Proc. of Monitoring, Prediction and Mitigation of Water-Related Disasters (MPMD2005), pp. 59-64, 2005

Assessment of dam flood control using a distributed rainfall-runoff prediction system

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ABSTRACT: This paper presents the development of a rainfall-runoff prediction system that enables the simulation of flood attenuation processes due to dam operation. The case study in the Yodo River basin demonstrated that the system can simulate complex dam operations such as preliminary release, peak attenuation, and cooperative operations by multiple dams. The assessment of dam effects on flood peak attenuation using the system developed indicated that in 1960 the flood discharge caused by the 30-year return period rainfall (Q_{30}) corresponds to the allowable maximum flood discharge at Hirakata, while in 2000, the Q_{100} corresponds to this discharge as a result of the peak attenuation due to newly constructed dams.

1 INTRODUCTION

Through the operation of dam reservoirs the flow regime of rivers are regulated to achieve a variety of objectives such as: flood attenuation, water supply, and power generation. These flow regulations form the existing flow in rivers. Hence it is difficult to find a river with natural flows in many parts of the world.

Hydrological study has generally paid more attention to the understanding of the physics of natural water flow. The importance of this kind of scientific approach is obvious, but at the same time we should recognize the importance of understanding human impact on flow regimes such as highly regulated flow from dam reservoirs.

In terms of flood attenuation by dams in Japan, on which this paper focuses, it is clear that the construction of dams has increased the safety level against flood disasters. On the basis of this, we are now expected to make decisions whether we continue putting more effort into increasing the safety level by structural measures, including dam construction, or we shift to more emphasis on preserving the watershed environment by accepting some floods. Understanding the current flood safety level, considering the effect of flood attenuation by existing dams, is essential to make the decisions. Understanding how these dams can attenuate different magnitude of floods is important.

This paper presents a dam operation model that can predict outflow and water level of multi purpose dams with the conditions of inflow, upstream rainfall and cooperative operations among several dams. The hydrologic prediction system, the combination of the dam models and a proposed rainfall-runoff model, is applied to one of the largest and highly regulated Japanese basins, the Yodo River basin (7,281 km^2). Following the test simulations of a typhoon induced flood event, we assess dam effects on flood attenuation to investigate how the flood safety level has been increased since 1960 against different magnitude of floods.

2 A DISTRIBUTED RAINFALL-RUNOFF PREDICTION SYSTEM

2.1 Whole structure of the system

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

1. River element model: The kinematic wave model is applied to the river segment, which is prepared from the digital river-network data and the location information of lakeshores.
2. Sub-catchment element model: The saturated-unsaturated subsurface and surface runoff model is applied to all grid-cells composing a sub-catchment. We used a digital elevation model to calculate the flow direction and to define the sub-catchment of each river segment.
3. Lake element model: 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 and its outflow is simulated with the dam element model applied to the Setagawa dam, which controls the outflow from the lake.

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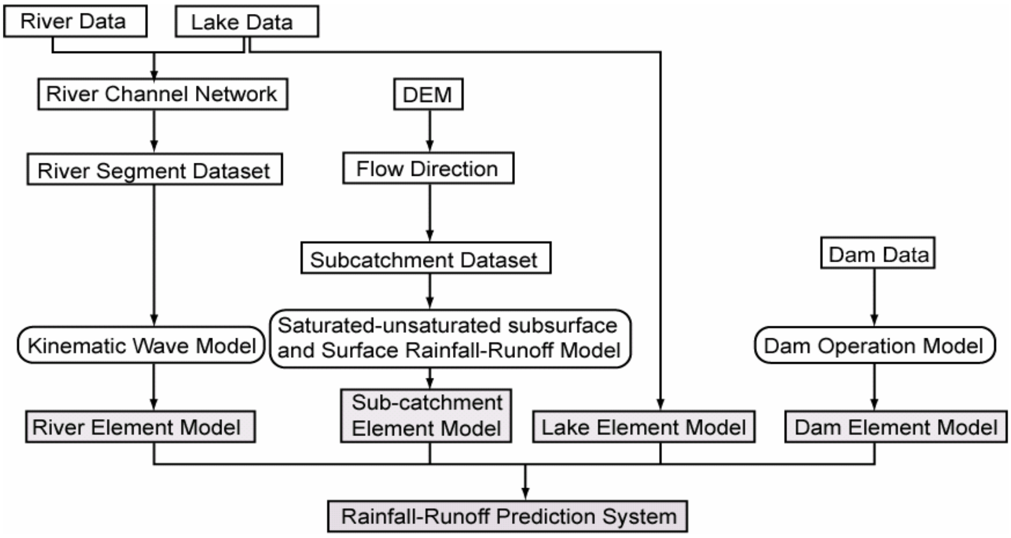


Figure 1. Data processes and the whole structure of the system

4. Dam element model: Construct a dam operation model and apply it to dams in the basin. We refer to this site-specific dam model as a dam element model.

2.2 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 pore, and surface flow on the soil surface. In this figure, the soil depth is D [m], the water stage corresponding to the saturated water content is d_s [m], and the water stage corresponding to maximum water content in the capillary pore is d_c [m].

Figure 2 (b) shows the stage-discharge relationship of the model. Let k_c and k_a be saturated hydraulic conductivities in capillary pore and in non-capillary pore, respectively, and $v_c = k_c i$, $v_a = k_a i$, then the relationship between the discharge par unit width q [m^2/s] and the stage 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 β [-] is the parameter to describe the reduction of hydraulic conductivity in capillary pore as the water content reduces. β equals k_a / k_c so as to keep the continuity of the stage-discharge relationship between the capillary pore and the non-capillary pore layers. Combining this stage-discharge relationship (1) and the continuity equation, we simulate rainfall-runoff from each grid-cell. The simulated discharge will be inflow of downstream grid-cell. The water flow is routed until it reaches a river segment.

2.3 Dam element model

By formulating the dam operation rules and decision-making processes used by 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, the case study basin in this paper, are multi-purpose dams. Although each dam has different operating rules, we can categorize the following six common operation processes for flood attenuation (Ichikawa et al., 1999): Ordinary operation, Operation under flood warning, Preliminary release operation, Peak attenuation operation, Flood release operation, and Post flood operation.

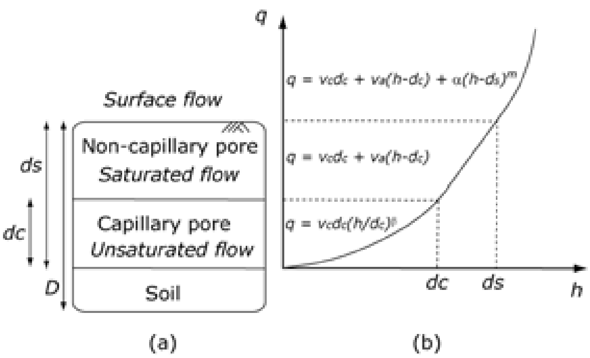


Figure 2. Schematic diagram of the soil layer (a) and stage-discharge relationship (b) of saturated-unsaturated subsurface and surface rainfall-runoff model

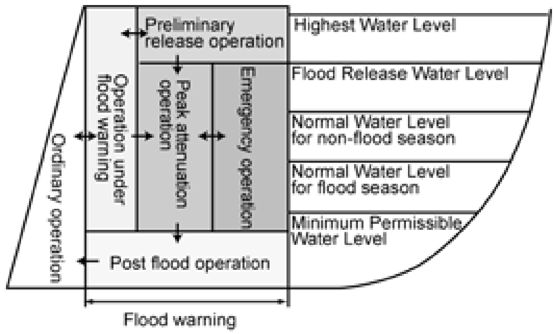


Figure 3. Dam operations and specified water level

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 hand side) shows how to shift the process from one to another, and Fig. 3 (right hand side) shows specific water levels that appear in the dam operation rules.

3 TEST SIMULATION

3.1 Study area

The Yodo River basin is analyzed 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 8,240 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 (7,281 km^2), 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 (1,596 km^2). Setagawa dam controls outflow from Lake Biwa (670 km^2), which is the largest Lake in Japan. Administrators operate all dams in the basin so that integrated flow regime control can be undertaken. The mean annual precipitation of the Yodo River basin is about 1,600 mm.

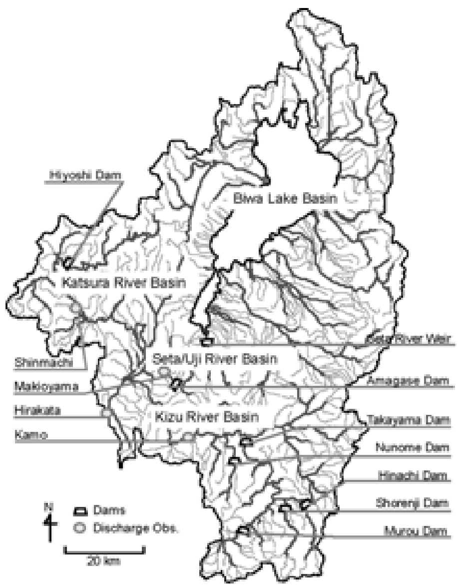


Figure 4. The Yodo River basin (upper Hirakata: 7281 km^2)

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

Dams	Completed year	Catchment Area [km^2]	Flood control capacity [10^6 m^3]
Setagawa	1905	3848	2221
Amagase	1964	4200	20.0
Takayama	1969	615	35.4
Shorenji	1970	100	8.4
Murou	1974	169	7.8
Nunome	1998	75	6.4
Hiyoshi	1998	290	42.0
Hinachi	1999	76	9.0

3.2 Method

We conducted a test simulation using observed rainfall and discharge observed data during a typhoon event in 1997. The period of the simulation is from July 25 to July 29. We used the Thiessen polygon method to distribute rainfall data that is observed by 58 raingauge stations inside the basin. Estimated total rainfall during this event 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 landuse (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 [$m^{-1/3}s$] and urban area zone : 0.3 [$m^{-1/3}s$]). For the forest area zone, we used saturated-unsaturated subsurface and surface rainfall runoff model, and the parameters are as follows: n = 0.6 [$m^{-1/3}s$], D = 1.0 [m], d_s = 0.2 [m], d_c = 0.1 [m], k_s = 0.01 [m/s]. 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.

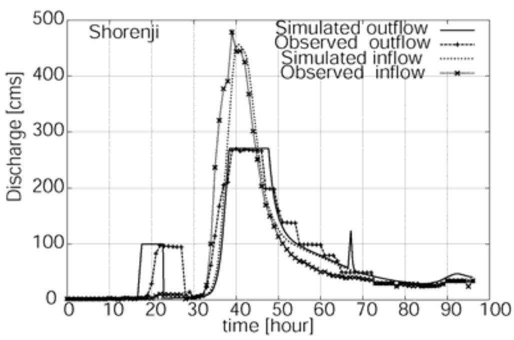
3.3 Results and discussions

Figure 5 (a) shows the simulated and observed inflow and outflow at Shorenji dam. The good agreement between the simulated inflow with the observed inflow verifies the rainfall-runoff model at the upstream of the dam. In terms of the simulated outflow, the dam element model could simulate the preliminary release and peak attenuation operations well.

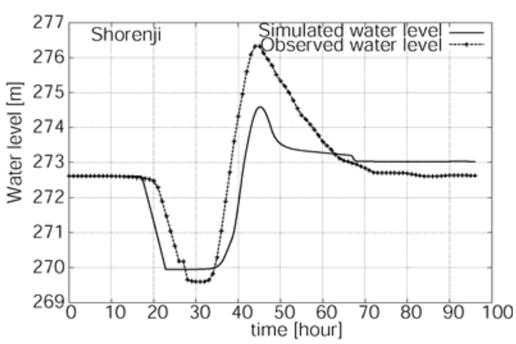
Figure 5 (b) shows the simulated and observed water level at Shorenji dam. Though the simulated water level does not perfectly match the observed water level, it shows the water level is drawn down by the preliminary release and it is increased by the peak attenuation operation.

Figure 6 shows the simulated outflow from Setagawa dam (a) and water level of Lake Biwa (b). There is one notable feature in this simulation result that the outflow is reduced from 300 cms to 200 cms temporarily around 35 hours to 50 hours after the simulation began. This reduction reflects the special operation rule: "Setagawa dam has to keep its outflow less than 200 cms when Amagase dam is under preliminary release or peak attenuation operations including their preparations". Figure 7 shows the simulated and observed inflow and outflow at Amagase dam, and we realize that it was under preliminary release operation from 35 hours to 50 hours. This kind of complex operations by multiple dams could be simulated well because the dam operation models and the rainfall runoff models interact with each other.

Figure 8 shows the simulated and observed hydrographs 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 500 cms.

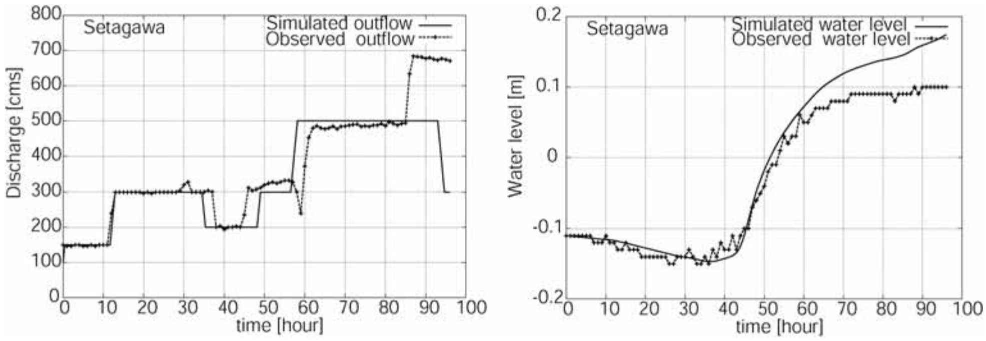


(a)



(b)

Figure 5. Simulated and observed inflow and outflow (a) and water level (b) at Shorenji Dam



(a) (b)

Figure 6. Simulated and observed outflow at Setagawa Dam (a) and water level of Lake Biwa (b)

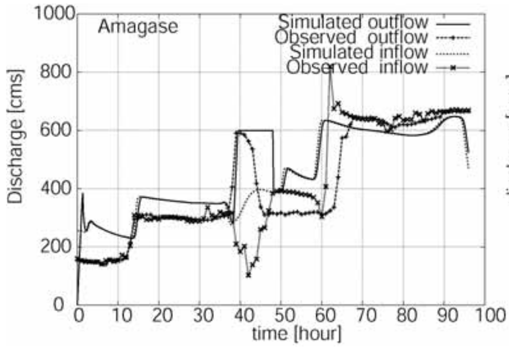


Figure 7. Simulated and observed inflow and outflow at Amagase dam

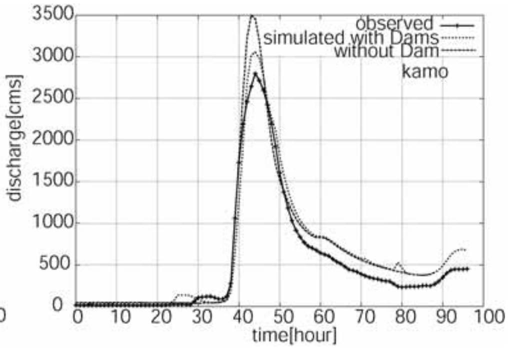


Figure 8. Simulated and observed discharge at Kamo

4 ANALYSIS OF THE DAM EFFECTS ON FLOOD ATTENUATION

4.1 Objectives

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.

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.

4.2 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 (August 1 to 3). 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 applied to the 1982 rainfall pattern. The factors are selected so that the modified rainfall events 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.

4.3 Results and discussions

Figure 9 shows the simulated peak discharge at Hirakata. The horizontal axis of the figure represents the return period of the input rainfall, and the vertical axis of the figure represents the simulated peak discharge. Different lines in the figure represent different years: for example, the line of 1980 represents the result simulated with the dams of Setagawa, Amagase, Takayama, Shorenji, and Murou because all of these dams commenced operations before 1980.

Firstly, looking at the results of 1960 when only Setagawa dam existed, it can be observed that peak discharge caused by the 30-year return period rainfall (Q_{30}) exceeds 12,000 cms, which is the allowable maximum flood discharge at Hirakata. By 1970 two other dams, Amagase dam and Takayama dam, had been constructed. The comparison between the lines for 1960 and 1970 indicates these two newly constructed dams succeeded in attenuating flood peaks from relatively smaller rainfall events up to around the 50-year return period. By 1980, two more dams, Shorenji dam and Murou dam, had been constructed. These dams enabled the peak discharge to reduce by about 2,000 cms compared with the discharge from the 100-year and 150-year return period rainfall. This is because Takayama dam located at the downstream of Shorenji dam and Murou dam had a flood control capacity large enough to regulate floods of this magnitude. By 2000, a further three dams, Nunome dam, Hinachi dam, and 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.

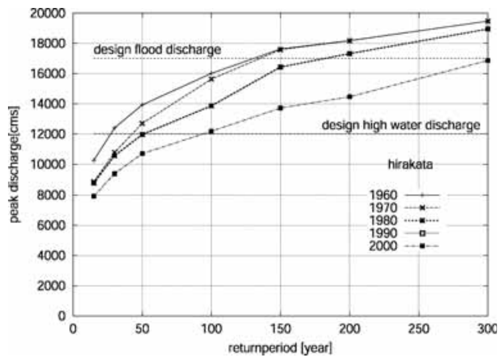


Figure 10. Simulated peak discharges at Hirakata with different magnitude of input rainfall. Years (1960, 1970, etc.) denote that the dams existed in the year are included in the simulation.

5 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 the simulation of the highly regulated rainfall-runoff processes in the basin. The conclusions of the assessment of dam effects on flood attenuation in the basin are summarized as follows:

1. 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.
2. 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.

6 ACKNOWLEDGEMENT

A part of this study is supported by “System Modeling Approaches for Assessment of Interaction Between Social Changes and Water Cycle (PI: Prof. Kaoru Takara, DPRI, Kyoto Univ.)”, which is conducted under CREST (Core Research for Evolutional Science and Technology) Program by the Japan Science and Technology Agency.

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