Literature Review: Groundwater in LSMs

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1. Abstract

The review also briefly justifies the inclusion of physically based groundwater representations within land-surface models and highlights a few of the obstacles facing modelers who seek to include aquifers in LSMs. Possible simplifying assumptions are presented. This review then outlines the methods used by four research groups to represent groundwater dynamics within land-surface models for use in climate models. All four sets of researchers run their augmented models on catchment scales and parameterize only two-directional vertical flow between the vadose and saturated zone.

2. Introduction

Meteorologists developed land-surface models (LSMs) to increase the physical realism of the lower-boundary condition of general circulation models of the atmosphere (GCMs). In the decades following their first inclusion in GCMs (Manabe, 1969), LSMs have evolved into highly sophisticated, physically based parameterizations of mass and energy transfer in the soil column and surface vegetation canopy. In most LSMs, water and heat transfer in the soil column is represented by physically based flux-gradient relationships. Correct solution of the governing equations of mass and energy transfer in the soil column requires that the lower boundary be accurately specified; yet most LSMs do not incorporate a physically based representation of the groundwater table as their lower boundary condition. Several climate researchers have recently addressed this problem. This review briefly justifies the inclusion of aquifers within LSMs, outlines several challenges for modelers seeking to include a representation of groundwater within LSMs and potential simplifying assumptions that may be used to deal with such problems. The review sketches recent work in the field and then provides a more in-depth assessment of the steps taken by two groups of researchers to parameterize aquifer–soil-column interactions within LSMs.

Comprehensive representation of the hydrologic cycle within models of the climate system requires the inclusion of a physically based representation of groundwater within land-surface models (LSMs). Groundwater provides an additional degree of freedom for the global hydrologic cycle, storing large amounts of freshwater and buffering climate variability in regions where it is in close contact with surface hydrologic processes. Groundwater sustains streamflow during recession periods and augments streamflow during intense precipitation events. The position of the groundwater table determines the vertical soil moisture profile, which plays a primary role in determining evaporative fluxes and the surface energy balance (e.g., Chen and Hu, 2004). The soil moisture profile also controls the rate of infiltration of precipitation and its subsequent partitioning into surface and subsurface runoff. The presence of a groundwater table in or near the soil surface contributes water to evaporative fluxes and sustains vegetation during drought (NRC, 2004).

In concept, representation of subsurface water flow is simple because it depends entirely on the flow of mass down a potential energy gradient according to Darcy's law:

$$\boldsymbol{q} = -\boldsymbol{K}\nabla\boldsymbol{h} \tag{1}$$

Where q is the darcian velocity ($\boldsymbol{q} = \boldsymbol{Q}/A$, where Q is the volumetric discharge [L^3/T] and A is cross-sectional area of flow [L^2]), $\boldsymbol{K}$ is the hydraulic conductivity tensor (L/T), and $\nabla\boldsymbol{h}$ is the hydraulic head gradient. The negative sign represents the flow of water from regions of high hydraulic head (i.e., high potential energy) to regions of low hydraulic head (i.e., low potential energy).

In practice, obstacles abound for modelers who aim to include a physically based representation of groundwater as the lower boundary condition in LSMs. On regional and larger scales, observational measurements for flow rates ($\boldsymbol{q}$ in Equation 1 above), hydraulic conductivity ($\boldsymbol{K}$ above) and hydraulic head ($\nabla \boldsymbol{h}$ above) are scarce in both time and space. The dearth of empirical data for all variables necessary to describe subsurface water flow makes challenging the accurate physical representation of groundwater within LSMs. (Such data-free conditions are probably the main reason for the climate-modeling community's sluggish inclusion of groundwater within LSMs.) The need to specify realistic lateral boundary conditions, which are essential for solution of the partial differential equations governing flow systems, presents an additional challenge. Over durations that span seasons and years, on a continental or global scale, lateral flow may be negligible (M. Rodell, personal communication), which would justify the use of models that parameterize only vertical flow. If lateral groundwater flow is to be parameterized within global and continental-scale models, then use of a constant hydraulic head boundary equal to mean sea level can be justified at land-ocean boundaries (although such an assumption neglects what may be a significant interaction between fresh groundwater and saline ocean water along continental margins). The lack of continental-scale subsurface flow maps limits the ability of land-surface modelers to develop lateral boundary conditions for subsurface flow in regional climate models, particularly because such models tend to be laid out on rectangular grids, which almost never coincide with natural groundwater divides.

Given the sizeable constraints presented by the lack of available data for model calibration, any representation of groundwater within LSMs will necessarily require far-reaching assumptions and simplifications. Several potential simplifying assumptions are:

1. *Neglect lateral flow in the subsurface.* This assumption eliminates the non-negligible problem of developing realistic lateral boundary conditions, but it eliminates a potentially significant mechanism for lateral redistribution of water and heat in the global hydrologic cycle.
2. *Assume that, on a climate-model grid-cell scale, all aquifers behave as do unconfined aquifers.* Representation of confined aquifers requires accurate, high-spatial resolution knowledge of the geology of subsurface layers, which is almost certainly unavailable on the scales and at the locations of interest to climate modelers. On scales of interest to climate modelers, subsurface interaction can likely be parameterized as an unconfined alluvial aquifer (J. Sharp, personal communication).
3. *Represent all aquifers, regardless of porosity structure, with equivalent porous media aquifers.* Hydrogeologic literature (e.g., Anderson and Woessner, 1991) justifies this approximation, especially on the scale of climate-model grid cells (typically ≥ 10 km).
4. *Assume that aquifers are homogeneous and isotropic* (thus, the hydraulic conductivity tensor becomes a scalar). This assumption is currently used even in many plot-scale groundwater models; however, new initiatives to use complex optimization algorithms to derive estimates of effective hydraulic conductivity (S. Pierce, personal communication) may make this assumption unnecessary.

5. *Neglect subgrid-scale variation in hydraulic conductivity.* This assumption is almost certainly necessary for the point calculations of the typical LSM, but it neglects extreme sub-grid-scale heterogeneity in hydraulic conductivity fields which control flow on a sub-catchment scale.
6. *Employ the same hydraulic conductivity values across model grid cells, regardless of variations in subsurface geology.* As the representative elemental volume of aquifer increases toward the grid-cell size, one may assume that inter-cell differences between the true hydraulic conductivity fields approach zero as the sample size (i.e., the representative elemental volume) approaches the “population” size. If this assumption is deemed reasonable, then the need to assign distinct hydraulic conductivity values to each model grid cell becomes less pressing.
7. *Treat the entire saturated zone as a single-layer aquifer.* Such an assumption allows for the use of the Dupuit assumptions (that is, the hydraulic gradient is equal to the slope of the water table and all flow within the saturated zone is horizontal), which have been found to yield realistic calculations of subsurface flow in regions where the hydraulic gradient is relatively slight. On spatial scales of interest to climate modelers, grid-cell mean hydraulic gradients (the change in potential energy per unit distance) are small, except, perhaps in mountainous regions.
8. *Limit the scale of the LSM domain so that only a single groundwater basin is represented.* This approach has the potential to demonstrate that aquifer-atmosphere feedbacks are significant components of the hydrological cycle, but clearly does not allow for a representation of groundwater that can be used on regional (multi-basin) and global scales, which is the typical scale represented by climate models. Such

models can reasonably assume no-flow lateral boundary conditions at groundwater basin divides. This assumption has been used by multiple research groups attempting to test potential formulations for possible inclusion in GCMs.

3. Overview of groundwater in LSMs.

This section provides a brief overview of recent contributions to the scientific community's attempts to include groundwater within LSMs. It is by no means an inclusive recounting of related research but instead highlights recent efforts to include a representation of aquifers within LSMs that are designed for use within GCMs.

York and colleagues (2002) were the first to take up the challenge of including an explicit, physically based representation of groundwater within a representation of the coupled land-surface and atmosphere. In subsequent years, additional researchers have presented new ideas for inclusion of aquifers in LSMs designed for use in climate models (e.g., Liang et al, 2003, Yeh and Eltahir, 2005, Maxwell and Miller, 2005). All published studies to date have chosen to neglect lateral flow between model grid cells (although York et al. [2002] included an explicit representation of subgrid-scale lateral flow within a single atmospheric column). All studies published to date have tested their models only on a catchment scale (presumably because validation data is not available).

The model of York and colleagues (2002) used a single layer to represent both soil and vegetation; this layer was coupled to a one-layer, horizontally discretized finite-difference aquifer model. The scientists linked the surface–subsurface model to a simple, vertically discretized model of the atmosphere. They ran the model over a single catchment in Kansas. NCEP reanalysis data provided the lateral boundary conditions for the atmosphere. The researchers assumed that catchment boundaries coincided with groundwater divides, which they represented as no-flow boundaries within the groundwater model. York et al. compared the output from the run with the groundwater module to output from a run with no representation of aquifers. They found that 5–20% of annual total evaporation was derived from the aquifer. Results also demonstrated that, during periods of drought, the position of the water table cannot be predicted solely on the basis of topography and that during drier years, lateral flow between aquifer grid cells sustained evaporative fluxes in low-lying areas.

Liang et al. (2003) augmented the three-layer Variable Infiltration Capacity (VIC-3L) soil model with a 99-layer variably saturated groundwater model that allows for precise location of the water table within the uniformly 5-m soil column. (They refer to their new model as VIC-GROUND.) The 99-layer groundwater module tracks the position of the water table within its uniformly spaced layers; at the end of each time step, the volumetric water content of each of the three soil layers in VIC-3L is set equal to the depth-weighted average volumetric water content of the contained groundwater sublayers. Evaporative fluxes are calculated using the same algorithms that are used in VIC-3LA unique feature of VIC-GROUND is its numerical solution method. The researchers solve the spatiotemporal variation in water table position with a hybrid numerical approach: VIC-GROUND determines the shape of the soil-moisture profile using a finite element method (which is more apt for determining a variable water table than finite difference); it determines temporal variation of the soil-moisture profile in time with an implicit finite difference method.

The water table position simulated by VIC-GROUND tracks reasonably well the observed water table depth in two watersheds in Pennsylvania over a six-year period of analysis.

When compared to a comparable simulation using VIC-3L, the VIC-GROUND–simulated lower soil layer is in general wetter than that in VIC-3L, and the two upper layers (0.0–0.1 m and 0.1–0.5 m) are drier than those in VIC-3L.Surface fluxes change accordingly.

In sensitivity studies, Liang et al. (2003) also found that the simulated water table was less sensitive to anomalously high input precipitation than it was to anomalously low input precipitation. Further analysis of model sensitivity led the researchers to conclude that when the precise location of the water table is not known, initializing the model water table to a shallower-than-expected depth instead of a deeper-than-expected depth reduced time to water table equilibration to the "true" water table. These results are consistent with general conclusion drawn by other researchers (e.g., Rodell et al., 2005).

Citing a need to be able to study communication between groundwater and soil water, Maxwell and Miller (2005) coupled a groundwater flow model ParFlow (Ashby and Falgout, 1996) to the Common Land Model (CLM) (Dai et al., 2003), which is a high-level LSM with sophisticated parameterizations of vegetation dynamics, surface-to-atmosphere fluxes, and subsurface heat and mass transport. (The code of the Common Land Model is closely related to the NCAR-developed Community Land Model [Bonan et al., 2002].) ParFlow is a variably saturated groundwater model that calculates the hydraulic pressure head at each node and derives the corresponding water saturation based soil-water retention curves according to van Genuchten soil parameters. They dub the coupled model "CLM.PF."

CLM.PF retains the CLM parameterizations for infiltration, evaporation, transpiration, surface runoff and subsurface runoff; the only differences between CLM and CLM.PF are the code used to calculate soil moisture and the method used to estimate soil-water retention curves.

Figure 1 provides a schematic representation of CLM.PF; note that “the uppermost cell layer in ParFlow” corresponds to “the first soil layer below the ground surface in CLM.” The authors do not specify the precise number of layers used in CLM.PF (although it can be assumed there are more than the 10 layers used in the original CLM); they also do not elaborate on the boundary condition used at the base of the ParFlow-derived saturated zone layers.

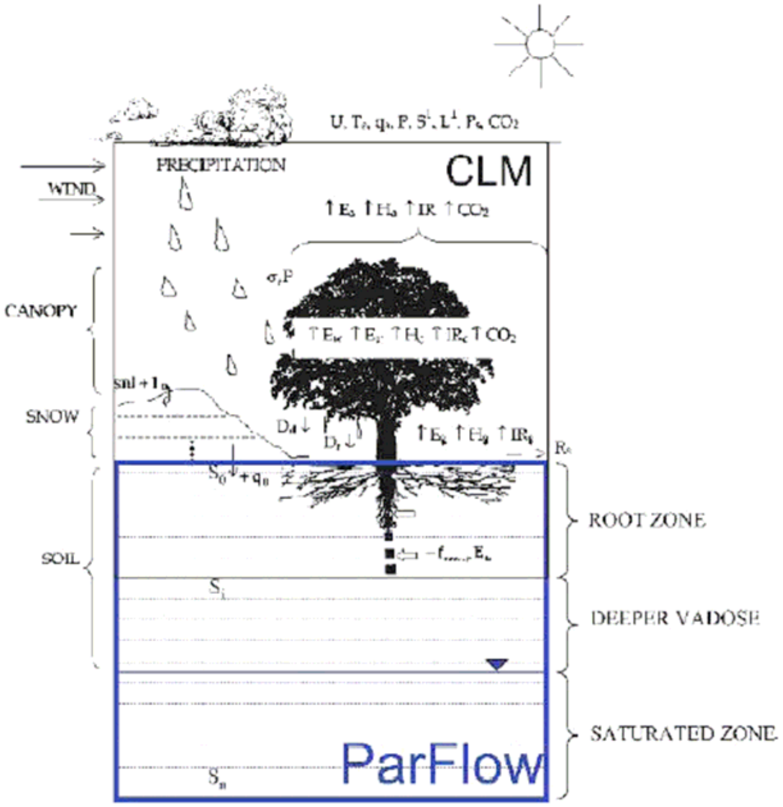

FIG. 1. Schematic of the coupled land surface–groundwater model. The lower box depicts the root zone, deeper vadose zone, and saturated zone represented by the ParFlow groundwater model. The upper box depicts the tree canopy, atmospheric forcing, and the land surface processes represented by CLM. Note the root zone, where the two models overlap and communicate.

Figure 1. Schematic representation of CLM.PF obtained from Maxwell and Miller’s 2005 paper.

As expected, the soil moisture profiles of CLM and CLM.PF display divergent responses to an imposed extreme climate scenario (two weeks of continuous rainfall [0.01 mm s^{-1}] with no insolation followed by five weeks of constant daylight and no precipitation. CLM.PF has faster infiltration and floods before the end of the constant-rain period; CLM never fully floods and dries out more quickly. Much of this difference is probably attributable to differences in the models' parameterizations of subsurface hydraulic parameters. (For example, in CLM, saturation excess runoff dominates removal of water from the surface layers; in CLM.PF, infiltration to deeper layers is the dominant mechanism for removal of water from the surface. This difference may be entirely attributable to the exponential decay of saturated hydraulic conductivity with depth in CLM and the relaxation of that assumption in CLM.PL; however, the authors imply that the greater infiltration in CLM.PF results from the explicit representation of a water table.)

Maxwell and Miller then ran CLM and CLM3.PF for 18 years (January 1966–December 1983) over a watershed in Valdai, Russia. The improvement in the simulated water table depth is indeed noticeable, but may be due simply to an increased soil-column depth in CLM.PF. Differences in surface fluxes (evapotranspiration, sensible heat) are negligible between CLM and CLM.PF. The paper does not present a convincing case that CLM.PF significantly improves the model's ability to simulate long-term water table dynamics even in the test-case zone Valdai, Russia. Only selected results are shown.

The primary contributions of Maxwell and Miller's research are (1) the addition of groundwater storage capacity to the CLM soil column and (2) the demonstration of the use of variably saturated code within the CLM soil column. Because ParFlow was developed by hydrologists with the original purpose of representing variably saturated flow in the subsurface, the code is likely well suited for this purpose (although further investigation on the part of this author is necessary before this assertion can be confirmed). ParFlow has proven itself computationally efficient and stable, even when time steps exceed 12 hours. This is a noteworthy characteristic for unsaturated–saturated flow codes, which are often unstable in part because of the disparate time-step requirements for the saturated and unsaturated zones. (Many codes representing flow in the vadose zone require time steps of less than a minute, while typical time steps in saturated flow models are often be on the order of days or months [Anderson and Woessner, 1991].) van Genuchten soil-water retention curves are the current standard in vadose-zone hydrologic modeling (B. Scanlon, personal communication), whereas the soil hydraulic property calculations used in CLM are calculated according to the empirical relationships derived by Clapp and Hornberger (1978) and Cosby (1984), which were derived using a relatively small set of observations and which are considered outdated by some segments of the hydrologic research community (B. Scanlon, personal communication). Because recharge from the vadose zone to the aquifer is a primary source of input to the aquifer, it is important that the vadose-zone water flow and the related vadose-zone–aquifer fluxes are accurately parameterized.

Although Maxwell and Miller's CLM.PF can likely be applied on a range of spatial scales, the model's unrealistic runoff generation mechanism makes it unlikely that the model can realistically represent groundwater-climate interaction in all but a few regions in which the water table is in reality relatively near the surface. Baseflow in CLM.PF is generated only in the bottom five layers of the original CLM layering scheme. Because there is no mechanism for water removal from the saturated ParFlow layers besides upward flux to the CLM soil column, during long model simulations, the model will likely overestimate soil column moisture in arid regions (after water has accumulated below the runoff-generating CLM layers). It should be noted that these conclusions regarding the validity of CLM.PF may be inaccurate: the paper describing the scheme and simulations is incomplete (e.g., the lower boundary condition for ParFlow is not specified), so the interested reader is left to her own imagination when attempting to decipher the intricacies of the parameterization.

Yeh and Eltahir incorporate a water-balance method for tracking the position of the grid-cell–mean water table within a climate-model–scale grid cell of the Land Surface Transfer Scheme, an NCAR-developed land-surface model of intermediate complexity. To incorporate water table dynamics into the LSM, Yeh and Eltahir employ a simple conservation of mass equation ($S_y(dH/dt) = I_{gw} – Q_{gw}$, where S_y is the specific yield of the aquifer, H is the hydraulic head at the water table, I_{gw} is the groundwater recharge flux [which can be either positive or negative] and Q_{gw} is the groundwater discharge to streams [always positive]). Using a relatively high-resolution observed hydrologic dataset for the state of Illinois, U.S.A., they derived an empirical relationship between groundwater runoff (Q_{gw}) and grid-cell–mean depth to the water table (The dataset includes a suite of hydrologic variables: precipitation, depth to water table, stream discharge, etc., are provided for sites spanning Illinois.)

The scientists ran their water-table–augmented model at a single point used to represent a single climate-model grid cell encompassing the state of Illinois. They drove the model with arithmetically averaged meteorological observations derived from a suite of sources for a period of 11 years and compared interannual mean output for each month from their model with arithmetically averaged output from the comprehensive hydrological dataset for Illinois. The new model performed well when compared to similar runs that did not employ the water table dynamics. Figure 2 shows a segment of the output included in Yeh and Eltahir’s paper.

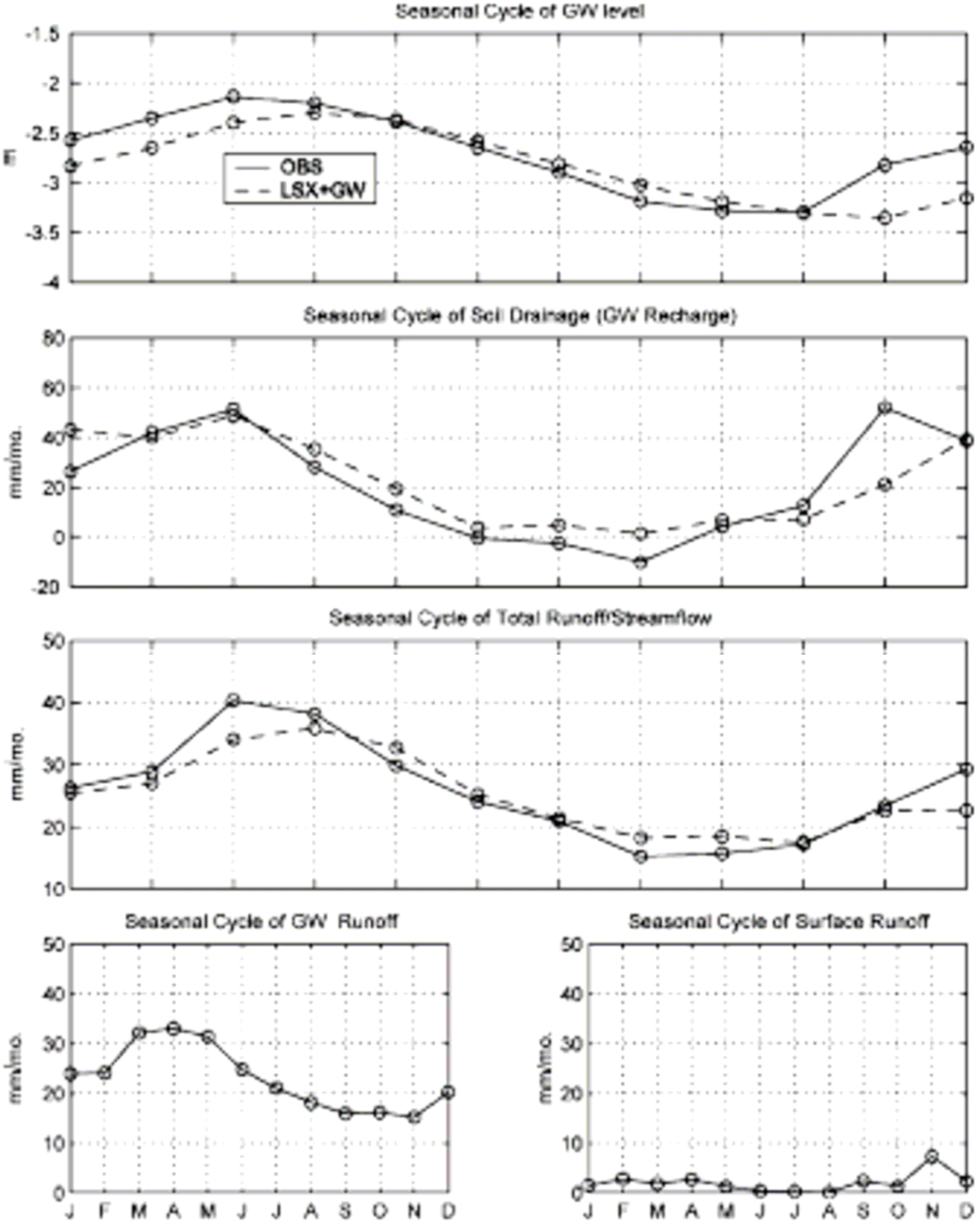

FIG. 11. The 11-yr (1984–94) average seasonal cycles of the simulated water table depth, soil drainage (i.e., groundwater recharge), and total runoff from the LSXGW simulation in comparison with the corresponding observations. The seasonal cycles of two runoff components, groundwater runoff and surface runoff, are also shown in this figure.

Figure 2. Comparison of runoff ratio, groundwater table position, and soil drainage as simulated by Yeh and Eltahir's augmented model with the same variables calculated from observations.

The water-balance approach described by Yeh and Eltahir is not at its core a physically based representation of groundwater flow, but it does provide an elegantly simple way to track the spatial and temporal variation of grid-cell–mean water table depth. Because it forms the interface between the vadose zone and the saturated zone, the water table is one of the most important aspect of groundwater dynamics to parameterize effectively.

A primary benefit of Yeh and Eltahir's contribution is the ease with which their model or a close analog can be easily added to the computer code of LSMs that span the gamut of model complexity. The conceptual model (that is, the explicit representation of groundwater-soil feedback) can be applied to other regions in which the aquifer is in direct communication with the soil profile. However, because their parameterization implicitly assumes that the water table is within the near-surface soil column, Yeh and Eltahir's model can only be realistically applied to regions with a shallow groundwater table, which limits its applicability to regional and global-scale models.

Few (if any) regions on Earth possess hydrologic and hydrogeologic records that are as spatially and temporally dense as those used for Illinois. Consequently, derivation of the groundwater-discharge–depth-to-water-table relationship in other regions will be next to impossible to derive empirically. Yeh and Eltahir (2005a) acknowledge this limitation but cite the potential for use of their water table parameterization when rigorous theoretical justification is provided for the associated groundwater-discharge–depth-to-water-table relationship.

In a companion paper, Yeh and Eltahir (2005b), the researchers introduce a mechanism for incorporating subgrid spatial variability of the water table into their newly developed scheme. The augmented scheme (also elegant) is not discussed in this review.

4. Conclusions and Future Work

Models described here provide an excellent foundation for future improvements to the representation of groundwater within LSMs. Although all of the models presented in this review improve the representation of groundwater within LSMs, none can be applied uniformly, “out of the box” on a continental or global scale; a parameterization that allows for regional-and-larger-scale application of groundwater-augmented LSMs will significantly expand the scope of the scientific questions that can be addressed with these newly improved models. Streamflow and groundwater dynamics are intimately linked. Future work should thus provide a physically based representation of aquifer–stream interaction. Finally, groundwater flow is an inherently a three-dimensional process. Representation of lateral groundwater flow (between model grid cells) and—in the longer term—in vertically discretized aquifer representations, provides a possible avenue for increased realism in the parameterization of aquifers within LSMs.

5. References

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