7 Flood Prediction in Japan and the Need for Guidelines for Flood Runoff Modelling

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FLOOD DISASTER AND FLOOD RUNOFF MODELLING IN JAPAN

About 50% of the population and 75% of the properties in Japan are located within flood prone areas, which form only 10% of the total land area of the country. About 70% of the total land area is mountainous and prone to sediment disaster, and considerable numbers of people live there too. Flood and sedimentation disasters occur every year in many parts of the country. In 2004, 10 typhoons hit Japan and 232 people lost their lives due to heavy rainfall disasters induced by the typhoons and the rainy front. In July 2003, debris flow disasters caused by a heavy rainfall in the central part of the Kyushu region left 19 people dead. In September 2000, a heavy rainfall hit the Nagoya area, the third largest industrial area in Japan. The flood disaster affected about 70 000 houses in the city area, and the economic loss due to this disaster was estimated at around 80 billion US dollars.

The role of a flood runoff model can be significant in the prevention and/or reduction of flood and sediment disasters. It can assist formulation of a flood protection plan and improvement of the existing flood warning systems. For this reason, many kinds of hydrological models have been developed and applied in Japan. The pioneering work on flood runoff modelling in Japan includes the physically based hydrological modelling by Ishihara & Takasao (1959, 1962), who achieved the theoretical development of the kinematic wave model for hillslope rainfall–runoff phenomena and proposed a variable sources area concept. Kimura (1960) proposed the storage function method, which is a simple nonlinear reservoir model. His model is still widely used for estimating design floods in Japanese river basins. The tank model proposed by Sugawara (1972, 1995) is also widely used in Japan. In the last two decades, several kinds of physically based distributed models have been constructed and applied, together with the development of numerical geographic information and radar rainfall observation technology. Thus, there are now many rainfall–runoff models in Japan; however, which model would be suitable in a particular hydrological environment is quite unknown. A method for evaluating rainfall–runoff models and guidelines for flood runoff modelling need to be developed.

NEED FOR A MODEL EVALUATION METHOD AND MODELLING GUIDELINES

As stated above, the storage function method is still widely used in practical engineering works in Japan, although there are many other models including physically-based distributed models. The basic reason for this is that there are no well-defined methods or indices that permit comparison of the performance and prediction uncertainties of different models. As shown in the Appendix, Japan PUB currently has five working groups. The first working group (WG1) is focusing on developing a model evaluation method that will be able to show the model performance and its prediction uncertainty. It is intended to evaluate existing lumped and distributed models using this method. This is expected to promote appropriate flood runoff model developments and to provide additional information for hydrological modelling.

A guideline or a widely accepted principle is also necessary for the construction of a proper model structure and to understand the scope of parameters under given conditions for rainfall–runoff modelling. For example, the model performance of a physically based distributed rainfall–runoff model may be better or worse than a traditional lumped model. It is necessary to clarify the specific conditions in which a distributed system shows better, or worse, performance than a lumped system according to their mutual evaluation or intercomparison. The guidelines may also be helpful to construction of a sound distributed rainfall–runoff model for practical engineering purposes and to definition of appropriate sizes for modelling catchment topography, for model-building units, for spatial resolution of radar rainfall measurement, etc. The guidelines may also be an important reference for developing rainfall–runoff models in ungauged basins.

FUNDAMENTAL RESEARCH ISSUES FOR ESTABLISHING MODELLING GUIDELINES

The results of a hydrological model depend on many factors, including the forcing inputs, process descriptions, parameters and landscapes. It is not easy to define their importance and compare their influences in modelling. Accurate descriptions of forcing inputs, processes, parameters and landscapes are practically impossible because of their heterogeneity in space and time. However, existing hydrological knowledge has already identified important processes and their limitations in describing the rainfall–runoff processes. In addition, scales and scaling effects are also significant in hydrological modelling. There exist certain thresholds in forcing inputs, parameter distributions, process recognition and landscapes that provide an acceptable accuracy in the modelling results. It is necessary to investigate these issues in detail and to identify the thresholds that define the appropriate scale of observation, process description, parameters and landscapes, for establishing the modelling guideline.

In particular, the essential knowledge to be acquired before developing the modelling guidelines is the understanding of scales for hydrological modelling, such as a size for catchment topography representation and a size for a model-building unit. In the discussions on representative elementary areas (REAs; Wood *et al.*, 1988) and further research such as Woods *et al*. (1995) and Bloschl *et al*. (1995), a fundamental building block for catchment modelling was analysed and examined numerically and by observation. The size clarified as the REA seems to be the minimum size of a model building block. The maximum size at which a lumped treatment of runoff processes is possible within a distributed system approach is also necessary and helpful for hydrological model development. Research effort in Japan over several decades has also attempted to define an appropriate size of sub-catchment in distributed analyses; however, the issue is still not successfully clarified.

Development of a modelling framework with appropriately sized topography representation and model sub-units is the starting point for constructing a reliable and sound rainfall–runoff model. The following sections briefly discuss the effect of the scale of topographic representation and the size of the building unit for rainfall–runoff modelling.

Effect of the scale of topographic representation

The size at which the catchment topography is represented and the values of the model parameters are closely related in rainfall–runoff modelling. Takasao & Shiiba (1978) illustrated this using a kinematic wave approximation for runoff routing. Assuming an open book watershed model, the continuity and momentum equations are:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r\cos\theta, \quad q = \frac{\sqrt{\sin\theta}}{n} h^m \tag{1}$$

where q is discharge per unit width, h is flow depth, and n is the roughness coefficient. Changing the variables using slope length L as $q^* = q/L$ and $x^* = x/L$, equation (1) leads to:

$$\frac{\partial h}{\partial t} + \frac{\partial q^*}{\partial x^*} = r\cos\theta, \quad q^* = \frac{\sqrt{\sin\theta}}{nL} h^m \tag{2}$$

The value of q^* at $x^* = 1$ represents the simulated runoff (per unit area) at the outlet of the slope. From equation (2) it is clear that the transformation process from rainfall to runoff is controlled by the value of $\sqrt{\sin\theta}/(nL)$. As long as $\sqrt{\sin\theta}/(nL)$ takes the same value, the simulation results are the same. In other words, the model parameter value identified using observed rainfall and runoff data is the value of $\sqrt{\sin\theta}/(nL)$. Under these conditions, it is impossible to get the value of n and L independently. This means that if the catchment topography is modelled in a different way and the value of slope length takes a different value, the value of n also takes a different value.

The dependence of the topographic index in TOPMODEL on the DEM grid size is further evidence of the effect of the size of topographic representation (e.g. Band & Moore, 1995; Pradhan *et al.*, 2004). The topographic index is defined as $TI = \ln(a/\tan\beta)$, where a is the upslope contributing area per unit contour length and $\tan\beta$ is the local slope. This may have different distributions depending on the size of the topography representation. Figure 7.1 shows the distributions of the topographic indexes obtained at the Kamishiiba catchment (210 km^2) in Japan with different grid sizes of the DEM (Pradhan *et al.*, 2004). The distribution shifts to the right as the size of the DEM grows coarser. This happens due to the change in upslope contributing area, which takes a larger value, but the local slope takes a smaller value at a coarser DEM of the same topography. Thus, the distributions of the topographic index are different depending on the size of the topography representation. This leads to a need for different model parameters making the whole model scale dependent.

These examples show that the size of topography representation affects the values of model parameters which are used to represent the runoff processes. The effect of the size of topographic representation on the model parameters is an undesirable phenomenon. Consequently, if the catchment topography is not modelled at an appropriate scale, the

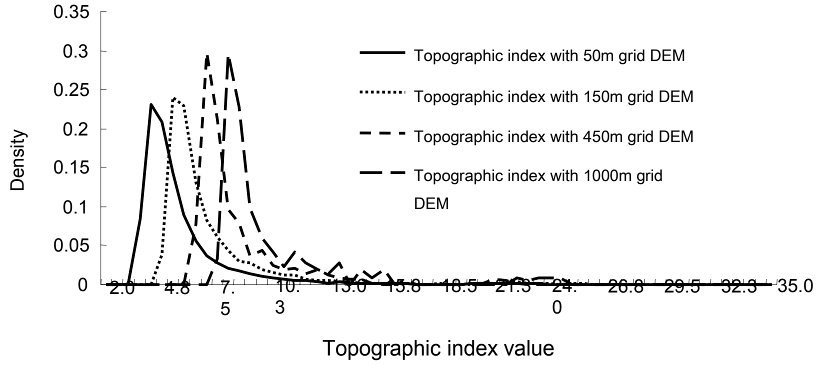

Fig. 7.1 *Effect of DEM resolution on density distribution of topographic index.*

overall understanding of parameter values (e.g. roughness coefficient) and their sensitivity may be meaningless, because the parameter values may include larger biases due to the effect of the size of topography representation. In this case, the model parameters do not represent the hydrological characteristics properly, which makes it difficult to transfer them to ungauged basins as reference values for the model parameters.

It is necessary to develop a transferable rainfall–runoff model and transferable model parameters in order to enable predictions in ungauged basins. To do so, it is necessary to identify an appropriate size for the topography representation to obtain the topographic attributes such as the topographic index distribution, slope length distribution, and area–distance distribution. This enables estimation of the values of model parameters which are transferable to different catchments. The appropriate size for topography representation in the mountainous regions of Japan is assumed to be less than 100 m, because the topographic attributes are highly scale dependent when the size of topography representation is larger than 100 m.

Size of building units for rainfall–runoff modelling

The size of a building unit for rainfall–runoff modelling is usually larger than the size required for topography representation. Explicit spatial distributions of hydrological variables are not necessary within this size. A lumped representation is enough to describe the rainfall–runoff processes within it. Alternatively, it is possible to describe them with statistical distributions of hydrological variability and model parameters. The size of the building unit needs to satisfy the condition that an explicit spatial distribution of the model parameter values and rainfall does not affect the simulated runoff at the outlet of that unit. At the given size there will not be any effect of channel routing within the unit, which helps to exclude the ambiguity of model parameters that separate the hillslope process and the channel routing process. This may be the maximum value of the homogenous region similar to the REA that plays a significant role in hydrology.

To examine this size, the influence of explicit spatial distributions of model parameters on runoff response was examined through numerical simulations (Tachikawa *et al.*, 2003). A distributed parameter model with a kinematic wave approximation was used, which routes the slope runoff along the flow lines determined by a 50-m grid based DEM as shown in Fig. 7.2. In each slope segment, the model assumes that permeable soil layers cover the hillslope as illustrated in Fig. 7.3. The soil layers are composed of a capillary layer in which unsaturated flow occurs, and a non-capillary layer in which saturated flow occurs. If the depth of water is larger than the soil depth, then surface flow occurs.

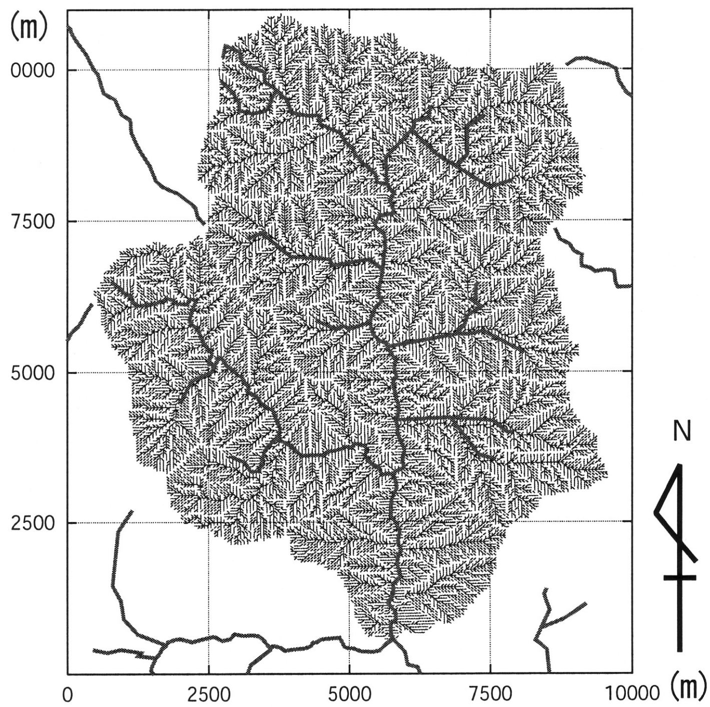

Fig. 7.2 *Flow lines derived from 50-m grid DEM for the upper part of the Kamishiiba catchment, Japan.*

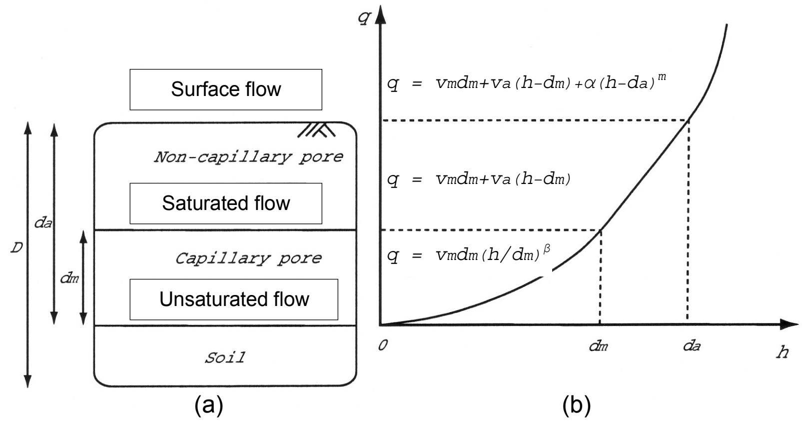

Fig. 7.3 *Model structure for the hillslope soil layer (a), and the discharge–stage relationship (b).*

The discharge–stage relationship:

$$q = \begin{cases} v_m d_m (h/d_m)^{\beta}, & 0 \le h < d_m \\ v_m d_m + v_a (h - d_m), & d_m \le h < d_a \\ v_m d_m + v_a (h - d_m) + \alpha (h - d_a)^m, & d_a \le h \end{cases} \tag{3}$$

represents the hillslope runoff phenomena. The equation combined with the continuity equation is solved for all slope segments, where $v_m = k_m i$, $v_a = k_a i$, $k_m = k_a/\beta$, $\alpha = \sqrt{i}/n$, i is hillslope gradient, k_m is saturated hydraulic conductivity for the capillary soil layer, k_a is hydraulic conductivity for the non-capillary soil layer, n is roughness coefficient, d_m is the depth of the capillary soil layer, and d_a is soil depth. The study area is the Kamishiiba catchment (210 km^2) in Japan.

The model parameters are identified using radar rainfall data of 1-km spatial resolution and 10-min temporal resolution with ground level raingauge calibration. It is assumed that the parameter values are the same throughout the catchment initially. The parameter values obtained are k_a = 0.01 m s^{-1}, n = 0.3 m$^{-1/3}$ s^{-1}, d_a = 0.55 m, d_m = 0.45 m, and β = 4.0. Then a lognormal random field having a mean of 1.0, standard deviation of 1.0, and correlation length of 1000 m is generated. This field creates the distributed parameter fields after multiplication with the calibrated parameter values.

Figure 7.4 shows simulated hydrographs at the catchment outlet. The results are obtained using different realizations of spatially distributed hydraulic conductivity, k_a. The largest difference in simulated discharge is about 50 m^3 s^{-1}, that is less than 5% of the mean simulated peak discharge. This shows that the effect of the explicit spatial distribution of the model parameters is quite small. Within the coverage of a 200 km^2 area, there is no significance of distributed hydrological responses even after re-organizing the model parameters vigorously. This indicates that the study size is

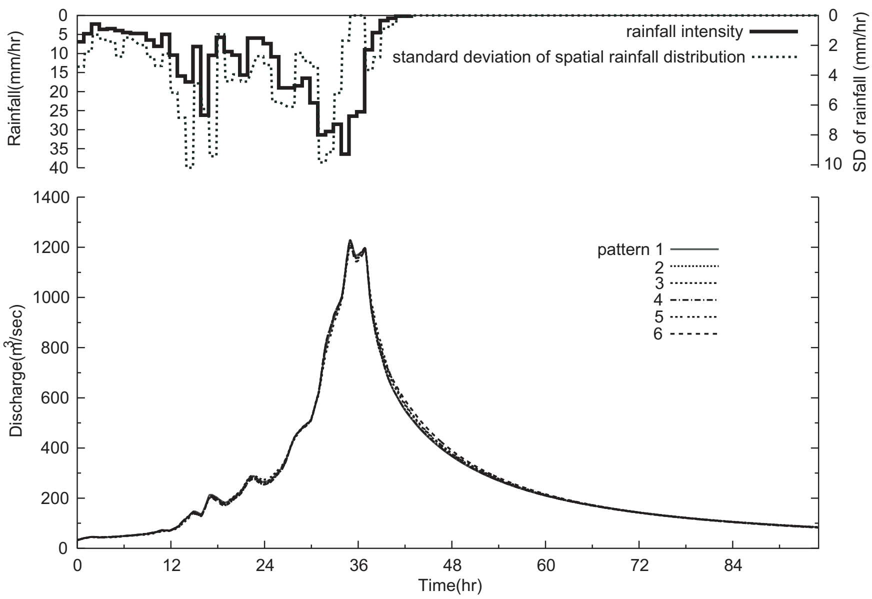

Fig. 7.4 *Simulated discharges at the outlet of the Kamishiiba catchment (210 km^2) with different spatial patterns of hydraulic conductivity.*

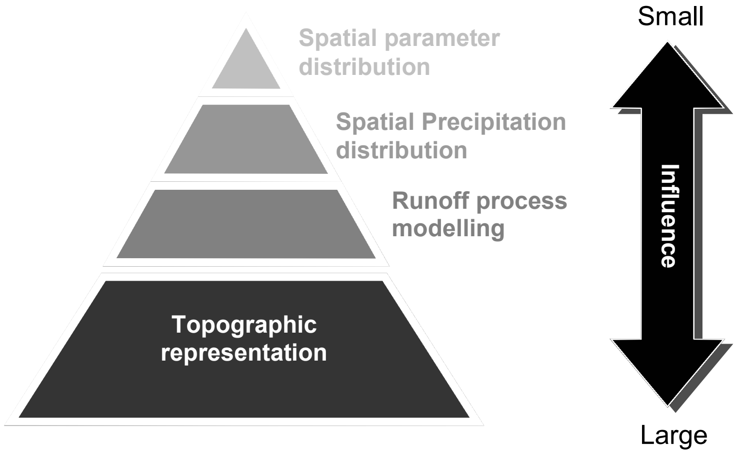

***Fig. 7.5** The order of importance of hydrological information at the scale of 200 km^2.*

within the size of a building unit. This study still does not confirm the maximum size of a building unit. To verify the maximum size of the building unit, it will be necessary to take larger catchments and to conduct runoff simulations with different model parameter distributions as well as to include different patterns of spatial rainfall distribution.

Figure 7.5 is a schematic figure showing the degree of influence of different hydrological components in the simulated runoff at the scale of 200 km^2 catchment. This is a perspective obtained through several test simulations and shows the level of importance of hydrological components for constructing flood runoff models in this study catchment. Noticing this kind of information can be very helpful for identifying the relative importance of different components in both model evaluation and construction, particularly at the starting point of a model-building process.

SUMMARY

Rainfall–runoff models have an essential role in preventing/reducing flood disasters. An evaluation method and modelling guidelines associated with quantifying prediction uncertainty are indispensable to promoting construction of better flood-runoff models with sound structure and robust parameters. There are several research issues that need thorough investigation in order to develop the evaluation method and the modelling guidelines. One of the essential issues is to clarify the effects of scale such as the size of topography representation and the size of the model-building unit. These will help in constructing the modelling guidelines. For example, after observing the topographic attributes at different sizes of topography representation, the appropriate size is suggested to be 100 m. Similarly, after observing no change in result due to vigorous re-organization of the model parameters (hydraulic conductivity) within a 200 km^2 area, the existence of a model-building unit is argued. Clarification of the size of a model-building unit and the order of importance of hydrological elements at a given catchment scale will be the starting point for development of a model evaluation method and modelling guidelines.

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APPENDIX
Japan PUB – SAKE

SAKE is the acronym for *Suimon Adventure for Knowledge Evolution*, where suimon is the Japanese for hydrology. Sake is homonymous for Japanese rice wine (sometimes written as saki in English), and also for salmon.

The structure of the five Japan PUB – SAKE working groups is illustrated in Figure 7.A.

Japan PUB – SAKE working group research titles

WG1: Establishment of a rainfall–runoff modelling guideline through development of an uncertainty evaluation method

WG2: Estimating frequencies of hydrological extreme events in ungauged basins by using scaling, regionalization, and historical record analysis

WG3: Relating hydrological diversity to landscape elements to establish a realistic PUB model

WG4: Global-scale hydrological modelling considering interactions between natural variation and anthropogenic activities

WG5: Downscaling of global hydrological information for local scale watershed managements in ungauged basins

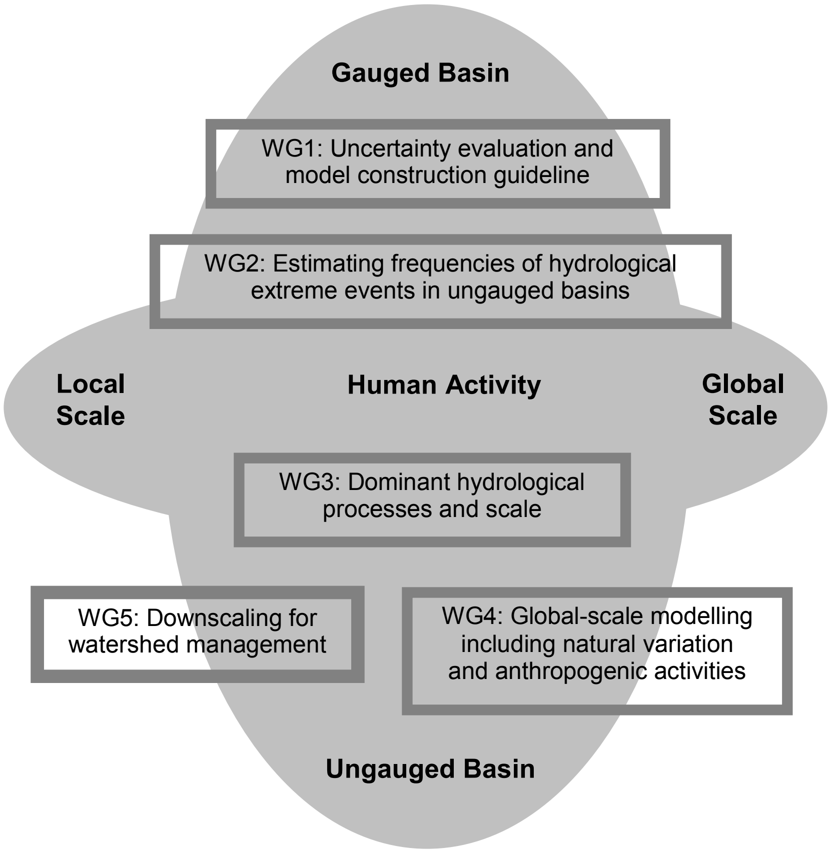

Fig. 7.A *Structure of Japan PUB working groups.*