**Title**
Evaluation of the effects of surface water and groundwater interactions on regional climate and local water resources

**Author**
Liang, Xu

**Publication Date**
2003-06-01

# Project Title: Evaluation of the Effects of Surface Water and Groundwater Interactions on Regional Climate and Local Water Resources

**Project number:** W-922 (Final Report) (June 2003)

**Duration:** 2 years (extended for a third year without cost)

**Investigator:** Xu Liang (Email address: liang@ce.berkeley.edu)
Department of Civil and Environmental Engineering
University of California at Berkeley

**Key Words:** Surface water and groundwater interactions, Soil moisture, Spatial scales, Land surface models, Water resources management, Water quality assessment

## Abstract

Knowledge on the state of soil moisture is essential for improving predictability of the global energy and water balances on seasonal to inter-annual time scales. The exchanges of moisture and energy between soil, vegetation, and snowpack and the overlying atmospheric boundary layer impacts the near surface atmospheric moisture and temperature. Thus, reasonable estimates of soil moisture could significantly improve the accuracy of simulating precipitation and surface temperature globally and regionally. If the soil moisture estimation (or parameterization) is not reliable, a fully coupled climate and land surface model may simulate an erroneous climatic state that the forecasted precipitation and temperature deviate significantly from the observed values, especially in numerical forecasting of the extreme events. In this project, the impact of surface and groundwater interactions on soil moisture, evapotranspiration, runoff, and recharge are investigated. Through the two year project (extended for the third year without cost), a new parameterization to represent surface and groundwater interaction dynamics for land surface models is developed and implemented into a the VIC-3L (Three-layer Variable Infiltration Capacity) model, which is a hydrologically based land surface scheme. The new version of VIC (called VIC-ground) is applied to a watershed in Pennsylvania over multiple years. Results show that VIC can properly simulate the movement of the daily groundwater table over multiple years at the study site. Preliminary comparisons of VIC simulations with and without considering the dynamics of surface and groundwater interactions show important impact of such interactions on partitioning of water budget components. Results also show that it takes 3 to 4 years to have the effects of the initializations of groundwater tables disappear when the groundwater table is initialized to be deeper than the observed level, while it takes much less time (e.g., about 1.5 years) if the groundwater table is initialized to be shallower than the observed level. In addition, preliminary sensitivity studies at the site show that there is a more significant persistent signature of the impact of the precipitation (ppt) when its amount is halved (i.e., 0.5ppt) than that when its amount is doubled (i.e., 2ppt).

## Introduction and problem statement

Surface and groundwater interaction is an important aspect in land-atmosphere interaction studies. A shallower water table is more likely to result in saturation excess runoff, to yield evaporation at the atmosphere-demanded rate, and to produce a net discharge of groundwater. On the other hand, deeper water tables generally indicate drier areas where evaporation is limited by the available soil moisture. In this situation, surface runoff is likely to be generated by the infiltration excess runoff mechanism, and the groundwater is recharged when the infiltration is enhanced. Under both conditions of the water tables, soil moisture is modified through the groundwater and surface water interactions. A number of studies have shown that soil moisture plays an important role in the global energy and water balances in the land-atmosphere system [e.g., Koster and Suarez, 1996; 1999; Entekhabi et al., 1999; Dirmeyer, 2000; Dirmeyer et al., 2000; Koster et al., 2000a; Koster and Suarez, 2001]. Knowledge of the state of soil moisture is essential for improving climate predictability from seasonal to interannual time-scales. For example, Entekhabi et al. [1999] showed the impact of soil moisture on numerical forecasting of extreme events, and the evidence that precipitation extremes over the United States are more strongly affected by soil moisture than by sea surface temperature. Dirmeyer [2000] showed that the inclusion of reasonable soil moisture could significantly improve the simulation of precipitation and surface temperature globally and regionally. However, the current generation of land surface models show a large spread in soil moisture estimations [Liang et al., 1998; Lohmann et al., 1998; Wood et al., 1998; Dirmeyer, 1999]. In addition to the impact showed by numerical simulations, field observations have also shown that the interactions between surface water and groundwater could alter hydrological consequences, such as runoff production [e.g., Waddington et al., 1993], water table fluctuations, and surface hydrology [e.g., Verry and Boelter, 1978; Taylor and Pierson, 1985; Whiteley and Irwin, 1986; Devito and Dillon, 1993; Devito et al., 1996; Katz et al., 1997].

## Objectives

The process of surface and groundwater interactions is closely related to the dynamics of soil moisture fluctuations, but it is not yet well represented. Therefore, the objectives of this project are (1) to develop a new parameterization scheme to describe the surface and groundwater interaction process, and (2) to incorporate it into land surface models to improve estimations of soil moisture which plays a significant role not only in improving the predictability of the numerical weather prediction models on regional climate, but also on agricultural irrigation, water resources planning and management. This project quantifies the effects of surface water and groundwater interactions on soil moisture, evapotranspiration, runoff, and groundwater recharge through a development of a new parameterization to represent surface and groundwater interaction dynamics for land surface models. The new parameterization is then implemented into a Three-layer Variable Infiltration Capacity (VIC-3L) model [Liang et al., 1994; 1996a; 1996b; 1999; Liang and Xie, 2001]. Validation of the new parameterization is conducted by applying it to a watershed in Pennsylvania over multiple years. The impact of the surface and groundwater interactions on surface water budget is investigated through sensitivity analyses.

## Procedures

Based on one dimensional Richards equation applied to unsaturated zone, we have

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left( D(\theta)\frac{\partial \theta}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z} \tag{1}$$

where $\theta$ is volumetric soil moisture content [$L^3/L^3$], $D(\theta)$ is the hydraulic diffusivity [$L^2/T$], $K(\theta)$ is the hydraulic conductivity [L/T], and *z* is vertical direction and assumed positive downward. The upper boundary condition (i.e., at the surface when $z = 0$) can be expressed as,

$$q_o(t) = K(\theta) - D(\theta)\frac{\partial \theta}{\partial z} \tag{2}$$

where $q_o(t)$ is the flux across the surface (i.e., $z = 0$). Let $\alpha(t)$ be the groundwater level which is the distance from ground surface to the water table (also called moving boundary here). For the saturated zone, we have,

$$\theta(z,t) = \theta_s, \quad \alpha(t) \le z \le L, \tag{3}$$

where *L* represents the depth from ground surface to the bedrock. The groundwater table (i.e., the moving boundary) separates the saturation region from the unsaturated zone. Although such a situation may not always occur in reality, Bear (1972) shows that such an assumption is a good approximation. The zero pressure condition and prescribed flux across the groundwater table are two common approaches used to describe the moving boundary. In this study, we use the latter. The moving boundary condition can be expressed by,

$$\left( K(\theta) - D(\theta)\frac{\partial \theta}{\partial z} \right)\Bigg|_{z=\alpha(t)} = Q_{b2} + E_2 - n_e(t)\cdot\frac{d\alpha}{dt} \tag{4}$$

where $Q_{b2}$ is subsurface flow rate from the saturated zone, $E_2$ is transpiration rate from the saturated zone, and $n_e(t)$ is effective porosity of the porous media which is a function of time. Here the effective porosity is defined as the absolute difference of soil moisture content between two time steps. The initial conditions, respectively, for the unsaturated and saturated zones are,

$$\theta(z,0) = \theta_o(z), \quad 0 \le z < \alpha(0), \tag{5}$$

$$\theta(z,0) = \theta_s, \quad \alpha(0) \le z \le L, \tag{6}$$

where $\theta_s$ is the soil porosity. The soil moisture profile $\theta(z,t)$ and groundwater table $\alpha(t)$ are to be determined by applying (1) and (3) with conditions (2), (4), (5), and (6). If the position of the groundwater table $\alpha(t)$ is determined, then the soil moisture profile $\theta(z,t)$ within the unsaturated zone can be determined by using mass-lumped finite element method (Xie et al. 1999) which allows for an upward flux of moisture from the groundwater table to the root zone in case the groundwater table lies below the root zone. In our approach, $\alpha(t)$ is to be determined dynamically for unsteady state conditions. Let

$$\overline{\theta(t)} = \int_{o}^{\alpha(t)} \theta(z,t)dz \tag{7}$$

Integrating (1) over soil depth $(0,\ \alpha(t))$ with (2) and (4), and considering subsurface flow rate from the unsaturated zone ($Q_{b1}$), bare soil evaporation from a thin layer (e.g., the top 10 cm soil depth in the VIC), and transpiration from a specified root region within the unsaturated zone, it yields,

$$\frac{d\bar{\theta}}{dt} - \frac{d\alpha}{dt}(\theta_s + n_e(t)) = p - R - Q_b - E_t \tag{8}$$

where $p$ is precipitation rate, $R$ is total surface runoff rate (i.e., infiltration excess and saturation excess runoff), $E_t$ is total combined evaporation rate which includes bare soil evaporation, and transpiration from the root region in both unsaturated and saturated zones, and

$$Q_b = Q_{b1} + Q_{b2}$$

Integrating (8) over time $(t,\ t + \Delta t)$, we have,

$$\alpha(t + \Delta t) - \alpha(t) = \frac{1}{\overline{\theta_s + n_e(t)}} \left[ \bar{\theta}(t + \Delta t) - \bar{\theta}(t) - \int_{t}^{t+\Delta t} (p - R - Q_b - E_t) \cdot dt \right] \tag{9}$$

where $\overline{\theta_s + n_e(t)}$ is the average of $\theta_s + n_e(t)$ over two time steps. The soil moisture profile $\theta(z, t + \Delta t)$ within unsaturated zone and the position of groundwater table $\alpha(t + \Delta t)$ at time $t + \Delta t$ are computed by applying finite element method in space and finite difference method in time. The numerical steps are briefly summarized below:

(a). Initializing $\theta(z,0)$ with $\alpha(0)$;

(b). Pre-estimate moisture profile $\theta(z, t + \Delta t/2)$ through linear extrapolation from the old moisture distribution. Compute the coefficient matrix associated with the finite element method using moisture profile $\theta(z, t + \Delta t/2)$;

(c). Compute $\theta(z, t + \Delta t)$. Iterate on $\theta(z, t + \Delta t)$ until it convergences;

(d). Compute $\alpha(t+\Delta t)$ based on $\theta(z, t+\Delta t)$ and $\alpha(t)$ with (9);

(e). Repeat steps (b)-(d) until $\alpha(t+\Delta t)$ convergences; and

(f). Repeat steps (b)-(e) for the next time step.

## Results

A watershed of Little Pine Creek near Etna in Pennsylvania is selected as the validation site. This is because this site has the required data available. At the watershed of Little Pine Creek near Etna, daily forcing data needed to run the VIC land surface model in water balance mode are available from a nearby surface meteorological station (Station ID # 366993) with latitude of $40^o30'$ and longitude of $80^o14'$, respectively. The information on vegetation, soil properties, and the VIC model parameters is obtained from the corresponding grid cell (at 1/8 degree resolution) compiled by the University of Washington. Figure 1a shows the daily precipitation time series from June 1, 1995 to December 31, 1997 at the watershed. Figure 1b shows a typical daily comparison of VIC model simulated streamflow with the observations for the period of October 1 to December 3, 1997. Figure 1c shows the daily comparison of groundwater table between VIC and observations for the period from June 1, 1995 to December 31, 1997. The comparison started on June 1, 1995 after the simulation of the first three years is discarded as a warm up period to reduce the soil moisture initialization effect. From Figure 1b, it can be seen that the model simulates observed streamflow quite well. From Figure 1c, it can be seen clearly that the VIC model can dynamically simulate the groundwater table well. Figure 2 shows that the comparison of evapotranspiration between VIC-Philip2 and VIC-Old2. The differences between them are that for VIC-Philip2 it has the new parameterization of surface and groundwater interactions implemented into the VIC land surface scheme while VIC-Old2 does not consider the effects of such interactions. From Figure 2, it can be seen that evapotranspiration from VIC-Philip2 is generally higher than that from VIC-Old2, and sometimes the differences can be quite large.

Table 1 lists the ratios of daily absolute differences between VIC-Philip2 and VIC-Old2 on evapotranspiration, total runoff, and volumetric soil moisture of the upper (i.e., layer 2) and lower (i.e., layer 3) layers to their corresponding daily mean values obtained from the VIC-Old2 (i.e., without considering the effects of surface and groundwater interactions). From Table 1, it can be seen that the effects of surface and groundwater interactions on evapotranspiration, runoff, and soil moisture can be significant.

Table 1. Ratios of absolute differences to their corresponding mean values from the VIC-Old2 for the period of June 1, 1995 to December 31, 1997.

| | Relative absolute difference (%) |
|---|---|
| Total runoff | 4 |
| Evapotranspiration | 19 |
| Soil moisture in layer 1 | 13 |
| Soil moisture in layer 2 | 14 |
| Soil moisture in layer 3 | 12 |

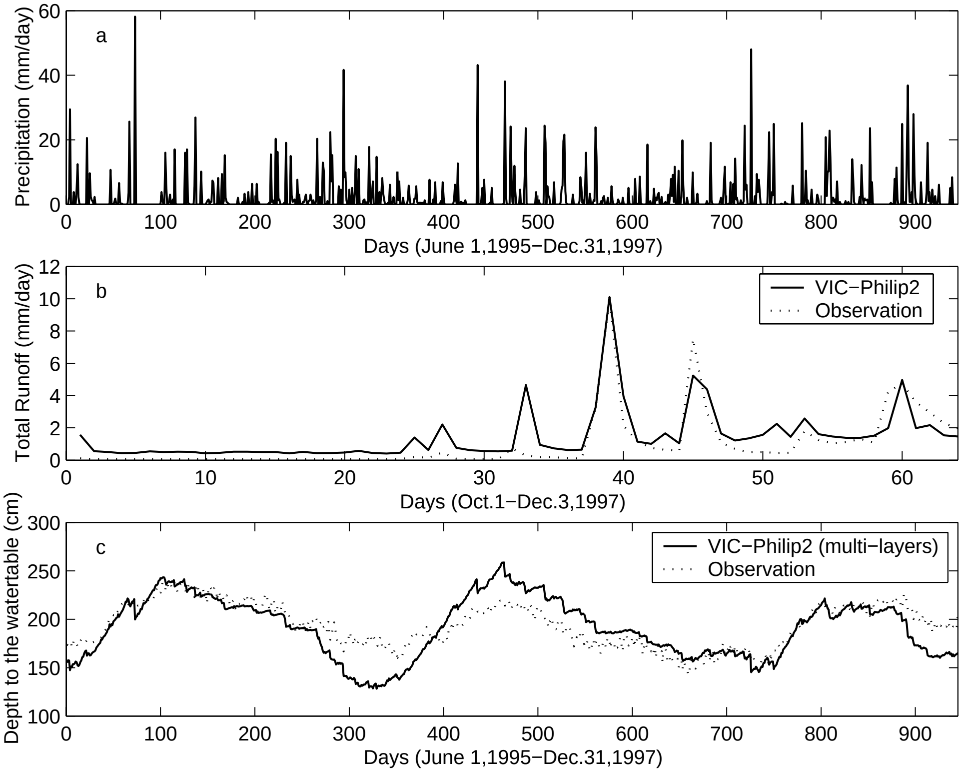

Figure 1. Comparison of model simulations with observations at the watershed of Little Pine Creek near Etna in Pennsylvania. (a) Daily precipitation time series for the period of June 1, 1995 to December 31, 1997; (b) comparison of daily simulated total runoff of VIC with observations for the period of October 1 to December 3, 1997; and (c) comparison of daily groundwater table simulated from VIC with observations for the period of June 1, 1995 to December 31, 1997.

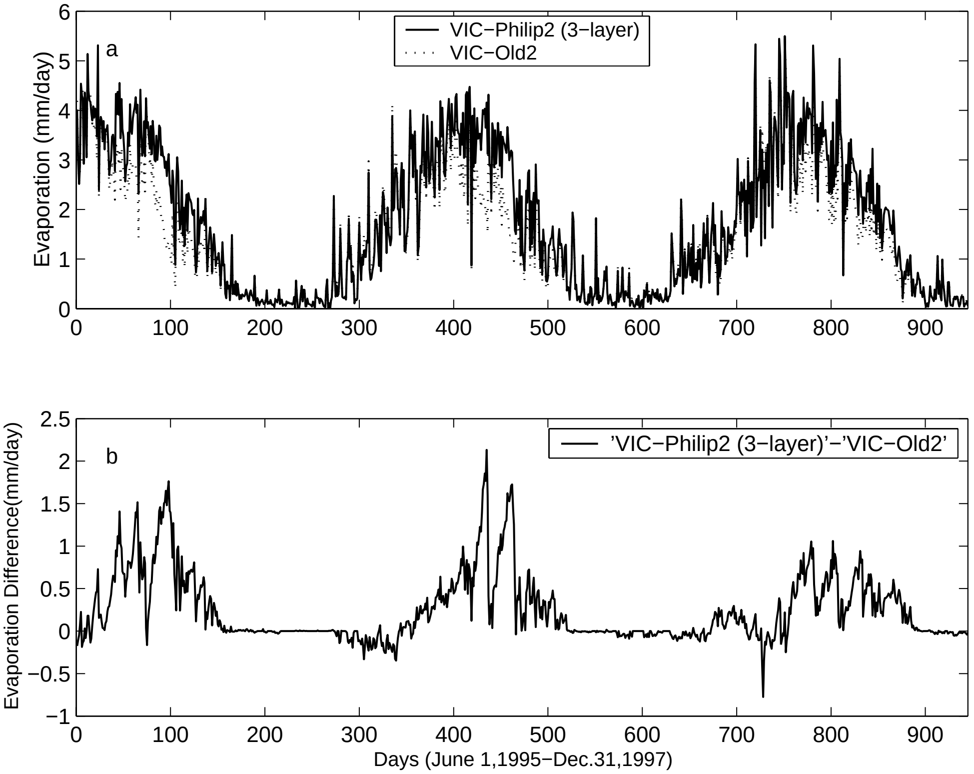

Figure 2. Comparison of evaporation at the watershed of Little Pine Creek near Etna in Pennsylvania for the period of June 1, 1995 to December 31, 1997: (a) comparison of evapotranspiration between considering the surface and groundwater interactions (solid line) and not considering such interactions (dotted line); and (b) difference between them as shown in (a).

## Primary conclusions

1. Both the patterns and magnitudes of the observed daily groundwater tables are simulated quite well by the new parameterization implemented into VIC over periods of multiple years. Sensitivity analyses of VIC on different initial groundwater table positions (figures not shown) indicate that the simulations of VIC are stabilized (or converge) after about 3 years at the site. Also, the convergence is faster for the conditions when the groundwater tables are initialized shallower (i.e., closer to the surface) at the site. Therefore, for situations where the observations of the initial groundwater levels are not available, it is better to initialize the groundwater table in VIC-ground with a wetter condition.
2. Sensitivity analyses under wet (i.e., 2ppt) and dry (i.e., 0.5ppt) scenarios show that the responses of the groundwater table are quite different. For the wetter scenario, the groundwater table presents a behavior with more high frequency components, while for the drier scenario, the groundwater table varies more smoothly with much less high frequency components involved. The change of the groundwater table from the control run (i.e., current condition) is much greater for the drier scenario (i.e., 0.5ppt scenario) than for the wetter scenario, indicating a more significant persistent signature in the drier scenario than that in the wet scenario. The different sensitivities of VIC to the 2ppt and 0.5ppt scenarios (figures not shown) are perhaps partially due to the nonlinear behavior of subsurface/baseflow runoff, and partially due to the evapotranspiration process. Also, the preliminary sensitivity results show that there may exist more significant interactions between the land surface and atmosphere under a transition from normal to dry condition (i.e., from the control run to 0.5ppt run) than that from the normal to wet condition (i.e., from the control run to the 2ppt run).

The preliminary results obtained through this project suggest that the impact of considering surface and groundwater dynamic interactions on surface fluxes and soil moisture in land surface modeling is significant, and that attention is needed. The work described here constitutes our first attempt to understand the influence and importance of the surface and groundwater interactions in hydrologic and climatic studies. The conclusions summarized here are based on the one study site. More studies are needed to generalize these findings. Also, further investigations of the impacts of the surface and groundwater interactions on soil moisture, and surface water and energy fluxes over larger areas under both wet and dry climate conditions are necessary. In addition, some improvements in VIC are needed in order to have better reflection of the impact of the surface and groundwater interactions in which the detailed soil moisture profile information is used explicitly.

## Publications

This project leads to two journal paper publications:

1. Liang, X., and Z. Xie, "Important factors in land-atmosphere interactions: Surface runoff generations and interactions between surface and groundwater," *Global & Planetary Change*, in press, 2003.
2. Liang, X., Z. Xie, and M. Huang, "A new parameterization for groundwater and surface water interactions and its impact on water budgets with the VIC land surface model," *J. Geophys. Res.*, accepted, 2003.

## References

Bear, J., 1972. Dynamics of Fluids in Porous Media, Dover Pub. Inc., New York, pp. 764.

Devito, K.J., Dillon, P.J., 1993. The influence of hydrologic condition and peat oxia on the phosphorus and nitrogen dynamics of a conifer swamp, Water Resour. Res., 29, 2675-2685.

Devito, K.J., Hill, A.R., Roulet, N., 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield, J. Hydrol., 181, 127-147.

Dirmeyer, P.A., Dolman, A.J., Sato, N., 1999. The pilot phase of the global soil wetness project: A pilot project for global land surface modeling and validation. Bull. Amer. Meteor. Soc., 80, 851-878.

Dirmeyer, P.A., 2000. Using a global soil wetness dataset to improve seasonal climate simulation, *J. Clim.*, 13(16), 2900-2922.

Dirmeyer, P.A., Zeng, F.J., Ducharne, A., Morrill, J.C., Koster, R.D., 2000. The sensitivity of surface fluxes to soil water content in three land surface schemes. J. Hydrometerology, 1(2), 121-134

Entekhabi, D., Asrar, G.R., Betts A.K., Beven, K.J., Bras R.L., Duffy C.J., Dunne T., Koster R.D., Lettenmaier D.P., McLaughlin D.B., Shuttleworth W.J., van Genuchten, M.T., Wei, M. -Y., Wood, E.F., 1999. An agenda for land surface hydrology research and a call for the second international hydrological decade. Bull. Amer. Meteor. Soc., 80(10), 2043-2058.

Katz, B.G., DeHan, R.S., Hirten, J.J., Catches, J.S., 1997. Interactions between ground water and surface water in the Suwannee river basin, Florida, J. Am. Water Resour. Asso., 33, 1237-1254.

Koster, R.D., Suarez, M.J., 1996. The influence of land surface moisture retention on precipitation statistics, J. Clim., 9(10), 2551-2567.

Koster, R.D., Suarez, M.J., 1999. A simple framework for examining the interannual variability of land surface moisture fluxes, J. Clim., 12(7), 1911-1917.

Koster, R.D., M.J. Suarez, and M. Heiser, Variance and predictability of precipitation at seasonal-to-interannual timescales, J. Hydrometeorology, 1, 26-46, 2000a.

Koster, R.D., Suarez, M.J., Ducharne, A., Stieglitz, M., Kumar, P., 2000b. A catchment-based approach to modeling land surface processes in a general circulation model: 1. Model structure, J. Geophys. Res., 105(D20), 24809-24822.

Koster, R.D., and M.J. Suarez, Soil moisture memory in climate models, J. Hydrometeorology, 2, 558-570, 2001.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99(D7), 14,415-14,428.

Liang, X., Lettenmaier, D.P., Wood, E.F., 1996a. A one-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. J. Geophys. Res., 101(D16), 21,403-21,422.

Liang, X., Wood, E.F., Lettenmaier, D.P., 1996b. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications. Global and Planetary Change, 13, 195-206.

Liang, X., Wood, E.F., Lettenmaier, D.P., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., Dickinson, R., Duan, Q., Ek, M., Gusev, Y., Habets, F., Irannejad, P., Koster, R., Mitchell, K., Nasonova, O., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L., Zeng, Q., 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) phase-2c Red-Arkansas river basin experiment: 2. Spatial and temporal analysis of energy fluxes. Global and Planetary Change (special issue), 19(1-4), 137-159.

Liang, X., Wood, E.F., Lettenmaier, D.P, 1999. Modeling ground heat flux in land surface parameterization schemes, J. Geophys. Res., 104(D8), 9581-9600.

Liang, X., Xie, Z., 2001. A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models. Advances in Water Resources (special issue on “Nonlinear Propagation of Multi-Scale Dynamics through Hydrologic Subsystems”), 24, 1173-1193.

Lohmann, D., Lettenmaier, D.P., Liang, X., Wood, E.F., D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., Dickinson, R., Duan, Q., Ek, M., Gusev, Y., Habets, F., Irannejad, P., Koster, R., Mitchell, K., Nasonova, O., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L., Zeng, Q., 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) phase-2c Red-Arkansas river basin experiment: 3. Spatial and temporal analysis of water fluxes, Global and Planetary Change (special issue), 19(1-4), 161-179.

Taylor, C.H., Pierson, D.C., 1985. The effect of a small wetland on runoff response during spring snowmelt. Atmosp.-Ocean, 23, 137-154.

Verry, E.S., Boelter, D.H., 1978. Peatland hydrology, in P.E. Greeson et al. (Ed.), Wetland function and values: the state of our understanding. Am. Water Resour. Assoc., Minneapolis, MN, pp.389-402.

Waddington, J.M., Roulet, N.T., Hill, A.R., 1993. Runoff mechanisms in a forested groundwater discharge wetland. J. Hydrol., 147, 37-60.

Whiteley, H.R., Irwin, R.W., 1986. The hydrologic response of wetlands in southern Ontario. Can. Water Res. J., 11, 100-110.

Wood, F., Lettenmaier, D.P., Liang, X., Nijssen, B., Wetzel, S.W., 1997. Hydrological modeling of continental-scale basins. Annu. Rev.Earth Planet. Sci., 25, 279-300.

Wood, E.F., Lettenmaier, D.P., Liang, X., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., Dickinson, R., Duan, Q., Ek, M., Gusev, Y., Habets, F., Irannejad, P., Koster, R., Mitchell, K., Nasonova, O., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L., Zeng, Q., 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) phase-2c Red-Arkansas river basin experiment: 1. Experiment description and summary intercomparisons. Global and Planetary Change (special issue), 19(1-4), 115-135.

Xie, Z., Zeng, Q., Dai, Y., 1999. An unsaturated soil flow problem and its numerical simulation. Advances in Atmosp. Sci., 16(2), 183-196.