Distributed Runoff Model Linking Surface with Groundwater Processes

Amin NAWAHDA[1], Toshiharu KOJIRI[2], and Kenji TANAKA[3]
[1,2,3] Water Resources Research Center, *Disaster Prevention Research Institute,* Kyoto University, Uji, Kyoto 611-0011
e-mail: [1] nawahda@wrcs.dpri.kyoto-u.ac.jp, [2] tkojiri@wrcs.dpri.kyoto-u.ac.jp, [3] ktanaka@wrcs.dpri.kyoto-u.ac.jp

I. Introduction

A method with multi-layer and mesh-typed runoff model using Hydro-BEAM (Hydrological River Basin Environment Assessment Model) is proposed to analyse 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.

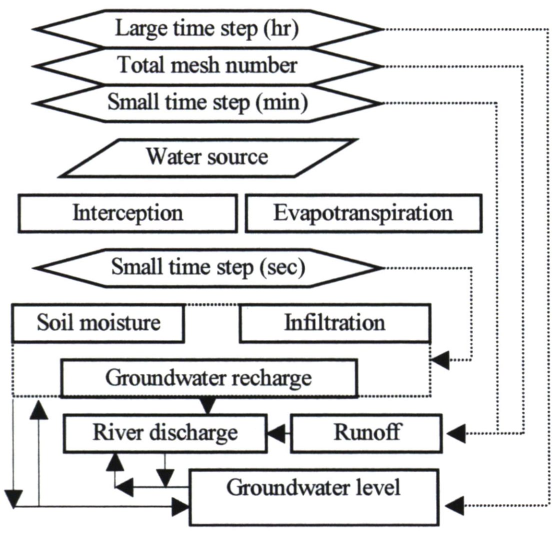

Fig. 1. The main flowchart of integrated Hydro-BEAM.

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 T., 2000).

In this study the watershed is treated more extensively with specific 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**.

II. Formulation of Integrated Hydrological Modeling

1. Spatiotemporal variability of hydrological parameters

The surface and subsurface hydrological parameters vary in space and/or time; this variability ability causes a significant change in the shape of the river hydrograph. The variability can be caused by the basin characteristics, precipitation, and human utilization of land. 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 availability of hydrological data.

The hydrological parameters are evaluated by using scaling methods and the scaling factors are derived by two steps; namely 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.

2. Runoff process

The meshes of the basin are classified into river and slop types, and then the kinematic wave model for unsteady one-dimensional flow is used.

3. Subsurface flow process

Richards equation Eq. (1) for unsaturated flow in one dimension (Richards L. A., 1931) is used to simulate the distribution of the soil moisture and to estimate the spatiotemporal groundwater recharge.

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

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, t is time.

4. Groundwater flow process

Quasi three-dimensional differential equation for the transient unconfined groundwater flow with Dupuit assumptions as illustrated in Eq. (2) is used as follows;

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

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.

5. Interception process

The interception process is highly affected by the rainfall intensity and the conditions of the interceptor. Similar to the interception by vegetation that was derived by Horton (1919), the interception caused by residential buildings can be treated as follows:

$$I = D + VEt_s \quad (3)$$

where I is the interception loss, D 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_s is the storm duration.

6. Evapotranspiration process (ET)

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 T., 2000). An empirical formula for the threshold temperature T_c is evaluated for each mesh in order to predict the formation of snow and rain (Park *et al.*, 2003).

$$T_c = 11.01 - 1.5e_a \quad (4)$$

where e_a is the vapor pressure and if $T \leq T_c$, then snowfall is judged. 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.

8. Basin division

The basin division approach can be defined as dividing the watershed that has a reservoir into upper and lower parts. The reservoir operation can be considered as a strong down stream control for the developed kinematic wave from the upper catchments, therefore the kinematic wave approximation will be no longer valid (Ishihara T., 1959). The seasonal 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 water in the reservoir. Two approaches are introduced in this study for estimating the release of the reservoir;

a) *Formulated operation rules*: For immediate supply from the reservoir, and according to this approach the reservoir is operated according to certain specified rules which can be represented in a polynomial form with respect to an objective release as follows;

$$Release = Qbase + Qdom + Qele + Qind + Qirr + QM \quad (5)$$

where *Qbase* is the river base flow, *Qdom* is the domestic water supply, *Qele* is the hydropower water supply, *Qind* is the industry water supply, *Qirr* is the irrigation water supply, and *QM* is the monitoring flow rate. The polynomial should have a positive coefficient especially for the last term, and must start from the origin.

b) *Iterative operation*: For separated supply from the reservoir, this approach is introduced for reservoirs which have detailed operation rules that encounter maintaining a minimum base flow in downstream river meshes or supplying human-related needs or maintaining a specific temporal storage as illustrated in **Fig. 2.**

III. Simulation Results

The proposed integrated Hydro-BEAM is applied to hourly data from the upper and lower catchments of the Yasu River. The simulated and observed daily discharges at Minakuchi station are shown in **Fig. 3.**

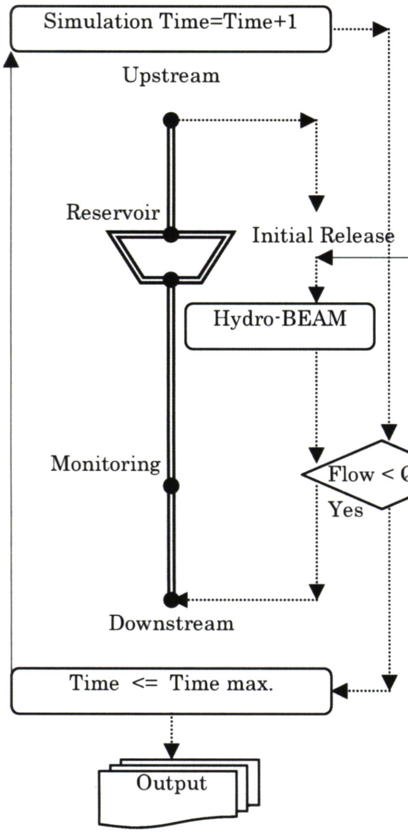

Fig. 2. Illustration of the iterative method for reservoir flow routing

The response of the river hydrograph due to upstream flow in upper catchments is shown in **Fig. 4.** 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 the 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 at every 10 sec, during this small time step the groundwater level is assumed to be steady and is not affected by the soil moisture. A demonstration for simulating the temporal soil moisture conditions and the distribution of groundwater potential heads are shown in **Fig. 6**. The operation of the Yasu dam is analysed for a period of ten years. The operation formulas take the shape of a polynomial of the order 6. The distributed groundwater levels for upper and lower catchments are shown in **Fig. 7**. Spatial distributions of river discharges and groundwater levels at the Yasu River basin are shown respectively in **Fig. 8**, and **Fig. 9**.

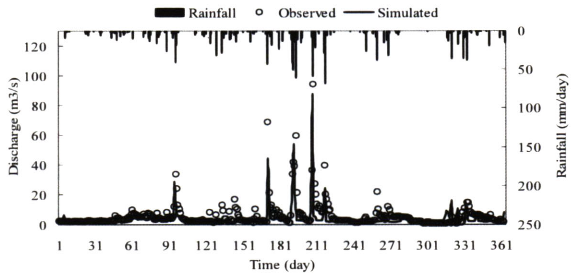

Fig. 3. Simulated and observed river discharges

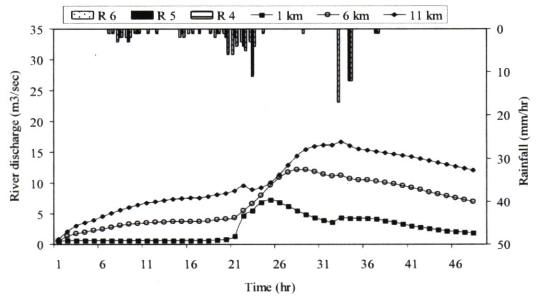

Fig. 4 Hourly river discharge in upper catchments

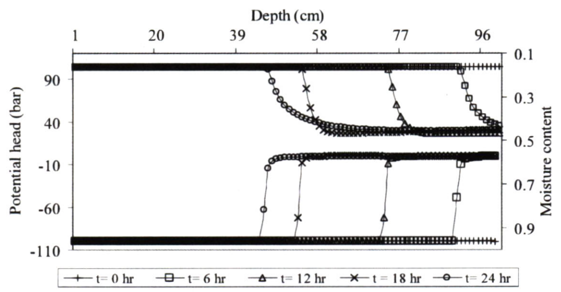

Fig. 5 Simulated soil moisture and potential heads.

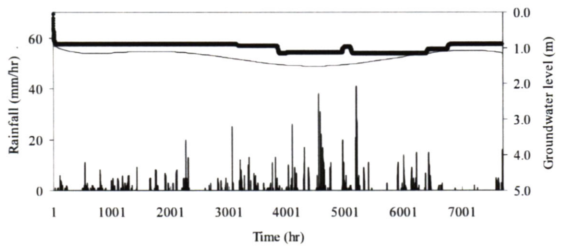

Fig. 6 Simulated and observed (*thin line*) groundwater level in the Yasu basin.

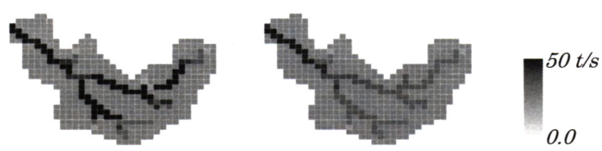

Fig. 7 Spatial distribution of river discharge at the Yasu River (1997/11/1, 8:00 AM-11:00 AM)

Fig. 8 Spatial distribution of groundwater level at the Yasu River basin (1997/11/1, 11:00 AM)

Case study for Seyhan River Basin

The global topographic resources were used to determine the distributed elevation map for the Seyhan basin, at first the Seyhan basin is divided into 4 km x 4 km cells as shown in **Fig. 9**, the satellite images are used to identify the river channel, and then the elevation map is used to determine the distributed sinks as shown in **Fig. 10**, the available data is coded for the Hydro-BEAM and a preliminary flow accumulation map is produced as shown in **Fig. 11**, this maps shows discontinuity in the distributed catchments especially in the lower Seyhan due to law slopes and existing sinks.

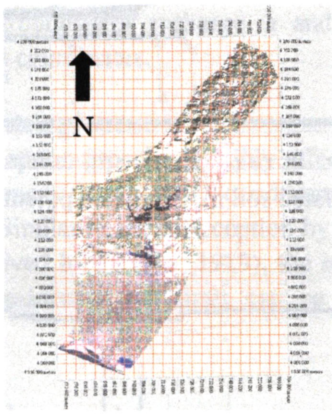

Fig. 9 4 km x 4 km cells of the Seyhan basin

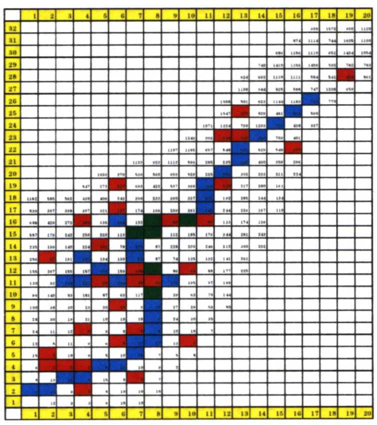

Fig. 10 DEM showing river channel (blue), sink (red), and dams (green)

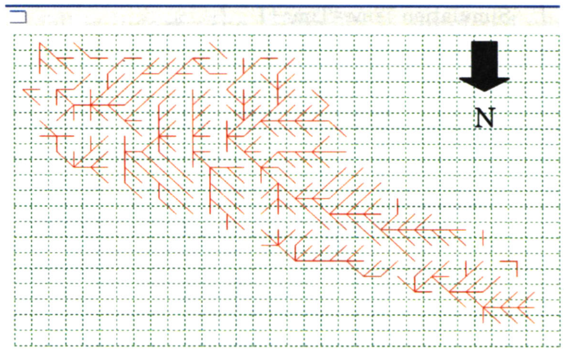

Fig. 11 Generated channel network

IV. Conclusion

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

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

(2002), pp 221-238.

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

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

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

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