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Proposal and Application of a New Theoretical Framework of Uncertainty Estimation in Rainfall Runoff Process Based on the Theory of Stochastic Process

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Abstract

The aim of this study is to clarify the effect of the uncertainty of inputs in respect of output by rainfall-runoff process. In Japan, we have performed runoff analysis using deterministic model such as storage function model in the past. However, natural phenomena have various uncertainties. For example, rainfall-runoff analysis includes uncertainties of parameters or structure of model, and observed value of rainfall and water level. In this study, we attend the uncertainty of rainfall which is input data of runoff analysis and introduce the theory of stochastic process to runoff analysis due to quantify the uncertainties stochastically. We indicate the theoretical framework to evaluate the uncertainties using the relationship among stochastic differential equation (SDE) and Fokker-Planck equation (FPE), because the lumped rainfall-runoff model is described by ordinary differential equation.

As a result, we introduce the theory of stochastic process to runoff analysis. And we make a suggestion of a new theoretical framework of uncertainty estimation regarding reliability analysis with the distribution of water level as external force and the failure probability of levee as resistance.

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Keywords: rainfall-runoff analysis; stochastic differential equation; Fokker-Planck equation; Langevin equation; uncertainty;

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1. Background and Aim

Due to the global climate change, the scale and frequency of natural disasters are more difficult to predict and measure. Extreme rainfall often brings an astonishing amount of water and causes very serious damage. According to the report of natural catastrophes 2014 "Analyses, assessments, positions 2015 issue", most of the loss events are caused by the meteorological events and hydrological events are the most natural events during 1980 to 2014. Here the natural disaster events can be subdivided into the following four types, geophysical events, meteorological, hydrological and climatological events. From this statistic result, we can observe that in addition to geophysical events, other events induced by weather or climate change are growing year by year. In particular, in East Asia, there are serval typhoons hit every year. Therefore, how to predict, prevent and reduce the loss from natural disasters is a very important issue.

However, most of the past studies on the analysis of natural disasters are based on the deterministic theory, it means that the analyses are only two results, safe or failure. It's not enough to illustrate the real environment because there are a lot of uncertainty factors that would affect the occurrence of disasters. Moreover, all these natural disasters would affect the human activities like economic, transportation, social development and so on. Therefore, the most important is how to evaluate the hazard of disasters by considering the uncertainty of the disasters.

The aim of this study is to clarify the effect of the uncertainty of inputs in respect of output by rainfall-runoff process, and introduce the theory of stochastic process and reliability analysis, the probability concept can be applied in the river engineering.

2. Basic equation of rainfall-runoff in the single slope

According to many approaches like an experiment, observation or numerical analysis, Yamada [1] proposed basic equation of a generalized rainfall-runoff model by mathematics. The equation applied to the single slope plays a very important role in the study. The following content is the summary of the rainfall-runoff model. The continuity equation is according to the relation between the submerged depth and the unit discharge of the single slope supposing a rectangular cross section as shown in Eq.(1). Furthermore, for the various runoff pattern the motion law is shown as Eq.(1), the average flow velocity of the cross section (the unit discharge) is shown as the multiplication ratio of the submerged depth. By combing Eq.(1) and Eq.(2), the unit discharge can be re-written as Eq.(3). Eq.(4)~Eq.(5) are the parameters of Eq.(3). The parameters α and m refer to the unsaturated soil from Shimura [2], Suzuki [3] and Kubota [4].

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(t) \tag{1}$$

$$v = \alpha h^{m}, \quad q = vh = \alpha h^{m+1} \tag{2}$$

$$\frac{\partial q}{\partial t} + aq^{\beta}\frac{\partial q}{\partial x} = aq^{\beta} r(t) \tag{3}$$

$$a = (m+1)\alpha^{\frac{1}{m+1}}, \quad \beta = \frac{m}{m+1} \tag{4}$$

$$\alpha = \frac{k_s i}{D^{\gamma-1} w^{\gamma}}, \quad m = \gamma - 1 \tag{5}$$

Here, v is the mean velocity of the cross section [mm/h]; h is the submerged depth [mm]; q is the unit discharge [mm2/h]; r(t) is the effective rainfall intensity [mm/h]; and α and m are the parameters of the watershed. About α and m, i is the gradient of slope; D is the depth of surface soil layer; γ is the non-dimensional of soil permeability; ks is the permeation coefficient of soil; w is the effective void ratio.