conclusion

In a tank cascade in Sri Lanka, we installed the water level monitoring system and successfully monitored the water levels of small earth dams from a remote location. This showed that the monitoring system can be installed in small earth dams in other tank cascades where the necessary communication state of the Internet and the duration of sunshine are available. The results showed that the monitoring system has applicability in Sri Lanka for predicting the risk of embankment overflow in tank cascades during heavy rainfall, and thus reducing the damage to people living downstream when small earth dams collapse. In the estimation system, analysis parameters were determined for such dams, and the water levels in nine dams were calculated from rainfall data. The hydrographs of analysis values corresponded to those of the measurement values for two dams. And the analysis values roughly matched the measurement values for four dams.

In order to apply the estimation system to small earth dams in Sri Lanka, a detailed field survey must be conducted on embankment water leakage and the relation between reservoir area and water level. As future work, we plan to validate the precision of analysis values for these small earth dams at different periods.

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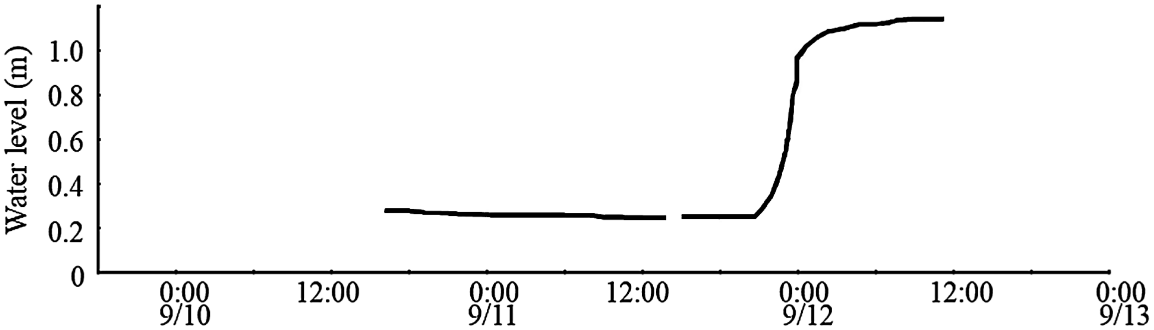
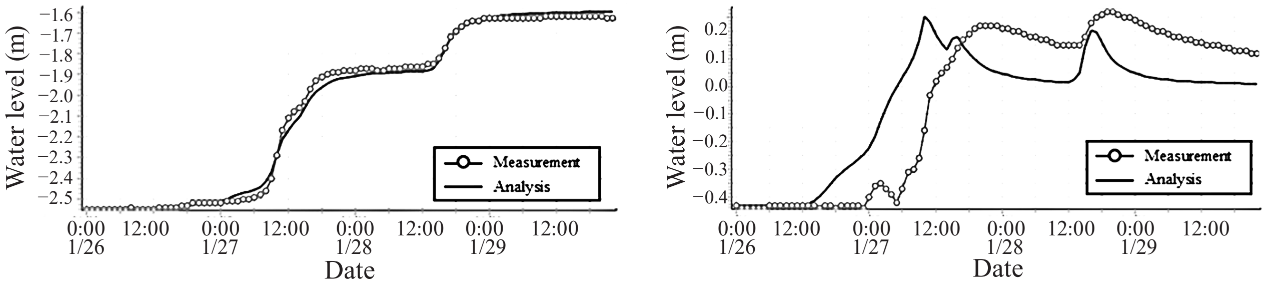
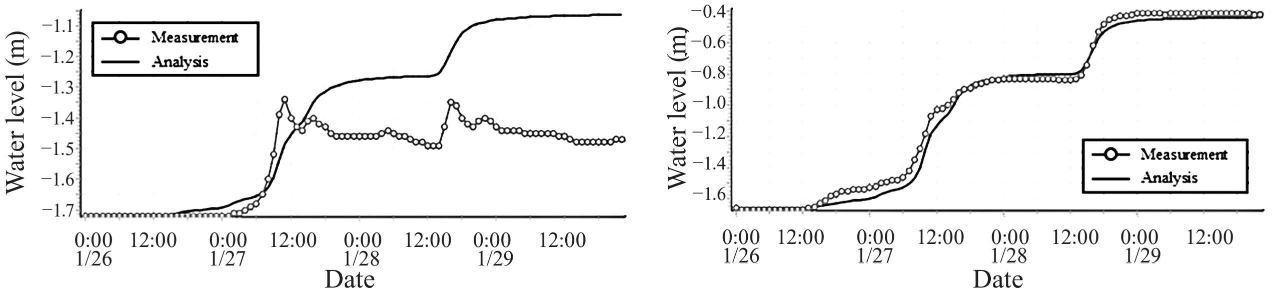


Fig. 7. Hydrograph of Tank 1 obtained by the monitoring system



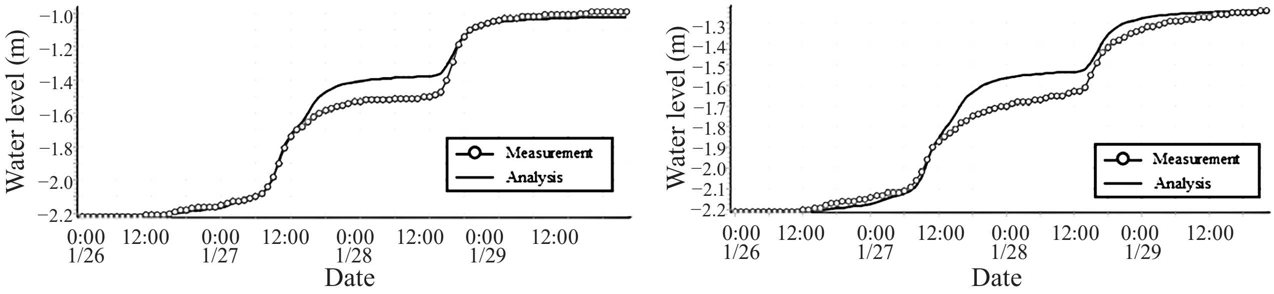
(a) Tank 1

(b) Tank 3



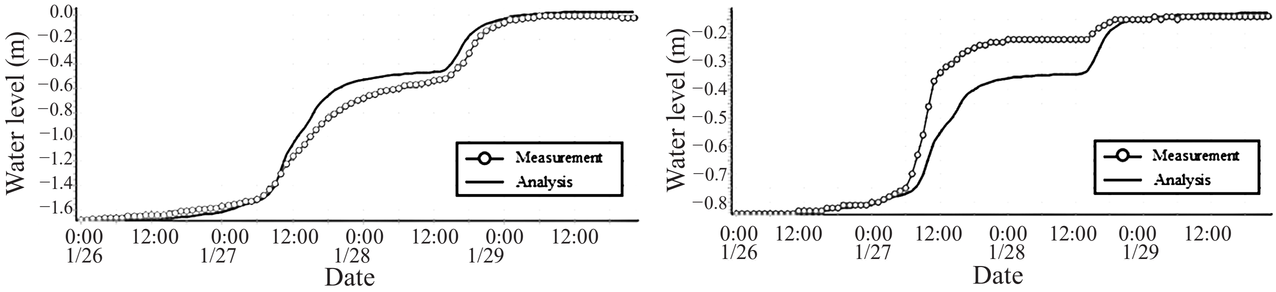
(c) Tank 4

(d) Tank 5



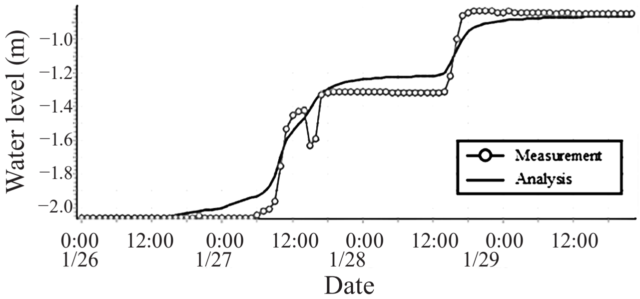
(e) Tank 6

(f) Tank 7



(g) Tank 8

(h) Tank 9



(i) Tank 10

Fig. 8. Hydrographs of measurement and analysis values for small earth dams

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