京都大学防災研究所年報 第45号 B 平成14年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 45 B, 2002

Groundwater Modeling Coupled with SVAT Model and its Application to the Yasu River Basin

*Tumaini KIMARO, Yasuto TACHIKAWA, and Kaoru TAKARA

* Graduate School of Civil Engineering, Kyoto University

Synopsis

A groundwater model coupled with a SVAT (Soil Vegetation Atmosphere Transfer) model to investigate the effects of landuse changes on the groundwater resources is constructed. The model uses operational meteorological data such as rainfall, vapor pressure, windspeed, long and shortwave radiation as well as soil and landuse data to estimate spatially variable recharge rate to be provided as source term to the groundwater model. A grid-cell based Noilhan and Planton model (Noilhan and Planton 1989) is used in the SVAT scheme. A two dimensional single layer unconfined aquifer model is assumed for groundwater flow simulation. Boundary conditions consist of Lake Biwa shoreline, rivers and a mountain range. The model is applied to the lower part of Yasu River basin at a grid resolution of approximately 400 m. The potential for application of the model in Yasu River basin is explored.

Key words: land use changes, recharge estimation, groundwater modeling, Noilhan and Planton model

1. Introduction

The Yasu River basin is one of the important basins of Lake Biwa and the Yodo River. It is located in Shiga Prefecture Honshu Island at approximately latitude 34°50" to 35°10" North and longitude 135°52" to 136°25" East. The basin is located in the headwaters for Lake Biwa and contributes to the inflow into the lake. Groundwater resources of the basin are mostly utilized in the lower part of the basin near Lake Biwa. This area consists of a mixture of built up areas and paddy fields. There is a high concentration of production wells in the area bout one well for each 1.5 sq km area. The total pumping load in the area is more than 100,000 tons per day which is used for water supply and industrial purposes.

Preliminary study of ground water levels in the lower Yasu River basin indicates that some parts of the basin have experienced significant draw down in the ground water levels. Among the eight sites where long series of ground water was available during this study, Otsukubo station seems to be the most affected as shown in Fig. 1 The objective of this study is to develop a suitable model for ground water movement and investigate possible causes for ground water depletion in the study area. The main assumption of the work is that land use changes among others have contributed to the change of water

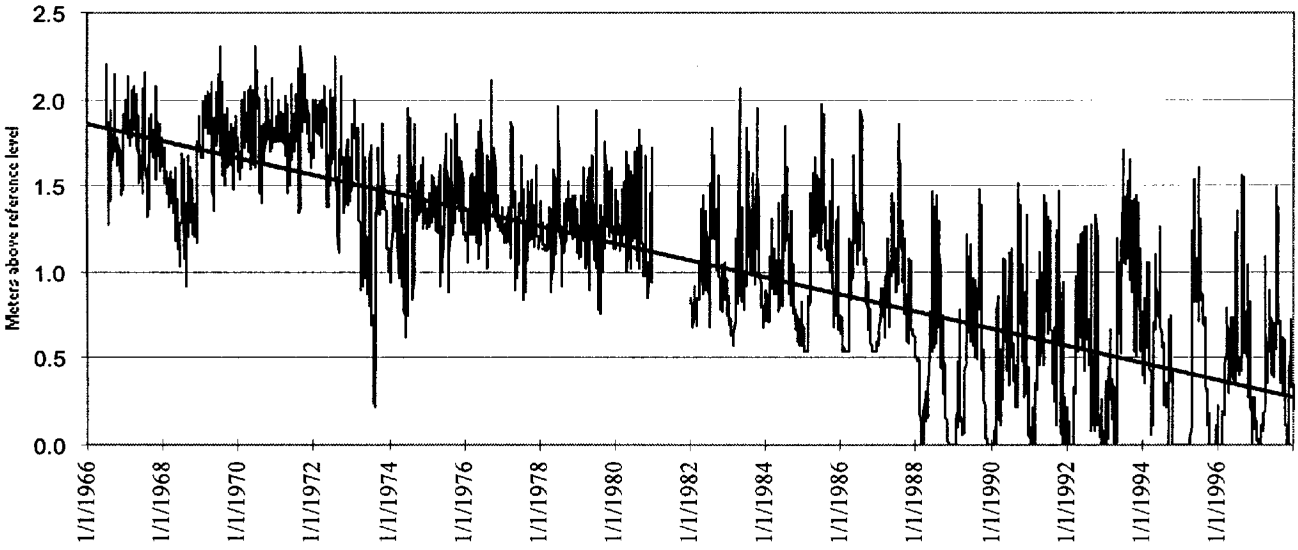

Fig. 1 Water level trend at the Otsukubo station in the lower part of the Yasu River basin

levels with different effects for different parts in the basin. In this study the Noilhan and Planton model is used to estimate ground water recharge. Since this model uses land use data, it can be used to study the effect of land use changes on groundwater resources when applied to estimate recharge.

2. Groundwater and Land use changes

In recent years there is much concern for conservation of natural resources including groundwater. As far as groundwater is concerned, the preservation of both the quality and quantity is essential for sustainable management of the resource. Although more emphasis is put on quality issue and there are many studies on pollution of groundwater from domestic agriculture and industrial wastes, the quantity issues also need to be addressed equally well.

The major landuse factor that affects groundwater is the infiltration which provides recharge to the groundwater reservoirs or aquifers. Infiltration is affected by landcover change e.g. from urbanization which result in impervious surfaces like roads and parking lots reducing infiltration and groundwater recharge. It has been proposed for example in a recent research by Yangwen et al. (2000) that measures to arrest this effect in rapidly urbanizing area be provided such as providing infiltration facilities to preserve the natural movement of the water in the water cycle. The mother lake 21 plan Nakamura and Nickum (2002) which will be carried out in the Lake Biwa basin including the study area plans to restore the infiltration capacity of the basin by a forestation.

Despite the obvious effects of urbanization on groundwater resources there is also concern for the effect of river improvement works on groundwater resources. Within the study area and in many other places in Japan river courses have been lined on the banks and in some cases man made rivers have replaced the natural courses shifting the natural path of flow for several kilometers to provide safety against floods. The compound effects to groundwater reserves are largely unknown but the fact is that such measures posses a real danger to the groundwater sources. This study proposes linking groundwater model with a land use sensitive recharge estimation mechanism in order to evaluate this amongst other effects.

3. Groundwater Situation in the Lower Yasu River basin

3.1 Water level data and Measurements

In order to develop groundwater model and

Table 1 Groundwater stations in Lower Yasu river basin with long term data

S/no	Well name	Location			Available water level data(digital data)
		Lon. (d m s)	Lat. (d m s)	Elevation of Station	
1	Mizuho	135.969109	35.102798	87.900	1969-1997
2	Yoshikawa	135.992816	35.116180	90.100	1966-1997
3	Hattori	136.00000	35.104623	88.387	1966-1997
4	Otsukubo	136.007902	35.090024	90.052	1966-1997
5	Takesyo	136.012931	35.079684	87.000	1982-1997
6	Ikehata	136.027299	35.057786	89.000	1979-1997
7	Yoshimi*	136.00000	35.057786	86.310	1978-1997
8	Shibukawa	135.972701	35.022506	95.200	1979-1997
9	Ishibe	136.054598	35.012265	102.000	1977-1997
10	Imahama	135.961207	35.102798	81.000	1977-1997

investigate the attendant problems, availability of water level and other aquifer data with sufficient temporal and spatial coverage and resolution is prerequisite. Within the vicinity of the study area groundwater measurement dates back to 1970's according to the data available with the Ministry of Land Transport and Infrastructure. There are about 11 groundwater levels stations at which data have been collected during the last 30 years. However these data have only recently been put in a digital data base and the process of validating it for research purposes is still going on. There are gaps in the time series and elevations of some gauging points are uncertain which causes difficulties in applying this data for research. In some cases the gauging points have been shifted or renamed without proper documentation such that it is difficult to infer which measurement refers to what location with certainty.

Recently (2001) six new groundwater monitoring stations have been established in the study area for research purposes. The groundwater level is monitored at one hour interval and data for five months has been collected up to the end of March 2002. Although short in temporal coverage this data presents the most accurate sources of groundwater level data to be used for research purposes. Figure 4 (page 7) shows the location of available water level measurement stations in the study area and the information regarding these stations is shown in Table 1. There is generally very low or no information regarding the aquifer data and geological information in the study area. During the study only two wells were identified with borehole data revealing the information about subsurface layers.

3.2 Groundwater level fluctuations Patterns

Generally groundwater level increases during the summer period reaching a maximum level in between August and September and falls during the winter. This kind of variation agrees with the pattern of variation of rainfall which peaks in summer and the irrigation season which starts around June when paddy fields are irrigated for a new crop It is noted that the levels has been dropping over the years as also shown earlier in Fig.1. There is a clear tendency of draw down in groundwater levels at Mizuho, Otsukubo, Ikehata, and Takesyo and to some extent Hattori, while the levels at Yoshimi, Shibukawa and Yoshikawa do not show any obvious signs of reducing.

4. Estimation of recharge

It is assumed that the recharge to ground water in the study area is mainly due to rainfall. To estimate this recharge the different landcover which cause spatial variability in the recharge rate needs to be considered. Areas with different types of land covers and large variations within a small area need careful consideration.

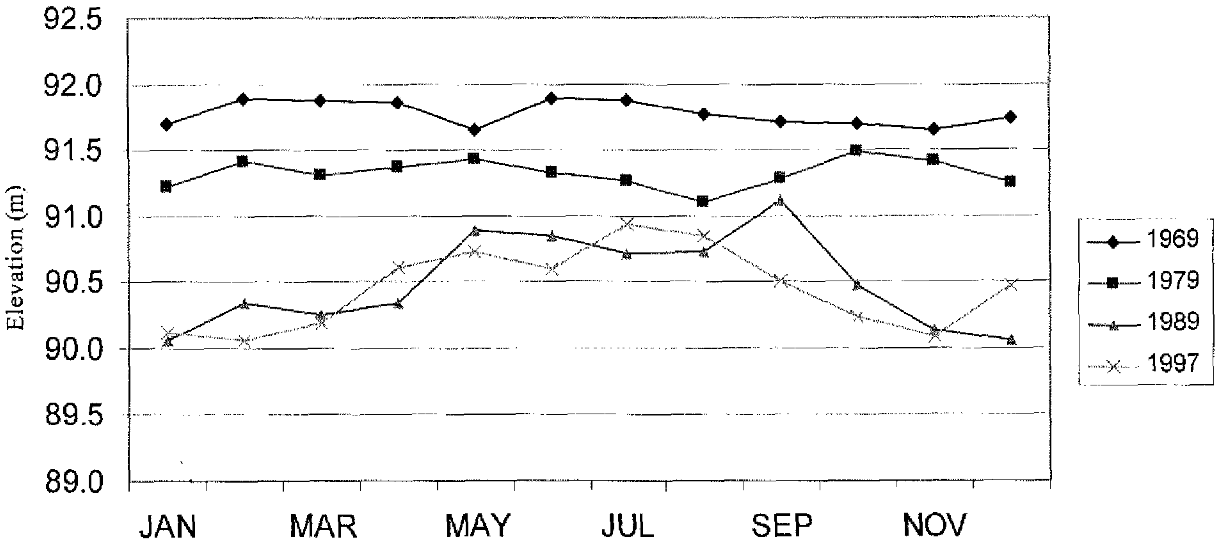

Fig. 2 The variation of monthly water levels at Otsukubo groundwater station

The Noilhan and Planton Model Noilhan and Planton (1989) simulate the vertical movement of water and energy based on soil data and land use dependent parameters namely albedo and leaf area index (LAI). Components of the hydrological cycle modeled include canopy interception and evaporation, ground level evaporation and transpiration. Further more the model can be used to calculate temperature and moisture content in the top soil layer and the deep soil layer. In this study the ground water recharge is estimated from the deep soil layer. The study area is divided into grids approximately 400 by 400 m. where recharge to ground water is calculated and provided as a source to a two dimensional groundwater model.

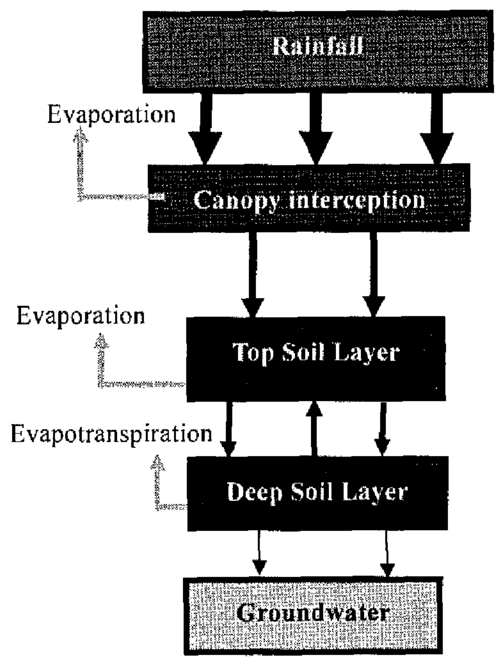

Fig. 3 Vertical Model Structure

4.1 The Noilhan and Planton Model

The Noilhan and Planton Model Noilhan and Planton (1989) is a parameterization scheme for land processes which was meant to provide input to a mosescale and large scale meteorological models. The model was proposed to be used in the present study because the meteorological data required to run the model could be easily obtained from operational data while land use dependent parameters provided and good opportunity for studying the effects of land use/land cover to groundwater recharge. The structure of the model is show in Fig. 3 and the following is a brief description of the model. For a full discussion of the model and land surface parameterization schemes the reader is referred to Noilhan and Planton (1989) and Sealers and Mintz (1986) among others.

The governing equations for energy and moisture movement in vertical direction applied for each grid are given at canopy level, ground level and deep soil level. Soil heat is described by temperature at the surface and deep soil layer by equations 1 and 2 below as

$$\frac{\partial T_s}{\partial t} = C_T G \frac{2\pi}{\tau}(T_s - T_2) \qquad (1)$$

$$\frac{\partial T_2}{\partial t} = \frac{1}{\tau}(T_s - T_2) \qquad (2)$$

where T_s is surface layer soil temperature [K], T_2 is the mean daily soil temperature [K] of deep soil layer over period τ obtained by force restore method (Bhumralcar 1975) and Blackdar (1976). In Equation 3 G is the heat storage rate in the soil vegetation medium, which is equal to the sum of all the atmospheric energy fluxes at the surface.

$$G = R_n - H - LE \qquad (3)$$

where R_n is the net radiation at the surface, H and LE the sensible and latent heat fluxes from the atmosphere.

The coefficient C_t in equation 4 is expressed as

$$C_T = 1 \Big/ \left(\frac{1 - veg}{C_G} + \frac{veg}{C_v} \right) \qquad (4)$$

where

$$C_G = C_{G_{sat}} \left(\frac{W_{sat}}{W_2} \right)^{b/2 \log 10} \qquad (5)$$

To complete the definitions the values of b and C_{Gsat} are referred to clap and Honberger (1978).

The moisture movement is modeled at canopy top soil and deep soil layers. The soil moisture at top layer (W_g) and in the deep (W_2) layer are given by

$$\frac{\partial w_g}{\partial t} = \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau}(w_g - w_{geq}), \quad 0 \le w_g \le w_{sat} \qquad (6)$$

and

$$\frac{\partial w_2}{\partial t} = \frac{1}{\rho_w d_2}(P_g - E_g - E_{tr}), 0 \le w_2 \le w_{sat} \qquad (7)$$

where P_g is the flux of liquid water reaching soil surface, E_g the evaporation at the soil surface, E_{tr} the transpiration rate, ρ_w the density of liquid water and d_1 an arbitrary normalization depth of ten centimeters. The two coefficients C_1 and C_2 and the surface volumetric moisture W_{geq} when gravity balances the capillarity forces have been calibrated for different soil moistures as discussed in Noilhan and Planton (1989).

The equation governing intercepted water at the canopy level is stated as

$$\frac{\partial w_r}{\partial t} = vegP - (E_v - E_{tr}) - R_r \qquad (8)$$

where P is the precipitation rate at the top of the vegetation, E_v the evaporation from vegetation including the transpiration E_{tr} and direct evaporation E_r when positive, and dew flux when negative (in this case $E_{tr} = 0$), R_r is the runoff of the interception reservoir. This runoff occurs when W_r exceeds a maximum value W_{rmax} depending on the density of the canopy. W_{rmax} is calculated according to Dickinson (1984) as

$$W_{r\max} = 0.2vegLAI[mm] \qquad (9)$$

For calculation purposes Equations 1 and 2 and 6 to 8 can be written in the following compact form

$$\begin{cases} \dfrac{\partial T_t}{\partial t} = f_1(T_s, T_2, W_2, W_g, W_r; t) \\ \dfrac{\partial T_2}{\partial t} = f_2(T_s, T_2; t) \\ \dfrac{\partial w_g}{\partial t} = f_3(T_s, W_g, W_2; t) \\ \dfrac{\partial w_2}{\partial t} = f_4(T_s, W_g, W_2, W_r; t) \\ \dfrac{\partial w_r}{\partial t} = f_5(T_s, w_r; t) \end{cases} \qquad (10)$$

where f_1 to f_5 are functions representing the right-hand side of the original equations 1-2 and 6-8 above. A five step Runge Kutta method William et al. (1995) was utilized to obtain a simultaneous solution of the system of equations (10) above for T_s, T_2, W_2, W_g and W_r while imposing the necessary conditions for moisture and energy balance.

The estimation of recharge is done by utilizing the deep layer moisture W_2 as

$$I=K_s(W_2/W_{sat})^{(2a+3)} \tag{11}$$

where I is groundwater recharge (L/T), K_s is saturated hydraulic conductivity (L/T), W_2, W_{sat} and a are defined before.

5. Groundwater Model

The groundwater flow is modeled as two dimensional flows in unconfined aquifer. The model receives recharge calculated by Noilhan Model previously discussed and can also simulate pumping and stream aquifer interaction. The variation through time of the phreatic surface level at each node is modelled by the nonlinear Boussinesq equation which combines the Darcy's law and principle of continuity. When recharge, pumping and leakage from confining layer are considered this equation is expressed as

$$\frac{\partial}{\partial x}\left(K_x b\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y b\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+q(x,y) - \frac{K_z}{2M(x,y)}\left(2H_o-h_t-h_{t+1}\right) \tag{12}$$

where x, y refers to the principal direction of flow in a Cartesian coordinates defined on the model domain, K_x, K_y and K_z are saturated hydraulic conductivities in the x, y and z directions, b is the saturated thickness of the unconfined aquifer, h is the hydraulic head, S is storage coefficient, M is the thickness of confining leaking layer, H_o head in leaking layer referred to the same datum like h, q is the pumping or artificial recharge rate defined as positive for pumping out from aquifer and t is time from beginning of simulation. The last term of equation (12) which can be used to model interaction between aquifer and surface water bodies such as lakes and rivers appears in Pinder and Bredehoeft (1968) while the rest of component are terms representing the Darcy's

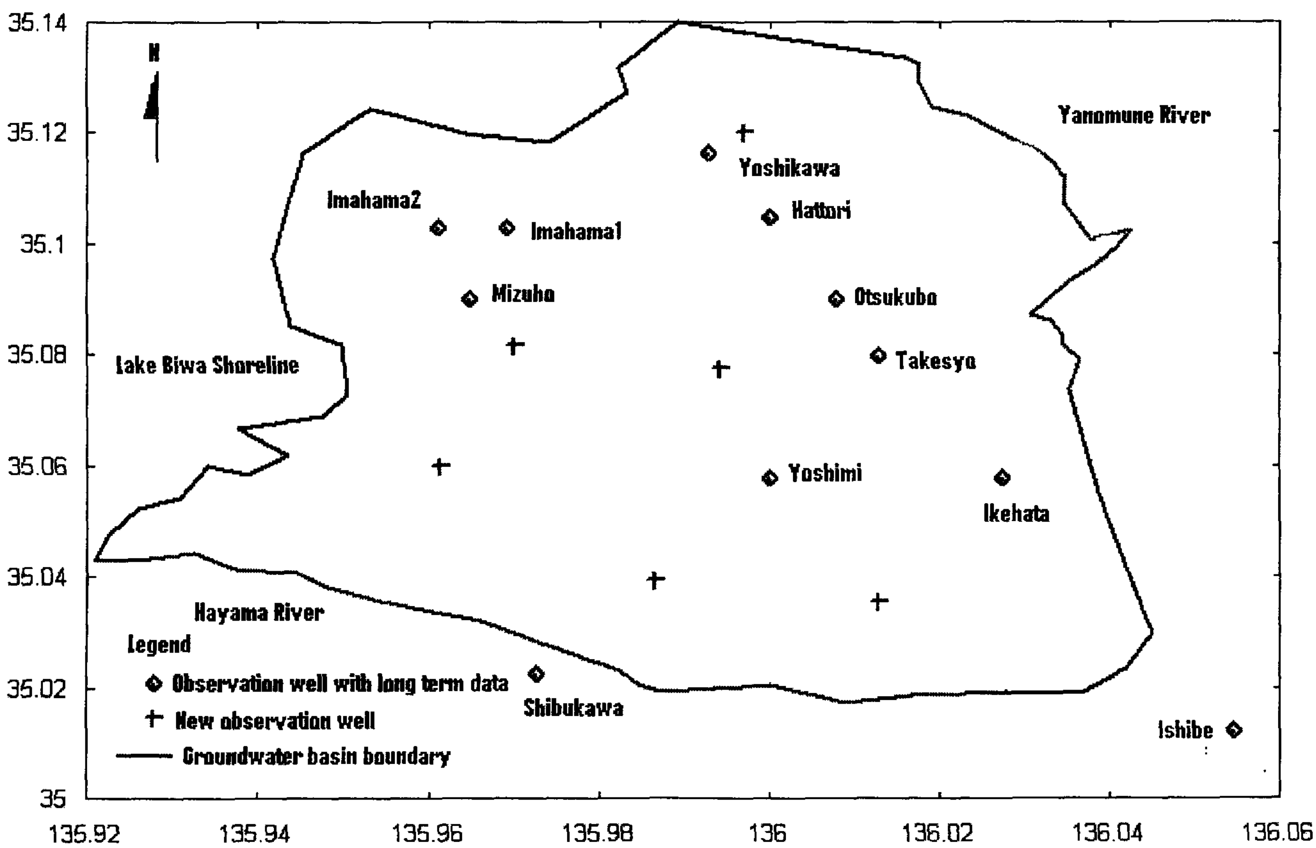

Fig. 4 Groundwater basin in the lower part of the Yasu River basin

law and continuity principle. Equation (12) was solved by implicit finite difference approximation using Alternating Difference Implicit method with Thomas Algorithm.

6. Applications to Yasu River Basin

6.1 The Noilhan Model

The objective of applying the Noilhan and Planton Model is to generate input to groundwater and a rainfall runoff models. The model has been applied in the lower part of the Yasu River basin using data collected from an experimental station. This station run by Flood disaster laboratory, DPRI Kyoto University, records ten minutes interval data for air temperature, wind speed, vapor pressure, long and shortwave radiation as well as albedo. Rainfall data used was from a nearby Tsuchiyama station. In the simulation the top soil is assumed to be sand. This was observed from several borehole data surveyed during the study. The soil parameters corresponding to this sand soil are obtained form clap and Honberger (1978). A simulation of 43 days is performed and results are presented in Fig. 5 to 7. All figures refer to the data from experimental station and assumed soil type (sand soil). Figure 5 shows the cumulative values of precipitation, simulated excess rainfall and evaporation from ground are given. The calculated excess rainfall follows the same patter as the rainfall and is consistently below the rainfall by a constant ratio. The trend of groundwater recharge is shown in Fig. 6. Groundwater recharge does not change immediately with rainfall as for the case of runoff. This is attributed to the fact that groundwater water recharge is derived from the deep soil layer moisture. This is not expected to vary rapidly but to change slowly during the season. On average during this time a groundwater recharge of 0.05 mm/day was obtained.

6.2 Application of the Groundwater Model

The groundwater model proposed is a single layer unconfined aquifer model. The groundwater basin in the study area is assumed to be bounded by Lake Biwa shore line in the north, Hayama River on the west, Yanomune River on the east and a mountain range on the south. The rivers and lake shore boundaries are assumed to be constant head boundaries, while the mountain range is assumed to form an impervious boundary. The composition and depth of the aquifer was inferred from borehole data in the study area. The top aquifer layer is assumed to be composed of a sandy soil layer with depth ranging from 8 – 16 meters underlain by a thick clay layer. The storage coefficient and hydraulic conductivity for this case are assumed to be $S = 0.01$ and $K = 0.004$ respectively. The groundwater basin is represented by a 2 X 2 seconds lat/long extent grind which on the ground is approximately 400 x 400 m grids. The principal direction of ground water flow is assumed to coincide with that of Yasu River. Initial conditions were estimated by ordinary Kriging using observed water levels at observation wells. A test application of the model using the recharge from Noilhan and Planton model is performed. Figure 8 shows the interpolated initial heads at the beginning of simulation and Fig. 9 shows the contours of the final heads after 1 day of pumping. It is seen that the effect of pumping has been well simulated.

7. Conclusions and Recommendations

In this paper the methodology for developing a coupled SVAT groundwater model in the lower Yasu River basin has been described. The SVAT model proposed is the Noilhan and Planton model (Noilhan and Planton 1989). The potential for using this model to produce distributed input to both rainfall run off and groundwater models has been tested using experimental data collected in lower the Yasu River basin. A single layer unconfined aquifer model has been described and the method for estimating the initial conditions proposed. Preliminary applications shows a high potential for developing this model for generating distributed input to both rainfall runoff model and groundwater model.

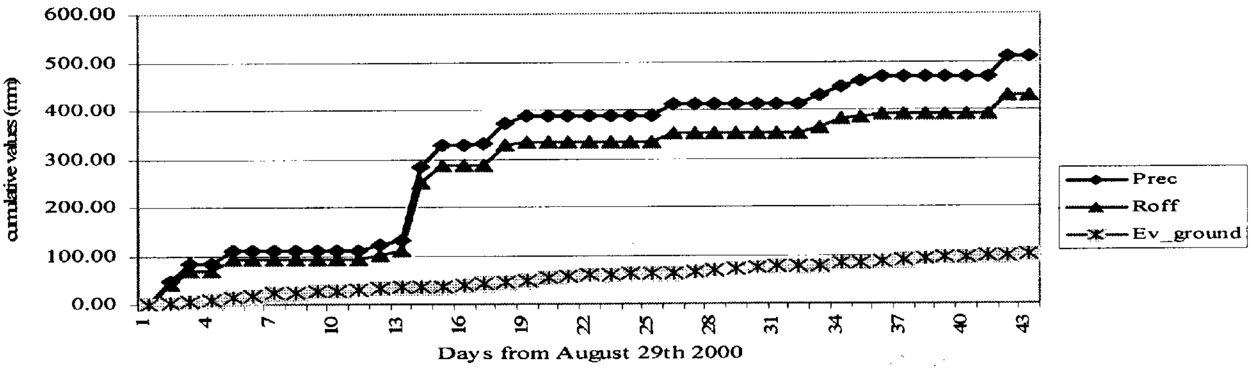

Fig. 5 Cumulative Precipitation, Runoff and Evaporation from ground by the Noilhan and Planton model

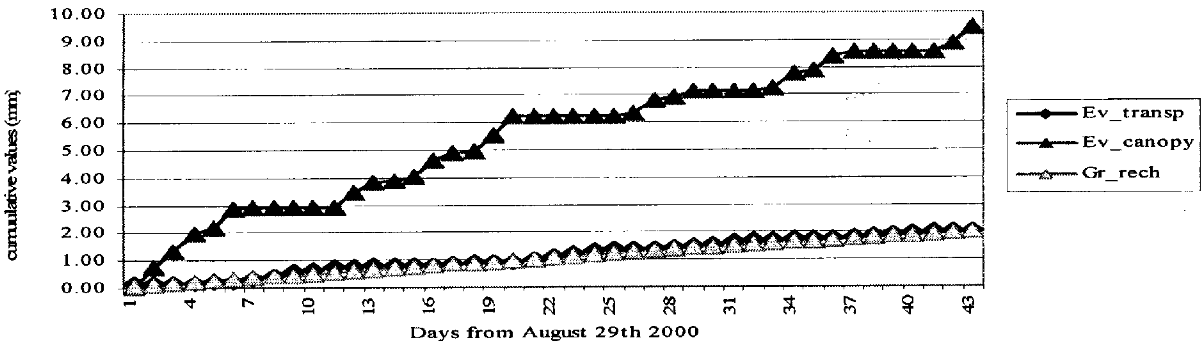

Fig. 6 Cumulative Evapotranspiration, Evaporation from canopy and Groundwater recharge by the Noilhan and Planton model

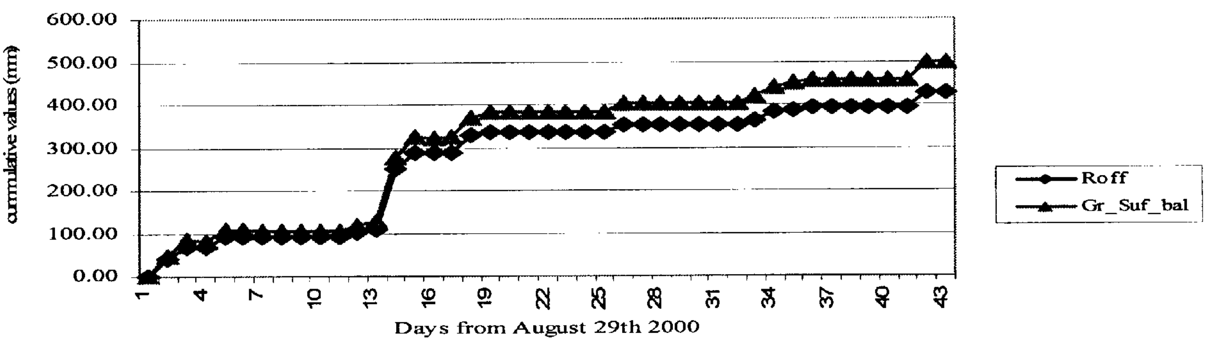

Fig. 7 Runoff and Moisture balance at the groundwater level by the Noilhan and Planton model

The distributed input in Yasu basin can be obtained with either distributed land cover parameters namely Leaf area index LAI, albedo and soil parameters, distributed climatic data or a combination both climate and landuse data. There is generally difficulty in obtaining groundwater data to define the conceptual groundwater model of lower Yasu River basin due to lack of documented borehole and pumping test data. There is however a high potential to obtain this data since the area has more than 60 wells as noted earlier in this study. These wells can provide useful information on the nature of subsurface layers and possible some pumping

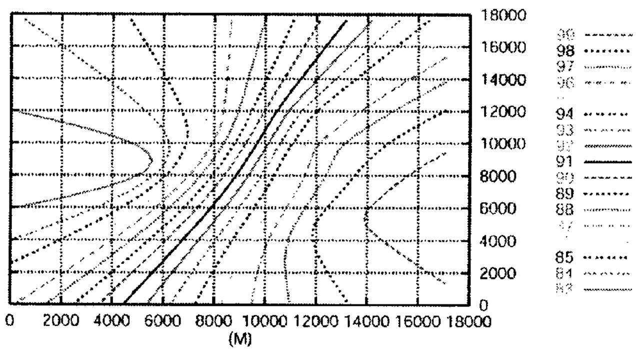

Fig. 8 Initial ground water level contours

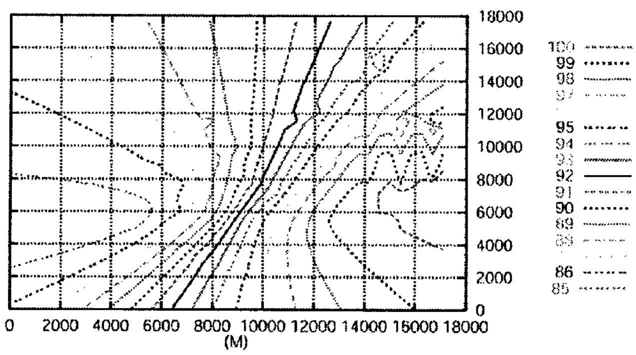

Fig.9 Ground water level contours after one-day simulation

test results can be obtained among them from groundwater consumers. It is proposed to update he groundwater database of lower Yasu river basin to include the information on borehole data and pumping test results

References

Bhumralkar, C.M., 1975: Numerical experiments on the computation of ground surface temperature in atmospheric general circulation model. *J. Appl. Meteor.*, 14, 67-100.

Blackadar, A.K., 1976: Modeling the nocturnal boundary layer. *Proc. Third Symp. On Atmospheric Turbulence, Diffusion and Air Quality*, Boston, Amer. Meteor. Soc., 46-49.

Clapp, R. B., and G. M. Hornberger, 1978: Empirical equations for some soil hydraulic properties. *Water Resorc. Res.*, **14**, 601-604.

Dickinson, R. E., 1984: Modelling Evaporation for the three dimensional global climate models. Climate Precesses and Climate Sensitivity. Geophys. Monogr., 29, 58-72.

J. Noilhan and S. Planton 1989: simple parameterization of land surface processes for Meteorological models. *Mon. Wea. Rev.* **117** 537-549.

Nakamura, M and Nickum, J.E., 2002: Mother Lake Plan 21 *introductory brochure to Lake Biwa comprehensive conservation plan,* Shiga Prefecture Government, Water Policy Administration Division.

P.J Sellers and Y. Mintz 1986: A simple biosphere Model (SiB) for use with general circulation models. *J. Atmos.Sci.*, 43, 6, 505-531.

William H, P, Saul A, T, William T. V and Brian P. F., 1995: numerical Recipies in C 2nd edition, ISBN 0-521-43108-5 Cambridge University Press, London UK.

Yangwen Jia, Guanghen Ni, Yoshihisa Kawahara and Tadashi Suetsugi 2000: Numerical Simulation of Groundwater Flow in Multi-Layered aquifers with a distributed hydrological Model. *Groundwater updates* K. Sato and Y. Iwasa (Eds) IAHR publication 259 – 26.

SVAT モデルを組み込んだ地下水モデルの開発とその野洲川下流域への適用

*キマロ　トゥマイニ・立川　康人・寶　馨
*京都大学大学院工学研究科博士課程

要　旨

野洲川下流域では、この30年間、流域の姿が大きく変貌し、それとともに地下水位が大きく減少する地域があるなど、流域の水循環が大きく変動している。本研究では、こうした水循環の変動が流域の変化との関連でどのようなメカニズムで起こっているのかを明らかにするために、滋賀県野州川下流域を対象とする流域水循環モデルを構築することを目的とする。ここで構築する水循環モデルは2次元の不圧地下水流動モデルと SVAT モデルとを組み合わせて構成される。SVAT モデルは、Noilhan and Planton (1989) によって開発されたモデルを改良し、深層土壌層からの地下水涵養量を推定できるようにした。この推定された涵養量および人工的な地下水利用を条件として、地下水流動モデルを用いて流域の地下水位変動をシミュレーションする。地下水位の初期条件は観測データをもとに Kriging 手法を用いて推定する。また境界条件は琵琶湖岸、河川水位、流域境界により設定した。対象流域を 約400m の格子で覆うシミュレーションモデルを構築し、試験的な水循環シミュレーションを行ったところ、良好な結果を得た。

キーワード：土地利用変化，涵養量推定，地下水モデル，Noilhan and Planton model