Distributed Runoff Model Linking Surface with Groundwater Processes

地下水と地表水流出過程を結合した分布型流出モデルに関する研究

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

Key words: Distributed runoff model, Parameterization, Saturated and unsaturated flow, Spatiotemporal distribution.

本研究は、多層メッシュ型流出モデルである Hydro-BEAM (Hydrological River Basin Environment Assessment Model) において、表面流・飽和中間流には Kinematic wave model を、不飽和中間流には Richards' equation、地下水には不圧地下水流を適用し、その総合化を図ったものである。流出モデルに関しては、流出、土壌水分量、地下水涵養量の動態をモデル化すると共に、表面貯留での初期損失を考慮した。また、ダム貯水池操作を組み込むための流域分割と、人間活動を考慮すべく土地利用の時間変化を用いた。モデルは初期条件やパラメータを最適化して、琵琶湖野洲川流域に適用し、地表水と地下水の間の動的関係を検証した。

キーワード: 分布型流出モデル、パラメータ化、飽和・不飽和中間流、時空間分布

I. INTRODUCTION

The hydrological cycle involves complicated interactions between atmosphere layer, surface and ground layers. A large-scale model was developed for areas with a shallow groundwater table, and it was found that 5~20% of the groundwater evaporates from the watershed each year (Jennifer *et al.*, 2002). The integrated hydrological modeling is achieved by dynamic linking and simultaneous calculation of the water cycle related processes. There will be almost no surface runoff unless the

surface soil is saturated, or a relatively impermeable surface exists there. The saturation condition depends on the groundwater level, evaporation, water uptake by plants, infiltration, irrigation, and other existing sinks or sources. Precipitation infiltrates in grids and the excess forms the runoff. The runoff flows laterally to a seasonal stream during rain events through the surface and subsurface layers (Johansson P., 1986).

Traditionally the lumped models simulate the formation of the surface runoff. Most of these models are based on the assumptions of uniformity and

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linearity in watersheds. In reality these assumptions include a high percentage of errors. The distributed rainfall-runoff (Hydro-BEAM) was introduced in order to overcome the shortcomings of these lumped models (Kojiri T., 2000). In Hydro-BEAM, the watershed is divided into two types of grids; terrain grids that have only excess precipitation as input, and river grids having both excess precipitation and river flow as input. The surface runoff in each grid is transformed into the corresponding next terrain or river grid. Each grid includes five land use types; mountain, paddy, agriculture, urban, and water body. At each grid the heat balance method is used to calculate the evaporation and snowmelt, and then the kinematic wave model is used for calculating the surface runoff. The linear storage model is used for groundwater flow modeling. The ground subsurface of the whole basin is divided into four uniform layers. The mass balance and the momentum equations are formulated as follows;

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

$$A = f(x, Q) = Q \quad (2)$$

where A is the discharge area, Q is the flow rate, q is the spatiotemporal effective rainfall, and f and Q are parameters. The general momentum equation from the first to forth layer is formulated according to Darcy's law.

In this study the watershed is treated more extensively with specific details. These details include distributed criteria for each grid 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 parameter

The surface and subsurface hydrological parameters vary in space and/or time; this variability causes a significant change in the shape of the

Fig. 1 The main flow chart of integrated Hydro-BEAM.

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 catchment is divided 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.

In the kinematic wave model the soil roughness affects both the speed of runoff and the infiltration rate, infiltration affects both the depth of the surface runoff and the groundwater recharge. Therefore for each type of soil and land use there is preliminary set of roughness and infiltration coefficients. These coefficients are evaluated by using scaling methods, 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 grid is shown in Fig. 2.

It shows the soil map based parameterization n_f^* ,

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

and the land use based parameterization n_j , where n is a surface hydrological parameter, L_j is the area percentage of the sub-parameter n_j , j is the number of the considered land uses or soils, and AM_i is the area of the i^{th} grid. An example is illustrated by the above figure. An infiltration coefficient for a grid with sandy soil (normalized $n^* \approx 1.0$) and city-typed land use ($n \approx 0.0$) has a value that is not large as if the parameterization is only based on soil map, and is not small as if it is only based on land use map. In other words the two values n and n^* represent the limits of the variability domain; therefore the value of infiltration coefficient is selected from this domain. In Hydro-BEAM the harmonic mean value is selected.

2. Runoff process

The grids of the basin are classified into river and slope types, and then the kinematic wave model for unsteady one-dimensional flow is used, and in Eq. (2) are computed by using Manning equation:

$$Q = \frac{\sqrt{\sin(\theta)}}{n_r} AH^{\frac{2}{3}} \quad (3)$$

where θ is the grid average slope, n_r is the roughness coefficient, and H is the hydraulic radius. The finite difference method is used to approximate Eq. (1) as shown in Eq. (4) its numerical solution is achieved by using the Iterative Newton Method (Chow V., 1988) as follows;

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{x} + \frac{A_{i+1}^{j+1} - A_i^{j+1}}{t} = \frac{q_{i+1}^{j+1} - q_i^{j+1}}{2} \quad (4)$$

where: $A_{i+1}^{j+1} = (Q_{i+1}^{j+1})$, $A_i^{j+1} = (Q_i^{j+1})$

3. Subsurface flow process

Richards' equation Eq. (5) 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.

$$C \frac{\partial}{\partial t} = \frac{\partial}{\partial z} \left[K \left(\frac{\partial}{\partial z} + 1 \right) \right] \quad (5)$$

where, C is the specific water capacity, ψ is the water potential head, K is the hydraulic conductivity, z is the vertical coordinate and t is time. The numerical solution for Eq. (5) is achieved by using the finite difference implicit scheme as given by Eq. (6) the boundary conditions can be handled by using Eq. (7) and Eq. (8) (Baker L., 1995b) as follows;

$$C_i \frac{t^{i+1} - t^i}{t} = \frac{1}{z} \left(K_{ip} \frac{t^{i+1} - t^i}{z} + K_{ip} \right) - \frac{1}{z} \left(K_{im} \frac{t^{i+1} - t^i}{z} + K_{im} \right) \quad (6)$$

Bottom node:

$$\left(C_i + \frac{t}{z^2} (K_{im} + K_{ip}) \right) t^{i+1} - \frac{t}{z^2} K_{ip} t_{i+1}^{i+1} = C_i t^i + \frac{t}{z} (K_{ip} - K_{im}) + \frac{t}{z^2} K_{im} \psi_0 \quad (7)$$

Surface node:

$$-\frac{t}{z^2} K_{im} t_{np-2}^{i+1} + \left(C_{np-1} + \frac{t}{z^2} K_{im} \right) t_{np-1}^{i+1} = C_{np-1} t_{np-1}^i + \frac{t}{z} (K_{im} + q_{inf} - P) \quad (8)$$

where ψ_0 is the initial constant potential head at the bottom of the unsaturated layer, q_{inf} is the infiltration flow rate including evapotranspiration, P is the uptake by plants, K_{ip} is the upward arithmetic mean of the hydraulic conductivities and K_{im} is the downward arithmetic mean of the hydraulic conductivities for two successive nodes in the vertical direction. The potential pressure-saturation relation is simulated using van-Genuchten style equations;

$$S = \frac{r - r_s}{r - r_s} = \left[\frac{1}{1 + (|d|/d)} \right]^{\frac{1}{n}} \quad (9)$$

$$K = K_s S_t \quad (10)$$

where S_r is the effective saturation, θ_r is the residual water content, θ_s is the saturated water content, and α and n are the van-Genuchten fitting parameters, h_d is the displacement pressure head, K_s is the saturated hydraulic conductivity and λ is the exponential soil parameter.

4. Groundwater flow process

Quasi-three dimensional differential equation for the transient unconfined groundwater flow with Dupuit assumptions is given by

$$\frac{1}{2} \left(K_x \frac{\partial^2 h^2}{\partial x^2} + K_y \frac{\partial^2 h^2}{\partial y^2} \right) = S \frac{\partial h}{\partial t} - R(x, y, t) \quad (11)$$

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. Iterative implicit Crank-Nicolson equation form is used to approximate the solution of the quasi-three dimensional partial differential equation for groundwater flow (Wang H. and Anderson M., 1982) as follows;

$$\begin{aligned} v_{ij}^{n+1} = & \frac{1}{\left(\frac{a^2 S}{4K\sqrt{v_{ij}^n}} + \right)} \left(v_{ij}^{n+1} \right. \\ & + \frac{a^2 S}{4K\sqrt{v_{ij}^n}} v_{ij}^n \\ & \left. + (1 - \chi) v_{ij}^n - v_{ij}^n \right) + \frac{a^2 R_{ij}^n}{2K} \end{aligned} \quad (12)$$

where $v = h^2$, $a = \sqrt{x^2 + y^2}$, i and j are displacement coordinates, n is time step index, $\chi = 0.5$, and vm is the arithmetic mean of the surrounding star heads, the available values for the hydraulic conductivity are only in the vertical direction, for alluvial deposits the ratio of horizontal and the vertical values varies from 2 to 20 (Bouwer H., 1978). The boundary conditions for the groundwater model are (a) known head, (b) known flow, and (c) known flow and head. The three types of boundary conditions have an interaction between the sub-models of the integrated Hydro-BEAM. The simulated groundwater level will be used in the unsaturated flow model, which is running with a small time step compared with the time step of the groundwater model, therefore the groundwater flow is assumed to be steady, and the distributed groundwater re-

charge is accumulated at every small time step.

5. Interception process

A fraction of rainfall is not contributing to the runoff formation due to interception. The interception occurs at the roof of houses in city grids, also occurs over the vegetation cover which has a certain storage capacity. A fraction of the intercepted water evaporates, another fraction falls to the ground in large drops or flows over the body of the interceptor to reach the ground surface. 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:

$$I = D + VEt \quad (13)$$

where I is the interception loss, D is the interception storage depth, V is the ratio of building's surface area to its projected area on the ground, E is the evaporation rate, and t is the storm duration. The interception by plants is formulated in order to include the seasonality, also the fluctuation of the leaf area indices is included in the estimation of both interception and evaporation amounts according to rainfall intensity.

6. Evapotranspiration process (ET)

Evapotranspiration is a description for both evaporation of liquid or solid water plus transpiration from plants, the temporal behaviors of weather conditions and the groundwater level affect the rate of ET. There are many methods to estimate ET according to the amount of available meteorological data. The heat and mass balance methods are used to evaluate ET for each grid in the watershed as a function of the net solar radiation (Kojiri T., 2000) as follows;

$$\text{Heat balance: } IR = T^4 + HS + IE + Q_q \quad (14)$$

$$\text{Input radiation: } IR = (1 - \text{ref})SR + LR \quad (15)$$

$$\text{Sensible heat: } HS = C_p C_H U (T_s - T) \quad (16)$$

$$\text{Latent heat: } IE = \ell C_E U (q_s - q_h) \quad (17)$$

where IR is the input radiation, σ is the Stefan-Boltzmann constant, T is the atmosphere temperature, HS is the sensible heat flux, IE is the latent

heat flux, Q_q is the storage heat, ref is the albedo, SR is the incoming solar radiation flux, LR is the long wave radiation, C_p is the specific heat at constant pressure, ρ is the atmosphere density, C_H is bulk coefficient of sensible heat, U is the wind velocity, T_s is the atmosphere temperature near surface grounds, q_s is the specific humidity at water surface temperature, q_h is the specific humidity of air, ℓ is the latent heat of vaporization, and C_E is the bulk coefficient of latent heat. ET is highly variable because it is affected by type of plant, growing stage, available soil moistures, and weather conditions.

7. Snowfall and snowmelt processes

The snowfall and snowmelt processes are simulated by using the energy balance at the earth's surface. A single layer of snow is assumed, then snowmelt, refreezing and cooling are formulated. An empirical formula for the threshold temperature T_c is evaluated for each grid in order to predict the formation of snow and rain (Park *et al.*, 2003)

$$T_c = 11.01 - 1.5e_a \quad (18)$$

where e_a is the vapor pressure. If $T > T_c$; then rainfall, if $T \leq T_c$; then snowfall. The snowmelt is simulated with an updated energy balance equation that includes the snowmelt heat Q_m , temperature near the snow surface T_{SN} , snow cover stored heat Q_s , rainfall heat Q_r , and the latent heat for the snow layer is given by

$$Q_m = IR - T_s^4 + HS + LE + Q_s + Q_r \quad (19)$$

The snowmelt related processes are evaluated according to the following conditions;

- 1) Temperature rise: $Q_m \geq 0$ and $T_{SN} < 0$
- 2) Snow melt: $Q_m \geq 0$ and $T_{SN} = 0$
- 3) Refreezing: $Q_m < 0$ and $T_{SN} = 0$
- 4) Cooling: $Q_m < 0$ and $T_{SN} < 0$

8. Reservoir operation and change of basin situation

1) Basin division

The basin division approach can be defined as dividing the watershed that has a reservoir into upper and lower parts. Compared with the lower

catchments, the upper catchments of the watershed are subjected to precipitation that differs in time and amount, also the stratigraphy of the lower part differs from the upper part. The analytical solution for the conservation of mass and momentum Eqs. (1) and (2) show that the speed of the kinematic wave is affected by the runoff depth. Therefore the wave propagation from the upper catchments to the lower catchments will be subjected to the kinematic wave shock (Shin H., 1979). On the other hand the reservoir operation can be considered as a strong downstream control for the developed kinematic wave from the upper catchments, therefore the kinematic wave approximation will be no longer valid if the reservoir operation is not included (Ishihara T., 1959). Also the probabilistic nature of the reservoir operation hardens the process of integrating with the physical hydrological models, due to different simulation and operation times. Therefore 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 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;

$$\text{Release} = Q_{base} + Q_{dom} + Q_{ele} + Q_{ind} + Q_{irr} + Q_M \quad (20)$$

where Q_{base} is the river base flow, Q_{dom} is the domestic water supply, Q_{ele} is the hydropower water supply, Q_{ind} is the industry water supply, Q_{irr} is the irrigation water supply, and Q_M 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 operating*: For separated supply from the reservoir, this approach is introduced for reservoirs which have detailed operation rules that involve maintaining a minimum base flow in

downstream river grids or supplying fluctuation human related needs or maintaining a specific temporal storage. At first Hydro-BEAM is initialized with an actual storage and release amounts. Then the seasonal user-defined main operation constraints such as maximum and minimum storage and/or allowed water levels are formulated into the iterative method, because the calculating order in Hydro-BEAM is achieved from the upstream to the downstream simultaneously, therefore a reservoir in the upper catchments will be operated before the runoff contribution in the lower catchments is calculated. Therefore an initial guess of release is assumed then Hydro-BEAM simulates the runoff down to the monitoring point then the river discharge is compared with the desired discharge QM as illustrated in Fig. 3, this procedure is repeated until certain difference or a maximum number of iterations are achieved. The iterations

are performed according to the user-defined operation time in order to save computing time. The output of the iteration method is used to simulate the fluctuation of the storage, in order to calculate the storage the calculated releases and the Hydro-BEAM simulated inflow at the reservoir are routed linearly. There will be a deficit between the observed and simulated storages, this deficit can be used to estimate the hidden losses of the reservoir.

2) Dynamics of land use

The changes of land uses within the water-shed will occur dynamically in space and/or in time. Therefore modeling the hydroclimatic processes in the watershed such as stream flows, evapotranspiration, and soil moisture, Hydro-BEAM allows for an automatic adjustment of the distribution of land uses for each grid. On the other hand the hydrological parameters are also subjected to the same dynamic behavior. Therefore a seasonal parameterization for surface roughness, infiltration, and irrigation amounts is prepared to simulate the dynamics of land uses. This behavior of land is related to the residence time of water in the watershed and to the human utilization of land. The land use dynamics approach can be applied for deterministic schemes or stochastic schemes by considering several scenarios of hypothetical changes in land uses.

III. CASE STUDY: THE YASU RIVER BASIN

The Yasu River is located in Shiga prefecture, Japan, and is one of the main water sources for Lake Biwa. Averaged annual precipitation for the regions ranges from 1550-2050 mm for the lower and upper catchments, respectively. The area of the whole basin is 445 km² (see Fig. 4) The length of the river channel is 95 km. Small river flows and draw down of the groundwater level in the lower catchments and conservation of the water quality are the main concerns in the Yasu River basin.

Many studies have been carried out for developing a hydrological model for the Yasu River basin. The tank model was used for simulating the runoff

Fig. 3 Illustration of the iterative method for reservoir flow routing.

Fig. 4 The Yasu River basin / Japan.

and the operation of reservoirs for the upper catchments(Kato T., 2002).

In the lower catchments of the basin a groundwater model was developed to investigate the impacts of land use changes (Kimaro T., 2002) and the simulation results show a draw down of the groundwater levels. Though the mentioned studies were limited to sub-catchments in the Yasu River basin, the researchers thought that there might be a strong relation between the exploding urbanization and the change in land uses, and the change of both groundwater levels and shape of the hydrographs of the Yasu River.

The distributed spatiotemporal hydrological data for the Yasu River basin were collected at necessary monitoring stations. 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 distributed sinks, water consumption, and seasonal measurements of the hydrological parameters.

The basin is divided into one kilometer by one kilometer square grids. Then land uses are classified into five types as follows; 1) mountains and forests 2) paddy fields 3) farms 4) urban areas 5) water bodies. There are two reservoirs the Yasu and the Aoto reservoirs. The reservoirs are used to supply domestic water (0.080 m³/sec) and to satisfy industrial water demand (0.533 m³/sec)

During the past 30 years (1970-2000) detailed measurements of meteorological data, groundwater levels, and runoff were measured along the Yasu River. Most of the simulated hydroclimatic

processes require specific geological data and soil data like soil type, porosity and hydraulic conductivity. Despite the need of soil and geological data, fine resolution data is not available in digital form.

The soil characteristics and geological data are extracted from the already available hardcopy soil maps. The geological structures are used to determine the boundaries of the groundwater model. The data used for the geological analysis also extracted from drillers' logs. This information was used to prepare geological cross sections in Yasu River basin. There are four main types of rocks such as 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 grid. There are five main soil types; gray low land, gray, peat, not matured soil, and dry brown forest soils. **Table 1** lists some of the field sampling analysis.

According to the drillers' logs and geological cross sections of the study area, there are mainly unconfined and confined layers respectively. The number of boring wells is so large, they are available at every 100 m between section A and section B (see Fig. 5.) The unconfined layer is not the

Table 1 Distributed physical soil parameters at Yasu River basin.

Location	θ (%)	Porosity (%)	K (cm/sec)
Farms	36	49.9	0.0322
Mountain	27.7	68.3	0.607
Paddy	48.9	49	0.00034

Fig. 5 Geological sections at the Yasu River basin.

same in all grids (see Fig. 6.) therefore a constant average thickness is assumed all over the basin, and 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 (see Fig. 7.) The ranges for hydraulic conductivities for each sub-layer are listed in Table 2.

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. The recharge sources are mainly the rainfall and irrigation. The

Fig. 6 Distributed representative boring wells.

Fig. 7 Distributed hydraulic conductivities.

Table 2 Distributed stratigraphy in the lower Yasu River basin.

Layer name	Height (m)	K (cm/sec)
Ag	3	10E-2 – 10E0
Ks	2	10E-6 – 10E-5
Ksg	1	10E-3 – 10E-4
Kg	11	10E-2 – 10E-4

Fig. 8 Distributed weather and gauging stations at the Yasu River.

time series data of the observed groundwater levels and groundwater extraction amounts have not been sufficiently available for the whole basin. Limited investigations conducting the amounts of pumped water were carried out. Therefore the involved uncertainty is evaluated by the manual calibration of the model. Three-dimensional simulations for the unconfined groundwater levels were also 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. There are many weather stations and rain gauges distributed all over the Yasu River basin. Among these stations there are only six stations with a reliable time series data. The locations of these stations are shown in Fig. 7. These data includes 30 years of hourly meteorological data, hourly water intake, and hourly-observed river stage.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed integrated Hydro-BEAM is applied to hourly data from the upper and lower catchments. Initial saturated depth profiles were evaluated according to the distributed groundwater levels. The undefined parameters were adjusted by trial and error in order to minimize the residual errors between the calculated and the observed data. Snow depth, and evapotranspiration are shown in Fig. 9. Precipitation and the corresponding runoff in the Yasu River basin outlet are

Fig. 9 Sim ulated evapotranspiration and snow depth in upper Yasu River Basin (1997)

shown in Fig. 10. There are three discharge observation stations at the Yasu River basin. The correlation values between observed and calculated values vary within the basin. The fluctuations are caused by the calibration of the model. Since the hydrological parameters of the distributed land uses and soils are varying for each grid, the calibration of the discharge at one station will not necessarily lead to good agreements between the observed and simulated values at other observation stations.

The river discharge measurements at the Yasu River are performed daily. The daily measurements do not show the propagation of the kinematic wave from the upper catchments due to averaging of hourly readings. The simulated and observed daily discharges at Minakuchi station are shown in Fig. 11.

The response of the river hydrograph due to upstream flow is not the same for upper and lower catchments, the runoff related wave transfers faster in lower catchments. Fig. 12, and Fig. 13.

Fig. 10 Sim ulated river discharge and measured rainfall in lower Yasu River basin (1997)

Fig. 11 Sim ulated and observed daily river discharges at Minakuchi station (1997)

Fig. 12 Time series of hourly river discharge in upper catchments.

Fig. 13 Time series of hourly river discharge in lower catchments.

show the plots of the flow hydrographs at various points along the river channel in the upper and lower catchments, respectively. It can be seen that the peak discharge is transferred as the runoff wave in the upper streams (1 km, 29 km). In these Figures the spatiotemporal distribution of the flow hydrograph can be seen for many points along the river channel. This change is caused by the difference in flow accumulation networks and the hydrological characteristics of the catchments. These characteristics include rainfall, parameters for infil-

Fig. 14 Time series of river discharges for land use change scenarios.

tration and roughness coefficients that are highly affected by both land uses and soil distribution.

The model is highly affected by the distribution of both land use and soil type in each grid. Many scenarios have been simulated for identifying the hydrological impacts of urbanization. Fig. 14 shows the impact of changing (30%) of the agricultural areas into residential areas, and the related change in the river hydrographs in the upper Yasu River basin. In this figure, LU1f and LU2f represent the future shapes of the hydrographs LU1a, and LU2a, respectively. Large points compose the forecasted hydrographs.

The distributed soil moisture is highly affected by the existing sources and sinks within the unsaturated subsurface layer. By considering the spatiotemporal parameterization, which is caused by the land use dynamics the soil moisture profile for each cell is simulated. 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. At every large time step the groundwater level is updated in order to set the lower boundaries for the unsaturated flow model. Since the initial potential head for dry conditions is smaller than any of the distributed hydraulic con-

Fig. 15 Simulated spatiotemporal soil moisture contents in lower Yasu River basin.

ductivities, it is assumed that the soil will absorb a certain amount of the applied sources. This amount is highly affected by the existing utilization of land and seasonality. 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 discharges 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. A demonstration for simulating the temporal soil moisture conditions is shown in Fig. 15.

Fig. 16 Simulated groundwater level in the Yasu River basin.

Fig. 17 Spatial distribution of river discharge at Yasu River(1997/11/1)

The groundwater level for each grid is simulated by the dynamic linking between the surface water models and groundwater model in the integrated Hydro-BEAM. The distributed groundwater levels for upper and lower catchments are shown in Fig. 16. Spatial distributions of river discharges and groundwater levels at Yasu River basin are shown respectively in Fig. 17, and Fig. 18.

The operation of the Yasu dam is analyzed for a period of ten years. The operation of the dam illustrates some of the unique problems, associated with a dam designed for flood protection and for storing of the runoff form the upper catchments. This type of dams requires a seasonality-based operation rules, and in Hydro-BEAM the monthly operation is simulated according to the formulated operation method. The operation can be formulated as a polynomial of the order 6 as illustrated by Eq. (21) Table 3. illustrates the monthly formulation of the storage- release functions.

$$Release = \sum_{i=1}^6 a_i RS^i \tag{21}$$

where a_i is the polynomial coefficients, RS is the reservoir storage. Then the unsteady inflow hydrograph from the upper catchments is routed through the reservoir, the initial outflow and as well as the initial storage, must be known. Using continuity the storage for a time step is given by

$$2RS_j = I_{j-1} + I_j - RI_{j-1} - R(RS_j) \tag{22}$$

where I is the inflow and RI is the release. The RS value can be used to calculate RI for a time step by applying an iteration method.

The operation of Yasu dam and Aoto dam is formulated according to the explained methodology

Fig. 18 Spatial distribution of groundwater level at Yasu River basin(1997/11/1, 11:00 AM)

Table 3 Formulated monthly operation rules for the Yasu dam.

Month	a_1	a_2	a_3	a_4	a_5	a_6
1	0	298.7	-32278	12992	-23820	10400
2	0	2.00E-15	-4.00E-11	4.00E-07	-0.0017	2.689
3	8.00E-18	-3.00E-13	4.00E-09	-2.00E-05	7.83E-02	-1.03E+02
4	0	2.00E-15	-6.00E-11	6.00E-07	-0.0025	4.176
5	0	2.00E-16	-6.00E-12	5.00E-08	-0.0002	0.3352
6	3.00E-19	-7.00E-15	7.00E-11	-4.00E-07	9.00E-04	-9.48E-01
7	0	0.00E+00	2.00E-11	-4.00E-07	0.0029	-6.289
8	1.00E-20	-3.00E-16	2.00E-12	-9.00E-09	2.00E-05	-1.28E-02
9	3.00E-19	-6.00E-15	4.00E-11	-2.00E-07	3.00E-04	-1.81E-01
10	0.00E+00	5.00E-15	-5.00E-11	2.00E-07	-2.00E-04	1.16E-01
11	1.00E-18	-1.00E-13	1.00E-09	-6.00E-06	1.10E-02	-7.48E+00
12	4.00E-19	-7.00E-15	5.00E-11	-2.00E-07	4.00E-04	-2.75E-01

in the previous section. The monthly formulated operation is applied to Yasu dam, then the calculated release is added to the simulated runoff in order to

Fig. 19 Modified dam release at Aoto Dam (dashed line) 1997.

estimate the inflow at Aoto dam. The operation at Aoto dam is evaluated according to the river discharge at Yasu River station, which is located 15 km far away. Fig. 19 shows the actual release at Aoto dam and the periods where the operation of Aoto dam has failed to satisfy the monitoring value ($1.68 \text{ m}^3/\text{sec}$). Therefore Hydro-BEAM is used to identify these faults in dam operation and optimizes the release by using the iterative operation method.

V. 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 spatio-temporal 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.

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