京 都 大 学 防 災 研 究 所 年 報 第47号 C 平成16年3月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 47 C, 2004

Distributed Runoff Model Linking Surface with Groundwater Processes

Amin NAWAHDA*, Toshiharu KOJIRI, and Shuichi IKEBUCHI

* Graduate School of Engineering, Kyoto University

Synopsis

A method with multi-layer and mesh-typed runoff model using Hydro-BEAM (Hydrological River Basin Environment Assessment Model) is proposed to analyze the integrated hydrological processes. The spatiotemporal simulation is calculated with the kinematic wave model for surface runoff, Richard's equation for unsaturated subsurface flow and the unconfined flow for groundwater. The initial loss of rainfall due to interception by depression storage reprocess is considered here. Moreover the basin division and land use dynamics are introduced to encounter reservoir operation and land utilization with human activities. The proposed model is calibrated for different initial conditions and parameters, and applied into the Yasu River to verify the dynamic linkage between surface and groundwater.

Keywords: Distributed runoff model, Parameterization, Saturated and unsaturated flow, Spatio-temporal distribution.

1. Introduction

The hydrological cycle involves complicated interactions between atmosphere layer, surface and ground layers. The integrated hydrological modeling is achieved by dynamic linking and simultaneous calculation of the water cycle related processes. Traditionally the lumped models simulate the formation of the surface runoff. These models are based on the assumptions of uniformity and linearity of watersheds. In reality these assumptions encounter a high percentage of errors. The distributed rainfall-runoff (Hydro-BEAM) was introduced in order to overcome the shortcomings of lumped models Kojiri (2000). At each mesh the heat balance method and then the kinematic wave model are used for calculating the surface runoff. The linear storage model is used for groundwater flow modelling. The ground of the whole basin is divided into four uniform layers. The mass balance and the momentum equations are formulated as follow;

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q\left(t,x\right) \qquad (1)$$

$$A=f\left(x,Q\right)=\alpha Q^{\beta} \qquad (2)$$

where A is the discharge area, Q is the flow rate, q is the spatiotemporal effective rainfall, and α and β are the parameters of Manning equation. The general momentum equation from the first to forth layer is formulated with Darcy's law. In this study the watershed is treated extensively with more details. These details encounter distributed criteria for each mesh such as; geological cross sections, soil maps, dynamics of land uses, sinks and sources, and other hydroclimatic processes. The flow chart of the calculation procedure for the integrated Hydro-BEAM is shown in Fig. 1.

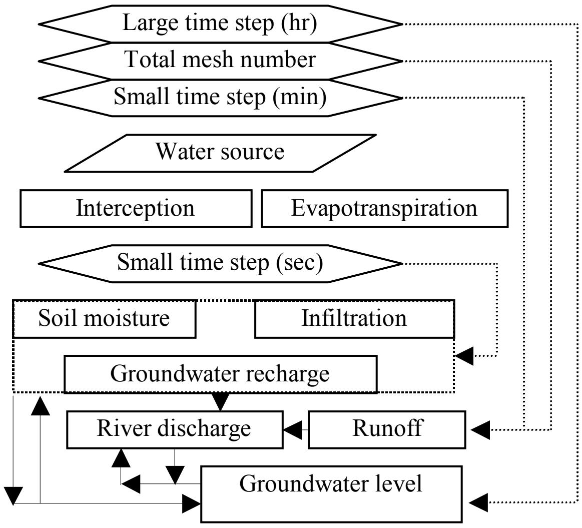
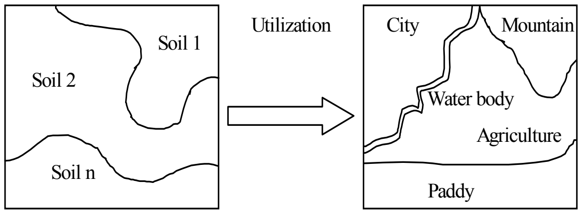


Fig. 1 The main flowchart of integrated Hydro-BEAM

2. Integrated hydrological modeling

2.1 Spatiotemporal variability of hydrological parameters

The surface and subsurface hydrological parameters vary in space and/or time; this variability causes a significant change in the shape of the river hydrograph. Therefore the watershed is divided into catchments, each catchement is girded into square grids, and each grid is connected to a drainage network represented by a channel segment. The variability of the hydrological parameters for each grid is integrated, and then the grid is divided into elements of uniform parameters. The number of elements is decided by the surface properties and the availability of hydrological data. In kinematic wave model the soil roughness affects both the speed of runoff and infiltration rate, infiltration affects both the depth of the surface runoff and the groundwater recharge. Therefore for each type of soil and land uses there are a preliminary set of roughness and infiltration coefficients. These coefficients are evaluated by using the scaling methods and the scaling factors are derived by two steps; first is soil sampling from different locations in the watershed and second is to use the probability densities and auto correlation structures for the calibration. The rational method for calculating the representative infiltration and roughness coefficients for each mesh is shown in Fig.2. It shows the soil map based parameterization n^*, and the land use based parameterization n, where n is a surface hydrological parameter, L_j is the area percentage of the sub parameter n_j, and A is the area of the i^{th} mesh. The two values for a hydrological parameter repre-sent the space of variability, and an optimized value must lye within the boundaries of this space.



$$n_i^* = \frac{\sum n_j^* L_j}{A_i} \quad , \quad n_i = \frac{\sum n_j L_j}{A_i}$$

Fig. 2 Integrated hydrological parameters based on distributed soils and land uses

2.2 Subsurface flow process

Richards equation Eq. (3) for unsaturated flow in one dimension Richards (1931) is used to simulate the distribution of the soil moisture and to estimate the spatiotemporal groundwater recharge.

$$C\frac{\partial \Psi}{\partial t} = \frac{\partial \Psi}{\partial z}\left[K(\Psi)\left(\frac{\partial \Psi}{\partial z}+1\right)\right] \tag{3}$$

where, C is the water capacity, ψ is the water potential head, K is the hydraulic conductivity, z is the thickness of the unsaturated layer, and t is time.

2.3 Groundwater flow process

Quasi three-dimensional equation for the transient unconfined groundwater flow with Dupuit assump-tions as illustrated in Eq. (4) is used;

$$\frac{1}{2}\left(K_x\frac{\partial^2 h^2}{\partial x^2} + K_y\frac{\partial^2 h^2}{\partial y^2}\right) = S\frac{\partial h}{\partial t} - R(x,y,t) \tag{4}$$

where h is the groundwater level, K is the hydraulic conductivity, S is the specific yield, R is the distributed groundwater recharge, x and y are the displacement coordinates, and t is time.

2.4 Interception process

A fraction of rainfall is not contributing with the runoff formation, caused by interception. Similar to the interception by vegetation as it was derived by Horton (1919), the interception caused by residential buildings can be derived as follows;

$$I = C + VEt \tag{5}$$

where I is the interception loss, C is the interception storage depth, V is the ratio of building's surfaces area to its projected area on the ground, E is the evaporation rate, and t is the storm duration.

2.5 Evapotranspiration process (ET)

Evapotranspiration is a description for both evaporation and transpiration by plants, the temporal behaviours of weather conditions and the groundwater level are affecting the rate of ET. There are many methods to estimate ET according to the amount of available metrological data. The heat and mass balance methods are used to evaluate ET for each mesh in the watershed as a function of the net solar radiation Kojiri (2000). The snowfall and snowmelt processes are simulated by using the energy balance at the earth's surface. An empirical formula for the threshold temperature T_c is evaluated for each mesh in order to predict the formation of snow Park *et al* (2003);

$$T_c = 11.01 - 1.5e_a \tag{6}$$

where e_a is the vapor pressure. If $T \leq T_c$; then snowfall. The snowmelt is simulated with an updated energy balance equation that includes the snowmelt heat, temperature near the snow surface, snow cover stored heat, rainfall heat, and the latent heat for the snow layer.

2.6 Reservoir operation and change of basin situation

The basin division approach can be defined as dividing the watershed that has a reservoir into upper and lower parts. Compared with the lower catchment the upper catchments of the watershed is subjected to dry and wet precipitations that differ in time and amount, also the stratigraphy of the lower part differs from the upper part. The wave propagation from the upper catchments down to the lower catchments will be subjected to the well known shock wave, because of the flow of water from high levels to low levels in the lower catchments Shin (1979). On the other hand, the reservoir operation can be considered as a strong down stream control for the developed kinematic wave from the upper catchments, so the kinematic wave approximation will be no longer valid if the reservoir operation is not included Ishihara (1959). The seasonality of the reservoir operation, and the extremes of the seasonal water demands and safety operation are set in the hydrological model, and then linear storage model is used for routing the reservoir.

The changes of land uses within the watershed will occur dynamically in space and/or in time. Therefore Hydro-BEAM allows for automatic adjustment of the distribution of land uses for each mesh. On the other hand the hydrological parameters are also subjected to the same dynamic behavior.

3. Case study: The Yasu River Basin

The Yasu River is located in Shiga prefecture, Japan. The area of the whole basin is 445 km^2 . The hydrological data for the Yasu River basin were prepared. Spatial data includes, geological formation, soil map, elevation, land uses, slope, flow direction, and existing sewers. Temporal data includes; meteorological data, land utilization, groundwater level, operation of existing sinks, water consumption, and seasonal measurements of the hydrological parameters. There are two reservoirs; the *Yasu* and the *Aoto* reservoirs. The reservoirs are used to supply domestic water and to satisfy industrial water demand. The geological cross sections from the Yasu River basin are analysed; there are four main types of rocks: granite; chert; sandstone; and limestone. The soil and the geological maps are used in order to distribute the soil types and geological formations for each mesh. There are five main soil types; gray low land, gray, peat, not matured soil, and dry brown forest soils. According to the boring logs and geological cross sections of the study area, there are mainly unconfined and confined layers respectively, the unconfined layer has an average thickness of 11 m. The hydraulic parameters of the unconfined layer are determined by the rational method for the surface sub-layers. The groundwater divide in south, north, and east of the Yasu Basin forms the basin boundaries. These boundaries are assumed to be no-flow boundaries, the western boundary will be used for calibrating the groundwater model. Three-dimensional simulations for the unconfined groundwater levels were carried out. A one-year simulation was done by using these data and by applying physical parameters obtained from field. These data was set as initial conditions for the groundwater flow model.

4. Simulation results and discussion

Integrated Hydro-BEAM is applied to hourly data from the upper and lower catchments. Initial saturated depth profiles were evaluated according to the distri-buted groundwater levels. Precipitation and the corresponding runoff in the Yasu River basin outlet are shown in Fig.3. The groundwater level for each mesh is simulated by the dynamic linking between the surface water models and groundwater model in the integrated Hydro-BEAM. The distributed ground-water levels for the lower catchments are shown in Fig.4.

The soil moisture profile for each mesh is simulated by considering the spatiotemporal parameterization which is caused by the land use dynamics. At the start of the rain seasons the soil is assumed to be dry, and according to the soil types and depths of groundwater the potential head at the boundary of the unsaturated layer is evaluated. At Yasu River basin the groundwater potential head value ranges from -40 to -100 m, the soil layer is divided into (100) divisions between the surface and the groundwater level. Then the soil moisture and the distribution of the potential head is simulated every 10 sec, during this small time step the groundwater level is assumed to be steady and is not affected by the soil moisture. At every large time step the groundwater level is updated in order to set the lower boundaries for the unsaturated flow model. Then the calculated soil moistures will be accumulated for every large time step and used for estimating the distributed recharge to groundwater model. Also the model simulates the distributed discharge from groundwater storage, because the accumulated soil moisture can be negative in the case of dry weather conditions and extensive water uptake from the subsurface layers.

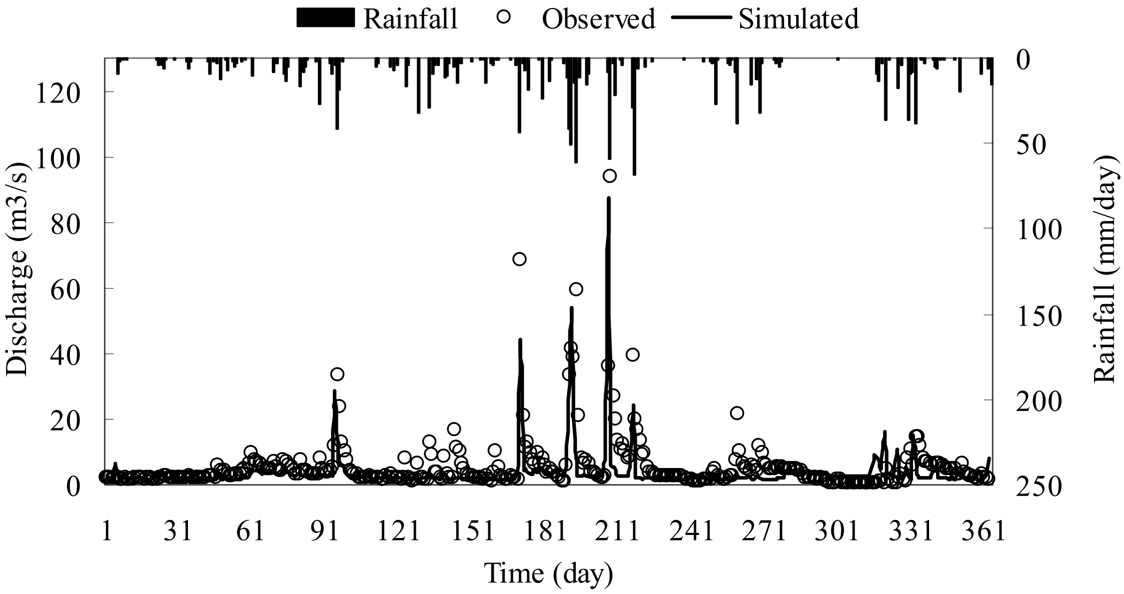


Fig. 3 Simulated and observed daily river discharges at Minakuchi station (1997)

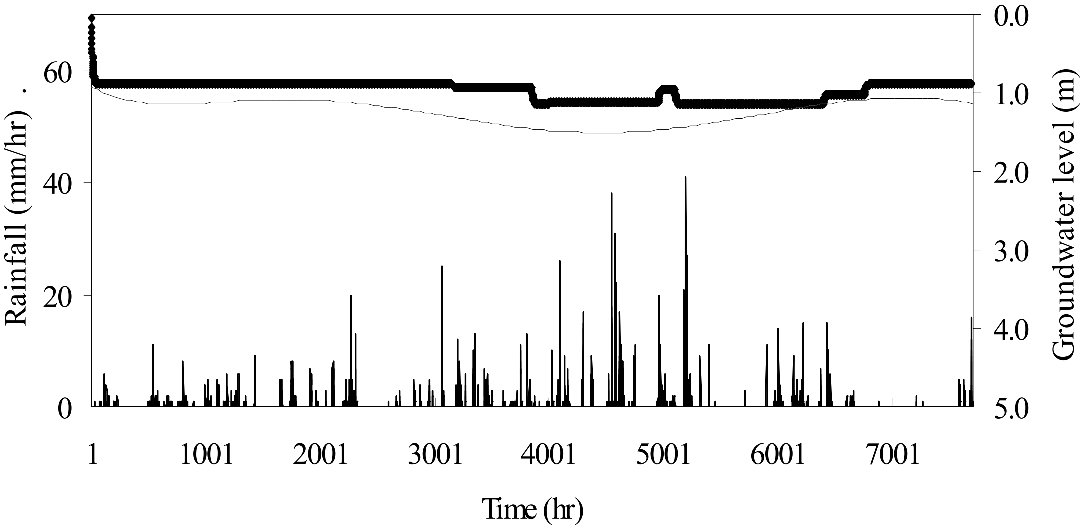


Fig. 4 Simulated and observed (thin line) ground-water levels in lower Yasu basin

5. Conclusions

A general framework for the integrated hydrological modeling has been presented. The framework includes three main linked models: distributed rainfall-runoff model, unsaturated flow model, and unconfined groundwater model. The importance of linking the three models has been illustrated and emphasized. Manual calibration has been conducted for the case study of the Yasu River basin. The simulated groundwater levels and the river discharges show a good agreement with the observed values, but in certain catchments there was a poor agreement with the corresponding observed data.

The manual calibration procedure for the model parameters doesn't succeed in finding global optimal values; the spatiotemporal fluctuations of the basin characteristics might harden the attempts for finding global optimal parameters for every catchment within the basin. The integrated hydrological modeling including groundwater and surface water might require long time periods for automatic calibration and more research is needed in this subject.

References

Ishihara T. (1959): Fundamental researches on the unit hydrograph method and its application, *Japan Society of Civil Engineers*, Vol. 60, No. 3-3, pp. 19.

Horton R. E. (1919): Rainfall Interception, *Monthly Weather Review*, Vol. 47, No. 1, pp. 603-623.

Kojiri T. (2000): GIS-based environment model for water quantity and quality with river basin simulation, *Annual DPRI, Kyoto University*, Vol. 44, No. 1, pp. 150-160.

Park J., Kojiri T., Tomosugi K. (2003): Development of GIS based distributed runoff model for environmental assessment, *Japan Soc. Hydrol. & Water Resources*, Vol. 16, No. 1, pp. 541-555.

Richards L. A. (1931): Capillary conduction of liquids through porous media. *Physics 1*, pp. 318-333.

Shin H. (1979): *Modeling of rivers*, 1st edition, Wiley.

要旨

統合的な水文過程を解析するために、Hydro-BEAM(Hydrological River Basin Environment Assessment Model)をベースとした多層メッシュ型流出モデルを提案する。表面流出にはキネマティックウェーブモデルを、不飽和地中流にはリチャーズ式を、地下水流には非圧地下水モデルを用いて時空間的な解析がなされる。ここでは窪地貯留や樹冠遮断に伴う降雨の初期損失が考慮されている。さらに、貯水池操作や人間活動に伴う土地利用変化に対応するために、流域分割や土地利用のダイナミクスが導入されている。ここで提案するモデルは異なる初期条件やパラメータを用いてキャリブレーションされ、地表水と地下水の直接的な結合（dynamic linkage）を検証するために、野洲川流域に適用された。

キーワード： 分布型流出モデル，パラメタリゼーション，飽和不飽和地中流，時空間分布