0038-075C/00/16505-384–397
Soil Science

May 2000
Vol. 165, No. 5
Printed in U.S.A.

A MODEL FOR WETLAND HYDROLOGY: DESCRIPTION AND VALIDATION

R. S. Mansell[1], S. A. Bloom', and Ge Sun*

WETLANDS, a multidimensional model describing water flow in variably saturated soil and evapotranspiration, was used to simulate successfully 3-years of local hydrology for a cypress pond located within a relatively flat Coastal Plain pine forest landscape. Assumptions included negligible net regional groundwater flow and radially symmetric local flow impinging on a truncated conical pond, deciduous cypress trees and shallow-rooted perennial undergrowth in the pond area, and pine trees in the upland area as well as within the outer 20% of the wetland area. A minimal observed parameter set of daily rainfall, daily air temperature, soil characteristics, and pond geometry provided model input. The model described temporal patterns of daily pond water and groundwater table elevations with relatively small average signed deviations of -2 and +11 cm, respectively. Potential exists for the model to be utilized as a predictive tool for wetland hydrology, even for conditions where available empirical data for a given site is minimal and appropriate simplifying assumptions are utilized. (Soil Science 2000;165:384–397)

Key words: Wetland hydrology, model simulation, cypress pond, evapotranspiration, pine forest.

WETLAND ecosystems provide benefits such as wildlife habitat, groundwater recharge, water purification, and biomass production (Walbridge, 1993). However, the hydrology of wetlands is spatially and temporally complex as a result of the transition between transitory fresh water ponds within shallow topographical depressions and surrounding terrestrial landscapes. Recent hydrological investigations of forest wetlands in the Southern United States provide a useful database for the coastal plains (Crownover et al., 1995; Sun et al., 1995;Amatya et al., 1996;Amatya et al., 1997).

Cypress-pine flatwood forests (CPFF) wet-, lands are defined by cypress swamps or ponds located in coastal plain pine forests, and CPFF are associated with shallow unconfined aquifer systems characteristic of flatwoods landscapes in the lower Atlantic and Gulf Coastal Plain provinces of the southeastern U.S. (Crownover et al., 1995). CPFF wetlands in Florida are important ecosystems for timber production and are suspected of being environmentally sensitive to land disturbance. Forest best-management practice guidelines are available but lack sufficient scientific support. A need exists to develop management level hydrological models to assist forest managers in making sound decisions.

The hydrology of these shallow wetlands is complex because the ponds are characterized by temporally variable volumes and surface areas of free water. Although more than 80% of annual rainfall on CPFF wetlands may be returned to the atmosphere by evapotranspiration (ET) (Ewe1 and Smith, 1992), the balance of rainfall (R) and ET is nonuniformly distributed seasonally. During the winter months (November-March), standing water occurs as the result of conditions in which R > ET (Sun, 1995). During the spring and summer months, surface water in cypress ponds is subject to periodic disappearance because of infrequent R and high ET.

---

[1] 2169 McCarthy Hall, PO Box 110290, Soil and Water Science Department, University of Florida, Gainesville, FL 32611-0290. Dr. Mansell is correpsonding author. E-mail: rsm@gnv.ifas.ufl.edu

Florida Agricultural Ep. Stn. Journal Series R-07508.

*USDA Forest Service, Rakish, NC.

Received June 30, 1999; accepted Jan. 10, 2000.

The hydrology of CPFF ponds also reflects the hydrology of surrounding pine forests in flatwoods and landscapes. Surface water in cypress wetlands is known to be coupled with groundwater in surrounding upland pine forests. (Heimburg, 1976). Net flows occur between pond surface water and subsurface groundwater in response to both regional and local groundwater flows. Water flow for wetland ponds, as well as for shallow lakes, is commonly categorized by three hydrological modes: (i) groundwater discharge (i.e., localized pond recharge), where ponds act as variable strength water sinks, (ii) groundwater recharge (i.e., localized pond discharge), where ponds act as variable strength water sources, and (iii) flow-through (i.e., regional flow), where groundwater is transmitted through ponds (Anderson and Munter, 1981; Crownover et al., 1995; Sun et al., 1995).

Groundwater discharge and recharge modes typically occur in relatively flat terrain and are often governed by localized groundwater flow; whereas the flow-through mode is often governed by regional groundwater flow, particularly in sloping landscapes. For conditions of minimal regional flow, pesticides and fertilizers applied to upland pine forest immediately surrounding a cypress pond are more likely to contaminate surface water during groundwater recharge than in discharge modes (Fares et al., 1997). During the flow-through mode, contaminants applied to the forest on the up-stream side of a pond may be particularly vulnerable to transport into the surface water. Even in relatively flat terrain, the flow-through mode has been reported to be a common occurrence in CPFF ponds, particularly when average water tables occur near the soil surface (Crownover et al. 1995).

To date, only a few hydrologic models have been applied to forest wetlands, and those models do not feature dynamic interactions between standing water bodies in the landscape while coupled with realistic ET submodels. A forest hydrology model DRAINLOB was developed from the field-scale agricultural drainage model DRAINMOD (Skaggs, 1984) to model water management effects (controlled drainage) on the hydrology of loblolly pine plantations on North Carolina coasts (McCarthy et al., 1992). However, dynamic interactions between groundwater and variable ponds are not included in DRAINLOB. A distributed, watershed-scale forest hydrology model, FLATWOODS, was developed to describe daily hydrological cycle for cypress-pine flatwoods (Sun et al., 1998a). That model utilizes a one-dimensional unsaturated flow submodel in the vadose zone coupled with a two-dimensional saturated flow submodel beneath the water table. However, because of its large spatial scales and model structure, FLATWOODS is limited in its descriptions of interactions between surface water and groundwater.

In this work, a multidimensional model for variably saturated water flow in porous media is utilized to describe local hydrology for an individual cypress pond located within a Coastal Plain pine forest with sandy soils over a 3-year period (1992-1994). This model explicitly includes temporally variable ponds and dynamic interactions with the surrounding landscape and also includes a relatively simple but realistic description of ET.

MODEL DESCRIPTION

The local hydrology of a cypress pond/flatwood forest system was modeled using WETLANDS, a multidimensional water flow and solute transport numerical model that provides dynamic linkage between pond water, groundwater, and unsaturated soil zones. Radial symmetry was assumed in the model. WETLANDS is an altered form of the VS2DT model (Variably Saturated Two-Dimensional Transport) developed by the U.S. Geological Survey (Healy, 1990; Lappala et al., 1987). Model alterations include incorporation of (i) a specifiable surface pond having seasonally dynamic water levels over variably inundated areas; (ii) utilization of the Priestley-Taylor Equation to estimate potential evapotranspiration rate ET, (L T^{-1}) from a minimum set of daily weather data (Fares and Mansell, 1996); (iii) coupled evapotranspiration for multiple plant species with specifiable root zones; and (iv) hydrodynamic linkage in time between surface water in a pond and surrounding water in the porous subsurface (soil water and ground water). Boundary conditions available in VS2DT have been extended by other researchers (Munster et al., 1994) but, to our knowledge, not as extensively as in WETLANDS.

The Physical System

A CPFF wetland utilized specifically in the model includes a cypress pond and the immediate surrounding flatwood area (Fig. 1). In order to simplify the process of modeling water flow within the complex CPFF wetland environment, several simplifying assumptions were made: (i) the overall landscape was assumed to be flat since reported slopes range from 0 to 1.6% and no

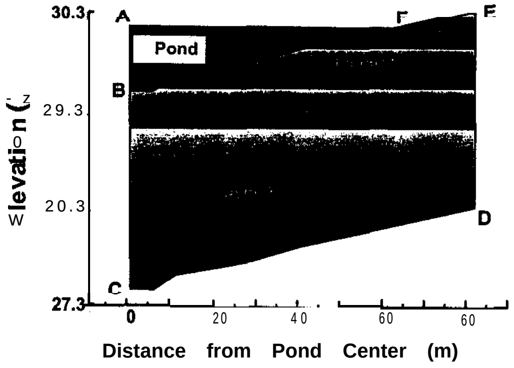

Fig. 1. Schematic cross section for one half of the flow domain for the simulated CPFF system providing locations for soil layers and pond boundaries. The letter F designates the maximum radius of the inundated pond.

flowing streams were within the immediate vicinity although surface flow eventually drained into the Santa Fe River via interconnected wetlands (Sun, 1995); (ii) the effective pond geometry was approximated as a quasi-circular cone with a maximum radius $R_{p\text{-max}}$, maximum pond water height $h_{p\text{-max}}$, and irregularly shaped lower boundary reflecting the volume of each contour level of the actual pond; (iii) the lower boundary of the system was parallel to the ground surface (Sun, 1995); (iv) flow symmetry occurs along a vertical axis passing through the center of the pond; (v) a groundwater divide with zero horizontal water flux was present along a radius at the edge of the simulated physical system based on an assumption of nonregional flow; (vi) a lower boundary condition of zero water flux exists; and (vii) radially symmetric flow may occur either into or out of the pond from the surrounding soil. These assumptions translate the simulated flow domain into a large, circular, cross-sectional surface area over the subsurface flow domain surrounding a smaller, circular pond with an irregular, cone-shaped bottom boundary.

In the modeled system, elevation of the soil surface was set as 30.30 m (point E in Fig. 1), corresponding to the elevation of the upland well. The lowest level in the pond was set as 29.47 m (point B in Fig. 1), based on the depth of the pond. The horizontal limit used here for the flow domain was 81 m from the pond center (points A-C), reflecting the distance between the pond well (point A in Fig. 1) and the only upland monitoring well (point E in Fig. 1) for this CPFF system (Sun, 1995). The bottom of the soil profile was assumed to parallel the ground surface and to occur 2 m below the ground surface (Sun, 1995). The geometry of the pond bottom was determined by converting the volume of each successive contour level from the topographical map of the area (Sun, 1995) into a corresponding volume for a conical pond at the same elevation. The maximum hydrologic influence of the individual cypress ponds on groundwater movement in the flatwood forest was reported to extend approximately 25 m into the flatwoods landscape, thus justifying placement of a circular groundwater divide at 81 m radius (Sun, 1995).

The maximum pondwater height ($h_{p\text{-max}}$) was set to 0.60 m to reflect the maximum observed values over the 3-year monitoring period and is assumed to represent the elevation where surface overflow or outflow is allowed to occur from the pond. Pond levels exceeded this maximum simulated pond height by 6, 4, and 2 cm at days 278, 279, and 280 in 1992. These atypical values were regarded as sampling anomalies and were thus disregarded in setting $h_{p\text{-max}}$. Simulated pond overflow was assumed to provide surface drainage to a downstream pond but was not actually measured (Sun, 1995). The pond outflow elevation, in turn, sets the maximum boundary for the pond ($R_{p\text{-max}}$) at 62.8 m, and that boundary was used to delineate the upland and wetland areas.

Plant distributions across the terrain were set according to the general pattern observed by Sun (1995), i.e., cypress trees and shallow rooted (root depth of 0.5 m) undergrowth were assumed to occur over the circular area of the maximum pond radius ($0 < x < 62.8$ m), and pines were assumed to occur on the distal edge ($50.2 \leq x \leq 62.8$ m) of the pond as well as the uplands ($62.8 \leq x \leq 81$ m).

Water Flow Equations

The system was modeled by solving two coupled equations simultaneously, the first of which is Richards equation (Hillel, 1980) for describing two-dimensional variably saturated water flow for isotropic subsurface porous medium beneath and surrounding the pond

$$C_w(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right)-\frac{\partial K(h)}{\partial z}-Q_{water} \qquad (1)$$

where $h(x,z) = H(x,z) + z$ is the water pressure head (L), $H(x,z)$ is the total or hydraulic head (L), x is horizontal distance (L), z is depth (L) below the soil surface, t is time (T), K (h) is the hydraulic conductivity (L T^{-1}) for a given pressure head h, $Q_{water} = Q_{evap} + Q_{trans} - Q_{rain}$ is a combined volumetric sink-source term (T^{-1}), Q_{evap} is the soil evaporation sink (T^{-1}), Q_{tran} is a transpiration sink (T^{-1}), Q_{rain} is a precipitation source corrected for canopy interception (T^{-1}), $C_w(h) = \partial\theta/\partial h$ is the specific water storage capacity (L^{-1}) for a given value of h, and θ is volumetric water content (L^3 L^{-3}). Although Eq. (1) is defined for a rectangular grid, the corresponding equation for cylindrical coordinates is analogous to replacing x with the radius r' as the horizontal coordinate since $x = r' \text{ Cos } \theta' \equiv r'$ when $\theta' = 360$” is the maximum angle of rotation (Lapalla et al., 1987).

The second equation that is coupled with Eq. (1) provides the rate of change for water volume in the pond (L^3 T^{-1}), based on a water budget accounting for all inputs and outputs.

$$\frac{dV_{pond}}{dt} = [R_{pond} - I_{pond} - E_{pond} - T_{pond}]\, A_{surf-pond} + [\Psi_{in} - \Psi_{out}]\, A_{subsurf-pond} + [Y_{in} - Y_{out}] \tag{2}$$

where R_{pond} is the precipitation rate over the pond (L T^{-1}); I_{pond} is the rainfall interception rate by the cypress and pine trees located within the pond (L T^{-1}); E_{pond} is the surface water evaporation rate for the pond (L T^{-1}); T_{pond} is transpiration rate from trees within the inundated pond area (L T^{-1}); Ψ_{in} is the subsurface inflow rate for the pond (L T^{-1}); Ψ_{out} is the subsurface outflow rate for the pond (L T^{-1}); Y_{in} is the surface inflow rate for the pond (L^3 T^{-1}); Y_{out} is the surface outflow rate for the pond (L^3 T^{-1}); V_{pond} is the volume of surface water in the pond (L^3) at time t (T); and $A_{surf-pond}(t)$ and $A_{subsurf-pond}(t)$ represent time-dependent surface (L^2) and subsurface (L^2) areas of water in the pond. The term $[R_{pond} - I_{pond} - E_{pond} - T_{pond}]\, A_{surf-pond}$ provides the net rainfall over the pond area. At any point along the pond-soil interface, the subsurface inflow rate is set by the water pressure head values in the soil adjacent to the point, and the subsurface outflow rate is set by the depth of water in the pond at the point. By iterating the solutions of Eqs. (1) and (2) during a time step, the soil and pond systems are dynamically linked.

Evapotranspiration

Normalized water uptake distributions for a CPFF landscape involving multiple plant species were utilized for determinations of (i) potential evaporation rates $E_P(x,t)$ that vary with time and horizontal distance across the flow domain using weighted leaf area index LAI(x,t) values; (ii) potential transpiration rates $T_P(x,t)$ that vary with time and horizontal distance using weighted albedo $\beta(x,t)$ values; and (iii) seasonally adjusted potential transpiration rates $T_P(x,t)$ that change with time for deciduous trees such as cypress using a dimensionless transpiration coefficient $\varphi_i(t)$ for each plant species (Fig. 2).

Simple empirical models are often used to relate potential transpiration (T,) to leaf area development with time (Tanner and Jury, 1976; Smajstrla, 1982). A dimensionless transpiration coefficient, $\varphi(t)$, such that $0 \leq \varphi(t) \leq 1.0$, is multiplied by T_P to provide seasonally adjusted potential transpiration, i.e., $T_P{}^*(t) = \varphi(t)T_P$ (Hanks, 1985). Though $T_P{}^*(t)$ is also influenced by the seasonal change in LAI, in a system with a single plant species, this approach is sufficient. However, for systems with multiple plant species with varying degrees of co-occurrence across a terrain and with time variable canopies, i.e., differing degrees of deciduousness, a mechanism must be provided to allocate potential transpiration among the species at a point in time and to alter that allocation with the changing state of the canopy.

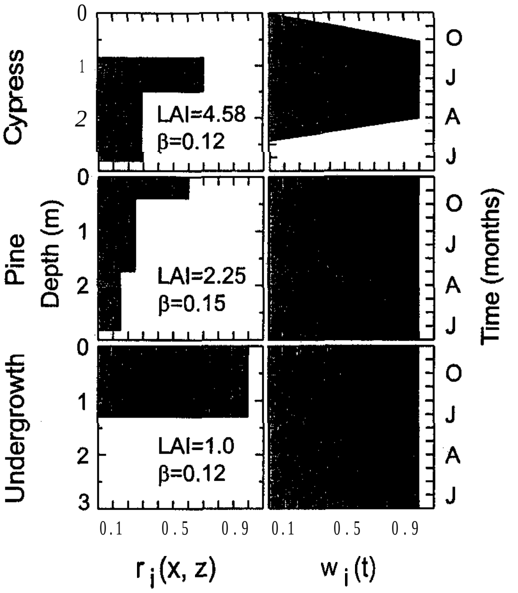

Fig. 2. The root activity (or density) and the dimensionless transpiration coefficient, W_i, for the plant species used in the simulation along with the species-specific maximum leaf area index (LAI) and albedo values for those species. Root activities for pine were taken from Van Rees (1984) and were arbitrary for cypress and undergrowth. LAI values were from Liu (1996) for cypress and pine and was arbitrary for undergrowth. Albedo values were taken from similar plants (Hanks and Ashcroft, 1980).

In the model, this requirement is satisfied by first defining the normalized water uptake distribution, χ_i for the ith plant species, for each of N plant species as

$$\chi_i(x,t) = \frac{\int_{z=0}^{z_{root}(i,x)} r_i(x,z)\,\varphi_i(t)dz}{\sum_{j=1}^{N}\int_{z=0}^{z_{root}(i,x)} r_j(x,z)\,\varphi_j(t)dz} \tag{3}$$

where r_i (x,z) is the weight fraction of the roots in a depth interval relative to the total weight of roots in the root zone for a given location x (Nimah and Hanks, 1973), $Z_{root}(i,x)$ is the maximum rooting depth for plant species i, which was permitted to vary with horizontal location x, and φ_i (t) is a transpiration coefficient (dimensionless) for plant species i that ranges from 0 to 1.0, depending on relative degree of leaf presence in the canopy for that species. Normalizing the uptake distribution ensures that over each vertical slice of the flow domain

$$\sum_{j=1}^{N}\int_{z=0}^{z_{root}(j,x)} \chi_j\ (x,z)\ \varphi_j\ (t)\ dz = 1.0 \tag{4}$$

For current simulations, N = 4, such that cypress trees in the wetland, understory vegetation in the wetland, and pine trees (both in the pond and in the uplands) are considered. Understory plants were not used in the upland forest. The root zones for these plants are shown schematically in Fig. 2. The ET submodel has been validated previously by comparison with actual data for turfgrass grown in lysimeters (Fares and Mansell, 1996).

A given plant species exhibits a species-specific pattern of temporal variation in the leaf area index, varying from some minimum to some maximum value over an annual cycle. The transpiration coefficient, φ_i (t), can then be estimated by dividing the temporal variation in LAI by the maximum LAI. For a nondeciduous species, the best estimate of LAI(t) is the mean LAI over the annual cycle. For a deciduous species, a minimum response curve can be approximated by defining four temporal points in the annual cycle, (i) the time of the first leaf appearance (φ (t) = 0), (ii) the time when the full canopy is achieved (φ (t) = 1), (iii) the time of first leaf fall (φ (t) = 1), (iv) and the time when total defoliation occurs (φ (t) = 0), as well as performing linear interpolations between these points.

LAI (including canopies and open areas between canopies) was measured earlier for the wetlands and uplands over time (Fig. 3) by Liu (1996). The mean LAI for the uplands was 2.25. When that value was assigned to pine, the product of that value and the φ_{pine} (1.0 at all times) generates an acceptable approximation to the observed temporal pattern (Fig. 3). The mean overall value for the wetlands (cypress) was 3.22, and the mean of the values from March to November was 4.58. Using the latter value as the species-specific LAI for cypress and multiplying by $\varphi_{cypress}$ (Fig. 2) produces an acceptable approximation to the observed pattern (Fig. 3).

To extend LAI(t) to LAI (x,t), i.e., to accommodate variation in multiple species root activities over the terrain, the species-specific leaf-area index (LAI_i) (Fig. 2), the relative root density (χ_i (x,t), Eq. (3)), and the relative state of the canopy for the ith plant species (the transpiration coefficient, φ_i (t)) can be summed over all plant species to give the weighted leaf area index, i.e.,

$$LAI(x,t) = \sum_{i=1}^{N} \chi_i(x,t)\ LAI_i \tag{5}$$

Potential evaporation rates, E_p, (L T^{-1}) for the soil surface under forest conditions were calculated according to an equation by McKenna and Nutter (1984)

$$E_p(x,\ t) = ET_p(x,t)\ e^{-0.4\ LAI(x,t)} \tag{6}$$

where ET, is the potential evapotranspiration rate (L T^{-1}) and LAI(x,t) is a weighted leaf area index for all plants present at location x and time t. Eqs. (5) and (6) were also utilized for water surfaces in vegetated ponds. For the hypothetical case of a nonvegetated pond, evaporation was assumed to proceed at the potential rate ET,.

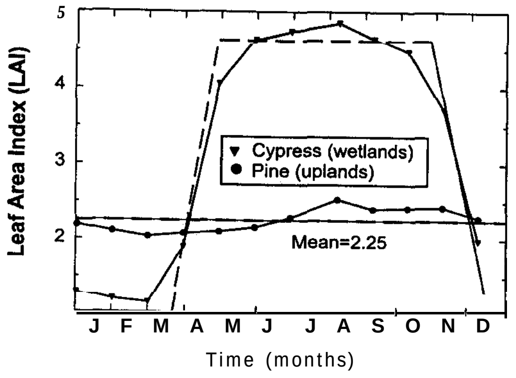

Fig. 3. Observed leaf area indices (LAI) (Liu, 1996) (solid lines) and the product of the transpiration coefficient (φ) and the species-specific maximum LAI (dashed lines) for pine and cypress.

Potential transpiration rates $T_p(x,t)$ were calculated by subtracting potential evaporation rates $E_p(x,t)$ from the total potential evapotranspiration rates $ET_p(x,t)$. The Priestley-Taylor Equation was used to estimate $ET_p(x,t)$ rates that vary in horizontal space and time for vegetated pondwater and soil surfaces (Priestley and Taylor, 1972).

$$ET_p\,(x,z{=}0,t) = \frac{\alpha}{\lambda}\left[\frac{\Delta}{\Delta+\gamma}\right]\,[R_n\,(\beta(x,t)) - G] \quad (7)$$

where six input parameters include γ the psychrometric constant; λ the latent heat of vaporization; A the gradient of the saturation vapor pressure-temperature curve evaluated at air temperature; R_n daily total net solar radiation at the surface of the earth; G daily soil heat flux; and α the Priestley-Taylor Coefficient, assumed to be a constant that typically varies over the range $0.6 \leq \alpha \leq 1.1$ (Spittlehouse and Black, 1981) for coniferous forests with no intercepted water. Since $G << R_n$ is commonly assumed to occur for 24-h calculations of ET, (Jones, et al., 1984), G was assumed to be negligible in Eq. (7). The Priestley-Taylor Coefficient α represents the ratio E_{max}/E_{eq}, where E_{max} is the maximum 24-h evapotranspiration rate for well-watered vegetation, and E_{eq} is the equilibrium evapotranspiration rate (Black, 1979). For simulations reported here, an α value of 0.75 was obtained by calibration of model simulations and experiment data for pondwater level and groundwater elevation in the associated upland forest for an experimental pond other than the one reported here (i.e., Pond #C). While low growing agronomic crops have reported α values of 1.1 and 1.3, forests typically have values less than 1.1 (Black, 1979). Moreover, Black (1979) reported $\alpha = 0.8$ for a Douglas Fir forest in Western Canada, thus implying that the value used here is reasonable. An equation used for estimating the daily total net radiation R_n utilizes surface albedo or reflectivity β as given in Fares and Mansell (1996). In that equation, R_n is inversely proportional to β. Albedo values used in Eq. (7) were weighted according to spatial root distributions for N plant species using

$$\beta(x,t) = \sum_{i=1}^{N} \chi_i(x,t)\,\beta_i \quad (8)$$

where β_i is an albedo for an individual species i. Albedo values used for cypress, undergrowth, and pine trees are given in Fig. 2 and the values for unvegetated soil and pondwater were 0.15 and 0.065, respectively (Hanks and Ashcroft, 1980).

Potential evapotranspiration rates $ET_p(x,t)$ were calculated using the Priestley-Taylor Equation because it is computationally simple and requires a minimal weather data set that is generally available through local weather records. The data set includes minimum (T*„(t)) and maximum (T”„(t)) daily air temperatures, location latitude, altitude of the ground surface, ratio of actual to maximum number of sunshine hours per day (given as monthly values), day of the year (DOY), and surface albedo β (Stagnitti et al., 1989; Fares and Mansell, 1996). Procedure for utilizing the weather data set to calculate input parameters for the Priestley-Taylor Equation are presented by Fares and Mansell (1996). With appropriate input values, Eq. (7) can be used to estimate daily rates for potential evapotranspiration ($ET_p(x,t)$) that vary in horizontal space and time. Equation (7) is a simplified form of the Penman Equation that is most reliable in humid climates (Priestley and Taylor, 1977).

Actual evaporation rates E(x,t) for surface soil are related to the evaporation sink $Q_{evap}(x,z,t)$ in Eq. (1) and were calculated as upward water fluxes ($L\ T^{-1}$) using the approach in the VS2D model by Lappala et al. (1987):

$$E(x,t) = -\,K(h)\,\frac{[h - h_{Atm}]}{\Delta z_0/2} = Q_{evap}\,(x,z,t)\,\Delta z_0 \quad (9)$$

where AZ, represents the thickness of the uppermost soil node (L) and h_{Atm} is the pressure head of the atmosphere (L) as determined by substituting the relative humidity h,. of the atmosphere into the Kelvin Equation (Hillel, 1980). Following Lappala et al. (1987), $h_{air} = 0.90$ and $h_{Atm} = -1450$ m of water. Equation (9) is forced to apply over the range $0 \leq E(x,t) \leq E_p(x,t)$. Evaporation ceases ($E(x,t) = 0$) if either $K(h) = 0$ or $h = h_{Atm}$.

The water uptake rate by plant roots Q_{trans} in Eq. (1) was calculated using a modified form of the approach used in VS2D (Lappala et al., 1987) to permit transpiration from major plant species with roots distributed spatially across the flow domain. The water extraction sink is calculated as the sum of individual uptake rates for N maximum plant species

$$Q_{trans}(x,z,t) = \sum_{i=1}^{N} Q_{trans-i}(x,z,t) \quad (10)$$

where the uptake rate (T^{-1}) for each species i is given as

$$Q_{trans-i}(x,z,t) = K(h)\,[h_{root-i} - h(x,z,t)]\,\chi_i(x,t) \quad (11)$$

with K(h) being the soil hydraulic conductivity ($L\ T^{-1}$) corresponding to soil water pressure head

(L) h, h_{root-i} being the root water pressure head (L) for plant species i, and χ_i being a root activity function in space and time (L^{-2}) for a given plant species. The reciprocal of the term K(h) [h_{root-i} − h] in Eq. (11) represents the combined hydraulic resistance to water flow in roots and in the soil. Equation (11) limits the actual transpiration T(x,t), which varies with time and horizontal distance across the surface of the flow domain, such that

$$T(x,t) \equiv \sum_{i=1}^{N} \int_{z=0}^{z_{root}(i,x)} Q_{trans-i}\ (x,z,t)\ dz \leq T_p\ (x,t) \quad (12)$$

where $T_p(x,t)$ is the potential transpiration rate (L T^{-1}). Although it is mathematically feasible for T(x,t) > T_p (x,t), this is unrealistic. In this situation, Eq. (11) was scaled according to

$$Q^*_{trans-i} = \frac{T_p(x,t)}{T(x,t)}\, Q_{trans-i} \quad (13)$$

to ensure that actual transpiration did not exceed potential transpiration. In Eq. (11), the permanent wilting point pressure head of − 150 m of water (Hillel, 1980) was used for h_{root} for both pine and cypress trees. Equations (10) through (13) specify that actual transpiration T(x,t) = 0 occurs in horizontal space and time when soil water suction h ≤ h_{root} or when hydraulic conductivity K (h) = 0. Within the maximum pond area, $Q_{trans} = Q_{trans\text{-}pines} + Q_{trans\text{-}cypress}$, where $Q_{trans\text{-}pines}$ and $Q_{trans\text{-}cypress}$ are transpiration rates for pine and cypress trees, respectively. Within the upland forest, $Q_{trans} = Q_{trans\text{-}pines}$.

In order to incorporate the 1994 harvesting of cypress and pine trees within the maximum pond area into the simulation, the transpiration coefficients for these species were set to zero on Day 851 (May 1) and maintained until Day 1014 (September 10).

Precipitation and Canopy Interception

The precipitation source, Q_{rain}, (T^{-1}) was related to rainfall rate R (L T^{-1}) by the relationship

$$R(x,t) - I(x,t) = Q_{rain}\ (x,t)\ \Delta z_0 \quad (14)$$

where AZ, is the thickness of the uppermost soil node and I(x,t) is the canopy interception rate calculated using

$$I = \sum_{i}^{N} S_i \text{ if } R \geq I, \text{ otherwise } I = R \quad (15)$$

where N is the number of plant species present, i.e., interception cannot exceed the rainfall. S_i in Eq. (15) is the species-specific interception capacity, defined as

$$S_i = f_{w_i}\ LAI_i(x,t) \text{ if } S_i \leq f_{w-\max_i} \text{ otherwise } S_i = f_{w-\max_i} \quad (16)$$

where f_w is the water film thickness, LAI(x,t) is the weighted LAI, and $f_{w-\max_i}$ is an empirical parameter, the maximum water film thickness. Following Rutter et al. (1975), a value of 0.2 mm for f_w was used for all plant species and values of 0.56, 0.02, and 0.02 mm were used for $f_{w-\max_{cypress}}$, $f_{w-\max_{pine}}$, and $f_{w-\max_{undergrowth}}$, respectively (Sun, 1995). The LAI value used in Eq. (16) occurs within the range LAI,, ≤ LAI ≤ LAI_i where the minimum value is defined as

$$LAI_{min} = \sum_{i=1}^{N} \Theta_i\, \chi'_i\ (x,t)\ LAI_i \quad (17)$$

where 0 ≤ Θ_i ≤ 1 is a dimensionless stem-to-canopy ratio (a value of 0.5 was used here for cypress trees (Rutter et al. 1975)), and χ_i' is defined by modifying Eq. (3) for the special condition $\varphi_i(t)$ = 1 .O for deciduous cypress trees. Equation (17) permits rainfall interception by stems of cypress trees during winter periods when transpirational activity is zero.

Soil Description

Hydraulic conductivity for variably-saturated soil was described as a function of soil water suction head h using the analytical model of van Genuchten (1980) in which K_s is the hydraulic conductivity at water saturation θ_s of the soil, m = 1 − 1/n, n, and α are constants describing soil water characteristic data (0 versus h) for a forested Spodosol (Table 1) similar to that of the GNF site (Philips et al., 1989). Thicknesses of soil horizons were also based upon the description given by Philips, et al. (1989).

Boundary Conditions

Boundary conditions were specified using Eqs. 18 through 21. The zone along the sides of the two-dimensional flow domain over which a specific condition was imposed is indicated by the characters A through F in Fig. 1 and in the annotations to these equations. Radially symmetric flow was assumed. The two vertical boundaries were specified by:

$$-K(h)\ \frac{\partial h}{\partial x} = 0 \qquad \text{for } z \in [A,C], [D,E] \quad (18)$$

and the bottom of the flow system (2.83 m soil depth) was specified by:

TABLE 1

Hydraulic properties for soil layers used in the K-pond CPFF system (Phillips et al., 1989)

Layer	Thickness (cm)	α	n	θ_s ($cm^3\ cm^{-3}$)	θ_r	K_s ($cm\ h^{-1}$)
#1 (sandy A & E horizons)	40	0.032	2.96	0.400	0.110	30
#2 (spodic horizon)	45	0.015	3.84	0.460	0.210	6
#3 (E' horizon)	20	0.019	3.84	0.350	0.070	10
#4 (argillic Btg horizon)	140	0.021	3.64	0.350	0.070	2

$$-K(h)\frac{\partial h}{\partial z} = 0 \qquad \text{for } x \in [C,D] \tag{19}$$

These boundaries are thus prescribed as no-flow boundaries and reflect the assumption of no regional flow. Soil/atmosphere and pondwater/atmosphere interfaces of the system were flux boundaries that can receive water as rainfall or lose it through ET and were specified by:

$$q_0(x,t) = -K(h)\left[\frac{\partial h}{\partial z}-1\right] \text{for } x \in [A,E] \tag{20}$$

where $q_o(x,t)$ is the rainfall flux imposed along the soil surface at a given time t. Subsurface flow into and out of the pond was prescribed as a flux boundary condition and was specified by:

$$q_{op}(x,z,t) = -K(h)\left[\frac{\partial h}{\partial x}+\frac{\partial h}{\partial z}-1\right] \text{for } x \in [B,F] \tag{21}$$

where $q_{op}(x,z,t)$ is the subsurface flux into the pond ($q, < 0$) or from the pond ($q_{op} > 0$).

The solution of Richards' water flow equation requires knowledge of the initial distribution of the pressure head within the flow domain where h_o is the initial pressure head distribution in space.

$$h(x,z,t) = h_o(x,z) \text{ at } t = 0 \tag{22}$$

Initial (January 1, 1992) pressure heads were assumed to be at equilibrium with an observed water table location at the pond well at a depth of 1.16 m (i.e., 29.14 m elevation). The pond was thus assumed to be dry initially.

The uppermost soil surface (30.30-m elevation) and exposed pond sides received or lost water according to the prevailing rainfall or surface evaporation. Water reaching the soil surface (rainfall) was partitioned into infiltration and excess water. For conditions of water saturation of surface soil, a simple surface flow system was used whereby excess water is routed to the next node on the left (toward the pond center). If excess water occurred at all surface nodes, excess water would reach the free surface water of the pond. Thus, runoff from the upland was approximated as a one-dimensional process directed toward the pond over the upper surfaces of successive soil columns. For simplicity, the pond and the adjacent uplands were regarded as a hydrologically isolated system and the boundary conditions were so established.

Discretization

The SIP (Strongly Implicit Method) finite difference numerical technique was used in the WETLANDS model to solve the water flow equation using a block-centered regular finite-difference discretization scheme (Lappala et al., 1987). Spatial discretization of the #K-pond CPFF flow system was accomplished with a variable grid size. The horizontal node spacing was set constant at Ax = A r' = 50 cm, and the vertical node spacing ranged from $0.1 \leq$ Az ≤ 20 cm. The smallest Az values were imposed at the pond center and near the soil surface, respectively. Time discretization was accomplished by starting with a small At value and automatically increasing the value as hydraulic gradients decreased to provide a range of $10^{-4} \leq$ At $\leq 10^{-1}$ days.

DESCRIPTION OF EXPERIMENTAL SITE

Simulations of pond-water and watertable depths for a CPFF system were compared with published field data collected from a rather flat 40-ha GNF research site in the flatwoods of northcentral Florida (Sun, 1995). The GNF site was located at 82" 15' W longitude and 29" 47' N latitude. Pond cypress (*Taxodium ascendens* Brongn) dominated the vegetation in the wetland for pond #K along with slash pine (*Pinus elliotti* Engelm) and black gum (*Nyssa sylvatica var. biflora* Sarg). The dominant canopy tree in the uplands was slash pine with an understory of saw palmetto (*Serenoa repens* Small) and gallberry (flex *glabra* Gray) shrubs. The 30-year-old pine plantation was thinned in 1986 leaving 500 trees per hectare (Sun, 1995). Cypress and pine trees in the maximum pond area were harvested on May 1, 1994. The soil type was predominantly Pomona fine sand (a Spodosol; Utic Haplaquods; sandy, siliceous, thermic) (Sun, 1995). Impermeable blue-green clay approximately 3 to 5 m beneath the general GNF area separates the shallow sandy surficial aquifer from an underlying artesian secondary aquifer. In the vicinity of the #K wetland, the clay layer was observed to be roughly parallel to and 2 m below the ground surface (Sun, 1995).

Water levels were obtained during 1992-1994 at wells located at the pond center and at an upland location 81 m from the pond center. Water table elevations were continuously recorded using punch-tape recorders. Daily temperature extremes (minimum and maximum) were taken from weather station data collected at the Gainsville Airport, located 8 km from the study site. The average annual air temperature was 21 "C, with a mean monthly low of 14 °C in January and a high of 27 °C in July. Daily rainfall was recorded at the site. Annual rainfall amounts for 1992, 1993, and 1994 represented 113.7 (1512 mm), 85.5 (1137 mm), and 93.2% (1240 mm) of a 60-year average (1330 mm) (Sun, 1995). For this paper, 1993 is referred to as the dry year, 1992 as the wet year, and 1994 as the average year with respect to rainfall. Annual rainfall patterns are typically characterized by two distinct dry periods (April-June and October-December). Detailed information about the experiments are provided in Sun (1995).

RESULTS AND DISCUSSION

Hydrology of the #K pond CPFF was simulated for 3 years (1992-1994) using the WETLANDS model. Measured daily pond depths and groundwater table depths in the uplands forest were compared with corresponding simulated values.

Pond ad Water Table Elevations

Observed daily water elevation of the #K pond and associated water tables during 1992, 1993, and 1994 compared favorably with appropriate simulated values, as shown in Fig. 4, 5, and 6, respectively. Deviations of simulated from observed values were summarized using the Average Absolute Deviation (AAD) (Munster et al., *1994):*

$$AAD = \left[\frac{1}{n}\right] \sum_{i}^{n} |S_i - O_i| \qquad (23)$$

Overall 3-year AAD values were 13 and 16 cm for the pond and uplands, respectively (Table 2). AAD errors were maximal in the dry year (1993) and minimal in the wet year (1992), an expected pattern since elevation differences are magnified

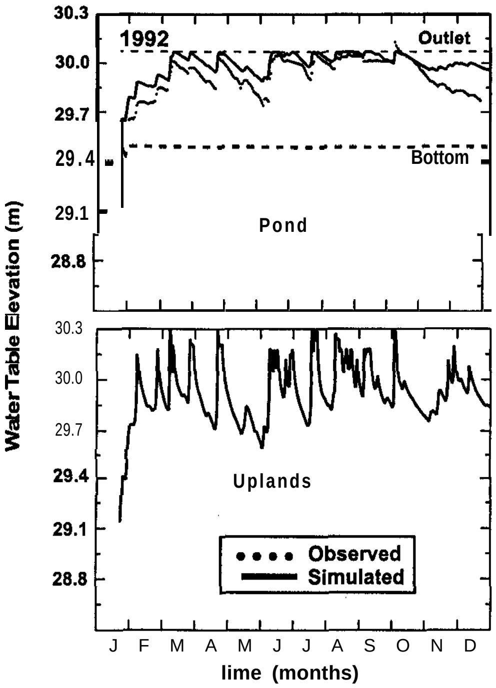

Fig. 4. Simulated (smooth lines) and observed (discrete points) levels of surface water in the pond and water table in surrounding upland during 1992. Day number one represents January 1, 1992.

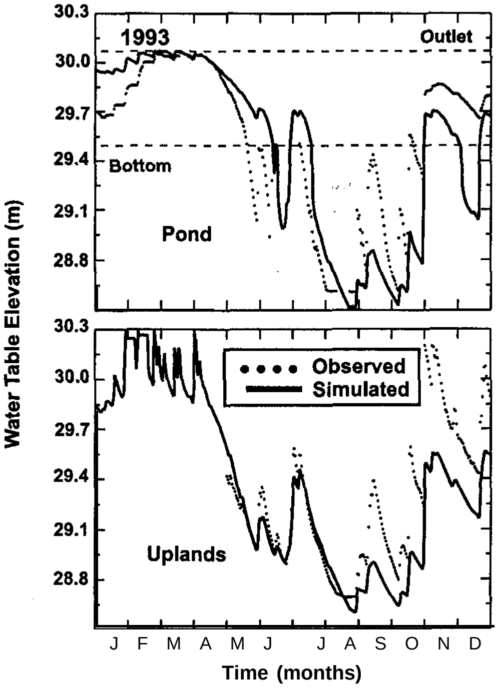

Fig. 5. Simulated (smooth lines) and observed (discrete points) levels of surface water In the pond and water table in surrounding upland during 1993.

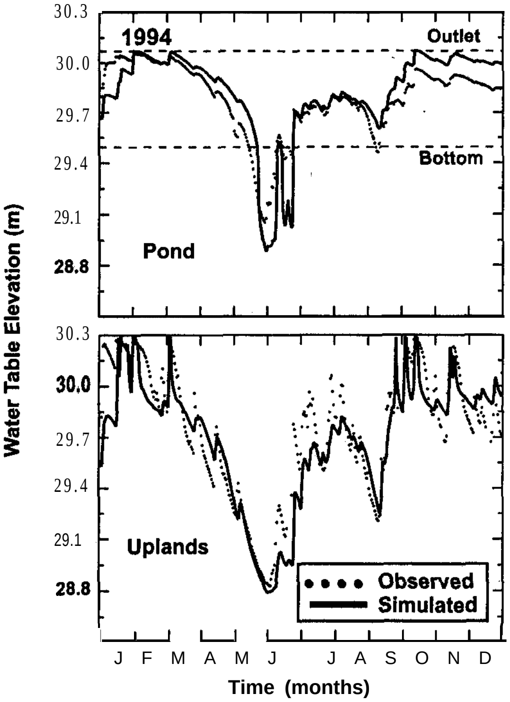

Fig. 6. Simulated (smooth lines) and observed (discrete points) levels of surface water in the pond and water table in surrounding upland during 1994.

when the pond is empty and cannot exceed the outflow level when the pond is full. When the AAD was calculated using signed rather than absolute values, overall errors were only -2 and + 11 cm for pond and uplands, respectively, thus indicating that pond level predictions were acceptable whereas uplands predictions tended to be overestimates (wetter than reality).

Setting model transpiration coefficients to zero for trees in the pond mimicked the overt effects of harvesting trees in May 1994. However, the compensatory increase in the proportion of evaporation resulted in essentially the same predicted quantity of water removed by evapotranspiration. Close examination of Fig. 6 during the initial post-harvest period from June to October 1994 reveals very close approximation of observed to simulated water levels in the pond. Thus tree harvest within the pond was concluded to have had a negligible effect on pond water level during 1994.

TABLE 2

Mean AAD deviations of predicted and observed pond water and water table elevations, and simulation mass balance errors. Standard Deviations are given as SD in parentheses

Year	Cypress Pond (cm)	Uplands (cm)	Simulation Error (%)
1992	7.5 (5.5)	na	-0.061
1993	22.0 (18.7)	21.1 (18.4)	0.050
1994	10.1 (8.5)	12.9 (11.0)	0.010
overall	13.0 (13.6)	16.3 (15.0)	0.013

na = not applicable due to lack of observations for indicated period and location

Placement of a no-flow lower boundary (i.e., clay layer) in the model approximately parallel and 2 m below the ground surface seems to be justified during the long summer dry period of 1993 when no standing water appeared and a groundwater table developed in the pond area (Fig. 5). During August 1993, observed and simulated groundwater tables reached minimal elevations of 28.6 and 28.7 m and 28.5 and 28.6 m, respectively, for the center of the wetland and at the upland well. Locations of the no-flow boundary in the wetland and upland well sites in the model were established at 27.4 and 28.3 m, respectively.

From October through December of both 1992 and 1994, the model overestimated water level in the pond, and this overestimation is a major source of error. This period corresponds roughly to the alteration in the pond canopy due to the deciduous nature of cypress or to harvesting. These discrepancies suggest a possible need to explore increasing the magnitude of alpha in the PET estimates (Figs. 4 and 6) in the pond area specifically for these periods.

As expected, simulated water levels in the cypress pond were shown to be sensitive to pond geometry, i.e., the relationship between water storage volume and pond shape. This sensitivity was most apparent during dry periods when very little surface water was present in the pond.

Although the model assumptions include zero regional flow, this constraint should not be interpreted literally as meaning that regional flow does not occur in the CPFF system. If regional flow were to occur such that only moderate and slow alterations appeared in the regional water levels, i.e., approximately equal quantities of water entering and exiting a defined area over a given time period, the net effect of such a flow on the experimental physical and time scales would be negligible. By making the assumption of negligible net regional flow and producing reasonable match to reality under the assumption simply indicates that there was no appreciable introduction or drainage of water from the system that cannot be explained on the basis of precipitation and evapotranspiration within the experimental system.

Spatial Distributions of Water Levels

Net water input (NWI) provides, a convenient single parameter that incorporates the net influence of rain and evapotranspiration in a forest. Net Water Input is defined here as the sum R-I-ET, where R is rainfall, I is canopy interception, and ET is evapotranspiration. For this paper, NWI was calculated with the model because components I and ET were simulated.

A radial transect showing a cross-section of simulated water levels in the pond and associated water table during selected days is presented in Fig. 7. Day 540 during 1993 represents a period of very negative cumulative NWI, with no surface water occurring in the pond and water table levels occurring beneath the pond bottom. Day 180 during 1992 represents a period of very high positive cumulative NWI, with near maximum water level in the pond and slightly higher water table level in the uplands. During this period, ground water in the uplands tended to flow to the wetlands. Day 360 in 1992 also represents a period of high cumulative NWI but with lower water table in associated groundwater, indicating subirrigation of the surrounding upland forest. On Day 720 in 1993, the pond had a small amount of water in the bottom and a relatively low water table level in the upland.

Net Water Input

Wetlands tend to occur in topographical depressions across a landscape and are thus subject to periodic inundation with surface water. Frequency of ponded water conditions in the depression tends to be influenced heavily by net water input. During seasonal periods of high NWI (i.e., low ET, low I, and/or high R), wetlands tend to collect surface water as well as provide surface runoff to streams or lakes, and during periods of low NWI (i.e., high ET, high I, and/or low R), surface water storage in wetlands tends to decrease.

Simulated canopy interception accounted for approximately 7.4% of reported rainfall over the 3-year period, with highest interception percentage (8.9%) occurring in the dry year (1993), lowest interception percentage (6.4%) occurring in the wet year (1992), and with an intermediate value (7.3%) occurring in the average year (1994). Given the relative constancy of interception over the S-year period and the limited amount of water involved, interception is unlikely to be a strong controlling factor in water table elevation relative to rainfall and evapotranspiration.

Cumulative net water input (NWI) obtained during simulations are reported in Fig. 8 for 1992, 1993, and 1994. Periods with positive cumulative NWI values (characterized by frequent rainfall and low ET demand) indicate potential for enhanced rise in surface water level in the pond as well as water table elevations in the associated uplands, whereas periods with negative cumulative NWI (characterized by infrequent rainfall and high ET demand) indicate the likelihood of depressed pond levels and water tables. Positive cumulative NWI values were observed from January through April, indicating relatively wet winter and spring seasons for all 3 years. The wettest year, 1992, had a simulated annual cumulative NWI of 49.7 cm. Only positive cumulative NWI values occurred during 1992 and, on average, increased steadily throughout the year. The driest year was 1993, with an annual cumulative NWI of only 3.3 cm and predominantly negative, NWI values from the middle of May through the

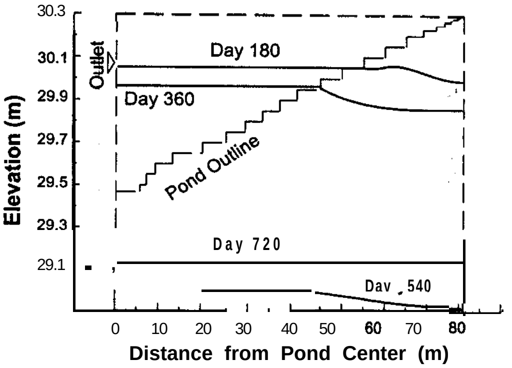

Fig. 7. A spatial transect across the pond and associated upland forest showing water levels in the pond and water tables in the upland for selected dates.

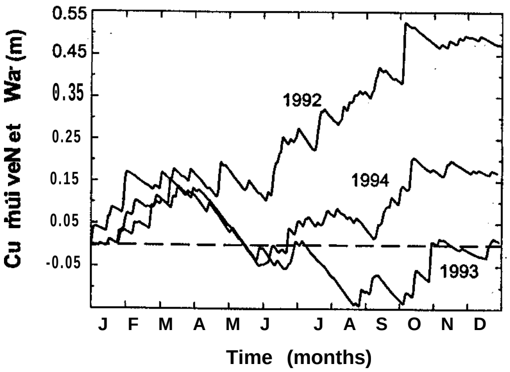

Fig. 8. Cumulative net water input (NWI) for 1992, 1993, and 1994 simulations.

end of October. The annual cumulative NWI value of 19.0 cm for 1994 was intermediate for the other years. The NWI pattern for 1994 was very similar to 1993 during the first 6 months but provided only positive values during the last 6 months.

Both the lowest pondwater levels and water table elevations occurred during conditions of negative cumulative NWI generated by low rainfall and high ET demands. Simulated and measured pond water levels followed very similar patterns throughout the three annual periods. However, simulated levels tended to overestimate observed values, especially during periods of low cumulative NWI.

Surface water occurred in the pond throughout the wet year of 1992 as a result ofpositive cumulative NWI. Simulated water table elevations were within the upper 60 cm of soil during 1992 (data were not available for comparison). Because rainfall was low during the dry year of 1993, giving negative cumulative NWI values, the #K pond was empty for a long period, especially during summer and early fall seasons.

However, during the average rainfall year of 1994, surface water occurred in the pond during most of the year. An exception occurred during May and June when the pond was drained because of negative cumulative NWI conditions. Simulations of water table elevations in the upland during 1993 and 1994 provided reasonable description of observed data. As expected, water table elevations in the surrounding uplands at 81 m distance from the pond center were not dramatically influenced by changes in levels of surface water in the pond.

Simulated water removal from the CPFF system by actual ET accounted for 99.2% of the potential ET_p for the 3-year period reflecting relatively high cumulative NWI so that soil water storage over the flat topography was rarely a major limitation to transpiration and evaporation. Overall water balance for the 3-year simulation revealed that total water loss by ET and pond overflow from the system represented 92% of water input (R-I) with an 8% increase in system water storage (pondwater, groundwater, and soil water). Evapotranspiration and overflow from the pond provided 85% and 15%, respectively, of total water loss from the system, indicating the vital importance of ET to water balance in the #K wetland. These values are consistent with reports by Heimburg (1976) and Sun (1995).

SUMMARY AND CONCLUSIONS

Simple cone-shaped geometry for cypress ponds and local minimal weather data-sets were utilized for 3 years as the primary input for the WETLANDS computer model to produce a successful simulation of pond water and groundwater table elevations in a selected cypress pond/flatwood pine forest system. Evapotranspiration and rainfall provide the primary hydrological outputs and inputs, respectively, for the flat landscapes characterizing CPFF ecosystems..

Favorable comparisons of simulated and observed daily elevations of pond water and groundwater table surfaces for the selected CPFF system indicate that major aspects of the complex wetland hydrology were adequately described by the relatively simple assumptions within the model, including the assumption of zero net regional flow. Model simulations suggest that the hydrology for the CPFF wetland system is driven by seasonal fluctuations in the cumulative net water input NWI. Elevations of both pond water and groundwater tables rose during periods of increasing cumulative NWI and fell when cumulative NWI decreased. Pond and water table levels rose during winter months when magnitudes of cumulative NWI became more positive. During brief periods, net water flow occurred radially from the upland pine forest into the pond (groundwater discharge mode). However, during most of the 3 years, negative NWI tended to lower pond and upland water table levels as net water flow occurred radially from the pond to the surrounding pine forest (groundwater recharge mode).

Given the capacity to successfully describe the hydrology of the CPFF system, the WETLANDS model provides a potential tool for investigating chemical transport between surface water and ground water in forested cypress-pine wetlands. Long-term hydroperiods in pine forests may be simulated when climate data are available. The model provides a tool to study hydrology and water quality of similar isolated wetlands (e.g. Carolina Bays) that are common in the southeastern U.S.

ACKNOWLEDGMENT

This research was supported, in part, by a grant from the National Council of the Paper Industry for Air and Stream Improvement, Inc. (NCASI).

REFERENCES

Amatya, D. M., R. W. Skaggs, and J. D. Gregory. 1996. Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina Coastal Plain. J. Hydrol. 181:211–232.

Amatya, D. M., R. W. Skaggs, J. D. Gregory, and R. B. Herrmann. 1997. Hydrology of a drained forested pocosin watershed. J. Am. Water Res. Assoc. 33: 1-12.

Anderson, M. P., and J. A. Munter. 1981. Seasonal reversal of groundwater flow around lakes and the relevance to stagnation points and lake budgets. Water Resour. Res. 17:1139-1 150.

Black, T. A. 1979. Evapotranspiration from a Douglas Fir stand exposed to soil water deficits. Water Resour. Res. 15:164–170.

Crownover, S. H., N. B. Comerford, D. G. Neary, and J. Montgomery. 1995. Horizontal groundwater flow patterns through a cypress swamp-pine flatwoods landscape, Soil Sci. Soc. Am. J. 59: 1199–1206.

Ewell, K. C., and J. E. Smith. 1992 Evapotranspiration from Florida pond cypress swamps, Water. Resour. Bull. 28:299–304.

Fares, A. 1996. Environmental impact of unharvested forest buffer zones upon cypress-pond systems in coastal plains regions: modeling analysis. Ph.D. dissertation, University of Florida. Gainesville, FL.

Fares, A., and R. S. Mansell. 1996. A potential evapotranspiration prediction submodel for multidimensional water flow in soils. Soil Crop Sci. Fla. Proc. 55:36–45.

Fares A., R. S. Mansell, and S. A. Bloom. 1997. Hydrological/environmental impacts of tree harvesting within flatwood pine forests upon local wetlands. *In* Subsurface Hydrological Responses to Land Cover and Land Use Changes. M. Taniguchi (ed.). Kluwer Academic Publishers, Norwell, MA, pp. 167-186.

Hanks, R. J., and G. L. Ashcroft. 1980. Applied Soil Physics. Springer-Verlag, New York.

Hanks, R. J. 1985. Crop coefficients for transpiration. *In* Advances in Evapotranspiration. ASAE St. Joseph, MI, pp. 430-438.

Healy, R. W. 1990. Simulation of Solute Transport in Variably Saturated Porous Media with Supplemental Information on Modification to the U.S. Geological Survey's Computer Program VS2D. U.S. Geological Survey, Water Resources Investigations Report 90-4025.

Heimburg, K. 1976. Hydrology of some north-central Florida cypress domes. M. S. thesis, University of Florida, Gainesville, FL.

Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York.

Jones, J. W., L. H. Allen, S. F. Shih, J. S. Rogers, L. C. Hammond, A. G. Smajstrala, and J. D. Martsolf. 1984. Estimated and Measured Evapotranspiration for Florida Climate, Crops, and Soils. Agricultural Experiment Stations, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, Technical Bulletin 840.

Lappala, E. G., Healy, R. W., and E. P. Weeks. 1987. Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media. U.S. Geological Survey Water-Resources Investigations Report 83-4099.

Liu, S. 1996. Evapotranspiration from cypress (*Taxodium ascendens*) wetlands and slash pine (*Pinus elliottii*) uplands in north-central Florida. Ph.D. dissertation, University of Florida, Gainesville, FL.

McCarthy, E. J., J. W. Flewelling, and R. W. Skaggs. 1992. Hydrologic model for drained forest watershed. J. Irrig. Drainage Eng. 118:242–255.

McKenna R., and W. L. Nutter. 1984. Some modifications to CREAMS for forested applications. Forest Resources Research Report, School of Forest Resources, University of Georgia, Athens, GA.

Munster, C. L., R. W. Skaggs, J. E. Parsons, R.O. Evans, J. W. Gilliam, and M. A. Breve. 1994. Simulating aldicarb transport in a drained field. Trans. Am. Soc. Agric. Eng 37:1187–1824.

Nimah, M. N., and R. J. Hanks. 1973. Model for estimating soil water, plant, and atmospheric interrelations, I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37:522–557.

Phillips, L. P., N. B. Comer-ford, D. G. Neary, and R. S. Mansell. 1989. Simulation of soil water above a water table in a forested spodosol. Soil Sci. Soc. Am. J. 53:1236–1241.

Priestley, C. H. B., and R. J., Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Wealth. Rev. 100:81–92.

Rutter, A. J., A. J. Morton and P. C. Robins. 1975. A predictive model of rainfall interception in forests, II. Generalizations of the model and comparison with observations in some coniferous and hardwood stands. J. Appl. Ecol. 12:367–380.

Skaggs, R. W. 1984. DRAINMOD—a water management model for shallow water table soils, User's Guide. North Carolina State University, Raleigh, NC.

Smajstrla, A. G. 1982. Irrigation Management for the Conservation of Limited Water Resources: Project Completion Report. Agricultural Engineering Department, University of Florida, Gainesville, FL.

Spittlehouse D. L., and T. A. Black. 1981. A growing season water balance model applied to two Douglas fir stands. Water. Resour. Res. 17:1651–1656.

Stagnitti, F., J.-Y. Parlange, and C. W. Rose. 1989. Hydrology of a small wet catchment, Hydrological Processes 3:137–150.

Sun, G. 1995. Measurement and modeling of the hydrology of cypress wetlands-pine uplands ecosystems in Florida flatwoods. Ph.D. dissertation. University of Florida, Gainesville, FL.

Sun, G., H. Riekerk, and L.V. Korhnak. 1995. The hydrology of cypress wetland-upland ecosystems in Florida flatwoods, In Versatility of Wetlands in the Agricultural Landscape. Campbell, K. L. (ed.). Am. Assoc. Agric. Eng., Orlando, FL, pp. 489-500.

Sun, G., H. Riekerk, and N. B. Comerford. 1998a. Modeling the fores hydrology of wetland-upland ecosystems in Florida. J. Am. Water Res. Assoc. 34:827–841.

Sun, G., H. Riekerk, and N. B. Comerford. 1998b. Modeling the hydrologic impacts of forest harvesting on flatwoods. J. Am. Water Res. Assoc. 34: 843-854.

Sun, G., S. G. McNulty, J. P. Shepard, D. M. Amatya, H. Riekerk, N. B. Comerford, R. W. Skaggs, and L.

Swift, Jr. 1999. Effects of Timber Management on Wetland Hydrology in the Eastern United States. For. Ecol. Manage. (in press).

Tanner, C. B., and W. A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. J. 68:239-243.

Van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. Proc. 44: 892-898.

Van Rees, K. C. J. 1984. Root distribution of slash pine plantation on a flatwood Spodosol. M.S. thesis, Univ. of Florida, Gainesville, Fl.

Walbridge, M. R. 1993. Functions and values of forested wetlands in the southern United States. J. Forestry 91:15-19.