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Distributed rainfall–runoff analysis in a flow regulated basin having multiple multi-purpose dams

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Abstract This paper presents hydrological predictions and flood safety assessment in a flow regulated basin with multi-purpose dams. A distributed rainfall–runoff prediction system is developed by incorporating a dam reservoir operation model into a physically based rainfall–runoff model for simulating a highly regulated Japanese river basin, the Yodo River basin (7281 km^2), in which eight multi-purpose dams are currently operated. The test simulation for typhoon events verified that the system can simulate complex flood control operations such as preliminary release, peak attenuation, and water level maintaining. Following the test simulation, the developed system was applied to assess the flood safety level of the basin. The numerical experiments indicated that the basin is safe for a rainfall event of a 100-year return period due to the newly constructed multi-purpose dams, whereas it was safe only for a rainfall event of a 30-year return period in 1960.

Key words dam model; distributed rainfall–runoff model; flood safety level; flow regulation; human impact; peak attenuation; Yodo River basin

INTRODUCTION

The alterations of the hydrological cycle caused by environmental change indicate that observed information with past or current conditions may not be applicable for future predictions. It is essential for the perspective of Prediction in Ungauged Basin (PUB) to understand the scientific background of hydrological alterations induced by human activity and to predict the future hydrological cycle based on this understanding. One of the crucial flow regime changes is caused by dam reservoirs.

There are mainly two approaches for the assessment of flow regime change induced by dam reservoirs. One is the data driven approach (ex. Batalla *et al.*, 2004), which uses discharge data observed before and after dam constructions; the other one is the model approach, which uses hydrological models incorporated with dam reservoir models. The advantage of the model approach is the possibility of conducting various hypothetical experiments such as simulating unexperienced extreme flood events. Montaldo *et al.* (2004) combined dam models with a distributed rainfall–runoff model to simulate the effects of the dams on flood attenuation. Since the purpose of the dams they treated in their research was limited to hydroelectricity production, the dam could be modelled with a simple storage function.

This paper focuses on flood control with multi-purpose dams, which are operated in a complicated manner based on dam operation rules. The dam model developed in this study predicts outflow and water level with the input information of inflow, upstream rainfall and cooperative dam operations by modelling dam operation rules. A hydrological prediction system is constructed by incorporating the dam models with a distributed rainfall–runoff model. We developed this system for a highly regulated Japanese river basin, the Yodo River basin (7281 km^2). By using the system developed, we assess dam effects on flood control to investigate how the flood safety level has been increased by newly constructed dams and to understand which range of flood magnitudes the dams can regulate effectively.

This paper is composed of three main parts. The first part discusses the development of the rainfall–runoff prediction system incorporating dam models. The second part verifies the system with a typhoon rainfall event. The third part presents analysis of dam effects on flood control. Finally, we conclude with some insights into contributions of rainfall–runoff analysis considering human impacts to PUB.

A DISTRIBUTED RAINFALL–RUNOFF PREDICTION SYSTEM INCORPORATING A DAM OPERATION MODEL

Whole structure of the rainfall–runoff prediction system

The rainfall–runoff prediction system is constructed based on the "Object-oriented Hydrological Modelling System (OHyMoS)". The following four kinds of element models compose the whole system (Fig. 1).

(a) River element model: The kinematic wave model is applied to a river segment, which is prepared from the digital river-network data and the location information of lakeshores. Each river segment is cut to be about 3 km length.
(b) Sub-catchment element model: A saturated-unsaturated subsurface and surface runoff model (Tachikawa *et al.*, 2004) is applied to all grid-cells composing a sub-catchment. We used a digital elevation model with 250 m resolution to calculate the flow direction and to define the sub-catchment of each river segment.
(c) Lake element model: The lake element model is a simple mass-balance model to simulate water level from inflow, outflow, and rainfall information. We apply this model to Lake Biwa, of which outflow is simulated with the dam element model.
(d) Dam element model: A dam operation model is constructed with an "if-then" style based on each dam operation rule. We apply it to eight multi purpose dams in the basin. We refer to this site-specific dam operation model as a dam element model.

Sub-catchment element model

Figure 2 (a) shows a schematic diagram of the soil layer of the model, which takes into account three types of flow: unsaturated flow in capillary pore, saturated flow in non-capillary pores, and surface flow on the soil surface. In this figure, the soil depth is D (m), the water depth corresponding to the water content is d_s (m), and the water depth corresponding to maximum water content in the capillary pores is d_c (m).

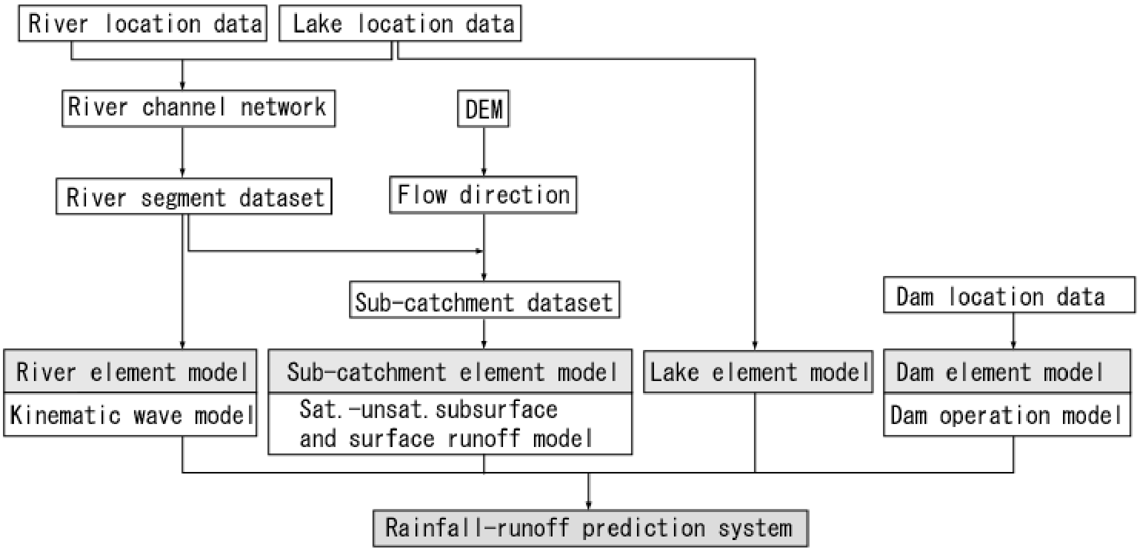

Fig. 1 Data processes and the whole structure of the system.

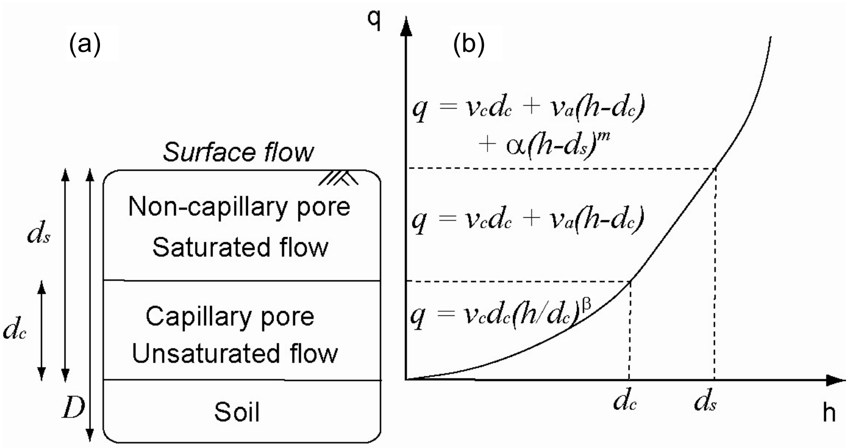

Fig. 2 Schematic diagram of the soil layer: (a) and stage–discharge relationship; (b) of saturated–unsaturated subsurface and surface runoff model.

Figure 2(b) shows the relationship between water depth and discharge of the model. Let k_c and k_a be saturated hydraulic conductivities in capillary pores and in non-capillary pores, respectively, and $v_c = k_c i$, $v_a = k_a i$ (i: slope), then a relationship between the discharge per unit width q ($m^2\ s^{-1}$) and the water depth h (m) are described as follows:

$$q = \begin{cases} v_c d_c \left(\dfrac{h}{d_c}\right)^\beta, & (0 \le h \le d_c) \\ v_c d_c + v_a(h - d_c), & (d_c < h \le d_s) \\ v_c d_c + v_a(h - d_c) + \alpha(h - d_s)^m, & (d_s < h) \end{cases} \tag{1}$$

where α equals to $i^{1/2}/n$; n is Manning roughness coefficient ($m^{-1/3}$ s^{-1}]. β [–] is the parameter to describe the reduction of hydraulic conductivity in capillary pore as the water content decreases. β equals k_a/k_c so as to keep the continuity of the depth–discharge relationship between the capillary pore and the non-capillary pore layers. Combining this depth–discharge relationship (1) and the continuity equation, we simulate rainfall–runoff from each grid-cell. The simulated discharge forms inflow to the downstream grid-cell. The water flow is routed until it reaches a river segment.

Dam element model

By formulating the dam operation rules and decision-making processes of dam operators, we develop the dam operation model. It predicts the outflow and water level of a dam with the input information of inflow, average rainfall in the dam catchment, and operation status of other related dams.

All the dams located in the Yodo River basin are multi-purpose dams. Although each dam has different operating rules, we can categorize all the flood control operations into the following six common operation processes (Ichikawa, 2001): Ordinary operation; Operation under flood warning; Preliminary release operation; Peak attenuation operation; Flood release operation; and Post flood operation.

Each dam is always under one of the six operations, and we formulate the conditions to shift from one operation to another with if-then equations. Figure 3 (left) shows how to shift the process from one to another, and Fig. 3 (right) shows specific water levels that appear in the dam operation rules.

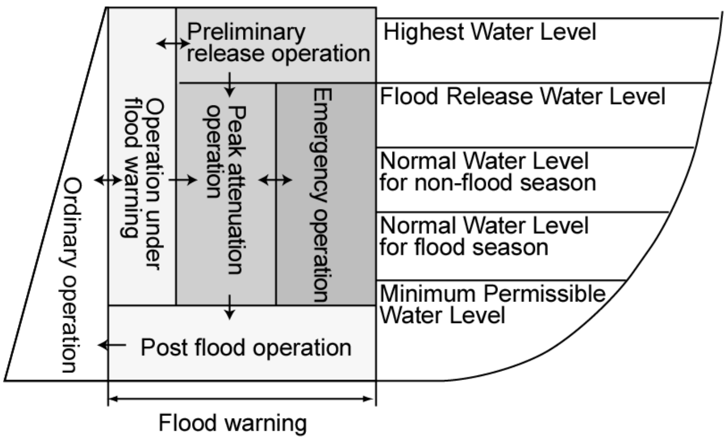

Fig. 3 Operation status and specific water levels of dam operation model.

TEST SIMULATION

Study area

The Yodo River basin is analysed in this case study because it is a typical Japanese river basin highly regulated by multi-purpose dams. The total area of the Yodo River basin is 8240 km^2. In this case study, since Hirakata is the main design target location for designing dams and other river works, we focus on the upper Hirakata basin (7281 km^2) (Fig. 4), and refer to this basin as the Yodo River basin in this paper.

There are eight multi-purpose dams inside the basin and five of these dams are located in one of the sub-basins, called the Kizu River basin (1596 km^2). The Setagawa weir controls outflow from Lake Biwa (670 km^2), which is the largest lake in Japan (Table 1). The mean annual precipitation of the Yodo River basin is about 1600 mm.

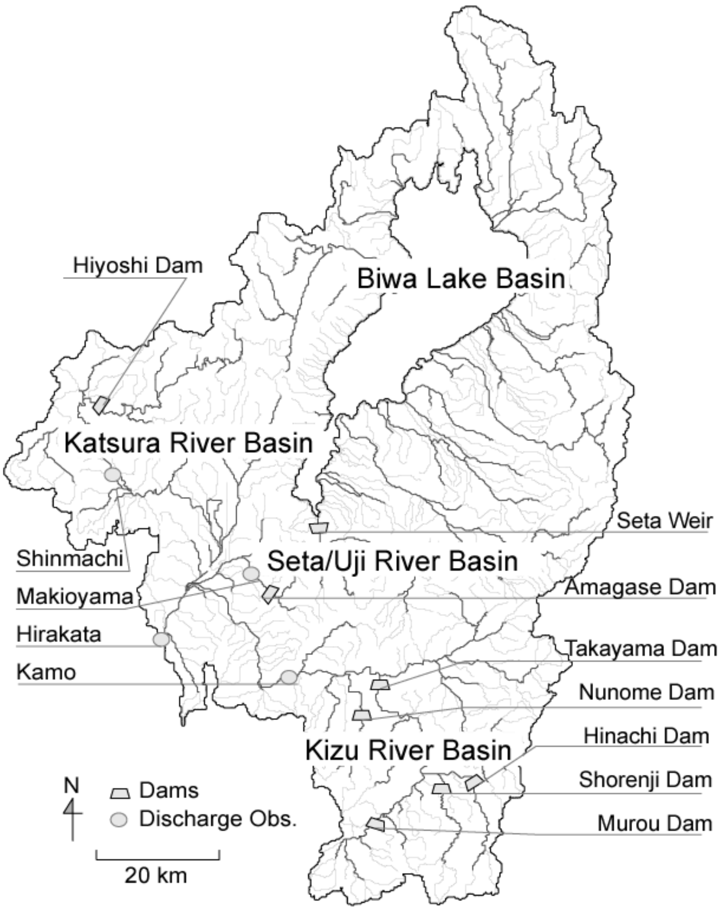

Fig. 4 Yodo River basin (7281 km^2).

Table 1 Properties of the dams in the Yodo River basin.

Dams	Operation start year	Catchment area (km^2)	Total volume (10^6 m^6)	Flood control capacity (10^6 m^6)
Seto	1905	3848	–	2221
Amagase	1964	4200	26.3	20.0
Takayama	1969	615	56.8	35.4
Shorenji	1970	100	27.2	8.4
Murou	1974	169	16.9	7.8
Nunome	1992	75	17.3	6.4
Hiyoshi	1998	290	66.0	42.0
Hinachi	1999	76	20.8	9.0

Simulation conditions

We conducted a test simulation using observed rainfall and observed discharge data during a typhoon event in 1997. The period of the simulation is from 25 to 29 July. We used the nearest neighborhood method to distribute rainfall data that is observed by 58 raingauge stations inside the basin. The estimated total rainfall over the basin is 149 mm.

We divide the whole basin into three zones depending on the land use, and assign different parameters in the different land use zones. There are three land use categories: forest, paddy field, and urban area, among which forest is the dominant land use (63%). A rainfall–runoff model considering surface flow is used for the paddy field zone and the urban area zone by substituting zero in d_c and d_s in equation (1), therefore, only the Manning coefficient n is a parameter of the surface rainfall–runoff model (paddy field zone: 1.0 ($m^{-1/3}$ s^{-1}) and urban area zone: 0.3 ($m^{-1/3}$ s^{-1})). For the forest area zone, we used the saturated-unsaturated subsurface and surface rainfall–runoff model, and the parameters are as follows: n = 0.6 ($m^{-1/3}$ s^{-1}), D = 1.0 (m), d_s = 0.2 (m), d_c = 0.1 (m), k_s = 0.01 (m s^{-1}). Six dams and Biwa Lake are also simulated in the rainfall–runoff simulation system. Two dams constructed after 1997 are not included in this simulation.

Simulation results

Figure 5 shows the simulated and observed inflow and outflow at the Shorenji dam. The good agreement between the simulated inflow with the observed inflow verifies the rainfall–runoff model at the upstream of the dam. The outflow from the dam operation model shows that the preliminary release and peak attenuation operations were properly simulated. Figure 6 shows the simulated and observed water level at the Shorenji dam. It shows that the water level is drawn down by the preliminary release and it is increased by the peak attenuation operation.

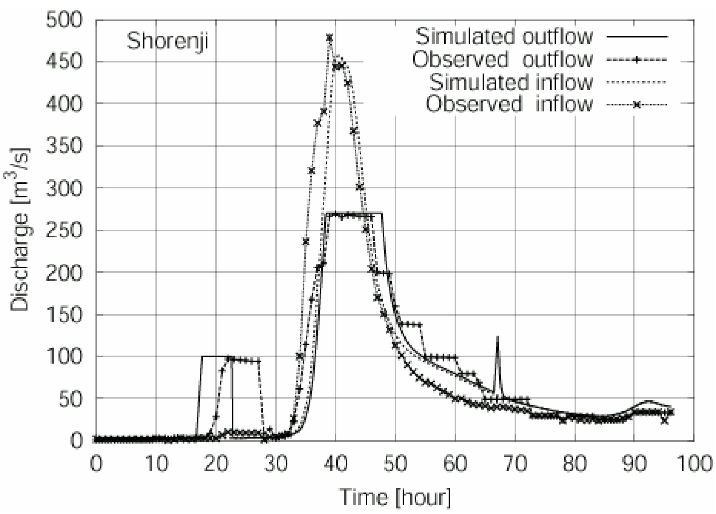

Fig. 5 Simulated and observed inflow and outflow at Shorenji dam.

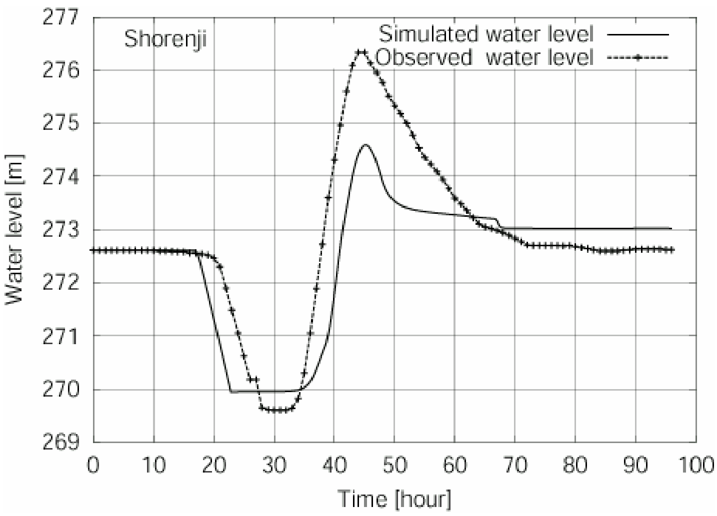

Fig. 6 Simulated and observed water level at Shorenji dam.

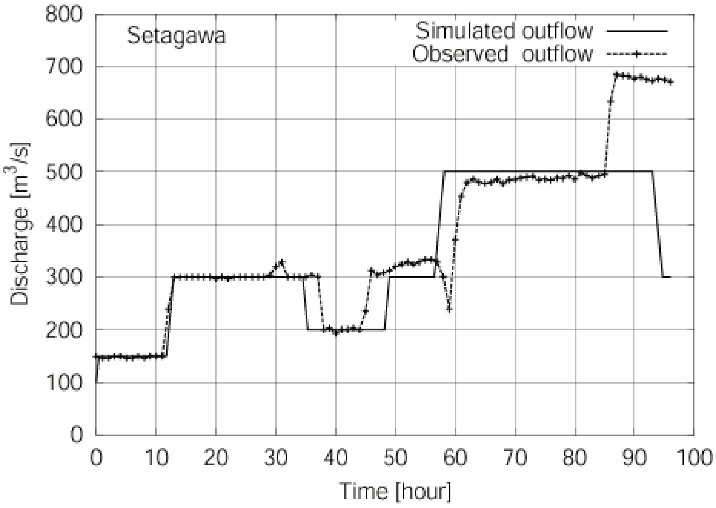

Fig. 7 Simulated and observed outflow at Seta weir.

Figure 7 shows the simulated and observed outflow from the Setagawa weir and Fig. 8 shows the simulated and observed water level of Lake Biwa. Note that the outflow is reduced from 300 $m^3 s^{-1}$ to 200 $m^3 s^{-1}$ temporarily around 35 h to 50 h after the simulation began. This reduction reflects the special operation rule: "The Setagawa weir has to keep its outflow less than 200 $m^3 s^{-1}$ when the Amagase dam is under preliminary release or peak attenuation operations including their preparations". Figure 9 shows the simulated and observed inflow and outflow at the Amagase dam, and we realize that it was under preliminary release operation from 35 h to 50 h. This kind of complex operation by multiple dams could be simulated well because the dam operation models and the rainfall–runoff models interact with each other.

Figure 10 shows the simulated and observed discharge at Kamo. The simulation result excluding the dam element models is also displayed in the figure. By comparing simulated hydrographs with and without dams, it was concluded that the dams located upstream of Kamo could attenuate the peak flood by around 1300 $m^3 s^{-1}$.

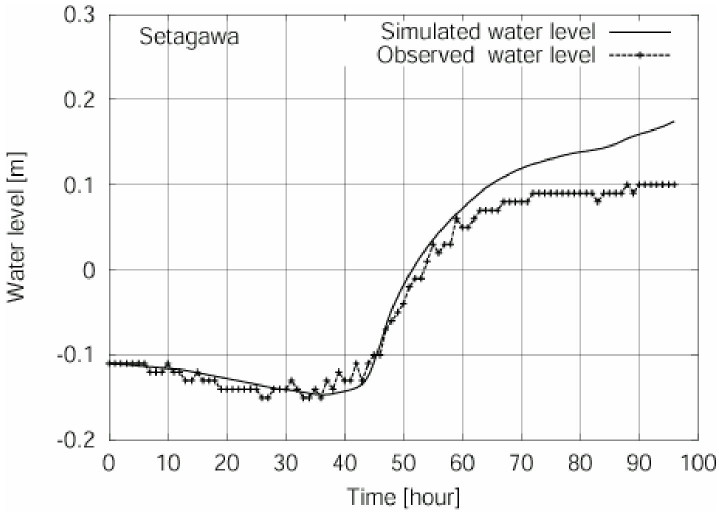

Fig. 8 Simulated and observed water level of Lake Biwa.

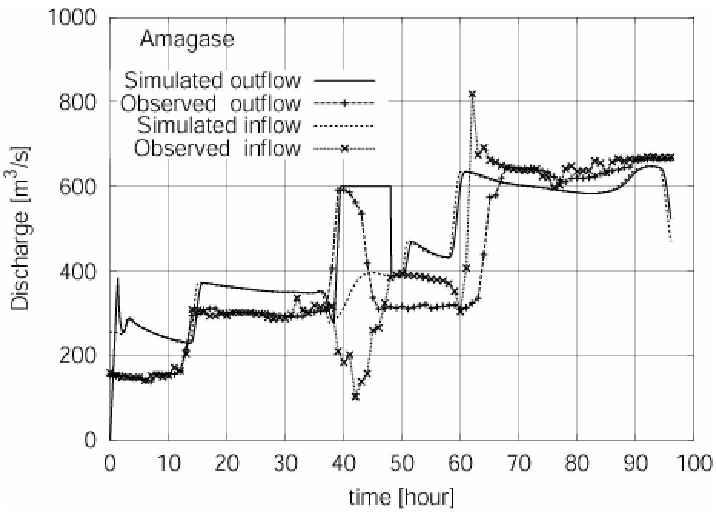

Fig. 9 Simulated and observed inflow and outflow at Amagase dam.

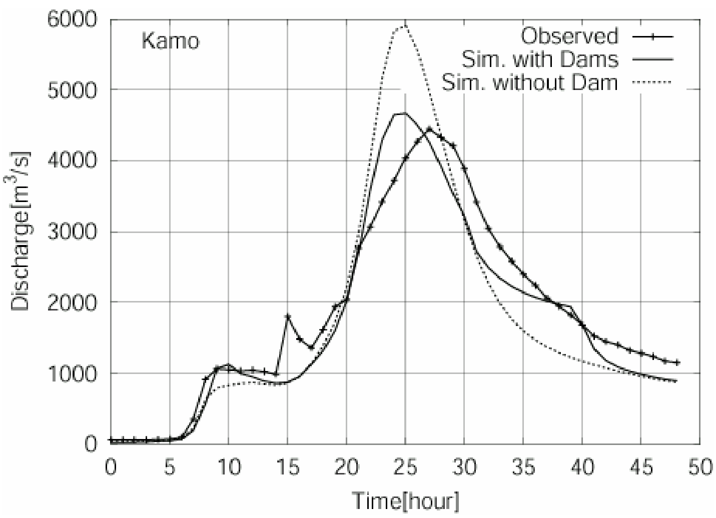

Fig. 10 Simulated discharge (with and without dams) and observed discharge at Kamo.

ANALYSIS OF DAM EFFECTS ON FLOOD CONTROL

Construction of large-scale dams is believed to have improved the safety level of a catchment against flood disasters. However, it is not clear to what extent these dams have improved the safety level or which range of flood magnitudes dams can regulate efficiently. In terms of the Yodo River basin, there are currently eight large-scale dams in the basin and seven dams were constructed after 1960 (Table 1). Conducting rainfall–runoff simulation using the developed rainfall–runoff prediction system, we evaluate how the flood safety level of the Yodo River basin has been progressively increased over the period 1960 to 2000 with respect to rainfall events of different magnitude.

METHOD

Rainfall–runoff simulations were implemented considering the dams that were operated at the beginning of the following years: 1960, 1970, 1980, 1990, and 2000. The simulated peak discharges at Hirakata are examined to discuss the effect of the dams. The rainfall event used in this study is the typhoon event observed in 1982 (1–3 August). This event was chosen because it was the largest event since 1980 when enough rainfall–discharge sequences were available to conduct the simulation.

Furthermore, in order to examine which flood magnitude the dams can attenuate the peak, some factors were multiplied to the 1982 rainfall pattern. The factors are selected so that two-day total rainfall amounts in the Yodo River basin correspond to the following return periods: 30, 50, 100, 150, 200 and 300 years. The same parameters and the initial conditions used in the test simulation are used for this assessment.

RESULTS AND DISCUSSION

Figure 11 shows the simulated peak discharge at Hirakata. The different lines represent different years. Firstly, looking at the results of 1960 when only the Setagawa weir existed, it can be observed that peak discharge caused by the 30-year return period rainfall (Q_{30}) exceeds 12 000 m^3 s^{-1}, which is the allowable maximum flood discharge at Hirakata. By 1970, two other dams, the Amagase dam and the Takayama dam, had been constructed. The comparison between the lines for 1960 and 1970 indicates these two newly constructed dams successfully decrease flood peaks from relatively smaller rainfall events up to around the 50-year return period. By 1980, two more dams, the Shorenji dam and the Murou dam, had been constructed. These dams enabled the peak discharge to reduce by about 2000 m^3 s^{-1} compared with the discharge from the 100-year and 150-year return period rainfall. This is because the Takayama dam located at the downstream of the Shorenji dam and the Murou dam had a flood control capacity large enough to regulate floods of this magnitude. By 2000, a further three dams, the Nunome dam, the Hinachi dam, and the Hiyoshi dam, had been constructed. It is noteworthy that, in 2000, the allowable maximum flood discharge was exceeded by the discharge from the 100-year return period rainfall (Q_{100}), whereas in 1960 this value was exceeded by the Q_{30} peak discharge.

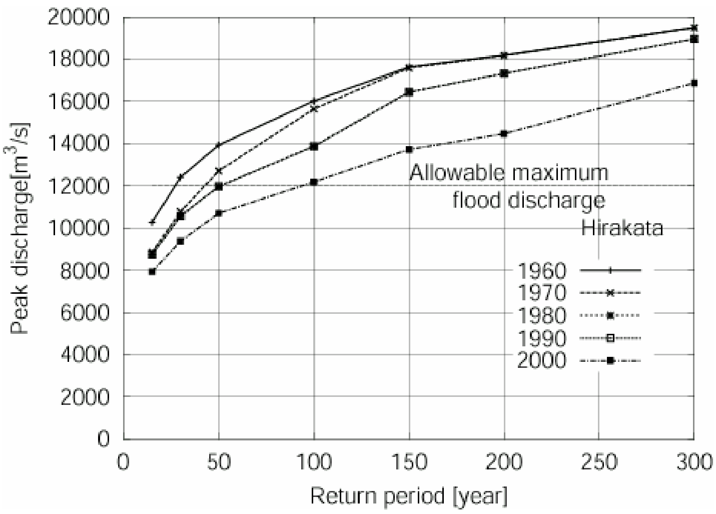

Fig. 11 Simulated peak discharges at Hirakata with different magnitude of input rainfall. Years (1960, 1970, etc.) denote that the dams existed in the year are included in the simulation.

CONCLUSIONS

A rainfall–runoff prediction system was developed for the Yodo River basin. The combination of the dam operation models and the rainfall–runoff models enabled to simulate highly regulated rainfall–runoff processes. The conclusions of the assessment of dam effects on flood attenuation in the basin are summarized as follows:

(a) The dams constructed in the 1960s were effective in attenuating relatively small flood peaks caused by the rainfall event with the magnitude of the 50-year return period or smaller. On the other hand, the dams constructed after 1970 were effective in attenuating relatively larger flood peaks caused by the rainfall events with the magnitude of the 100-year return period or larger.

(b) Q_{30} corresponds to the allowable maximum flood discharge at Hirakata in 1960, while Q_{100} corresponds to it in 2000. However, we found that it has not achieved the initial design target: the discharge caused by smaller than the 200-year return period rainfall cannot exceed the allowable maximum flood discharge.

As it is discussed in this paper, the hydrological cycle in a catchment and flood potential are altered by human activity, which makes observed historical records not directly applicable for future predictions. Modelling the water cycle and the effect of human activity such as dam reservoir operations is one of the solutions for this type of ungauged basins.

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