Annual Journal of Hydraulic Engineering, JSCE, Vol.54, 2010, February

FULLY DYNAMIC GROUNDWATER REPRESENTATION IN THE MATSIRO LAND SURFACE MODEL

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Despite significant development of land Surface models (LSMs) over recent years, the representation of near surface hydrological processes is still problematic. In particular, the lower boundary condition of the soil model is often assumed as ‘a free (gravity) drainage’ or ‘a zero moisture flux’ largely neglecting the interaction between groundwater (GW) reservoir and land surface hydrological fluxes. GW affects the prediction of soil moisture and subsequently land-surface hydrological fluxes and regional climate. This study investigates the effect of integrating a GW representation into a LSM, Minimal Advanced Treatments of Surface Integration and RunOff (MATSIRO). The MATSIRO-GW model has enhanced the partitioning of runoff, as well as saturated-unsaturated zone soil moisture. The total runoff and water table depth simulations have been significantly improved. Evapotranspiration in the dry season has been enhanced due to increase in soil moisture resulting from upward capillary flux from GW reservoir.

Key Words: *groundwater, MATSIRO, water table depth*

1. INTRODUCTION

Earlier general circulation models of climate merely used leaky bucket approximation to represent land surface hydrologic processes[1]. Land Surface Models (LSMs) have since developed considerably in terms of representation of hydrological processes including vegetation dynamics, surface resistance, and snow schemes that calculate time- and space- varying momentum, heat and moisture fluxes to the lower atmosphere[2],[3].

However, most LSMs still employ a soil model with a simplified lower boundary condition, such as a free (gravity) drainage or a zero moisture flux, and neglect the interaction between groundwater (GW) and land surface hydrological fluxes making it difficult for them to reproduce realistic water balance. This interaction is particularly strong for humid regions where the water table usually lies near ground surface and groundwater runoff is often the dominant runoff generation mechanism. Under such conditions, the regional climate interacts with groundwater through the exchange of water fluxes (groundwater recharge and capillary flux) near the water table. The water balance computed by LSMs can be significantly improved by the inclusion of groundwater processes[4] and in addition to atmospheric sources of surface water, currently considered in LSMs, groundwater sources are considered necessary to estimate the runoff and air temperature correctly[5].

Consequently, the linkage between the land surface hydrology and the groundwater aquifer has received growing attention during last few years. Salvucci and Entekhabi[6] evaluated surface and groundwater interactions with a steady-state statistical approach and revealed significant shifts in evapotranspiration and runoff.

The Minimal Advanced Treatments of Surface Integration and RunOff[7] (MATSIRO) was developed to represent all major hydrologic processes governing water and energy exchanges between land and atmosphere in a physically based way. A simplified TOPMODEL[8] approach is used to estimate surface and base runoff separately. But simplified representation of topography, using grid scale mean slope and standard deviation of elevation, is often non-representative of the local scale topographic conditions and hence the predicted base runoff is generally low resulting to unrealistic partitioning of runoff.

Moreover, lack of explicit representation of groundwater process in MATSIRO undermines selection of the proper lower boundary condition in the prediction of soil moisture. Accurate soil moisture prediction can reduce the uncertainty in future climate prediction[9), 10)].

In this study, we illustrate the effect of groundwater representation in simulation of major land surface hydrological fluxes and state variables by MATSIRO.

2. DESCRIPTION OF MODELS

MATSIRO was developed to be coupled with the atmospheric general circulation model, CCSR/NIES AGCM, which was developed at the Center for Climate System Research (CCSR), the University of Tokyo, and the National Institute for Environmental Studies (NIES) for climate studies at the global and regional scales.

The canopy has a single layer, whose albedo and bulk coefficients are evaluated on the basis of a multilayer canopy model. The fluxes are calculated from the energy balance at the ground and canopy surfaces in snow-free and snow-covered portions considering the subgrid snow distribution. The interception evaporation from canopy and the transpiration on the basis of photosynthesis are treated.

However, the lower boundary of the unsaturated soil column is not the water table but is assumed to be bed rock and there is no explicit representation of GW aquifer. The soil moisture can be depleted by soil evaporation, root uptake by vegetation for transpiration, and the base runoff. Therefore, if base runoff is negligible, the deep soil layers are often saturated.

Originally, MATSIRO's soil column is 4 m deep with 5 soil layers. But in this study, the soil column has been extended to depth of 10 m with 12 soil layers. Fig. 1 shows the soil layer resolution for both the cases.

For MATSIRO with groundwater representation, the depth of unsaturated soil column depends on the location of the water table. When the water table is shallow, there are fewer unsaturated soil layers than when it is deep and the Richard's equation[11)] of soil moisture movement is solved for these unsaturated layers only. Hence, the model represents a fully dynamic coupled saturated-unsaturated interaction mechanism with continuous exchange of moisture flux near the water table.

(a)	(b)
(1)- 5 cm	(1) -5 cm
(2)- 20 cm	(2)- 20 cm
(3)- 75 cm	(3)- 75 cm
(4)- 1 m	(4)- 1 m
(5)- 2 m	(5)- 1 m
	(6)- 1 m
	(7)- 1 m
	(8)- 1 m
	(9)- 1 m
	(10)- 1 m
	(11)- 1 m
	(12)- 1 m

Fig.1 Resolution of soil layers in MATSIRO (a) Original (b) New [*Note: The dimensions are not to scale and number in parenthesis indicate layer number from ground surface*].

Following section presents a brief description of the original MATSIRO runoff scheme and the groundwater scheme to be integrated into the model.

(1) Original runoff scheme

A simplified TOPMODEL[8)] is used to calculate the runoff (surface and subsurface) considering the horizontal heterogeneity of the soil moisture caused by topography. The grid cell topography is assumed to be repetition of sub-grid topography as shown in **Fig. 2**.

The uniform slope angle β_s and the distance between ridge and valley L_s are related as Eq.(1a),

$$L_s = 2\sqrt{3}\sigma_z / \tan\beta_s \qquad (1a)$$

where, σ_z is the standard deviation of the subgrid elevation.

The base runoff (Q_{gw}) is calculated as Eq.(1b),

$$Q_{gw} = \frac{K_0 \tan\beta_s}{f_{atn} L_s} \exp(1 - f_{atn} d_{gw}) \qquad (1b)$$

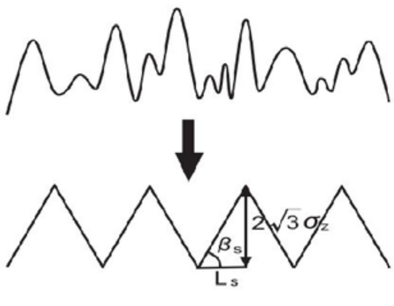

Fig.2 Schematic diagram of simplification of subgrid topography used in TOPMODEL for MATSIRO[7)].

where, K_0 is the saturated hydraulic conductivity of soil at the ground surface, f_{atn} is the attenuation coefficient of saturated hydraulic conductivity (K_0) with depth, and d_{gw} is the mean water table depth in the grid cell.

The mean water table depth is calculated based on unsaturated matric potential of soil and degree of saturation of the soil layers. The soil moisture is examined from the lowest soil layer upwards. If a layer that becomes unsaturated for the first time is assumed to be the nth layer, the mean water table depth (d_{gw}) is estimated as Eq.1(c),

$$d_{gw} = Z_{g(n-1/2)} - \psi(n) \tag{1c}$$

where, $\psi(n)$ is the unsaturated matric potential of the nth layer, $Z_{g(n-1/2)}$ is the depth to the top of nth layer.

Based on the mean water table depth, the saturated area fraction within the grid cell is calculated as Eq.(1d),

$$A_{sat} = 1 - \exp(f_{atn} d_{gw} - 1) \tag{1d}$$

where, A_{sat} is the saturated area fraction within the grid cell. Hence, the partitioning of the runoff is sensitive to estimation of this variable and unrealistic estimation of the water table depth may lead to erroneous partitioning of runoff.

Hereafter, MAT-ORI will be used to denote the original version of MATSIRO.

(2) New scheme with groundwater representation.

The groundwater (GW) representation (scheme and parameterization) based on Yeh et al.[12] has been incorporated in MAT-ORI to replace the existing TOPMODEL based base runoff generation scheme.

A simple lumped non-linear groundwater aquifer has been added below the unsaturated soil column, whose water balance can be expressed as Eq.(2a),

$$S_y \frac{dH}{dt} = I_{gw} - Q_{gw} \tag{2a}$$

where, S_y is the specific yield of aquifer, H is the water table depth, I_{gw} is inflow to the aquifer, and Q_{gw} is outflow from the aquifer (base runoff).

I_{gw} is the net drainage flux from lowermost soil layer to the groundwater reservoir. It is estimated as algebraic sum of two oppositely oriented moisture fluxes; gravity drainage (equal to hydraulic conductivity of the lowermost unsaturated soil layer) from unsaturated zone to saturated zone, and capillary flux in the opposite direction. The water table depth is updated in a prognostic manner based on inflow and outflow to/from groundwater aquifer.

Then, groundwater runoff at local scale is formulated using threshold type relationship as Eq.(2b),

$$\begin{aligned} Q_{gw} &= K(d_0 - d_{gw}) \quad && if \quad 0 \le d_{gw} \le d_0 \\ Q_{gw} &= 0 && if \quad d_{gw} \ge d_0 \end{aligned} \tag{2b}$$

where, K [1/T] is the outflow constant inversely proportional to the aquifer residence time, d_0 [L] is the threshold water table depth at which groundwater runoff is initialized and d_{gw} [L] is the mean water table depth.

To represent a non-linear dependence between local scale and grid scale water table depth, Yeh et al.[13] proposed a statistical-dynamical approach as Eq.(2c),

$$E\left[Q_{gw}\right] = \frac{K\lambda^{\alpha}}{\Gamma(\alpha)}\left\{ d_0 \left[\frac{(\alpha-1)!}{\lambda^{\alpha}} - e^{-\lambda d_0}\sum \frac{(\alpha-1)!}{k!}\frac{d_0^k}{\lambda^{\alpha-k}}\right] - \left[\frac{\alpha!}{\lambda^{\alpha+1}} - e^{-\lambda d_0}\sum \frac{\alpha!}{k!}\frac{d_0^k}{\lambda^{\alpha-k+1}}\right]\right\} \tag{2c}$$

where, $E[Q_{gw}]$ is the expected value of grid-scale groundwater runoff, α and λ are shape and scale parameters respectively of the assumed gamma distribution of water table depth variation within the grid cell, and $\Gamma(\alpha)$ is the gamma function.

Hereafter, MAT-GW will be used to denote the MATSIRO with groundwater representation.

3. STUDY DOMAIN AND DATASETS

A 1^{o} grid cell (90^{o}W, 40^{o}N) representing Illinois region is the study area. Illinois is unique in availability of wide spectrum of observational data. The simulation period is from year 1985 to the end of year 1999 (15 years) and the forcing time step is 3-hourly.

In an offline simulation of both versions of MATSIRO, seven input atmospheric forcing variables are required viz. precipitation, downward longwave and shortwave solar radiation, near surface air temperature, humidity, pressure, and wind speed. Precipitation data was retrieved from the EarthInfo Inc. (http://www.earthinfo.com). Air temperature, humidity, and pressure were derived from National Climate Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html) Surface Airway dataset. Downward longwave and shortwave radiations were interpolated from 6-hourly NCEP-NCAR reanalysis data[14]. The processing of data is explained in detail in Yeh et al.[15]

The external parameters required for MAT-ORI are the types and properties of soil and vegetation, standard deviation of elevation, and mean topographic slope within the grid cell. The soil type and parameters are based on International Satellite Land Surface Climatology Project (ISLSCP)-II (http://islscp2.sesda.com/ISLSCP2_1/html_pages/islscp2_home.html) and vegetation class and properties are adopted from International Geosphere-Biosphere Project (IGBP) (http://www.igbp.net) and the University of Wales respectively. The topographical parameters were derived from GTOPO30 (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

The parameters for MAT-GW were adopted from the Yeh et al.[13] as d_0 = 3.50 m, K = 30.0 /month, S_y = 0.08, and α = 4.0.

Model validation is based on monthly direct observations of soil moisture, water table depth, runoff, estimated evapotranspiration (using water balance) and groundwater recharge. The dataset on soil moisture and water table depth were acquired from the Illinois State Water Survey (http://www.isws.illinois.edu/data.asp).

4. RESULTS AND DISCUSSION

The model validation for 1-dimensional simulation of Illinois is presented here. Two criteria were selected for evaluating model performance; Nash-Sutcliffe coefficient[16] (N.S. values in figures) and mean bias (Bias values in figures).

The Nash–Sutcliffe coefficient describes the matching extent of the variations of compared variables and bias reflects the relative error of the long term mean values of simulated variables.

Table 1 Components of mean monthly water balance.

Variables	Observed	MAT -ORI	MAT -GW
Precipitation	82.27	82.27	82.27
Total Runoff	26.08	24.77	21.07
Base Runoff	14.72	0.39	14.05
Surface Runoff	11.36	24.38	7.02
Total Evaporation	54.93	58.01	61.65
Water Table Depth	-3.57	-0.91	-3.47
All variables are in mm/mon except water table depth in m			

Table 1 shows the long term mean monthly water balance components for observations and simulation results.

The mean monthly total runoff in both simulations matches the observation. However, component-wise, fast surface component is dominant runoff generation mechanism in MAT-ORI whereas slow base runoff component is dominant in MAT-GW.

The predicted mean water table depth is shallower than observation in MAT-ORI but it is deeper and matches the observed long-term mean in MAT-GW.

Fig. 3(a) shows the comparison between the observed and simulated total runoff. For MAT-ORI, the simulated runoff has higher peaks than observation but low flow is negligible. In MAT-ORI, the effect of delay in runoff prediction cannot be produced due to lack of groundwater representation. This implies that effective rainfall in

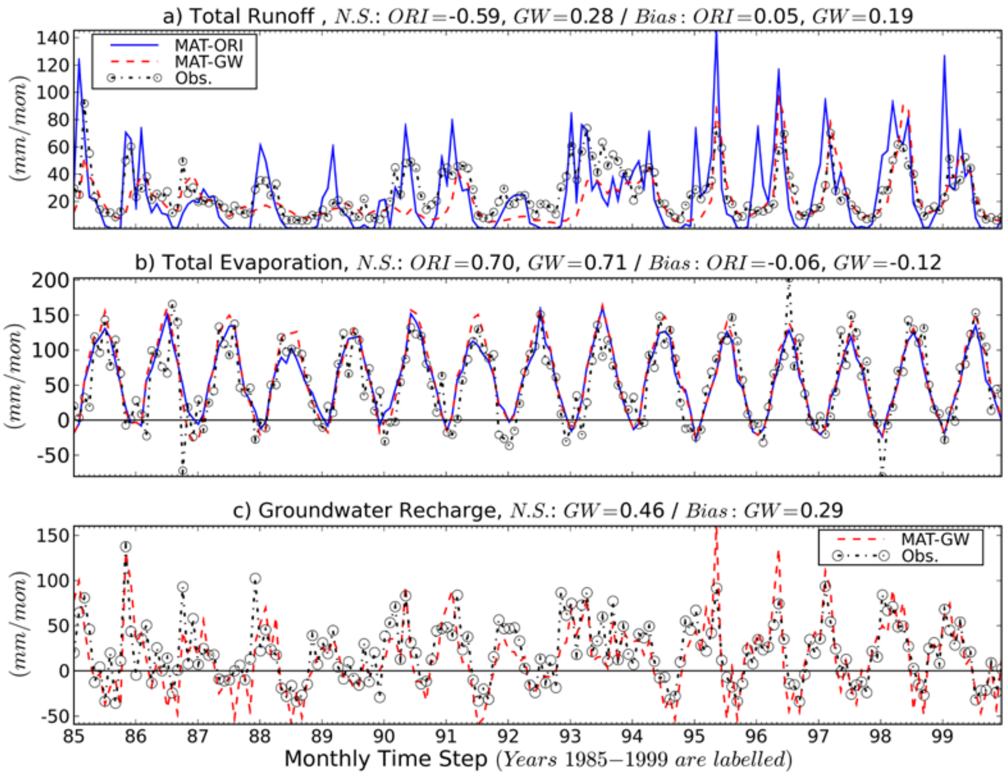

Fig. 3 Monthly time series of observed and simulated variables a) Total Runoff b) Total Evaporation and c) Groundwater Recharge [N.S.: Nash Sutcliffe Coefficient, Bias: Relative Error]

excess of soil moisture storage capacity is either evaporated or runs off as fast surface component. Inclusion of groundwater representation has enabled MAT-GW to integrate the groundwater delay process into runoff generation mechanism ensuring better prediction of runoff in both wet and dry seasons as shown in **Fig. 3(a)** and the long-term mean of base runoff also matches well with the observed value (estimated from observed total runoff using digital recursive filter[17]).

Due to negligible base runoff in MAT-ORI simulation, the deep soil layers are often saturated resulting to shallower water table depth compared to observation as shown in **Table 1**. The unrealistic prediction of shallow water table depth creates large saturated area within a grid cell, resulting to high surface runoff and subsequently incorrect partitioning of runoff as shown by negative N.S. value in **Fig. 3(a)**.

Fig. 3(b) presents the comparison of the observed and simulated evaporation. Both models show similar accuracies compared to observation. However, the mean monthly amount is higher than observation in both cases (**Table 1**). This is due to large negative values of observed evaporation in the winter season. The observed evaporation was computed from atmospheric water balance and not directly observed making the negative values possible. The simulated evaporation is negative if sublimation exceeds evaporation.

In MAT-ORI simulation, peak of evaporation is usually under-predicted. In a region with shallow water table, the feedback from groundwater can enhance the root zone soil moisture. In MAT-GW, the saturated-unsaturated zone interaction is dynamic and net upward moisture flux from groundwater reservoir to unsaturated soil column supports the evaporation in the dry season. The negative groundwater recharge (upward from groundwater reservoir to unsaturated soil column) can be simulated well with MAT-GW (N.S.=0.46) as shown in **Fig. 3(c)**. Hence, the prediction of peaks of evapotranspiration has been slightly enhanced.

Fig. 4(a) shows the variation of water table depth with positive values indicating the rise of water table. The variation is well captured by MAT-GW (N.S.=0.33) compared to MAT-ORI (N.S.=-0.10). The phase of the variation of water table in MAT-ORI is different than MAT-GW and observation. This occurs because in MAT-ORI, the variation in the water table is directly related to variation in soil moisture (**Fig. 4(b)** and **Fig. 4(c)**). However, in reality, the groundwater has longer residence time than soil moisture and hence the variation is not as rapid as that of unsaturated soil moisture. This process is well represented by MAT-GW.

The variation of soil moisture for top 1 meter and top 2 meter soil depth are presented in **Fig. 4(b)** and

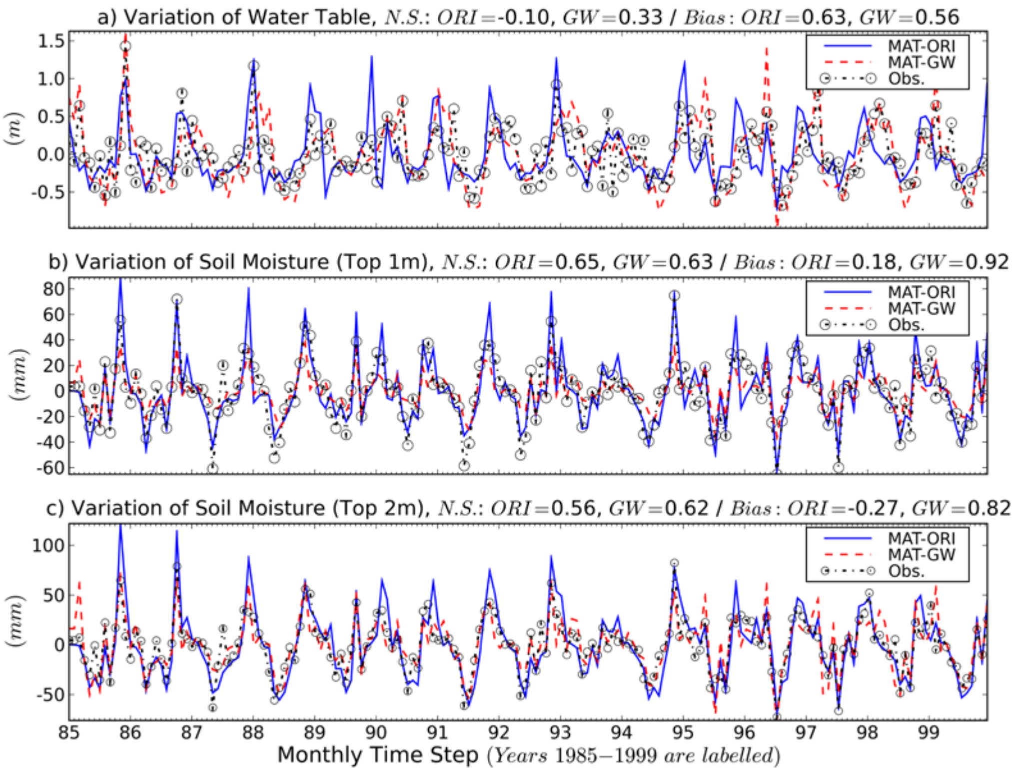

Fig. 4 Monthly variation of observed and simulated variables a) Water Table Depth b) Soil Moisture in root zone (top 1m soil) c) Soil Moisture in top 2m soil [N.S.: Nash Sutcliffe Coefficient, Bias: Relative Error]

Fig. 4(c) respectively. The positive values indicate the period of increase in soil moisture. Both models capture the variation of soil moisture well as shown by N.S. values in respective figures. For top 1m soil, which is the depth of the root zone, MAT-ORI has the largest amplitude suggesting that in dry season, the soil moisture is drier than the MAT-GW prediction and observation. MAT-GW considers the contribution from groundwater to unsaturated zone soil moisture. This is reason behind MAT-GW's improved prediction of peaks of evaporation (**Fig. 3(b)**).

MAT-GW slightly improves the prediction of variation of soil moisture in deep layers as shown by N.S. value in **Fig. 4(c)**. Surface soil moisture affects the near surface water and energy fluxes but deeper soil moisture can also enhance the drought and flood through positive soil moisture-rainfall feedback. The past rainfall governs the soil moisture availability which in turn governs the water availability (runoff) and evaporation from land surface and consequently the rainfall[18]. This positive feedback mechanism can be altered by groundwater as the deep soil moisture directly interacts with it. Hence, the prediction of variation of soil moisture in deep layers is significant for long-term prediction of length of extreme event like drought.

5. CONCLUSION

To improve the representation of the lower boundary condition of a LSM, MATSIRO, a simple non-linear groundwater reservoir was integrated into the soil model.

The comparison between the observation and the simulation results show that the prediction of the long term mean as well as temporal variation of the total runoff, and water table depth has significantly improved while enhancing the simulation of root zone moisture and evaporation in dry season. Also, variation of two major components of terrestrial water storage i.e. ground water and soil moisture have been separately validated against observation.

The amount of net groundwater recharge, which is the indicator of sustainable groundwater resources, can be explicitly estimated by MAT-GW.

The inclusion of groundwater process, which is one of the major processes of hydrological cycle commonly missing from LSM, has rendered the model to predict the groundwater-induced uncertainty in prediction of land surface hydrological fluxes and subsequently the regional climate.

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(Received September 30, 2009)