THE PHYSICALLY-BASED SOIL MOISTURE BALANCE MODEL DEVELOPMENT AND APPLICATIONS ON PADDY FIELDS

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Abstract. This physically-based hydrologic model is developed to calculate the soil-moisture balance on paddy fields. This model consists of three modules, the first is the unsaturated module, the second is the rice evapotranspiration module with SPAC(soil-plant-atmospheric-continuum), and the third is the groundwater and open channel flows based upon the interrelationship module. The model simulates the hydrological processes of infiltration, soil water storage, deep percolation or echarge to the shallow water table, transpiration and evaporation from the soil surface and also the interrelationship of the groundwater and river flow exchange. To verify the applicability of the developed model, it was applied to the Kimjae Plains, located in the center of the Dongjin river basin in Korea, during the most serious drought season of 1994. The result shows that the estimated water net requirement was 757 *mm* and the water deficit was about 5.9 % in this area in 1994. This model can easily evaluate the irrigated water quantity and visualize the common crop demands and soil moisture conditions

Key Words soil moisture balance, unsaturated modeling, evapotranspiration, physically-based hydrological model

1. INTRODUCTION

The supply of adequate irrigation is most important when there are limited water resources during a drought season. Adequate water is essential for crop production, and the optimal use of available water must be achieved for efficient rice production, high yields, and water resource managements. This requires a proper understanding of the effect of water rainfall and/or irrigation-on crop growth and soil moisture under different growing conditions (Doorenbos *et al.*, 1979).

Soil moisture simulations are an important tools for managing an irrigation system. They help to determine how much water to apply and when to irrigate. Soil moisture is critical for crop growth. By maintaining moisture within a certain range for a given soil and crop type, the best growing conditions can be achieved.

The vertical infiltration of groundwater accretion into stratified soil was researched by Sonu (1986). He considered the simultaneous movement of air and water in soil and used continuity equations. His study dealt with the vapor flow as diffusive process and that flow was governed by the concentration of vapor by Frick's law. The physical mechanism for the occurrence of the double peaks was explained by using Richards' equation and the concept of variable source area (Lee and Lee, 1996). The numerical scheme for dimensionless Richards' equation was developed to analyze the unsaturated flow in the heterogeneous porous media (Park and Sonu, 1999)

Richards' equation for variably saturated soil water flow has a clear physical basis. However Richards' equation is difficult to solve because of its hyperbolic nature and the strong non-linearity of the soil hydraulic functions which relate to water content, soil water pressure head, and hydraulic conductivity. Also, the abrupt changes of moisture conditions near the soil surface, which causes steep wetting fronts in dry soil or steep drying fronts in wet soils, may pose problems.

This study is adopted the FAO-Penman-Monteith equation to calculate the evapotranspiration which is recommended as the standard method for estimating reference and crop evapotranspiration by Smith *et al.* (1997).

This study focuses on the development of a physically-based hydrological model to calculate the soil-moisture balance on paddy fields. The main advantage of the proposed scheme is to solve automatically the top boundary conditions in iterative computing stages; head or flux conditions. To verify the applicability of the developed model, it was applied to the Kimjae Plains, located in the center of the Dongjin river basin in Korea, during the most serious drought season of 1994.

2. THEORY

2.1 Governing Equation

A one-dimensional governing equation for water balance of a non swelling, isothermal, heterogeneous soil can be written as (Campbell, 1985; Bidlake *et al.*, 1997)

$$\rho_W \frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}(f_l + f_v) - U(z) \quad (1)$$

where ρ_W is the density of water (kg/m^3), θ is the volumetric water content (m^3/m^3), f_l is the vertical liquid flux (kg/m^2/s), f_v is the vertical vapor flux (kg/m^2/s), z is the vertical depth (m), and t is time (s). $U(z)$ is a volumetric water sink term representing plant uptake of soil water (kg/m^3/s).

Diffusion through the air-filled pores maintains an exchange of gases between the atmosphere and the soil. For both portions of the pathway, the diffusion process can be described by Fick's law.

The volumetric water sink term, $U(z)$, is the plant uptake of soil water and the transpiration. These are two processes that can have a large effect on the soil water balance of vegetated areas. The driving force for this flow is a water potential gradient. The main resistances to liquid water are in the root and in the leaf.

Some of the non-linearity in Eq. (1) can be removed by using the Kirchhoff transformation (Gardner, 1958; Haverkamp *et al.*, 1977; Redinger *et al.*, 1984; Campbell, 1985). Hydraulic conductivity of unsaturated soil ($k(\phi_m)$) can be computed by using a simple equation obtained by Campbell (1974). The Hydraulic properties of soils as a function of soil texture give values of ϕ_e, k_s, b and other hydraulic properties for a range of soil texture in Rawls *et al.* (1992) and Campbell *et al.* (1998).

Analogous to Darcy's law is the exchange between an aquifer and a river and may be formulated as follows

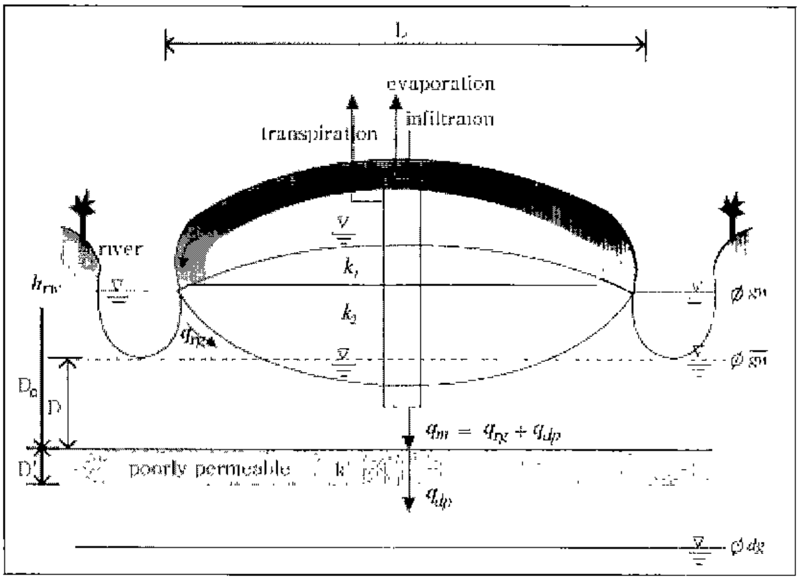


Fig. 1. Schematic Representation of the Flow Situation (Cauchy Lower Boundary Condition)

$$q_{rg} = -\frac{(\phi_{gw} - h_{rw})}{R} \tag{2}$$

where ϕ_{gw} denotes the groundwater potential, h_{rw} is the river water level, and R is the resistance to the flow, which is called the horizontal and the radial resistance (Ernst, 1978).

The flow to the deep aquifer is computed as follows (Belman *et al.*, 1983)

$$q_{dp} = -\frac{(\phi_{\overline{gw}} - \phi_{dg})}{c} \tag{3}$$

where $\phi_{\overline{gw}}$ is the level of the phreatic surface averaged over the area, ϕ_{dg} is the hydraulic head of the deep ground, and c is the vertical resistance of the poorly permeable layer ($c = d'/k'$, [sec]).

The vertical flux per unit area is now taken to pass the bottom of the soil system and is calculated as

$$q_m = q_{rg} + q_{dp} \tag{4}$$

where q_{rg} can be considered as the return or recharge flow.

2.2 Numerical Approach

The equation for soil moisture balance at a node can be approximately solved by using numerical techniques. The numerical approximation of Eq. (1) leads to the following finite-difference expression which is valid for all nodal points.

$$\frac{\rho_w \overline{C}_i\left(\psi_i^{j+1} - \psi_i^j\right)(z_{i+1/2} - z_{i-1/2})}{\Delta t} = \frac{k_{i+1}\psi_{i+1} - k_i\psi_i}{(1-n)(z_{i+1} - z_i)} - \frac{k_i\psi_i - k_{i-1}\psi_{i-1}}{(1-n)(z_i - z_{i-1})} + g(k_i - k_{i-1}) + D_{vi}\frac{e_s(T)M_w}{RT}\left(\frac{h_{i+1} - h_i}{z_{i+1} - z_i} - \frac{h_i - h_{i-1}}{z_{i+1} - z_{i-1}}\right) - U_i \tag{5}$$

where ψ is the sum of several component potentials, $\psi = \psi_m + \psi_g$. ψ_m is matric potential from the attraction between water and soil particles, proteins, cellulose, etc. ψ_g is gravitational potential, g is the gravitational constant (9.8 m/s^2) and h is the vertical distance from the reference height to the location where potential is specified (at ground surface $h = 0$). $\overline{C_i}$ is the water capacitance at the node. e_a is the ambient vapor pressure, M_w is the molar mass of water (0.018 kg/mol), R is the gas constant (8.314 J/mol·K), T is the temperature (K). The source term U_i in Eq. (1) combines all of the inputs and losses of water from the node. This might include water extraction by roots, condensation or evaporation. Superscript j is time step, subscript i is node point.

The above equation can be rearranged as follows

$$F_i = A_i \Delta\psi_{i-1} + B_i \Delta\psi_i + C_i \Delta\psi_{i+1} \tag{6}$$

where,

$$A_i = \frac{\partial F_i}{\partial \psi_{i-1}} = \frac{-k_{i-1}}{(1-n)(z_i - z_{i-1})} - \frac{ngk_{i-1}}{\psi_{i-1}} - D_{vi}\frac{e_s(T)M_w}{RT}\left(\frac{1}{z_i - z_{i-1}}\right)\frac{h_{i-1}M_w}{RT} \tag{6.a}$$

$$B_i = \frac{\partial F_i}{\partial \psi_i} = \frac{\rho_w(z_{i+1} - z_{i-1})\theta_i}{2b\,\psi_i dt} + \frac{k_i}{(z_{i+1} - z_i)} + \frac{k_i}{(z_i - z_{i-1})} - \frac{ngk_i}{\psi_i} - D_{vi}\frac{e_s(T)M_w}{RT}\left(\frac{-1}{z_{i-1} - z_i} - \frac{1}{z_{i+1} - z_{i-1}}\right)\frac{h_i M_w}{RT} \tag{6.b}$$

$$C_i = \frac{\partial F_i}{\partial \psi_{i+1}} = -\frac{k_{i+1}}{(z_{i+1} - z_i)} - D_{vi}\frac{e_s(T)M_w}{RT}\left(\frac{1}{z_{i+1} - z_i}\right)\frac{h_{i+1}M_w}{RT} \tag{6.c}$$

An appropriate procedure for the top boundary conditions while calculating the iterative solution of the Richards' equation may determine the success or failure of a numerical scheme (van Dam, 1999).

In the case of infiltration, a head-controlled condition applies, if the potential flux q_{top} exceeds the maximum infiltration rate I_{max} as well as the saturated hydraulic conductivity K_{sat}. The bottom boundary mass flux can be considered as the mass balance error of the system by Belmans *et al.* (1983). The mass balance error ε^j originates from keeping the groundwater level constant during the each time step Δt. The quantity ε^j consists of two components, $\varepsilon_n{}^j$ and $\varepsilon_m{}^j$. Hence,

$$\varepsilon^j = \varepsilon_n^j - \varepsilon_m^j \tag{7}$$

where $\varepsilon_n{}^j$ is the internal mass balance error and the component $\varepsilon_m{}^j$ is the source of the entire system like the river (open channel) inflow to the soil system and outflow from the soil system to the river.

If the mass balance error ε^j is positive, the groundwater is lowered to decrease water content and vice versa. The adjustment of the groundwater level, occurs in steps, when the cumulated mass error exceeds the specific quantity.

2.3 Evapotranspiration(ET)

In addition to climate, the actual crop ET_a depends on various soil factors and plant factors such as the degree of ground cover, plant leaf characteristics, and the surface roughness of the crop canopy. Plant factors are characterized by the crop coefficient that varies during the growing season and according to the model used to estimate ET.

Estimating the actual ET_a of a growing crop from meteorological observations requires a reference crop ET and the rice crop coefficient. the ET of a rice is calculated by

$$ET_{rice} = u^* k_c^{PM} ET_{PM} \quad (8)$$

where reference crop ET_{PM} is calculated by the following combination, which is based on the Penman-Monteith approach (Shuttleworth, 1992; Feddes and Lenslink, 1994); rice crop coefficients is developed the field experimental data in Korea (Ministry of Agriculture *et al.*, 1997) based on the method of Doorenbos and Pruitt (1977). So the above rice coefficient is needed to convert the crop factor using the Penman-Monteith method (Smith *et al.*, 1996). u^* is the dimensionless water uptake or loss rate (Campbell *et al.*, 1998)

The converting factor ET_{DP} / ET_{MP} can easily be derived from long-term meteorological records. The reference Evapotranspiration ET_{PM} is calculated as follows;

$$ET_{PM} = \frac{\Delta}{\Delta + \gamma^*}(R_n - G) + \frac{\gamma}{\Delta + \gamma^*}\frac{900}{T+275}U_2 D \quad (9)$$

where R_n is the net radiation (mm/day), G is the soil heat flux (mm/day), T is the air temperature (℃), U_2 is the wind speed at 2 m (m/s), and D is the vapor pressure deficit (kPa). The evapotranspiration can be divided by the transpiration and evaporation using the leaf area index (Arnold *et al.*, 1998).

2.4 Irrigation Requirement

The soil moisture balance in a paddy field has inputs of surface inflow S_i, rainfall R, outputs by the actual evapotranspiration ET_{act}, surface outflow S_o and percolation P

$$\Delta H = (S_i - S_o) + R - ET_{act} - P \quad (10)$$

Surface inflow from irrigation water continued from the seedling transplanting period in May to the drainage period in September. Rainfall and evapotranspiration are seasonal. Water requirement in a paddy field, W_{rt}, is defined as

$$W_r = \sum ET_{act} + \sum P + \sum S_o - R_u + L_o \quad (11)$$

In the Kimjae Plains, the irrigation water is almost totally recycled by pumping in a high groundwater district. W_r will be approximately obtained by $W_r \approx \sum ET_{act}$, if water is perfectly reused by pumping in a high groundwater district. The irrigation requirement is calculated as

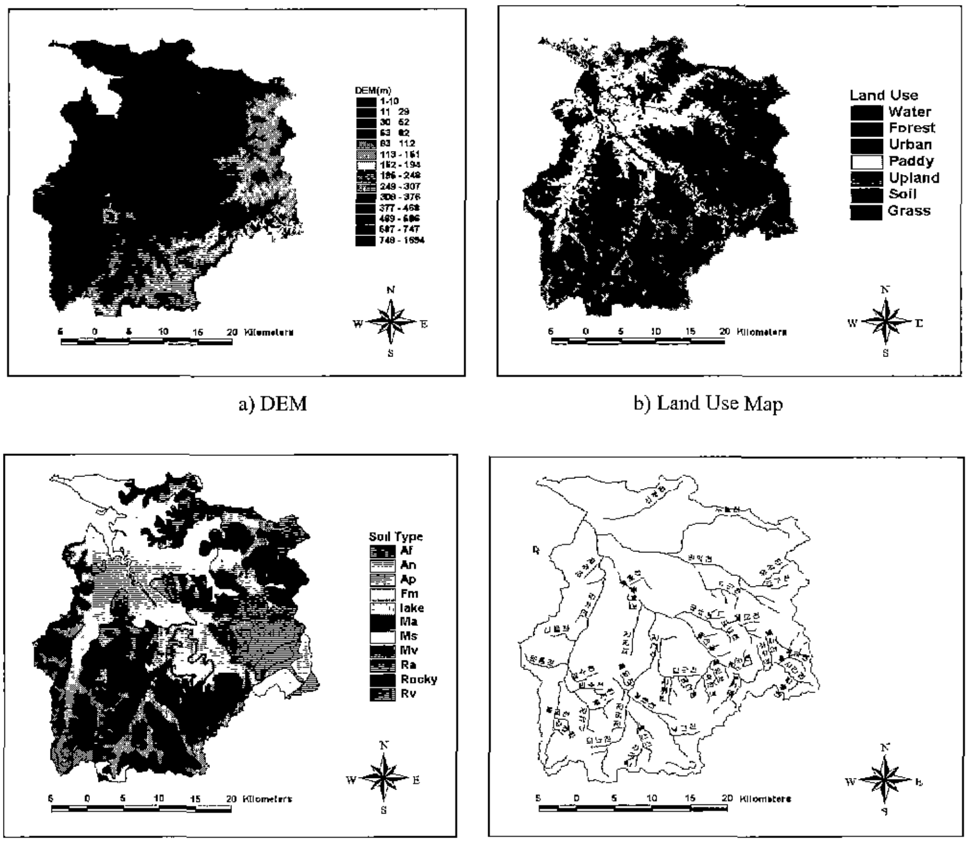
$$I_{ri} = W_r - R_e \quad (12)$$

where R_e is the effective rainfall.

In addition to these factors, water is required to saturate the soil for puddling before rice planting. The puddling water requirement W_p can be calculated as

$$W_p = I_{ri} + \Delta H_p + \Delta S \quad (13)$$

where ΔH_p is the water depth for puddling work, ΔS is the water volume required to saturate the soil. The standard value for puddling water is 142 mm (Kim, 1997).



a) DEM b) Land Use Map

c) Soil Texture d) River and Basin Delinination

Fig 2. Dong Jin River Basin Characteristics using GIS Tools. a) DEM. b) Land Use Map. c) Soil Texture. d) River and Basin Delinination

3. FIELD APPLICATION

3.1 The Study Area

In order to verify the applicability of the model, it was applied to the Kimjae Plains, located in the center of Dongjin river basin in west center of Korean peninsula, during the most serious drought season of 1994. The boundary of the basin is approximately 126° 37'E to 127° 07'E in longitude and 35° 27' N to 35° 50' N in latitude. The Dongjin river starts from Moak Mountain at an altitude of about 793.5 m. It flows west to the Yellow Sea. The area of the drainage basin is 1,147 km^2. The length of river is 52.4 km. (MOC & KOWACO, 1988)

This area is famous for wide paddy fields, called the Kimjae paddy fields. In this area one can see vast ground plains, with water mainly supplied by the Sumjin River Multi-Purpose Dam, built in 1965. The area is mostly based on Jurassic Daebo Granites, which have a conductivity of about 0.01 ~ 1 m/day. The soil texture is almost all soil consisting of silt clay loam (Fig. 2 (c)). Fig. 2 shows the (a) DEM, (b) land use map, (c) soil texture and (d) river and basin delinination of the Dongin River Basin.

Meteorological Data for calculating evapotranspiraion is gathered by the Jung-Ju meterological station, which is located in the center of the Donjin river basin. The drought events of 1994 were most serious since the Sumjin River Multipurposed Dam was built. Rainfall was 826.6 mm during that year, which was also the lowest precipitation since this station was constructed.

3.2 Program Description

This numerical model is developed with Visual Basic ver. 6.0, Excel input and other graphic chart using OCX. The program developed by this study provides various graphic results according to user options with GUI. Fig. 8 shows the model simulated irrigation results in 1994. This includes (a) soil moisture variation and (b) readable soil moisture and calculated soil moisture variation. This model consists of three modules; the first is the unsaturated numerical module, the second is the rice evapotranspiration module with SPAC (soil-plant-atmospheric -continuum) and the third is the groundwater and open channel flow based upon their interrelationship.

3.3 Estimation of Water Balance

There are several kinds of evapotranspiration according to the boundary conditions and applied methods; potential evapotranspiration, evaporation on water surface, reference evapotranspiration, and rice evaporation.

The Albedo values are applied for the different boundary conditions: 0.23 for soil surface and crop evapotranspiration, and 0.06 for water surface.

Choosing the Penman-Monteith approach means that the crop coefficient related to the method should be used for the analysis season. Through this model study we fine the ratio between evapotranspiration with FAO 24 (Doornbos *et al.*, 1974) to that with Penman-Monteinth is ranging from 1.13 for the high evaporation season(summer) to 0.85 for the low evaporation season (winter) (e. g. per 10 day period).

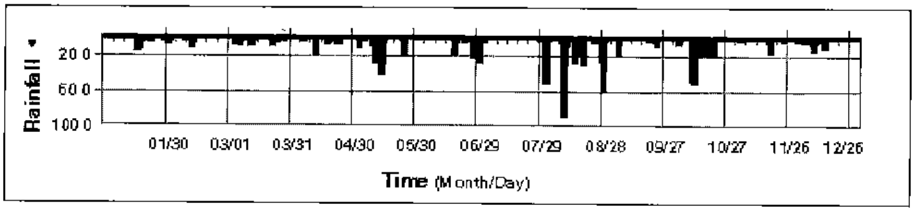
With this model, the values are estimated as: 1,392 mm for the soil potential evaporation, 1,654 mm for water surface evaporation, and 1,199 mm for reference crop.

In the case of rice , the reference evapotranspiration is 1132 mm with a FAO 24, and the actual evapotranspiration using the Penman-Monteinth method is 871 mm; 671 mm for actual transpiration and 200 mm for evaporation on the paddy surface. The difference is caused by the deficit of supplied water (the sink ratio u^* in Eq. (8)) and the ground heat flux consideration. Fig. 3 shows the variation of daily evapotranspiration in the paddy field during 1994.

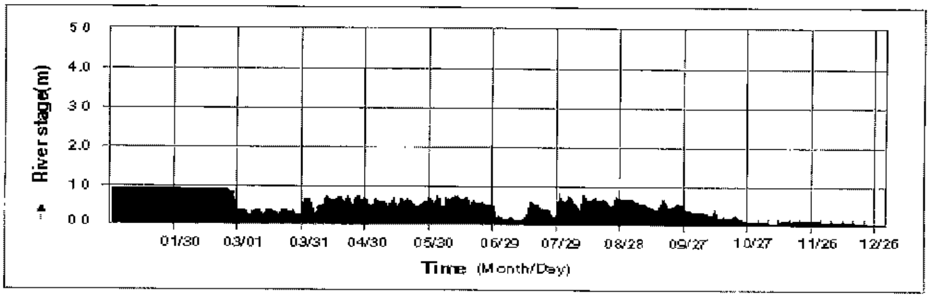
The irrigation season starts in early April, when paddy nurseries are being prepared and the paddy is sown. It ends at the end of August when the paddy starts ripening. The peak water use for paddy irrigation occurs in the months of May and June. Then, fields are filled up to a depth of 3～7 cm during the transplanting period (NEDECO, 1976).

Paddy rice fields are mostly grown under conditions of near soil saturation and submersion, loss through percolation should be minimal. A dense subsoil layer is obtained by puddling the wet soil which requires 100 to 200 mm of water, and some times up to 300 mm, including the pre-planting irrigation.

Continuous submergence, with intermittent drainage, is the most promising method. During and immediately after transplanting the water is kept at 5～7 cm for about ten days after transplanting to secure healthy growth of the seedlings. In the following tillering period, submer-



(a) Precipitation for the Kimjae Rice Paddy Field, Jung-Ju Meteorology Station, 1994



(b) Variation of Daily River Flow at the Sin-Tae-In Stage Station, 1994

Fig. 3 Variation of Daily Precipitation and River Stage in 1994. (a) Precipitation at Jung-Ju Meteorology Station. (b) River Stage at Sin-Tae-In Station.

gence is shallow (maximum 3 cm) to maintain high soil temperatures. Drainage and drying of the top soil is practised during this period since rice can tolerate a water shortage and root development is enhanced. Drainage must be complete 5~10 days prior to head development. During the head development, the paddy is irrigated frequently (3 days of irrigation and 2 days of dry). During heading the water is maintained at a 3 cm depth. From this time onward, adequate water once or twice during this period is sometimes practiced. During the ripening period, fields should gradually be drained to facilitate harvest operations.

Water evaporates from the upper parts of soil. Water is withdrawn rapidly from the top part of the soil profile. About 40% of the extracted water comes from the upper quarter of the root zone, 30% percent from the second quarter (Wes Wallender *et al.*, 1991). So in this study, the root density of rice accepted the above portions and the water extraction depth for irrigation can be considered as the upper quarter of maximum rice root depth (Sharpley and Williams, 1996).

The capillary fringe is increases with time lapsed; on Jan.1 1.2 m, on May. 30. 1.8 m, Dec. 31 2.0 m above the groundwater (see Fig. 7 (a) to (f)). Fig. 7 shows the daily variation of soil moisture profile between the ground surface and groundwater surface at 60 days intervals. Also, this model can well estimate the soil moisture conditions of the paddy.

The real irrigation from the Sumjin multipurposed dam in 1994 was 712 mm. With this model the water requirement for irrigation is estimated at about 757 mm under unlimited water supply conditions. This result shows that water deficit was about 5.9% in this area during 1994. Water use for the irrigation reserve and generation was definitely exhausted during the spring season and owing to this discharge the river flow was maintained high during the spring of 1994.

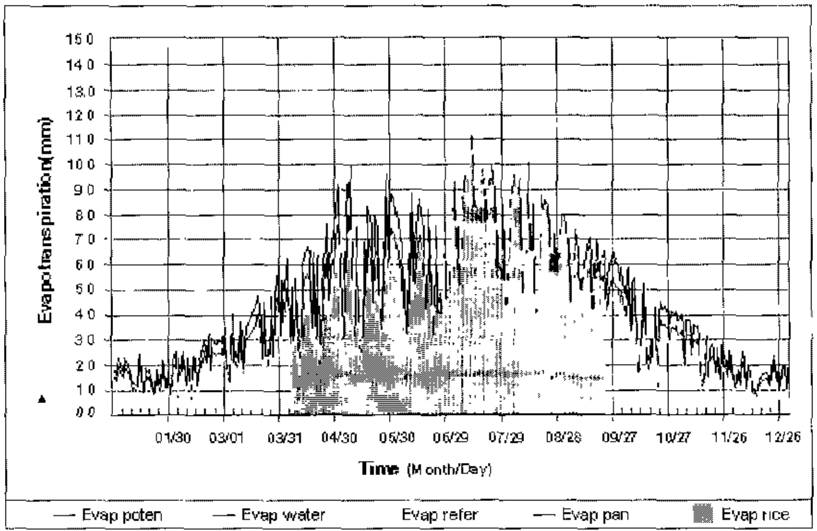
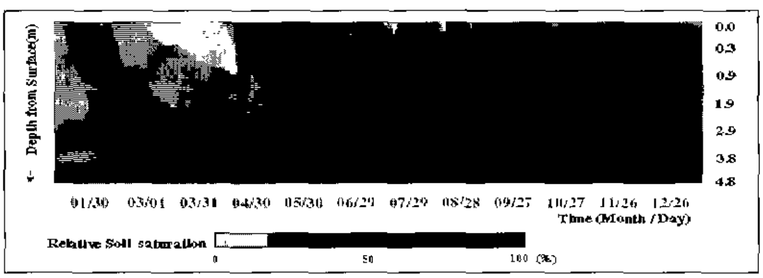
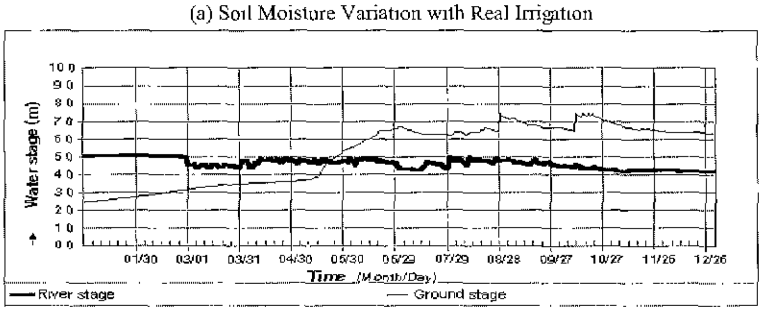


Fig.4 Variation of Daily Evapotranspiration on the Kimjae Paddy, 1994

The puddling water is estimated at about 348 mm in reality and about 298 mm in the model analysis. This difference comes from field guidelines in the field study and initial moisture conditions in the model. In order to avoid the initial moisture conditions in the model case the model needs the soil moisture to be preprocessed the year before. The standard values for puddling water are used – 142 mm (Kim, 1997).

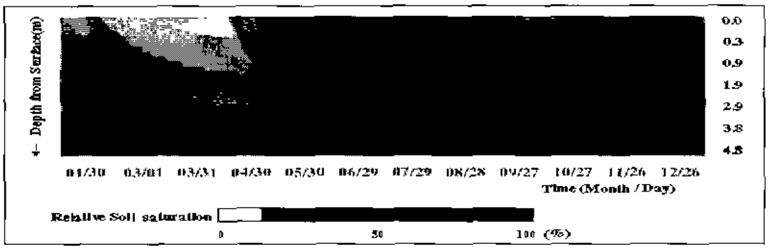


(a) Soil Moisture Variation with Real Irrigation

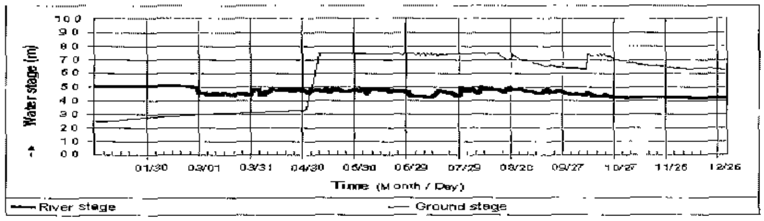


(b) Groundwater and River Stage Variations with Real Irrigation

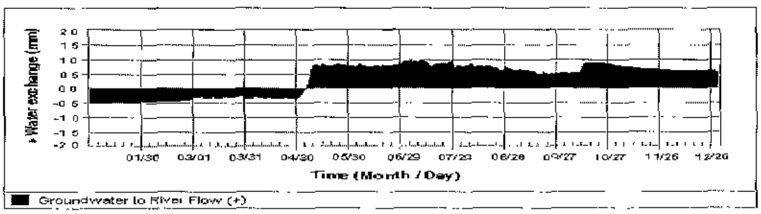
Fig 5. Real Irrigated Condition,1994 (a) Soil Moisture Variation (b) Groundwater and River Stage Variations



(a) Soil Moisture Variation with the Model of Simulated Irrigation

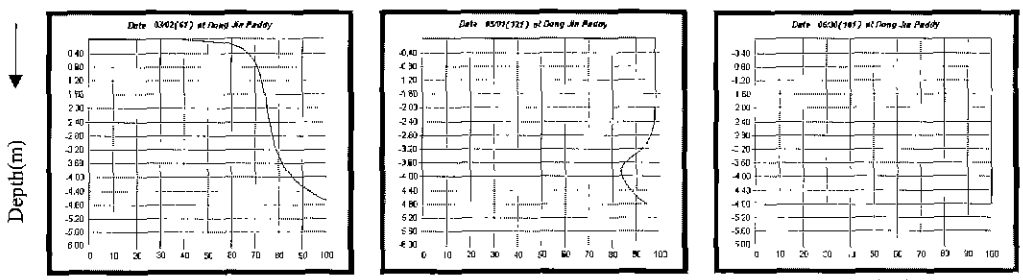


(b) Groundwater and River Stage Variations with Model of Simulated Irrigation

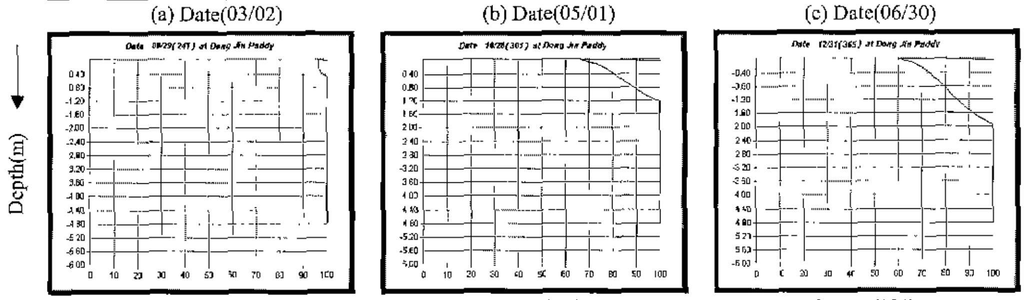


(c) River and Groundwater Exchange Variations with Model of Simulated Irrigation

Fig 6. Model of Simulated irrigation Results on the Kimjae paddy, 1994. (a) Soil Moisture Variation. (b) Groundwater and River Stage Variation. (c) River and Groundwater Exchange Variations



(a) Date(03/02) (b) Date(05/01) (c) Date(06/30)



(d) Date(08/29) (e) Date(10/28) (f) Date(12/31)

Soil-moisture content(%)

Fig 7. Profile of Soil Moisture Variation on the Kimjae paddy, in 1994.

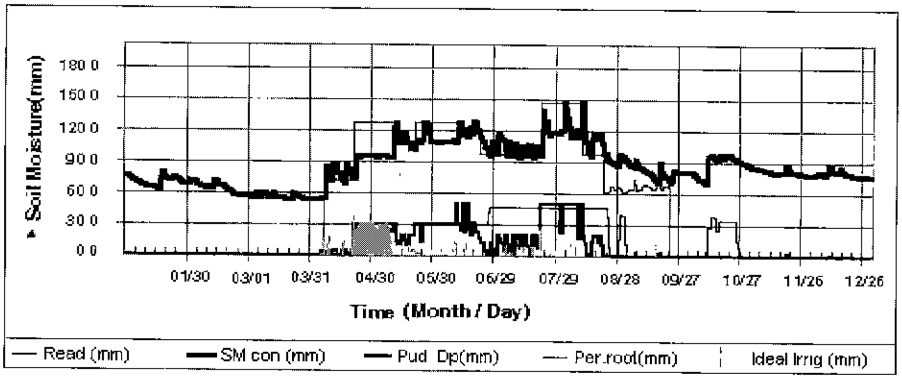


Fig 8. Model of Simulated Soil Moisture Variation, 1994

4. CONCLUSION

The physically-based hydrologic model developed in this study can be used to evaluate the soil-moisture balance on rice paddy fields and to simulate the hydrological processes of infiltration, soil water storage, deep percolation or recharge to the shallow water table, evapotranspiration and evaporation from the soil surface. This study also considers the groundwater and river flow exchange in the Kimjae paddy field.

The computational procedure yields the soil-moisture distribution, actual infiltration or surface evapotranspiration, and actual water uptake by crop or plant as functions of time. This study can be easily applied to other areas to evaluate the irrigation efficiency and agricultural water deficit considering the open channel and groundwater exchange. The developed model can visualize each hydrological process over variable time period. The capillary fringe can be also easily simulated.

This model can be used as a guideline for predicting crop water requirements when considering the soil moisture conditions. Also, this model can be applied in order to evaluate the soil moisture conditions of a river basin according to the different crops, plants, and other hydrological characteristics.

In the model soil-moisture contour map in Fig. 6(b) and Fig. 7(b), we have some problems in describing moisture density which comes from the VB graphic OCX. If there are observed groundwater information and soil moisture contents, some parameters used in this model can be estimated; the preference flow effect with optimization. Also, this one dimensional unsaturated flow model will need further development in the future.

Through this development and application of the Kimjae paddy field, we can summarize the results as follows;

1) The result shows that the estimated net water requirement in 1994 was 757 mm and the water deficit was about 5.9% when comparing with the real supplied quantity from the Sumjin multi-purpose dam for this study area.

2) The reference evapotranspiration is estimated at 759 mm on the Kimjae rice paddy area during 1994. The percolation quantity was about 877 mm.

3) The groundwater and river exchange quantity was estimated as approximately a maximum of 0.97 and a minimum of -0.52 mm/day (recharge)

4) The Groundwater level fluctuated greatly

within the 7.5 ~ 2.5 m range according to the recharge and river flow exchange during the studied season.

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