Landslide dam hydrological observation and hydrological balance calculation procedures

Soichi KAIHARA[1*], Noriko TADAKUMA[1], Yasumasa FUJIWARA[1],
Wataru SAKURAI[2], Makoto OYAMA[3] and Ryo SAKAI[2]

[1] Eight-Japan Engineering Consultants Inc. (3-1-21 Tsushimakyomachi, Okayamashi, Okayama, 7008617, Japan)
[2] Kii Mountain Area Sabo Office, Kinki Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism (1681 Sanzaicho, Gojoshi, Nara, 6370002, Japan)
[3] Kinki Regional Bureau, River Division, Ministry of Land, Infrastructure, Transport and Tourism (1-5-44, Otemae, Chuo-ku, Osaka, 5408586, Japan)
*Corresponding author. E-mail: kaihara-so@ej-hds.co.jp

Typhoon No.12 in September 2011 brought about record-setting heavy rainfall in the south of Nara Prefecture, with the result that a great number of landslide dams were formed in the south of Nara Prefecture and Wakayama Prefecture. If there is a rise of water level or overflow, the landslide dam may cause a serious erosion or corruption of the dam body. This makes it essential to measure the water level in the event of rainfall. This paper introduces the hydrological observation procedure for identifying the outflow characteristics serving as a reference for estimation of the landslide dam water level and the hydrological balance calculation procedure for positions where continuous inflow measurement upstream of the flooding reservoir of the landslide dam, as well as calculation examples.

Key words: landslide dam, hydrological observation, hydrological analysis, hydrological balance

1. Introduction

Typhoon No.12 in September 2011 caused a continuous rainfall in excess of 1000 mm in the south of Nara Prefecture, and formed 17 landslide dams in Nara Prefecture and Wakayama Prefecture. If there is a heavy rainfall subsequent to formation of the landslide dam and overflow is caused by increased water level, the dam body will be subjected to serious erosion and debris may be discharged into the downstream area. For example, the dam body of the landslide dam in Kuridaira area of Totsukawa Village of Nara Prefecture was eroded by the Typhoon No.18 in 2013 [*Sakurai et. al.*, 2014]. Estimation of the fluctuation in the water level in the event of rainfall constitutes a crucial item for risk management.

To estimate the water level in the landslide dam, it is required to identify factors such as the relationship between the rainfall and discharge in the relevant basin, and the volume of leakage. The following introduces the procedure for hydrological observation of the formed landslide dam and calculating the hydrological balance without continuous current measurement in the river channel upstream of the landslide dam. Further, the Kii Mountain Area Sabo Office, Kinki Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism conducted a hydrological balance

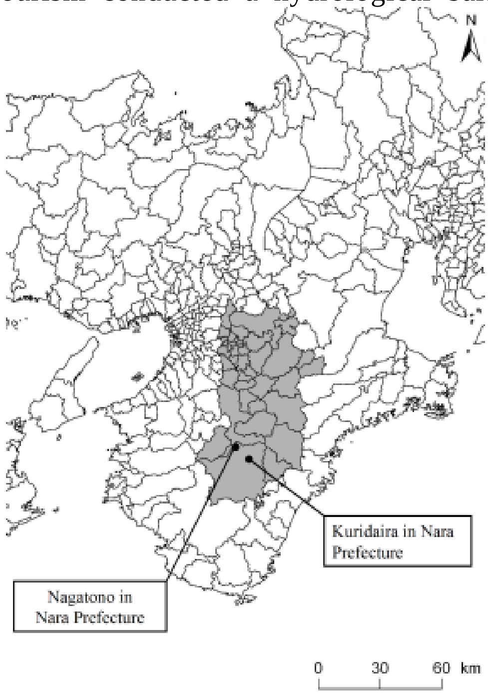

Fig. 1 Scope of study area

calculation at the time of a deluge in 2012, for two landslide dams (**Fig. 1** and **Table 1**) in the Kuridaira area and Nagatono area in the south of Nara Prefecture where countermeasure work is currently under way.

2. Hydrological survey for landslide dam hydrological balance calculation

2.1 Concept of landslide dam hydrological balance

A concept of landslide dam hydrological balance was summarized as **Fig. 2** for hydrological survey to identify hydrological balance on the periphery of the landslide dam.

Part of the rainfall upstream of the landslide dam enters the flooding reservoir. If the full water level is not reached, the water level will increase, and water is absorbed by increased water level. If the full water level has been reached, water is discharged into the overflow channel. Further, water in the flooding reservoir leaks from the landslide dam body or the bottom of the flooding reservoir. If a pump is used for drainage, water in the flooding reservoir is discharged downstream by the pump operation.

In hydrological observation to identify the landslide dam hydrological balance, it is necessary to identify the inflow into the flooding reservoir, changes of overflow rate and flow rate of drainage pump in order to identify the chronological changes of the hydrological balance factors illustrated in **Fig. 2**.

Table 1 The summary of landslide dam

Area	The height of the dam	Reservoir capacity	Catchment area
Nagatono	80 m	1.9×10^6 m^3	4.63 km^2
Kuridaira	100 m	5.1×10^6 m^3	8.95 km^2

2.2 Hydrological observation on the periphery of the landslide dam

Many of the landslide dams are formed in the mountainous region not provided with commercial power source. In hydrological observation of the landslide dam where an engine generator cannot be installed, it is necessary to select the equipment that can be operated without a commercial power source. Further, when the hydrological data obtained by measurement is to be used to estimate the water level of the landslide dam, it is necessary to use the measuring system capable of transmitting data via the mobile phone network, the Internet and others on a real-time basis.

To meet these requirements, the Nagatono area and Kuridaira area where landslide dams were formed by Typhoon No.12 in 2012 were provided with the hydrological gauges illustrated in **Fig. 3**, including rain gauges, water level gauges for flooding reservoir, water level gauges upstream of the flooding reservoir and rectangular weirs downstream of the landslide dam. To calculate the volume of water passing through the landslide dam body, water levels in the bore holes of two dam bodies were also measured. These gauges are used for measurement on a regular basis.

To measure the inflow into the flooding reservoir, it is necessary to work out an H-Q curve at the position of the water level gauge upstream of the flooding reservoir. To work out an H-Q curve, it is necessary to measure the flow velocity by continuous measurement or to measure the flow velocity locally by man power using a float at the time of flood. The river channel in the basin of a mountainous area has no structure such as a dam, and contains a great deal of fluctuation in the cross section of the river channel. Accordingly, the environment is not suited for measurement of the

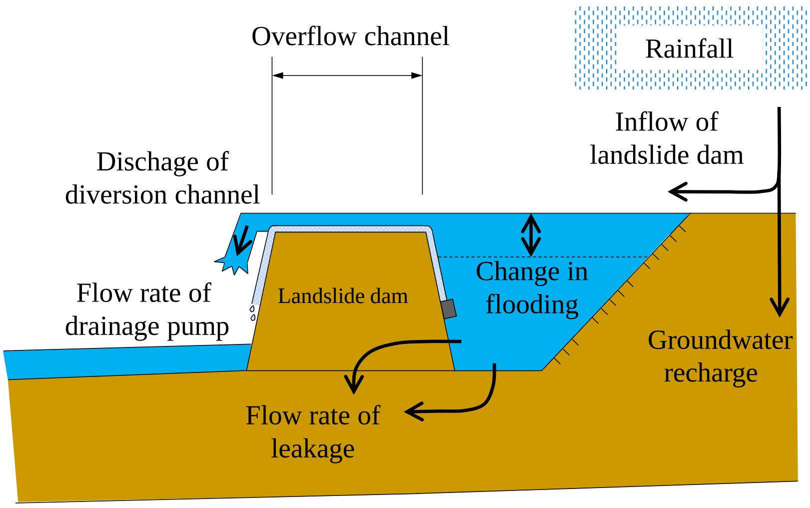

Fig.2 The concept of the hydrological landslide dam circumference

flow velocity. Further, there is no gauging equipment capable of continuous measurement of the flow velocity where there is no commercial power source, and gauging operation safety cannot be ensured when gauging the flow velocity at the time of flood by a float. These factors make it difficult to perform continuous measurement of the flow velocity.

However, even in the river channel in a mountainous area as in the area upstream of the flooding reservoir, the flow will be stabilized, and a magnetic current meter can be used to perform high-precision measurement of the flow velocity if the water level is low. Accordingly, this magnetic current meter was used to measure the flow rate measurement at the time of inspection of the gauges performed every month (**Photo 1** and **Fig. 3**).

In the Nagatono area, the spring water provides an environment suited for measurement, immediately downstream of the landslide dam. Thus, a rectangular weir was installed. For the water leaking from the landslide dam body, the flow rate becoming the surface water of the river channel downstream of the dam body was also measured.

3. Hydrological balance calculation procedure on the periphery of the landslide dam

3.1 Overview of hydrological balance calculation procedure for landslide dam

To estimate the full water level and overflow of the landslide dam, it is important to identify the height of rainfall that flows into the flooding reservoir and the volume of leakage. [*CHIBA et. al.*, 2012] has proposed a procedure for estimating the rainfall up to the full water level, pointing out the importance of identifying the effective rainfall by hydrological analysis.

When considering the hydrological balance of the landslide dam, it is important to identify the inflow into the landslide dam. As illustrated in 2.2, the flow rate at the time of deluge cannot be measured upstream of the landslide dam. Accordingly, when there was no overflow in the overflow channel, we paid attention to the fact that the inflow into the landslide dam was the result of adding the change in flooding reservoir to the flow rate of leakage in the landslide dam. Based on this, the hydrological balance was calculated [*Kinoshita et. al.*, 2013].

To put it more specifically, Darcy's law is applied to the data during the period of small inflow which can be subjected to high-precision measurement of the flow rate by a magnetic current meter, the change in flooding at that time (where the inflow is small and there is a small change in the water level of the flooding reservoir) and the water level in the bore hole of the landslide dam body. Then the coefficient of permeability of the dam body is obtained by backward calculation. Assume that the coefficient of permeability obtained by backward calculation does not change during the deluge. Then the flow rate of leakage in the event of deluge can be estimated. The result of adding the flow rate of leakage at the time of deluge to the change in flooding represents the inflow of the

Photo 1 Measuring the Flow rate by magnetic current meter

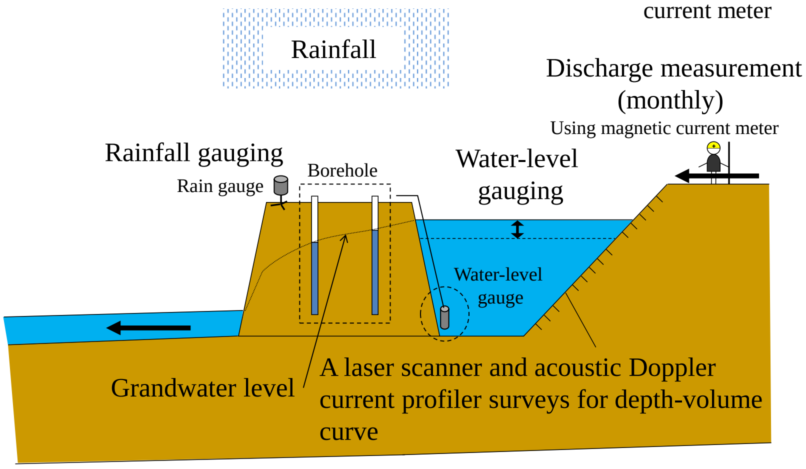

Fig. 3 The hydrological balance observation method for the landslide dam circumference

landslide dam. Further, if water is drained by pumping, the volume drained by pumping is added. If full water level is reached and overflow occurs, the overflow rate obtained by uniform flow calculation is added. **Fig. 4** shows the flow of a series of these calculations.

3.2 Coefficient of permeability of the landslide dam body used for calculation of the flow rate of leakage

In the period of lower water level with reduced flow rate upstream of the landslide dam, a high-precision H-Q curve is created, based on the result of measuring the flow rate by a magnetic current meter, to calculate the inflow during the period when there is no fluctuation in the water level of the landslide dam (Step 1 of **Fig. 4**). We paid attention to the fact that, when there is no fluctuation in the water level of the landslide dam, the inflow into the landslide dam and flow rate of leakage from the landslide dam are equal to each other. Based on this fact, the coefficient of permeability used for calculation of the landslide dam hydrological balance was obtained. To put it more specifically, using the data on the water level inside the two bore holes upstream and downstream installed on the crown of the dam body; we calculated the cross-sectional area of flow in the dam body and hydraulic gradient. This calculation yields the coefficient of permeability.

In two bore holes, the topographic line prior to generation of the landslide dam and the sectional area formed by the water level in the holes are assumed as a cross-sectional area of flow. The average value of the two sectional areas was assumed as the cross-sectional area of flow for calculation of the coefficient of permeability. Further, hydraulic gradient was obtained from the distance between two bore holes and the difference between water levels. Using the inflow (=flow rate of leakage) into the landslide dam at the time of smaller fluctuation in the water level of the landslide dam, cross-sectional area of flow in the dam body, and the hydraulic gradient obtained from the water levels in two bore holes, we calculated the coefficient of permeability in conformance to the following Darcy's law by backward calculation (Step 2 of **Fig. 4**):

$$Q = -k_s \cdot A \cdot \frac{\Delta h}{\Delta s} \tag{1}$$

Where Q: flow rate of leakage,
k_s: coefficient of permeability
A: cross-sectional area of flow
$\Delta h/\Delta s$: hydraulic gradient.

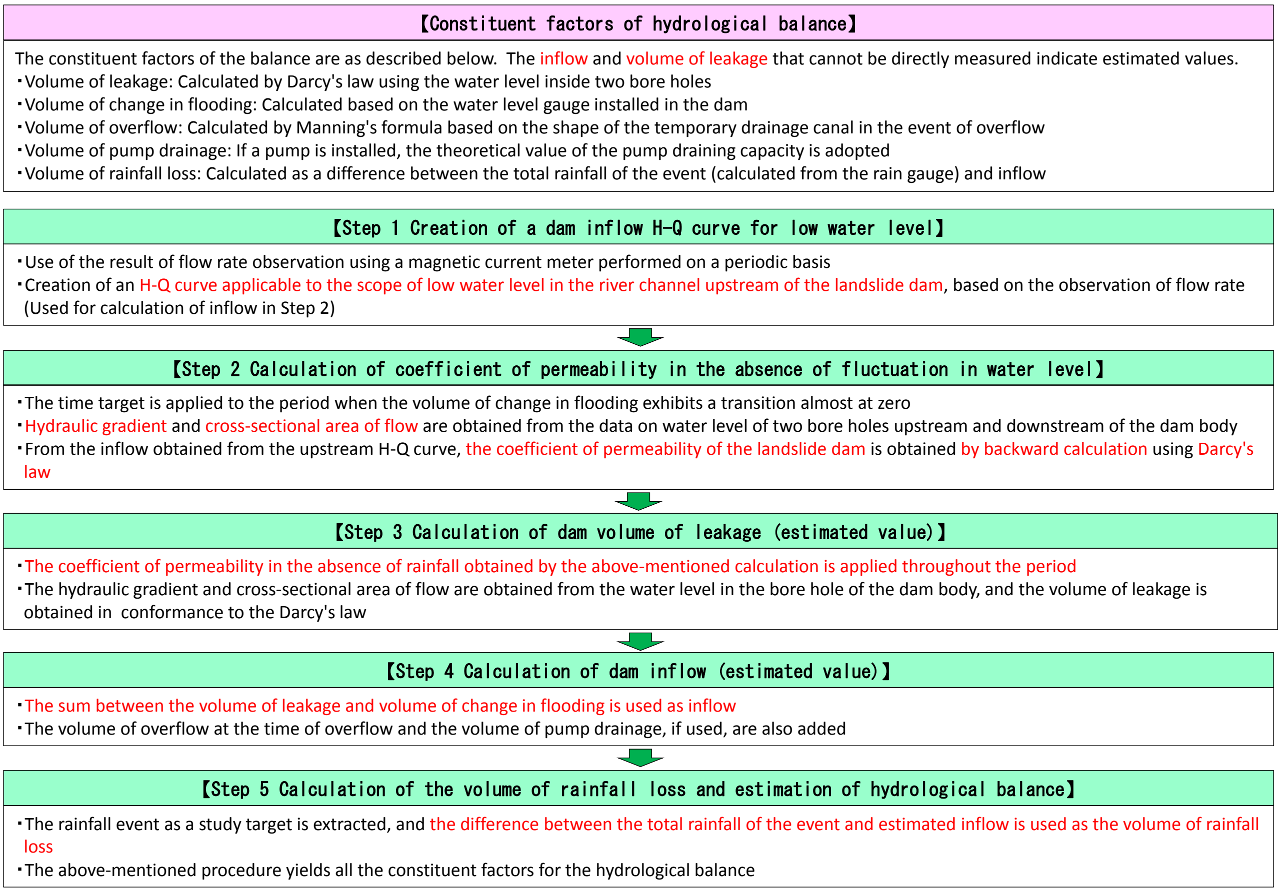

Fig. 4 Flow of calculation of hydrological balance in landslide dam

Fig. 5 and **Fig. 6** show the coefficient of permeability by backward calculation according to the above-mentioned procedure. They show that the values are approximately constant. We then calculated the average of the coefficients of permeability obtained from the above-mentioned backward calculation. We then calculated the flow rate of leakage at the time of deluge, using the average value of the coefficient of permeability obtained from the backward calculation and Formula (1) (Step 3 of **Fig. 4**).

3.3 Change in flooding, flow rate of drainage pump and overflow rate

An increase of inflow into the flooding reservoir causes an increase of the changes in flooding. This change in flooding was calculated based on the depth-volume curve created according to the data of the water level gauge of the flooding reservoir and the result of sounding by an ADCP (Acoustic Doppler Current Profiler). Further, the flow rate of drainage pomp was calculated on the basis of the pumping capacity and operation record. For the flow rate for the water discharged into the drainage canal after flooding reservoir is filled to the full level, the overflow rate can be calculated by uniform flow calculation since the drainage channel has a constant gradient.

3.4 Hydrological balance calculation

We calculated hourly values for rainfall by local observation, coefficient of permeability calculated backwardly as shown in 3.2, the flow rate of leakage obtained by Darcy's law, water level of the flooding reservoir shown in 3.3, change in flooding obtained from the depth-volume curve, flow rate of drainage pump, overflow rate and flow rate of the downstream river channel. Further, we obtained the total value of these flow rates, which were divided by the area of the basin. The result was then converted into the height of flow so that comparison with the rainfall could be made. Use of these procedures allows the hydrological balance to be identified, without the need of performing difficult measurement of the flow velocity upstream of the landslide dam. (Step 4·5 of **Fig. 4**)

4. Example of hydrological balance calculation in Nagatono area and Kuridaira area

In the hydrological balance calculation procedure discussed in Chapter 3, we calculated the hydrological balance for the major deluges of 2012 in the Nagatono area (**Fig. 7**) and Kuridaira area (**Fig. 8**).In the Nagatono area, higher percentages were observed in the volume of rainfall loss and dam flow rate of leakage in general. There was no overflow at the time of typhoon.

In the Kuridaira area, the percentage of the dam flow rate of leakage tended to be smaller. Further, the loss of hydrological balance was smaller and the overflow rate was greater at the time of Typhoon No.17.

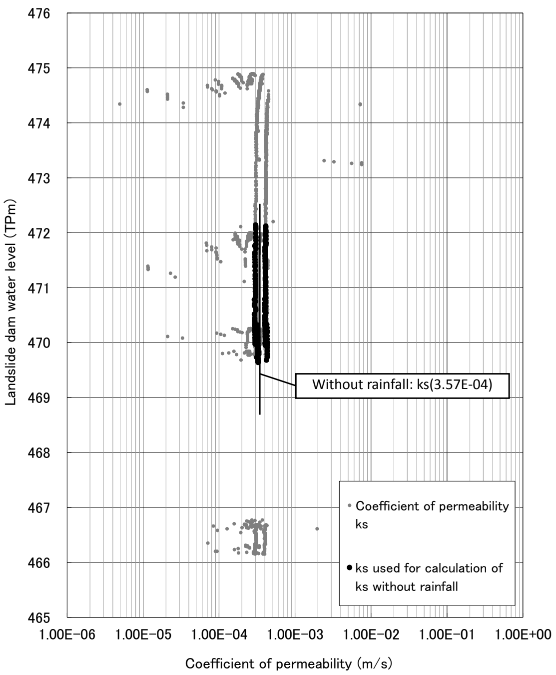

Fig. 5 Coefficient of permeability of landslide dam body obtained by backward calculation (Nagatono area)

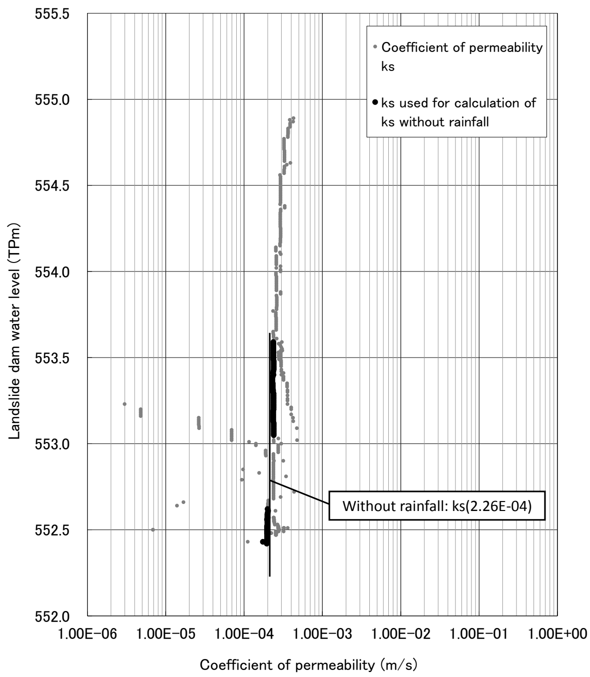

Fig. 6 Coefficient of permeability of landslide dam body obtained by backward calculation (Kuridaira area)

This can be considered to have been caused by a reduction in the water storage capacity of the basin and free capacity of the landslide dam flooding under the impact of the Typhoon No.16 having occurred two weeks before. **Fig. 9** illustrates each of the flow rates constituting the hydrological balance for the deluge in the Kuridaira area caused by Typhoon No.16 in 2012.

The dam inflow and change in flooding exhibit a linear behavior in conformance to the change in rainfall.

The dam flow rate of leakage and flow rate of drainage pump exhibit an almost constant value, where the percentage of the flow rate is smaller. The overflow occurred approximately at the end of the rainfall. The change in flooding was reduced with the overflow.

5. Conclusion

To estimate the water level at the time of deluge after formation of a landslide dam, it is necessary to identify the outflow characteristics of the basin. The inflow cannot be easily gauged due to environmental problems, for example, a current meter cannot be installed upstream of the landslide dam basin. However, the coefficient of permeability of the dambody can be calculated backward by using the water level data in the borehole of the landslide dam or by high-precision measurement of the flow rate with a magnetic current meter in the period of reduced inflow. Identification of hydrological balance has been enabled by estimating the flow rate of leakage and adding the change in flooding.

The hydrological balance calculation procedure introduced above has permitted the hydrological characteristics to be identified in the Nagatono area and Kuridaira area in the scope of this study.

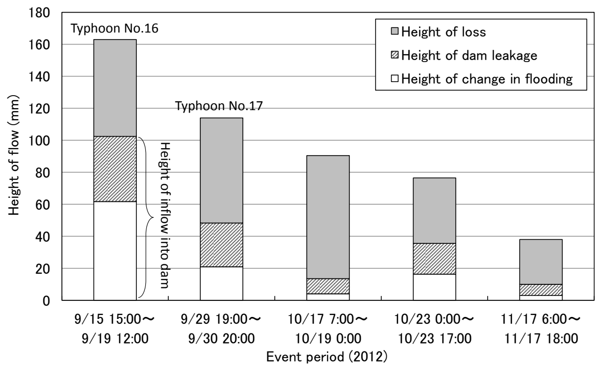

Fig. 7 Hydrological balance in the event of major deluge in 2012 (Nagatono Area)

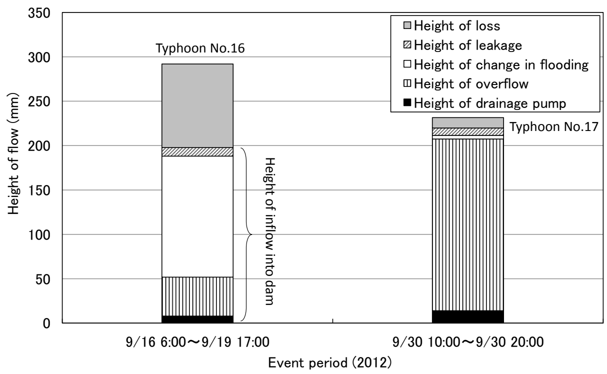

Fig. 8 Hydrological balance in the event of major deluges in 2012 (Kuridaira area)

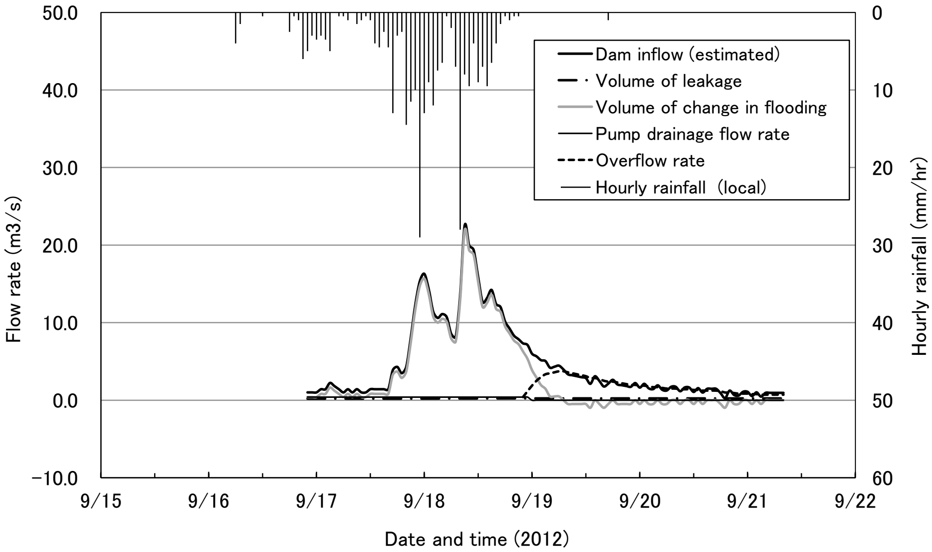

Fig. 9 Hydrograph of each hydrological balance element of Typhoon No.16 in 2012 in Kuridaira area

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