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Modeling considerations for vadose zone soil moisture dynamics

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Modeling Considerations for Vadose Zone Soil Moisture Dynamics

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
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MODELING CONSIDERATIONS FOR VADOSE ZONE SOIL MOISTURE DYNAMICS

Jing Zhang

ABSTRACT

Reproducing moisture retention behavior of the upper and lower vadose zone in shallow water table settings provides unique challenges for integrated (combined surface and groundwater) hydrological models. Field studies indicate that moisture retention in shallow water table settings is highly variably affected by antecedent state and air entrapment. The theory and vertical behavior of a recently developed integrated surface and groundwater model (IHM) is examined through comparisons to collected field data in West-Central Florida. The objectives of this study were to (1) Identify important considerations and behavior of the vadose zone for reproducing runoff, ET and recharge in shallow water table settings; (2) Develop a conceptual model that describes vertical soil moisture behavior while allowing for field scale variability; (3) Test the model against observations of the vertical processes; (4) Investigate the sensitivity of model parameters on model *vs.* observed vertical behavior, and (5) offer recommendations for improvements and parameterization for regional model application. Rigorous testing was made to better understand the robustness and/or limitations of the methodology of the IHM for upper and lower vadose zone. The results are also generally applicable and

useful to the upper zone and lower zone conceptualization and parameterization of stand alone HSPF and perhaps other surface water models. Simulation results indicate IHM is capable of providing reasonable predictions of infiltration, depth to water table response, ET distributions from the upper soil, lower soil and water table, and recharge while incorporating field scale variability of soil and land cover properties.

CHAPTER 1

INTRODUCTION

1.1 Background

Recent investigations of field data have shown that the hydrologic behavior of runoff, ET and groundwater recharge is controlled by vadose zone moisture which is strongly non-uniform (Rahgozar *et al.*, 2005). For example, observations from field data indicate that 50-70% of the total ET comes from a clearly identifiable distinct soil zone very near land surface (Rahgozar *et al.*, 2005). ET is an important element of the hydrologic cycle and is the dominant component of the annual rainfall of most regions, as high as 70 or 80% in Florida, (Bidlake, *et al.*, 1993). Unfortunately, ET can be the most difficult hydrologic process to analyze. Therefore, there is a strong need in hydrologic models seeking to predict continuous runoff and recharge behavior in shallow water table to simulate ET processes correctly (Ross *et al.*, 2005a). As ET is dependent on both surface and groundwater condition, this has given rise to the popularity of integrated surface and groundwater models.

In the last couple of decades, several integrated surface and groundwater models have been developed. Examples include MIKE-SHE (Refsgaard & Storm, 1995; DHI, 1998), MOD-HMS (HydroGeoLogic Inc., 2003; Panday and Huyakorn, 2004), SWATMOD (Sophocleous *et al.*, 1999), tRIBS (Vivoni *et al.*, 2003), FHM (Ross *et al.*,

1997) and IHM (Ross *et al.*, 2004). These models provide very different approaches in characterizing and describing the vertical behavior of the vadose zone.

One such model, the Integrated Hydrologic Model (IHM) integrates the significant surface and subsurface hydrologic processes of the hydrologic cycle into a single software package. Through the coupling of surface water and ground water process models, represented by HSPF (Bicknell, *et al.*, 2001) and MODFLOW (Harbaugh and McDonald, 1996) models respectively, IHM provides an advanced predictive capability of the complex interactions of surface water and groundwater features in shallow water table environments. The model is characterized by a deterministic, distributed-parameter, semi-implicit real-time simulation model, with variable time steps and spatial discretization. The model components explicitly account for all significant hydrologic processes including precipitation, interception, evaporation, runoff, recharge, stream flow, baseflow, and all component storages of surface, vadose and deep groundwater zones (Ross *et al.*, 2005a and b).

One particular problem for integrated hydrologic models applied to shallow water table environments is the effects from air trapped in the voids of the shallow vadose zone. It has been widely recognized that air entrapment plays a significant role in shallow water table environments at limiting infiltration and increasing water table response to infiltration. Another phenomenon found in these environments is a rapid rise in the water level of observation wells screened below the water table during high intensity rainfall events. The process, known as the Lisse Effect (Weeks, 2002), occurs when an intense rainfall event effectively seals the surface soil layer thus trapping the soil air below the advancing wetting front. As the wetting front advances, pressurization of the soil air

occurs. As a result of this increased air pressure, observation wells which are only screened below the water table show a rapid rise in water-level, despite the fact that the actual elevation of saturation is essentially unchanged. As mentioned in Weeks (2002) the effect was noted as early as 1932 by Thal Larsen in the village of Lisse, Holland and was given its name by Hooghoudt (1947).

Heliotis and DeWitt (1987), and Meyboom (1967) have reported observations of Lisse effect in water table hydrographs; however, their explanation is more from the point of view of identifying anomalies in water table observations rather than a way to quantify air pressurization. Weeks (2002) attempted to mathematically link air pressurization to the anomalous water level rise in observation wells, but his analysis was overly simplistic and proved useful only for calculating the maximum possible water-level rise for a specific soil type. Nonetheless the effort provides a background relating air-entrapment and water table fluctuations.

Some previous work has been done to improve the conceptual basis of the IHM. Ross *et al.*, (2005a) advanced a new model to provide a smooth transition to satisfy ET demand between the vadose zone and deeper saturated ground water. The resultant IHM (v.1) approach provided a more sound representation of the actual soil profile than the predecessor model, the FIPR hydrologic model (FHM) (Ross *et al.*, 1977). Shah and Ross (2006) explored vadose zone storage conceptualized in IHM (v.1) as well as the physics and mechanics of this moisture variability in shallow water table environments. Zhang and Ross (2006) showed the importance of differentiating upper and lower regions of the unsaturated zone (vadose zone). Field soil moisture observations and soil characterization data were used to formulate a recommended basis for the upper zone and lower zone in

IHM (v.1). Also, they developed a new methodology to describe relative moisture condition in both zones from field measurements to further test a model for soil hydrologic response.

In shallow water table, low gradient environments, the vertical behavior of the vadose zone, including the proximity of the water table has been shown in field observations to dictate the runoff and recharge rates for both seasonal and storm response (Rahgozar *et al.*, 2005). Therefore, for a model to adequately predict these processes, the water table fluctuation, soil moisture conditions, and ET fluxes from the vadose zone must be reproduced. With a very shallow groundwater table, the interaction between unsaturated and saturated groundwater becomes very strong. The groundwater table strongly influences the water content in the unsaturated part of the root zone and the groundwater table represents a moving boundary between saturated and unsaturated conditions. In conceptualizing a model such as IHM, questions arise as to how well is the ET from interception, upper zone, lower zone and groundwater predicted? Also, does the water table described in IHM reasonably represent a real observation? Aly (2005) applied a preliminary version of the IHM (v 0.9) to a small basin in West-central Florida. Results indicated that the model could reproduce gross ET and water table behavior but no distributed ET behavior was investigated. Therefore, extensive investigation of the theoretical basis of vertical processes and demonstration of the performance of ET distribution in longer duration applications are still strongly warranted.

1.2 Objective and Scope

In this study, considerations for modeling shallow vadose zone moisture dynamics with integrated models were investigated. There are four important issues that have been recently identified through field studies: 1) The hydrologic behavior of runoff, ET and groundwater recharge are controlled by vadose zone moisture which is strongly non-uniform. Observations indicate that the soil zone needs to be differentiated into a minimum of two separate distinguishable zones. 2) For a given depth to water, within both soil zones variable moisture retention also strongly effects hydrologic response. 3) Also, field-scale variability (strong differences in retention behavior) exists in shallow water table environments over very small spatial scales (<100 m) requiring a different moisture retention model. 4) And, finally, air entrapment plays a significant role in controlling infiltration and observed depth to water table in shallow water table environments.

Also, this study seeks to rigorously test one integrated hydrologic model against a detailed field-scale data set in West-Central Florida which includes soil moisture dynamics and ET distribution. The Integrated Hydrologic Model (IHM) uses a unique relative soil moisture approach for land segment integration and is intended to simulate the complex interaction between surface water and groundwater systems. No prior rigorous investigation or validation of this model for the upper and lower for performance and predictive capability of vadose zone response has been made. In this study, continuous field soil moisture observations and soil characterization data were used to formulate a new basis for the upper zone and lower zone for possible testing and use in

the IHM. Several tests were performed to illustrate how the new conceptual model reduces field-scale variability in soil moisture behavior and enhances representation of antecedent conditions. Evidence is presented to document the existence of prolonged (many days) air entrapment and excess pore pressures, which effect soil water storage and observed water table levels. The current study employed field data and numerical modeling to quantify the variation of air pressurization values. A simple analysis based on ideal gas law was also done to help understand air pressurization effects.

Finally, intensive sensitivity tests were applied to the IHM model to investigate dependent hydrologic process response including distribution of ET flux, depth to water table and recharge. It was desired that by reproducing field data in a calibrated model and performing sensitivity testing further insight would be gained concerning the reliability and calibratability of the model for regional scale investigations. Also, reproducing moisture retention behavior of the upper and lower vadose zone in shallow water table settings provides unique challenges for the integrated (combined surface and groundwater) hydrological models. The theory and vertical behavior of the IHM is examined through comparisons to collected field data in West-Central Florida. These objectives were to (1) test a model of the vertical processes controlling water table behavior, ET and recharge, (2) investigate the sensitivity of model parameters on model vs. observed vertical behavior, and (3) offer recommendations for improvements and parameterization for regional model application. Rigorous testing was done to better understand the robustness and/or limitations of the methodology of the IHM for upper and lower vadose zones.

CHAPTER 2

VADOSE ZONE CHARACTERIZATION IN SELECTED INTEGRATED SURFACE AND GROUNDWATER MODELS

Six models selected for further investigated included MIKE-SHE (Refsgaard & Storm, 1995; DHI, 1998), MOD-HMS (HydroGeoLogic Inc., 2003; Panday and Huyakorn, 2004), SWATMOD (Sophocleous *et al.*, 1999), tRIBS (Vivoni *et al.*, 2003), FHM (Ross *et al.*, 1997) and IHM (Ross *et al.*, 2004). Only in the cases of MIKE SHE was the linkage of groundwater and surface water components created as part of a unified model development process (i.e., specific focus of the code development). This fact illustrates the relative difficulty in designing integrated surface water/groundwater models. All the above models are relatively recent products. MODHM, SWATMOD and IHM were created by linking previously developed surface water and groundwater models. Only in the case of IHM are the component models (HSPF and MODFLOW) widely used in the industry.

2.1 SHE and MIKE SHE

Freeze and Harlan (1979) proposed a blueprint for distributed hydrological modeling using a physics-based representation of the underlying catchment processes. This blueprint was the basis for the development of the European Hydrological System SHE (Abbott *et al.*, 1986a, b) and MIKE SHE (Refsgaard & Storm, 1995). The original

MIKE SHE (DHI, 1998) model was developed and became operational in 1982, under the name Système Hydrologique Européen (SHE). The model was sponsored and developed by three European organizations: the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH. MIKE SHE is a physically based, distributed, integrated hydrological and water quality modeling system for regional scale investigation. It simulates the hydrological cycle including ET, overland flow, channel flow, soil water and ground water movement.

MIKE SHE is proprietary but the executable code is widely marketed and available for a substantial licensing fee. The source code is generally unavailable.

Two of the available unsaturated zone methods in MIKE SHE are 1) the full Richard's equation and 2) a simplified Richard's equation that neglects capillary tension. The full and simplified Richard's equation methods use real soil properties and soil moisture-relationships that can be developed using Brooks and Corey or van Genuchten relationships. A simplified wetland module that uses a linear relationship between depths to the water table and average soil moisture content and a linear infiltration equation can be used in place of the full and simplified Richard's equation modules.

MIKE SHE includes a simplified ET model that is used in the Two-Layer UZ/ET model in addition to the Kristensen and Jensen model. The Two-Layer unsaturated model divides the unsaturated zone into a root zone, from which ET can occur and a zone below the root zone, where ET doesn't occur. The Two-Layer UZ/ET module is based on a formulation presented in Yan and Smith (1994). The upper layer extends from the ground surface to the higher of the water table or the ET extinction depth (DHI, 2003). Several characteristics about the layer structure are summarized as follows:

- 1) It uses a conditional two layer soil structure, root zone and below root zone.
- 2) The upper layer varies and extends from the land surface to the higher of the water table or the ET extinction depth during the run; the lower layer extends from the bottom of the upper layer to the water table; If the water table is above the ET extinction depth, the thickness of the lower layer is zero.
- 3) There are three options in MIKE SHE for calculating vertical flow in the vadose zone: (1) the full Richards equation (2) a simplified gravity flow procedure (3) a simple two-layer water balance method for shallow water tables.

2.2 tRIBS

The TIN-based Real-time Integrated Basin Simulator (tRIBS) (Vivoni *et al.*, 2003) is a collection of C++ codes designed for distributed hydrologic modeling at small to mid-size catchment scales (Vivoni *et al.*, 2003). The object-oriented software design offers several advantages over traditional procedural programming. In particular, by grouping data and functions operating on these variables into distinct classes, it becomes possible to separate the various hydrologic processes operating on the TIN mesh from the procedures for creating the mesh itself (Tucker *et al.*, 2001). The object-oriented approach also allows for code modularity, facilitating model development for other applications through code integration or substitution of new process modules. Such a strategy permitted the development of the tRIBS model from the CHILD modeling framework (Tucker *et. al*, 2001) within a reasonable amount of time and effort. Hydrologic modules from the RIBS model (Garrote and Bras, 1995) and new hydrologic

process models were incorporated into the CHILD framework as separate classes. In addition, the modularity allowed for the integration of additional process modules and the potential for finite element modeling (FEM) within the existing mesh architecture (tRIBS User Manual, 2002). The tRIBS Distributed Hydrologic Model simulates the coupled surface and subsurface response to rainfall over complex topographies represented using multiple resolutions of triangular irregular networks (TINS). The public domain availability of tRIBS for both executable and source code is uncertain. It has some characteristics about layer structure as follows:

- 1) The model reports to account for a partially saturated vadose zone and predicts the land surface response to continuous storm and inter storm stresses.
- 2) In vadose zone, one-dimensional infiltration, modified Green-Ampt infiltration scheme (Cabral *et al*, 1992 and Ivanov, 2002) in the surface normal direction is redistributed by both the lateral fluxes in the vadose zone and in the phreatic aquifer during storm and interstorm periods.
- 3) No soil layer structure is apparent.

2.3 MODHMS

MODHMS (MODFLOW Hydrologic Modeling System) (HydroGeoLogic Inc., 2003; Panday and Huyakorn, 2004) is based on MODFLOW and includes additional modules to simulate overland flow, channel flow, and solute transport. MODHMS was developed by HydroGeoLogic Inc. Proprietary, and is not freely distributed. Prior to development of MODHMS, HydroGeoLogic developed a number of codes to deal with

variable saturated, variable density, and multi-phase flow and transport primarily driven by an interest in transport processes. MODHMS is reportedly a physically based, spatially distributed, finite difference, integrated surface water and groundwater model. It is actually a collection of codes used to interface with using the MODFLOW regular discretization. Datasets for an earlier version of MODHMS, MODFLOW-SURFACT, could be used to generate a basic framework for a MODHMS simulation. MODHMS is currently being test by St. Johns River Water Management District and the Southwest Florida Water Management District on basins exhibiting shallow water table conditions.

MODHMS is reportedly capable of modeling open channel flow and closed pipe flow (Priesmann slot) using the diffusive wave approximations. MODHMS also reportedly simulate structures (dams, weirs, culverts, and gates) with levels that vary between stress periods. Dynamic structure operations are not currently available in MODHMS. Overland flow is simulated using the diffusive wave approximation and special provisions are available for flow between the overland flow plane and channels that depend on channel bank geometry. The surface water components have not been extensively applied to watershed scale and design problems. Water-quality capabilities are currently not available for the surface water components in MODHMS.

Characterization of the verified vadose zone in MODHMS is as follows:

- 1) The effects of depressions which includes rills, furrows and other detention features as well as of storage exclusion have be taken into account in the model's storage term as well as in the horizontal flow conductance term.
- 2) The storage effects of depression storage and obstruction storage exclusion are modeled by assuming that the geometry of depressions and exclusions combined

has a maximum elevation and that the horizontal area covered by surface-water varies between zero and full area as the water level rises from land surface (defined here as the bottom of the depressions) up to this maximum elevation (land surface + height of depression storage + height of storage within obstructions).

2.4 SWATMOD

SWATMOD (Sophocleous *et al.*, 1999) links the USDA model SWAT with the USGS model MODFLOW (McDonald and Harbaugh, 1988). SWAT is a watershed-scale model used to predict water, chemical, and sediment movement in large basins. The model is used for extended time periods and not for single event flood modeling. The linked models are used to simulate long-term surface water and groundwater interactions, and do not simulate individual storm events. Time steps are typically daily or better. The SWATMOD model has been used to predict conditions during simulation of water shortage periods (Sophocleous *et al.*, 1999). SWATMOD is reported to be public domain open source code but agency distribution support does not exist.

- 1) A limitation of SWAT is its inability to model the unsaturated zone beyond the root zone. Therefore, percolation (recharge) is applied directly to the ground water table.
- 2) SWATMOD is really just a series of subroutines that links the two models: MODFLOW and SWAT. One subroutine, HYDBAL passes data between SWAT and MODFLOW and tracks the water balance of SWAT. The other MODSWB

links SWAT's hydrologic basins with MODFLOW's grid and converts SWAT's fluxes into flow rates for MODFLOW (Sophocleous *et al.*, 1999).

- 3) SWATMOD can be run in one of two modes. The first mode is where MODFLOW is treated as a subroutine of SWAT and is called at the end of each aquifer time step. The second mode involves SWAT and MODFLOW being performed successively and linked through a separate hydrologic balance data file (Sophocleous *et al.*, 1999).
- 4) Intended application watershed-scale model for long-term periods.
- 5) No soil layer structure.

2.5 FHM

In 1988, the Florida Institute of Phosphate Research (FIPR) funded a research project to develop an advanced hydrologic model used for phosphate mine reclamation in west-central Florida. The intended product was to include a dynamically coupled comprehensive surface water and groundwater model. Each model component was to represent state-of-the-art capabilities in hydrologic simulation, including codes which are in the public domain, widely accepted and validated and compatible for integration. A geographic information system (GIS) database, as well as other available digital hydrologic and meteorological data sources (Powers, *et al.*, 1989) provided extensive data needs for this model. The model was to possess sufficiently simple user interfaces to provide for rapid applications and assessment of model results (Fielland and Ross, 1991;

Ross and Tara, 1993). The result of this effort was the FIPR Hydrologic Model (FHM), an integrated model which coupled HSPF and MODFLOW.

- 1) The basis for the lower zone storage in FHM was assumed to be that part of the vadose zone above the capillary fringe of the water table limited by the upper limit value of HSPF (254 cm or 100 inches). Nominal storage was assumed to be equilibrium moisture content at field capacity, and lower zone storage ratios could vary from near zero to greater than 2.5, corresponding to near saturation of the lower zone. The FHM described spatially averaged ET behavior, but the parameterization (and calibration) was not explicitly tied to land use. This was considered a limitation of the FHM (and ISGW, a derivative model promoted by SDI, Inc.) and was one reason the model was later rewritten (Ross *et al.*, 2005a).
- 2) The FHM ET method was based mainly on coupling the ET methods of HSPF and MODFLOW.
- 3) The simplistic two-layer model.

2.6 IHM

In the mid-nineties an early version of the FHM was adapted and modified by SDI under the name Integrated Surface and Groundwater model (ISGW). SDI and Tampa Bay Water used ISGW in the west-central Florida region for well-field pumping and surface-water withdrawal investigations (SDI, 1999). Considerable review of that model and applications occurred through a series of projects (Ross, *et al.*, 1998; Waterstone, 2001; West Consultants, *et al.*, 2001). Recommendations resulted from those reviews to

reformulate the ISGW and apply, calibrate, and test the new model on a 4000 square mile region of west-central Florida. The outcome of a research effort to reformulate the theoretical and conceptual basis of the model resulted in the Integrated Hydrologic Model (IHM v. 1) (Ross *et al.*, 2004). All further reference to IHM v.1 will just be abbreviated IHM.

IHM was designed to reportedly provide an advanced predictive capability of the complex interactions of surface water and groundwater features in shallow water-table environments. The model can be characterized as deterministic, semi-distributed-parameter, semi-implicit, real-time formulation, with variable time steps and spatial discretization. Reportedly, the model components explicitly account for all significant hydrologic processes including precipitation, interception, evapotranspiration, runoff, recharge, irrigation flux applied to land, streamflow, wetland hydroperiod, baseflow, groundwater flow, and all the component storages of surface, vadose and saturated zones. Input requirements include precipitation and potential evapotranspiration time series, surface topologic features (i.e. land use, soils, topography and derived slopes), irrigation fluxes, hydrography characteristics, rating conditions, hydrogeologic parameters of the groundwater system and information about well pumping and surface-water diversions. Output includes detailed water balance information on all major hydrologic processes, including surface water and groundwater flows to wetlands, streams and lakes, evapotranspiration losses from all storages, reach stage, soil moisture, recharge to the groundwater system and storage, heads and fluxes in the groundwater system.

- 1) Fundamental to the IHM is the definition of the lower zone storage, which is the moisture variability available to the root zone for an given water table elevation

that is above the wilting point, or driest profile, for a given water table depth. For a deep water table the lower zone storage can exhibit the largest values incorporating the range of variable soil moisture retention to an effective depth below the root zone (Ross *et al*, 2005a).

- 2) It is said there are two zones in the vadose zone conceptualization in IHM, the upper zone and lower zone. The upper zone is just the few inches upper soil layer and lower zone is the zone from upper zone down to the water table. However, clear definitions are still needed.
- 3) The IHM reportedly uses a theoretically sound, three-layer step-wise linear soil moisture retention model as opposed to a van Genuchten or other analytical retention model.
- 4) There were other improvements reported in IHM ET concept compared to the predecessor FHM (see, e.g., Table 2.1 adapted from Ross *et al.*, 2005a).

Table 2.1. Similarities and Differences Between FHM and IHM ET Conceptualization
(adapted from Ross *et al.*, 2005a)

Component	FHM	IHM
Interception ET	Considered as first source	Considered as first source
Upper Zone ET	Depression storage and shallow soil storage ET. Considered nest if available, supply rate based on relative storage	Depression storage and shallow soil storage ET. Considered nest if available, supply rate based on relative storage
Lower Zone ET	<p>(1) Deeper root zone storage based on all moisture above the capillary zone.</p> <p>(2) Uses seasonally variable plant coefficient.</p> <p>(3) ET rate based on relative moisture and remaining potential.</p>	<p>(1) Deeper root zone storage based on all moisture above the capillary fringe in excess of the dry moisture profile.</p> <p>(2) Uses theoretically sound 3-layer soil moisture retention.</p> <p>(3) Base plant coefficients are seasonally variable, however, are dynamically adjusted by depth of water table</p> <p>(4) ET rate then based on relative moisture and adjusted remaining potential</p>
Groundwater ET	<p>(1) Uses MODFLOW linear extinction package.</p> <p>(2) Uses remaining potential after considering hierarchal storage contributions</p>	<p>(1) Uses MODFLOW linear extinction package.</p> <p>(2) Uses consistent plant coefficients with lower zone after considering relative depth of water table.</p> <p>(3) Partitions potential after hierarchal storage contributions are met, considering relative depth of water table.</p> <p>(4) Provides smooth transition to free surface evaporation as capillary zone transitions land surface.</p>

CHAPTER 3

OVERVIEW OF VERTICAL BEHAVIOR OF VADOSE ZONE IN IHM

Among processes modeled in the vadose zone in IHM are the water table fluctuation, soil moisture conditions, and ET fluxes and distributions. Details about the moisture flux and retention distribution concepts in IHM can be found in Ross *et al.*, (2004) and Ross *et al.*, (2007). Only a brief summary is provided herein for completeness.

3.1 IHM 3-Layer Soil Moisture Model

A 3-layer soil moisture model which is used as the basis for IHM landsegment integration, based on physical soil characteristics and representative of that soil type, describes the vadose zone storage behavior for any water table relative to the root zone (Figure 3.1).

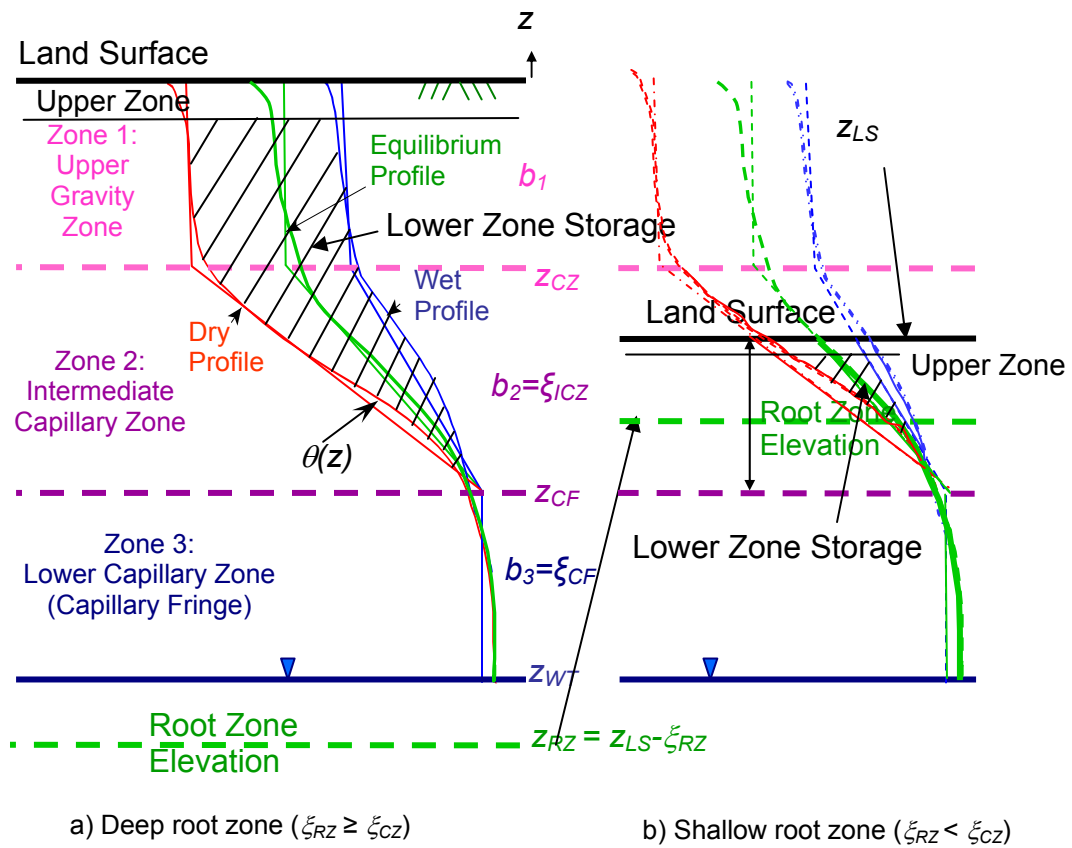


Figure 3.1. Three-Layer Soil Moisture Model (from Ross *et al.*, 2005a)

The first layer represents the near-saturation capillary fringe, followed by the intermediate capillary rise both assumed fixed by the soil type. For deeper water table conditions, the upper layer represents the nearly uniform soil moisture region above the capillary rise when the depth-to-water table is large enough for this layer to exist. Three profiles are shown corresponding to dry, equilibrium and wet soil moisture conditions of a mildly sorptive soil (e.g., fine sand or loamy sand). The thick lines on the figure represent the actual profiles in a uniform soil and the thin lines represent a stepwise, linear approximate profile developed for computational efficiency. A conceptual

representation of soil moisture is shown for a deep root zone in Figure 3.1(a) and for a shallow root zone in Figure 3.1(b).

Variability of the moisture profile is dependent on the antecedent moisture condition and the water table proximity to or within the root zone. Fundamental to the IHM is the definition of the lower zone storage which is the moisture variability available to the root zone for any given water table elevation that is above the wilting point, or driest profile, for a given water table depth. For a deep water table the lower zone storage can exhibit the largest values incorporating the range of variable soil moisture retention to an effective depth below the root zone (assumed to be the soil intermediate capillary zone thickness). This follows the physical behavior that within the root zone plants can reduce the moisture content to near wilting and therefore reduce the moisture retained (over a limited region) below the root zone due to capillary suction gradients. This is a formal definition for the lower zone soil storage, which, interestingly, is still true to the imprecise “hydrologically active” soil moisture definition used by HSPF and the original model, the Stanford Watershed Model (Bicknell, *et al.*, 2001). Following satisfaction of PET from interception and depression storages, remaining potential ET (*PET*) is applied (and partitioned) to the vadose zone storage (lower zone) and directly to groundwater (water table), depending on the proximity of the water table within the root zone described below.

3.2 Interception, Depression and Surface Detention Storage

Conceptually in an IHM and consistent with typical application of HSPF alone, interception is assumed to be the first extraction for a storm event and can be a significant loss if the land segment possesses substantial vegetative cover. As the interception storage capacity is filled, precipitation begins filling the surface depressions and, for pervious surfaces, infiltration commences. As rainfall proceeds, soil infiltration capacity diminishes with increasing soil moisture and Hortonian rainfall excess (with or without air entrapment) and/or saturation excess runoff can contribute to overland flow. The surface storages and unsaturated zone in IHM are depicted in Figure 3.2.

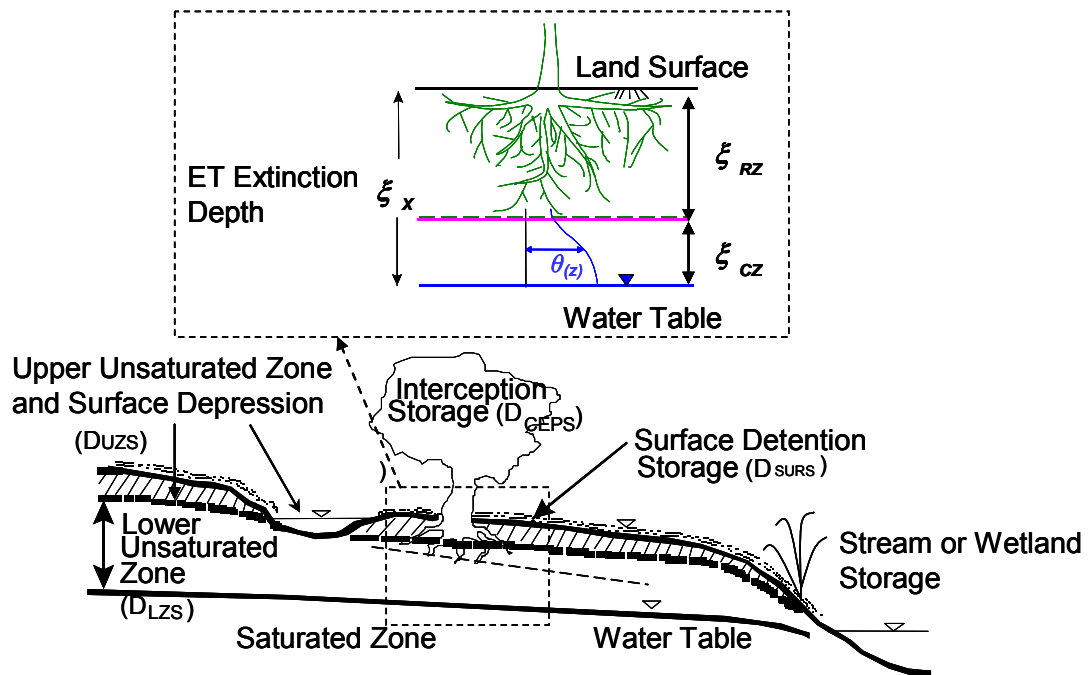


Figure 3.2. Storages Pertaining to the Vadose Zone Described in IHM

Interception storage (water stored on the canopy of vegetative cover, building roofs and other surfaces) is primarily a function of land use. In IHM, depression storage, also referred to as upper zone storage (D_{UZS}), includes micro-depression features such as cracks, potholes, small yard depressions, and water required to wet ground litter. Depression storage is primarily a function of surface conditions such as land use, topography, and time of year. Surface detention storage is water contained in rainfall excess that is available for runoff: rainfall that is not infiltration, interflow, or captured in interception or depressions. The amount of water in surface detention storage is a function of rainfall intensity, infiltration capacity, hydraulic slope, hydraulic length, Manning's roughness coefficient and degree of saturation of the lower zone. IHM uses these conceptual definitions in a more physically-based parameterizing of the empirical equations found in the component model HSPF (Bicknell, *et al.*, 2001; Ross *et al.*, 2004)

The following sections describe the components and equations used in this interpretation.

Assumptions and Equations

Water that is not intercepted and is in excess of infiltration is termed potential direct runoff (P_{PR}). Consistent with HSPF, surface depressions can capture much of the runoff in some landscapes. In HSPF (and IHM) surface depressions are referred to as upper zone storage. Then, the fraction of potential direct runoff which becomes upper zone storage, F_{UZFRAC} , is a function of the relative moisture condition of the upper zone determined by the ratio, R_{UZRAT} , of the upper zone storage, D_{UZS} , to the upper zone nominal (depression) storage, D_{UZSN} . Upper zone nominal storage is difficult to determine from land cover/soil conditions a priori so is normally adjusted during calibration. The

two equations below represent the method of subroutine UZINF2 in HSPF. The HSPF derived equation for F_{UZFRAC} (adapted from Bicknell *et al.*, 2001) when $R_{UZRAT} \leq 2$ (drier conditions) is,

$$F_{UZFRAC} = 1 - \left(\frac{R_{UZRAT}}{2} \right) \left(\frac{1}{4 - R_{UZRAT}} \right)^{3 - R_{UZRAT}} \quad (3.1)$$

when $R_{UZRAT} > 2$ (wetter conditions), the equation is,

$$F_{UZFRAC} = \left(\frac{1}{2(R_{UZRAT} - 1)} \right)^{2R_{UZRAT} - 3} \quad (3.2)$$

The inflow to upper zone storage, I_{UZI} , is determined by,

$$I_{UZI} = F_{UZFRAC} D_{PDRO} \quad (3.3)$$

where D_{PDRO} is the volume of potential direct runoff, which is determined based on lower vadose zone conditions described in later sections. Upper zone storage can then be calculated as,

$$D_{UZS}^t = I_{UZI}^t + D_{UZS}^{t-\Delta t_P} - I_{PERC}^t \quad (3.4)$$

where,

- (t) and ($t-\Delta t_P$) = superscripts refer to current and prior model time interval respectively
- I_{PERC} = vertical percolation from upper zone to lower zone per model time interval [L]; defined in the following sections
- Δt_P = the HSPF PERLND user defined computational time step (e.g., 15-mins.) [T]

The upper zone flux equations represent the only completely empirical equations included in IHM still used directly from HSPF. But, to date the treatment of depression storage as a hydrologic process is only by empirical equations.

Surface detention storage, D_{SURS} , is the volume of water stored on pervious or impervious land as temporary rainfall excess (instantaneous mean depth of the kinematic overland flow wave). D_{SURS} is a temporary land-surface storage that can become surface overland flow (runoff), infiltration, upper zone storage, or interflow. In HSPF, D_{SURS} is determined by subtracting infiltration, upper zone, interflow, and overland runoff fluxes from the moisture supply, D_{MSUPY} . For each model time interval D_{SURS} is determined by,

$$D_{SURS} = D_{PSUR} - Q_{SURO} \quad (3.5)$$

where,

D_{PSUR} = potential surface detention storage volume [L]

Q_{SURO} = overland runoff flow [L]

D_{MSUPY} = moisture supply to the surface detention storage process for the current model time interval [L]

3.3 Vadose Zone Storage

The vadose or lower zone in the IHM is defined as the remainder of the unsaturated zone between the upper zone and the saturated zone below the water table. It accounts for the much of the sustained transpiration burden of the vegetative cover.

Unique to the IHM, the lower zone storage is that part of the vadose zone moisture that does not affect the water table. Excess moisture in the vadose zone that becomes recharge

to the water table is not included in lower zone storage. In HSPF, soil moisture content is not explicitly calculated. HSPF considers the vadose zone soil moisture to be contained in the lower zone storage volume, D_{LZS} , representing the hydrologically active moisture. The infiltration, percolation from upper zone storage and evapotranspiration involving the lower zone are each a function of the relative moisture condition of the lower zone given by the ratio, R_{LZRAT} , defined as,

$$R_{LZRAT} = D_{LZS}/D_{LZSN} \quad (3.6)$$

where D_{LZSN} is a nominal storage volume equal to the moisture that can be stored in the vadose zone between the equilibrium moisture profile for $d_{WT} > \zeta_{CZ}$ and the dry moisture profile. The term equilibrium vadose zone storage is used to refer to D_{LZSN} which is computed in IHM for a lower zone thickness, b_{LZ} , as,

$$D_{LZSN} = \int_{b_{LZ}} \theta(z) \Big|_{\text{equilibrium}} dz - \int_{b_{LZ}} \theta(z) \Big|_{\text{dry}} dz \quad (3.7)$$

The dry moisture profile $\theta(z)_{\text{dry}}$ depends on depth-to-water table and the position of the top of the capillary zone. The lower limit of the dry moisture profile, the wilting point moisture content, can be reached only if the top of the capillary zone is below land surface.

For the IHM, considerable review and testing of the functional form and conceptual basis for D_{LZS} and D_{LZSN} were made (e.g., see Zhang and Ross, 2006). Nevertheless, the lower zone storage ratio, R_{LZRAT} , can be considered as a functional and now specifically defined expression for the relative vadose zone soil moisture condition.

For the IHM, the following limits for R_{LZRAT} result: (1) $R_{LZRAT} = 0$ corresponds to the dry moisture profile, (2) $R_{LZRAT} = 1$ corresponds to the equilibrium moisture profile and (3) $R_{LZRAT} > 1$ corresponds to a persistent moisture profile wetter than equilibrium. Note that short-term (< 1 day) transient moisture flux (i.e., from a wetting front) is not included in the lower zone storage but is tracked as groundwater recharge.

When d_{WT} is near or less than ξ_{CF} , additional functional limits on D_{LZSN} and specific yield must be used. To avoid numerical errors with division by zero, HSPF imposes the limit $D_{LZSN} \geq 0.01$. With the form proposed above, $D_{LZSN} < 0.01$ can occur as d_{WT} is near or less than ξ_{CF} . Therefore, when D_{LZSN} is calculated to be less than 0.01, IHM sets $D_{LZSN} = 0.01$ until such time as D_{LZSN} is calculated to be greater than 0.01 by integration algorithms of IHM. While $D_{LZSN} = 0.01$, specific yield is set to a functional lower limit by IHM which is discussed in a subsequent section. Also note that no mass balance concern is raised by this functional limit as the actual volume is D_{LZS} is allowed to vary to zero (wilt point) moisture condition.

HSPF also imposes a maximum limit $D_{LZSN} \leq 100$ for deep water table and root zone conditions. Recall, IHM defines the lower zone thickness, b_{LZ} , to be the thickness of the root zone above the water table. Given the definition for D_{LZSN} in equation 3.7, it is believed that the limit $D_{LZSN} \leq 100$ will not be violated for reasonable root zone thicknesses. Nevertheless, IHM applies this limit whenever computed D_{LZSN} exceeds 100. Again, no mass balance concern arises as D_{LZS} is functionally not limited.

3.4 Infiltration

Infiltration is the movement of water from the soil surface into the unsaturated lower zone with some high amounts becoming recharge in a simplified form of Philip's equation used in HSPF (Fielland and Ross, 1991). However, infiltration/recharge is derived from the unique interpretation for unsaturated soil (lower) zone storage in IHM. Percolation is defined as the vertical movement of water from upper zone storage to lower zone storage or saturated groundwater storage thus becoming an important component of groundwater recharge. IHM redistributes infiltration and percolation between vadose zone storage and recharge to the water table by considering the proximity of the water table and relative moisture condition of the vadose zone. The HSPF calculation, $(1-F_{LZFRAC})$, determines the fraction of the volume of infiltration and percolation that is redistributed to recharge. Disposition of infiltration into vadose zone storage and/or groundwater recharge is uniquely interpreted in IHM.

In the context of IHM, infiltration is simulated using the simplified Philip equation with concern for physical soil hydraulic conductivity, sorption behavior and time step sensitivity shown in previous study (Fielland and Ross, 1991; Geurink and Ross, 2006). Infiltration is a function of many factors including soil type, moisture content, air entrapment conditions, vegetative cover and the depth to the water table. Infiltration also depends upon redistribution (vertical downward movement of water within the soil) from previous events.

When infiltration exceeds the capacity of the unsaturated zone to vertically redistribute water for extended periods, surface saturation occurs. This can occur from

infiltration excess (precipitation exceeding infiltration capacity), with or without air entrapment excess void pressure, and/or fully saturation excess (saturated soil conditions) mechanisms. In IHM, fully saturation excess condition is only allowed over the distributed discretization provided by regular grid cells forming the MODFLOW ground water domain (Ross *et al.*, 2004). Where variable saturated cells exist, the infiltration rates for pervious land cover are adjusted downward in an area-weighted manner (Ross *et al.*, 2004). Code improvements to provide for explicit variable saturation are being considered and/or tested but are not yet implemented.

Infiltration in HSPF and IHM is a function of infiltration capacity (the maximum rate at which soil will accept infiltration), lower zone storage, D_{LZS} , and lower zone nominal storage, D_{LZSN} . Infiltration capacity is a function of soil and environmental conditions which can vary spatially. Infiltration capacity also varies with time as a function of the antecedent moisture condition ($R_{LZ RAT}$). When rainfall supply exceeds the infiltration capacity, water is allocated to other storages and fluxes (e.g., surface detention storage). Therefore, infiltration capacity is a function of both fixed and variable characteristics of the watershed. Generally, fixed characteristics include such parameters as soil type and land-surface cover; variable characteristics include soil surface conditions, soil moisture content and depth-to-water table. Fixed and variable characteristics vary spatially over the land segment. Traditionally, HSPF uses a linear probability density function (Figure 3.3) to account for spatial variation of infiltration over the land segment. This function allows for simple characterization of field-scale variability which has been shown to exist at the length-scales of 10's of meters in West-Central Florida (Zhang and Ross, 2006).

The linear probability density function (PDF) that describes the spatial variability of infiltration in IHM relates maximum to mean infiltration capacity. This linear PDF changes in time using algorithms to represent the dynamic nature of the infiltration

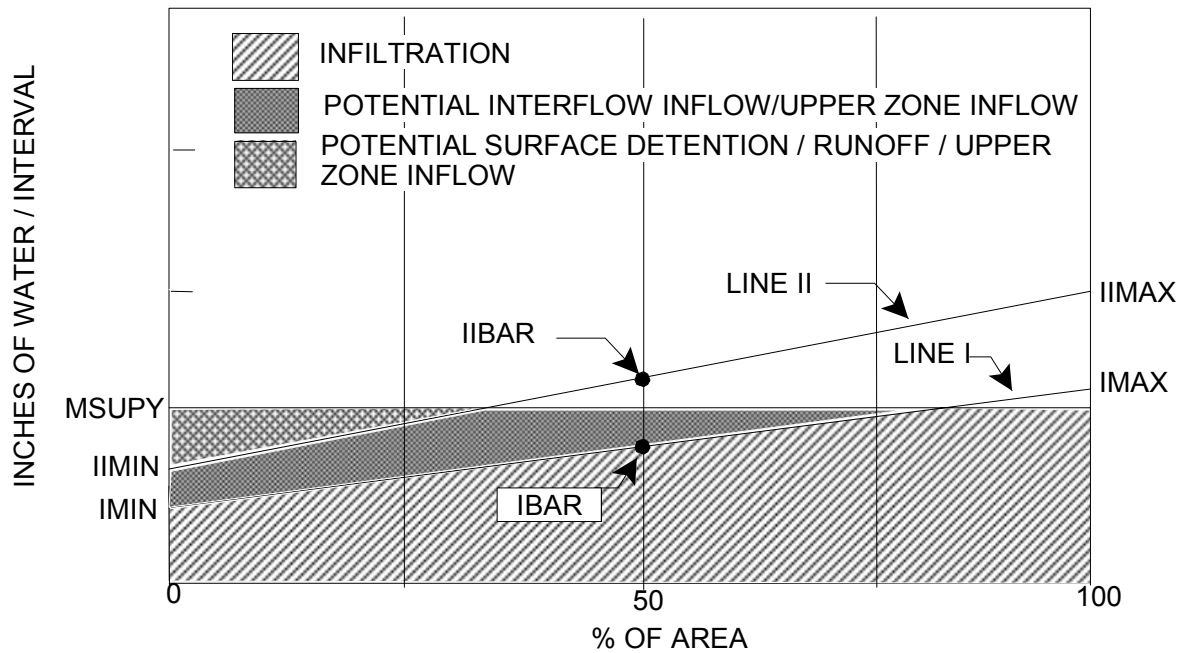


Figure 3.3. HSPF Linear Probability Density Function (after Bicknell, *et al.*, 2001)

capacity as a function of the changing soil moisture in the unsaturated zone. The governing equations represent the dependence of infiltration rate on soil moisture conditions and are based loosely on the work of Phillip (1957) as adapted into the Stanford Watershed Model (Crawford and Linsley, 1966), explored in Fielland and Ross, 1991.

IHM implements the infiltration PDF over pervious land segments in the following manner. The spatial mean infiltration capacity of the land segment \bar{I}_{IBAR} is

determined from relative soil moisture condition, represented by the ratio of D_{LZS} to D_{LZSN} . Unique to the particular water table depth derived from MODFLOW component, \bar{I}_{IBAR} is then multiplied by the landuse/soil based ratio of maximum to mean infiltration capacity, P_{INFILD} , to determine the maximum infiltration capacity of the land segment I_{IMAX} . The value of P_{INFILD} can vary from 1 to 2, with a value of 1 corresponding to spatially uniform infiltration and a value of 2 corresponding to the maximum spatial variability in infiltration. A value of 2 for P_{INFILD} yields a minimum infiltration capacity for the land segment, I_{IMIN} , of zero and a maximum infiltration rate I_{IMAX} , that is twice the mean.

$$\bar{I}_{IBAR} = P_{INFILT} \left[\frac{D_{LZS}}{D_{LZSN}} \right]^{-P_{INFEXP}} \quad (3.8)$$

$$I_{IMAX} = P_{INFILD} \bar{I}_{IBAR} \quad (3.9)$$

$$I_{IMIN} = 2\bar{I}_{IBAR} - I_{IMAX} \quad (3.10)$$

where,

P_{INFILT} = infiltration index [L/T], equal to the mean infiltration rate of the soil at equilibrium moisture condition and average water table depth;

\bar{I}_{IBAR} = soil moisture dependent spatial mean infiltration volume over the pervious segment per model time interval [L];

D_{LZS} = HSPF derived time and depth to water table dependent lower zone storage volume [L];

- D_{LZSN} = available soil moisture retention at equilibrium, depth to water table dependent lower zone nominal storage volume [L];
- P_{INFEXP} = soil retention based exponent (greater than 1) expressing the soil sensitivity to variable soil moisture higher for clays and lower for sandy soils (see Geurink and Ross, 2006);
- I_{MIN} = HSPF derived minimum infiltration rate expressed as a volume per model time interval [L];
- I_{MAX} = HSPF derived maximum infiltration volume per model time interval [L];
- P_{INFILD} = landuse based ratio of maximum to mean infiltration capacity over the subbasin (expressing variability in infiltration conditions over the land segment)

The I_{MIN} , \bar{I}_{IBAR} , and I_{MAX} points represent the infiltration line (Line I, see Figure 3.2). All moisture supply (D_{MSUPY}) below the infiltration line is considered as infiltration inflow, I_{INFIL} . Above the infiltration line, D_{MSUPY} is considered to be potential direct runoff, D_{PDRO} .

D_{MSUPY} consists of the precipitation water remaining after interception and upper zone storage are removed, plus lateral overland inflow from an adjacent land segment for the current model time interval, plus the surface detention storage remaining from the previous model time interval.

If the moisture supply is less than the minimum infiltration capacity, then all moisture is assigned to infiltration. If the moisture supply is greater than the maximum

infiltration capacity, then infiltration is the mean infiltration capacity, and potential direct runoff is the remaining moisture supply. When the moisture supply is greater than the minimum infiltration capacity but less than or equal to the maximum infiltration capacity, infiltration occurs variably over the whole domain. Also, potential direct runoff only occurs over part of the domain. In all cases, the infiltration potential line is established prior to calculation of the infiltration and the potential direct runoff each time step based on relative moisture condition of the soil. Water that is infiltrating combines with water that is percolating from the upper zone storage to the lower zone storage as lower zone inflow plus groundwater (water table) recharge.

3.5 Recharge

In the HSPF application within IHM, active groundwater storage is turned off because it is explicitly accounted for by the MODFLOW code and IHM integration components. In IHM, recharge to MODFLOW is the groundwater inflow volume, IGWI, from HSPF. Because of variable discretization, recharge from multiple land segments comprising a rectangular groundwater grid element must be area-weighted. Details about discretization can be found in Ross *et al.* (2004 and 2005b). However, due to the unique interpretation of the lower zone (LZ) in IHM, the percolation distribution function in HSPF warranted modification.

Consistent with the formulation of HSPF, the fraction of infiltration that becomes recharge to the water table is a function of the relative moisture condition of the LZ (R_{LZRAT}). Also, already noted, $R_{LZRAT} = 1$ corresponds to equilibrium moisture retention.

The fraction of infiltration percolation that stays in the LZ (recharges the vadose zone) is F_{LZFRAC} . Allowing for field-scale variability and potential significant macro-pores (bypassing through the vadose zone and all uncertainty in soil retention and percolation processes), the F_{LZFRAC} form can be take on the characteristic of the solid line in Figure 3.4 which is the default HSPF formulation. However, in field-scale observations (Rahgozar *et al.*, 2005) and theoretical investigations (Shah and Ross, 2006) distribution is shown to be more consistent with the formulation of the behavior depicted by lines 1, 2 and 3 in Figure 3.4. For this modified (optional) formulation, infiltration is completely vadose zone recharge until equilibrium retention is observed and water table recharge only commences for wetter conditions with this fraction rapidly approaching zero for sandy soils.

The fraction F_{LZFRAC} , controls the distribution of infiltration plus percolation from upper zone storage to vadose zone storage and recharge to the water table. The default form in HSPF allows continuous variation of F_{LZFRAC} for the complete range of R_{LZRAT} (i.e., some finite recharge occurs to the water table even when the soil moisture content is near wilting point) arguably unlikely in most cases. Therefore, the alternate conceptual basis for F_{LZFRAC} was sought that provided for vadose zone recharge to the equilibrium

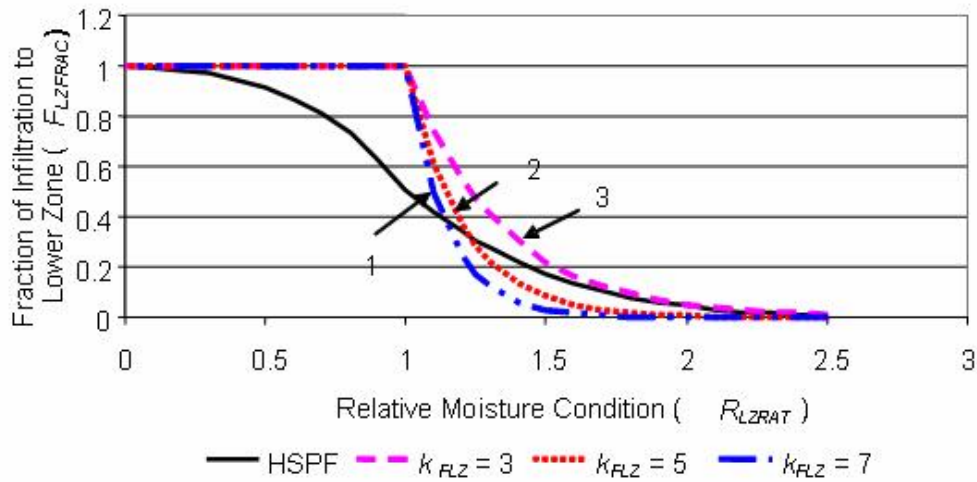


Figure 3.4. Distribution of Lower Zone Infiltration and Percolation

moisture content before there is water table recharge. This is simply,

$$F_{LZFRAC} = \begin{cases} 1 & \text{for } 0 \leq R_{LZRAT} \leq 1 \\ e^{-(k_{FLZ} R_{LZRAT})} & \text{for } R_{LZRAT} > 1 \end{cases} \quad (3.11)$$

Where, k_{FLZ} is a decay rate accelerator to account for the tendency for the wet soil moisture profile to reside near the equilibrium profile ($R_{LZRAT} = 1$) characteristic of more sandy soils. Refer to Figure 3.3 for a comparative plot of F_{LZFRAC} for the HSPF default formulation and for different parameters values for k_{FLZ} (e.g., $k_{FLZ} = 3, 5,$ and 7). IHM allows either use of the HSPF default or the alternate concept for F_{LZFRAC} .

3.6 Evapotranspiration

IHM partitions ET between surface storages, vadose zone storage and saturated ground water storage by considering evaporative flux from surface sources, proximity of the water table to land surface, relative moisture condition of the unsaturated zone, thickness of the capillary zone, thickness of the root zone and relative plant cover density in the manner of Ross *et al.* (2005a), briefly summarized below.

While both HSPF and MODFLOW have ET subroutines, which are often used separately, IHM actually employs both in a unique interpretation and hierarchical approach (see in Figure 3.5). IHM accounts for ET following user specification of a potential atmospheric evaporation-rate (PET) time series determined apriori based on estimates from open pan data, Penman reference ET calculations or other meteorologic data. IHM considers ET distribution in a unique hierarchal approach considering satisfaction of PET by surface-water storages first, starting with interception (Q_{CEPE}), then depression storage (Q_{UZET}) then proceeding to distribute reduced PET to the vadose zone (lower zone ET, Q_{LZET} , and/or water table, Q_{GWET}). Both vadose zone and saturated groundwater ET are dictated by vegetative cover characteristics, including monthly plant coefficient (PPC), root-zone (rhizosphere) depth (ξ_{RZ}), soil characteristics and depth to the saturated groundwater (d_{WT}). The extinction depth (ξ_x), and maximum ET surface (Z_{MAXET}) for the EVT package of MODFLOW are distinctively defined in the manner of Ross *et al.*, (2005a), following the physical behavior of extinction elucidated in Shah *et al.*, (2006).

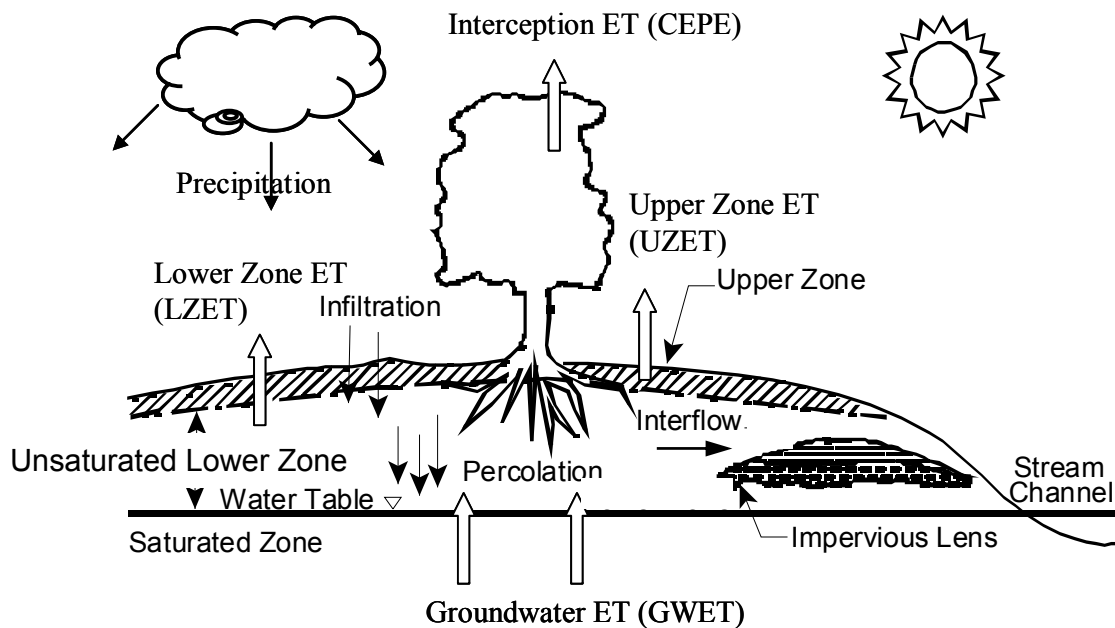


Figure 3.5. Vertical Moisture Fluxes and Storage in IHM

The ET concept of IHM considers water stored in the vadose zone and groundwater as one unit from which transpiration and direct evaporation from the soil occurs. Groundwater is available for ET through upward capillary flux from the water table into the root zone and from direct contact between the water table and the root zone. IHM provides a smooth transition from all unsaturated zones supporting ET, to shallow water table free surface evaporation. The same plant coefficients regulate water uptake for both unsaturated and saturated zones. Also, there is smooth transition from plant-based uptake rate to free surface (open water) direct evaporation as the water table nears land surface.

The definition for the lower zone presented in the previous section explicitly tracks the antecedent moisture variability (wet or dry conditions) for any given water table depth. All component partitioning (i.e., upper zone, lower zone and water table) are

true to the above moisture retention behavior. Groundwater is available for ET through upward capillary flux from the water table into the root zone and from direct contact between the water table and the root zone (Ross, *et al.*, 2005a).

In IHM, ET demand from saturated groundwater zone occurs only when the water table is above a well-defined groundwater ET extinction depth, ξ_x . The extinction depth has been theoretically shown to be the sum of the plant root zone thickness (ξ_{RZ}) and, roughly, the soil capillary zone thickness (ξ_{CZ}) (Ross, *et al.*, 2005a; Shah *et al.*, 2006) and this is the approach used in IHM. Consistent with field study observations in shallow water table conditions of Florida, IHM transfers more of the ET burden of plants to the water table than previous versions of the model (i.e., FHM) and other widely-used models (Ross, *et al.*, 2005a; Ross, *et al.*, 2004) to be more consistent with field observations in shallow water table hydrology (Rahgozar, *et al.*, 2005).

Another important variable in IHM is the monthly variable plant coefficient, P_{PC} (Ross *et al.*, 2005a). Vegetative ET (plant uptake) time series can be derived from field data, e.g., Rahgozar, *et al.*, (2005).

Typical applications of IHM then require the following input variables controlling ET: (1) User specification of an atmospheric open-water potential ET rate, $PET(t)$, which varies continuously in time, (2) Derived plant/soil extinction depth, ξ_x , (based on GIS overlays of vegetative root zone thickness plus soil capillary zone thickness), and (3) A vegetation based, monthly variable, plant coefficient, P_{PC} .

CHAPTER 4

METHODOLOGY FOR SIMULATING VADOSE ZONE

There are four important model considerations of recognized importance and investigated herein as combined factors for simulating vadose zone moisture. 1) Soils have predictable but highly variable moisture retention properties. 2) Recent investigation from field data have shown that hydrologic behavior including runoff, recharge and ET are controlled by vadose zone moisture retention which is strongly non-uniform. 3) Field-scale variability is pronounced, even for similar soils and land cover. 4) For shallow water table settings, air entrapment strongly effects infiltration and observations of water table. This chapter proposes the methodology to investigate these considerations for simulating vadose zone moisture retention behavior in IHM and follows up with a parameter sensitivity analysis for vadose zone prediction.

4.1 Soil Zonation

Recent investigations of field data have shown that the hydrologic behavior of runoff, ET and groundwater recharge is controlled by vadose zone moisture which is strongly non-uniform (Rahgozar *et al.*, 2005). Vertical observations indicate that the soil zone needs to be differentiated into a minimum of two separate distinguishable zones. For example, observations from field data indicate that 50-70% of the total ET comes from a

clearly identifiable distinct soil zone very near land surface (Rahgozar *et al.*, 2005). This top 10-20 cm of soil, effectively comprising the A horizon, has been proposed as effectively defining the upper zone (Zhang and Ross, 2006). Most soil moisture available to the root zone, especially in sustained dry periods, however, is stored in the lower part of the vadose zone, defined herein as the lower zone. Root moisture uptake from this layer contributes to the sustained soil ET burden. Field data is presented showing that these two zones can be and frequently are in different antecedent (i.e., relative wet or dry) states (following the work by Zhang and Ross, 2006). Data also indicates that stations in close-proximity exhibit significant field-scale variability. Most integrated models (noted in Chapter 2) do not differentiate the vadose zone (especially the hydrologically active vadose zone). For IHM, clear definitions are still needed.

4.1.1 2-Layer Soil Discretization in IHM

The surface storages and unsaturated zone in IHM are partitioned into two layers, the upper (UZ) and lower soil zone (LZ). The upper soil zone plays an important role in surface hydrologic response, which has a direct effect on the ET, including direct soil evaporation, infiltration, and runoff. Figure 4.1 is a simple conceptualization of the UZ and LZ as proposed by the IHM. Note the insert in Figure 3.2 shows the root zone, which in shallow water table settings, can extend down below the upper and lower vadose zone. The figure also depicts other pervious upland storages in the IHM

In the IHM, it is proposed that the upper zone includes shallow soil storage and surface depression storage from micro topography (horizontal scale < 1 m), meso-depression storage (1-100 m), and any larger storage features not explicitly included as

hydrography in the model. Micro-depression storage includes cracks, potholes, depressions, etc., on the land surface that can hold water and remove water from runoff supporting delayed infiltration and direct evaporation after each rainfall event. Water captured in these depressions and shallow soil moisture then consequently furnishes much of the post-storm event evaporation demand, thereby comprising a significant fraction of the annual hydrologic budget (Ross *et al.*, 2005a). For larger basin applications (with more coarse discretization), macro-scale depression storage features, including small isolated wetlands, ponds, and sinkholes, can become significant components of the pervious land segment depression storage.

The upper vadose zone is affected by the initial abstractions, interception and depression storages in the IHM. Interception is assumed to occur first during storm events and can be a significant loss if the land segment possesses substantial vegetative cover. As the interception storage capacity is filled, precipitation begins filling depressions and contributes to infiltration. Depending on antecedent conditions, depression storage (included in upper unsaturated zone storage D_{UZS}) is a significant rainfall capture mechanism with regards to generation of runoff and recharge and may reach capacity relatively quickly (Ross *et al.*, 2005a). Following rainfall, water moves out of the upper unsaturated zone storage and percolates to lower unsaturated zone, where it is available for sustained plant transpiration. Vadose zone water flux that becomes water table recharge (i.e., results in water table movement) is not part of the lower zone storage. A more thorough presentation of ET in the IHM can be found in Ross *et al.* (2004, 2005a).

The lower zone in the IHM is defined as the remainder of the unsaturated zone between the upper zone and the saturated soil above the water table. It accounts for the

sustained transpiration burden of the vegetative cover. Unique to the IHM, the lower zone storage is that part of the vadose zone moisture that does not affect the water table. Excess moisture in the vadose zone that becomes recharge to the water table is not included in lower zone storage.

Surface and soil hydrologic processes in the IHM are further discretized using irregularly shaped but hydrologically similar, hydrologic response units (HRUs). However, very small HRUs with like properties (e.g., grass land with similar soils) within a meteorological region are grouped for computation. Even within these HRUs, field-scale variability exists. For large regional applications, sufficient data does not exist nor is it practical to solve Richard's equation for each unique soil moisture distribution. Subsequently, runoff and recharge are distributed over irregular hydrographic discretization for surface water and regular (grid cell) discretization for below water table ground water flow computations. More detail about the discretization of IHM can be found in Ross *et al.* (2005b).

4.1.2 Upper Zone as the A Horizon

In West-Central Florida (i.e., coastal plain type) soils, there are several distinct layers or horizons of hydrological importance. When one examines a hole dug at the study site, what is observed is fairly typical of any of the upland soils in the Gulf coastal plain. These soils are made up of distinct soil layers consisting of O, A, B, C, E and R classifications. However, most of the coastal plain soils have, at most, three hydrologically distinct horizons, that is, the surface horizon A, the subsoil horizon B, and

the substratum horizon C which can be identified from soil classification data (Carlisle *et al.*, 1989). Some soils have an organic horizon O on the surface, or buried at some depth.

In this study, particular attention is paid to the A horizon which comprises the topsoil, rich in organic matter and typically darker in color than the deeper soils. The A horizon is the zone of major biological activity. Here, plants and animals and their residues interact with an enormously diverse and dynamic multitude of microorganisms. There is considerable moisture retention capability in pore spaces (including macropores) and readily available air. Macro-pores and extensive root matter are readily apparent in this layer. Figure 4.1 shows typical soil profiles in sedimentary soils and graphical depiction of upper and lower soil moisture zones.

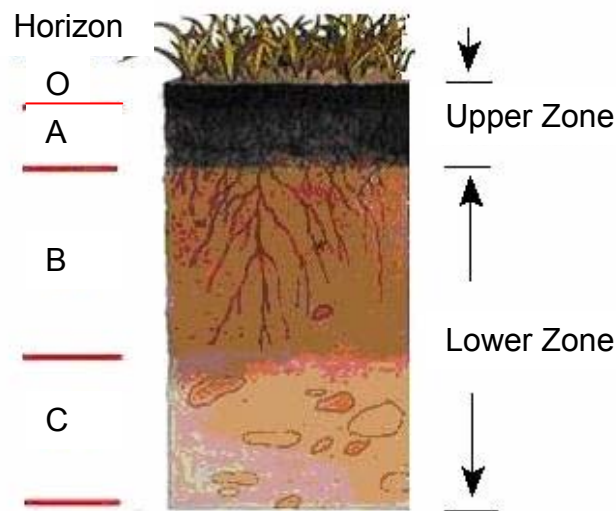


Figure 4.1. Typical Soil Profiles in Sedimentary Soils and Graphical Depiction of Upper and Lower Soil Moisture Zones (modified from NRCS web source)

Reviewing soil classification data (Carlisle *et al.* 1989), one finds that fine sand, fine sandy loams and sandy loams comprise the bulk of soils in Florida. The A horizon

averages 15 cm (± 5 cm) throughout the domain with very little variability in thickness (Figure 4.2).

Therefore, the upper zone can be conveniently described as the A horizon with distinct hydrologic properties characteristic of the top 10-20 cm soil layer for these coastal plain soils. This layer consists of extensive organic material and micro-

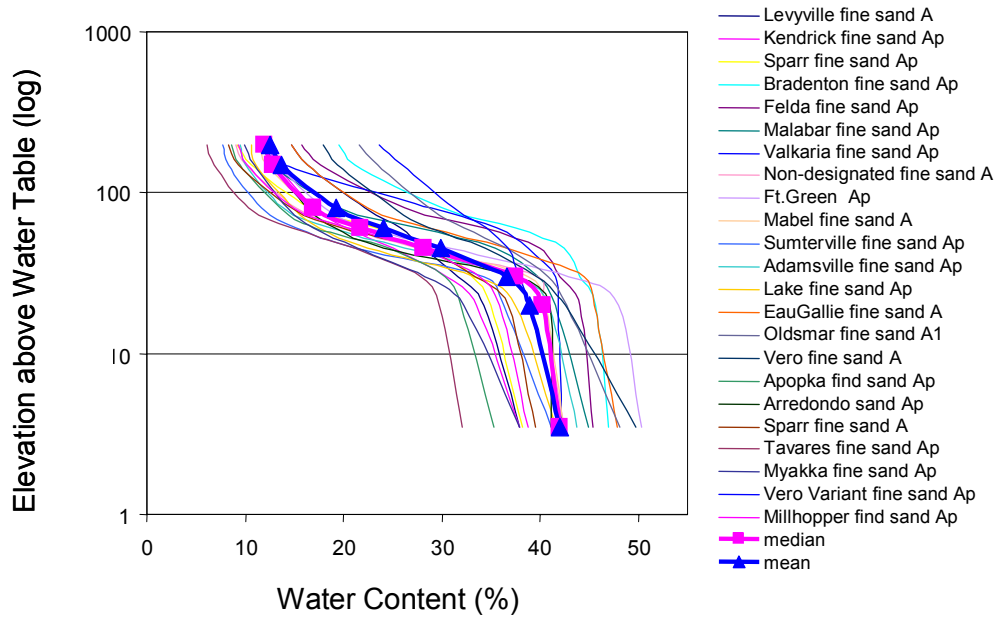


Figure 4.2. Equilibrium Moisture Retention Characteristic of the A Horizon in Florida Fine Sandy Soils

topography depressions that are indistinguishable as a storage unit. Also, the storage characteristics of this unit are governed by the proximity of the water table which is further explored below.

4.1.3 Observations from Field Studies

Nested transect shallow water table (5 m) wells were installed in an intensive study area located in a typical shallow water table, coastal Flatwoods and pasture land

setting in West-Central Florida (see Figure 4.3). The wells utilized for this investigation were designated as PS43, PS42, PS41, PS40, USF1 and USF3 (Figure 4.3).

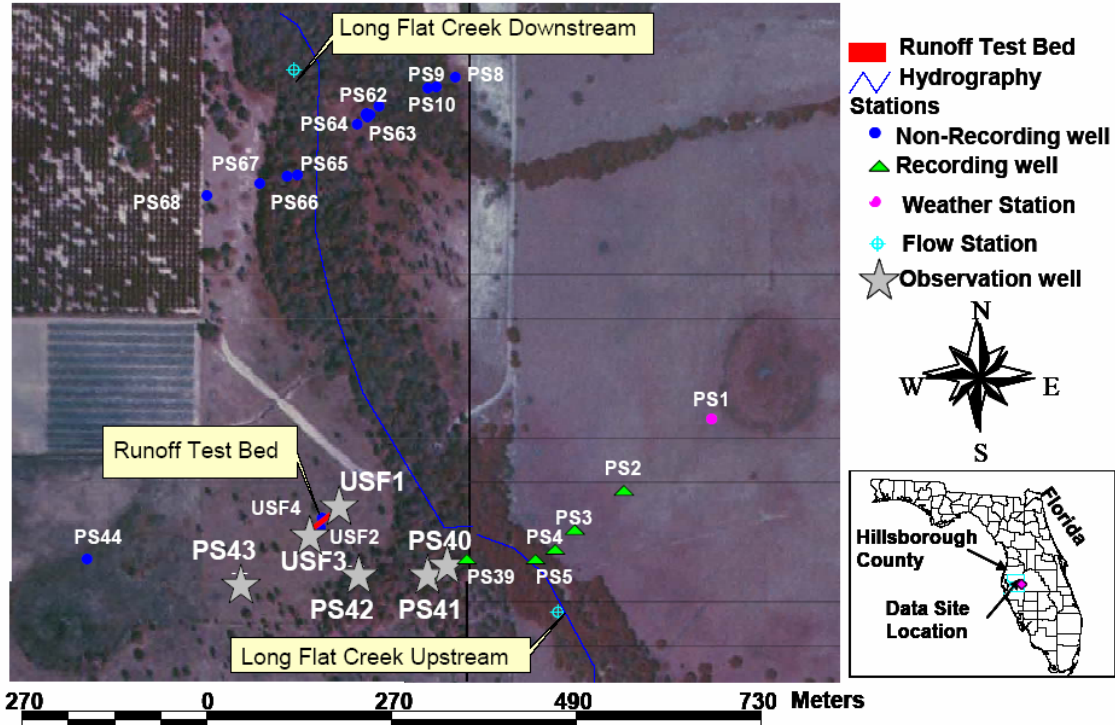


Figure 4.3. Location Map of Observation Wells and Soil Moisture Monitoring Sites

The vegetation in the upland area was primarily ungrazed Bahia grass. The vegetative communities adjacent to the stream were dominated by alluvial mixed Slash Pine/hardwood (water oak) forested wetland fairly typical of undeveloped West-Central Florida. Green foliage density at this site is nondeciduous but follows a typical seasonal pattern, reaching maximum coverage during summer wet periods (June to August) and minimum coverage during winter dry periods (December to February).

Vertical profiling soil moisture probes were installed adjacent to monitoring wells PS43, PS42, PS41, PS40, USF1 and USF3. Vertical resolution was achieved with sensor placement at 10, 20, 30, 50, 70, 90, 110 and 150 cm below land surface. The moisture

probes from PS43 to PS40 were along a downhill transect from the upland grassed area at PS43 to the riparian forest near the stream at PS40. Ten minute data were converted to daily average values for the period (1/1/2002-6/27/2004) for this analysis. All soils classified for the site are hydrologically similar to Myakka Fine Sand (Carlisle *et al.*, 1989). For the upper zone behavior, only the top sensor (10 cm) was used while the remaining seven sensors below were used to describe the lower soil zone moisture content.

An important observation from soil moisture measurements was the pronounced occurrence of field-scale variability. Figure 4.4 illustrates the variability in soil moisture from six synoptic observation wells at the study during a deep (a) and shallow (b) water table period. The spacing between these observation wells was relatively small horizontal distances (~100 m) in near identical hydrological settings. The distance between USF1 and USF3 was less than 30 m. These six observation wells were approximately 5 m deep, cased for the first meter and screened below that. The soil classification for all stations was Myakka Fine Sand. The moisture observations shown in Figure 4.4 are typical of the strong variability of moisture retention within field-scale horizontal dimensions of 10-100 meters. This scale of variability is clearly smaller than (or comparable to) the discretization scale of most regional models (>100-1000 m). Implications for this relative scale of high variability may be obvious but more is discussed about this to later in this study.

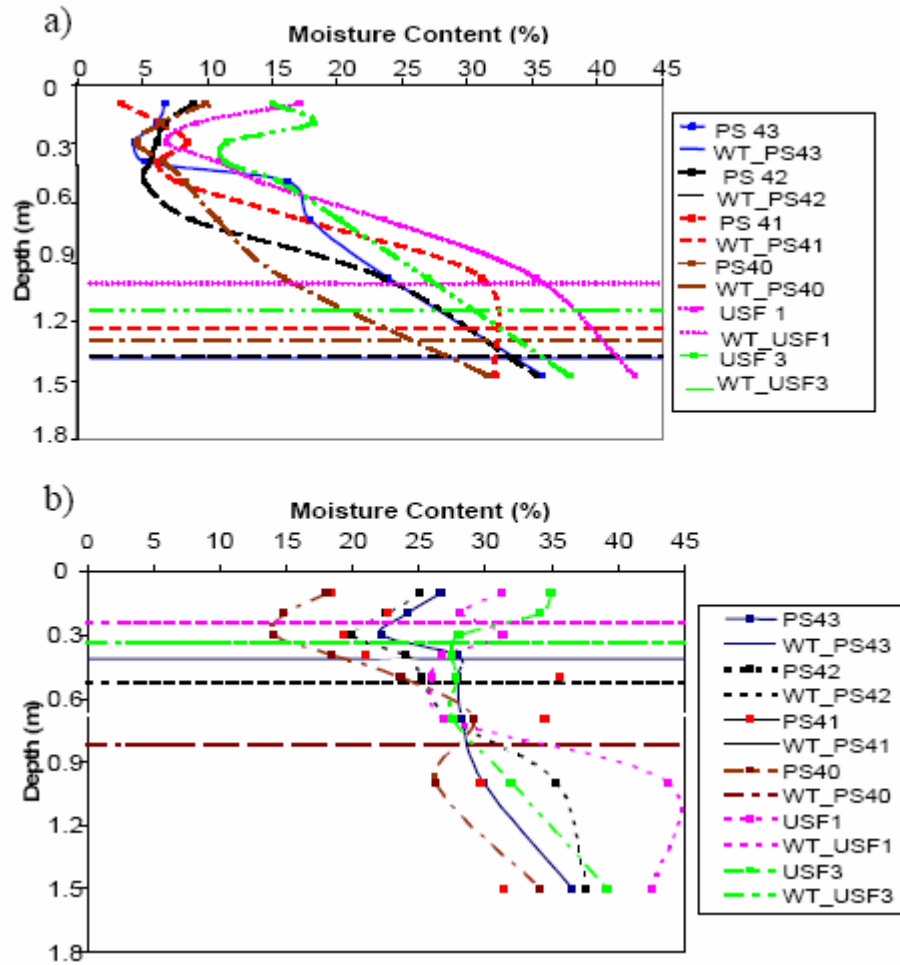


Figure 4.4. Representative Field-Scale Variability Shown by Concurrent Vertical Soil Moisture Observations from Six Stations in (a) Deeper Water Table Period; (b) Shallow Water Table Period

When plotting the observed total soil moisture, derived by depth integration over the respective vadose zones, against depth to water table for the upper and lower zones, respectively, several interesting observations can be made. First, strong vertical variability in moisture retention is observed at all stations. Second, it is observed that field-scale variability occurs in both zones for the six observation stations even though all six sites have the same soil classification (i.e., Myakka Fine Sand) and nearly identical texture classes. From daily observations (exhibiting daily characteristics very similar to this one

example) it was observed the total soil moisture is highly varied most of the time. What is offered as a hypothesis is that the different stations have slightly different moisture retention characteristics (from very small differences in % clays and/or organics) and slightly different depth to water table even though they are in similar antecedent condition. Consequently, what is proposed is a unique formulation of relative soil moisture and the abandonment of representation of actual soil moisture retention in the model through a proposed transformation utilizing the vertical and temporal mean moisture content at any particular depth to water table.

For a better understanding of the upper and lower soil zone behavior, one needs to examine a plot of the total soil moisture vs depth to water table for each station (example in Figure 4.5). The obvious tendency bands give us some inspirations: the mean and minimum curve may be used to present the tendency behavior of total soil moisture. Actual moisture content can be compared to the mean and minimum values to describe a quantitative relative moisture condition.

4.1.4 Formulation of Relative Moisture

For the hypothesis proposed above, the approach is to fit the mean and minimum total soil moisture curves to the band of observations. From observation data plotted (previously shown in Figure 4.4), it can be seen that these six stations all have much variability in the actual soil moisture distribution. A more effective expression for available soil moisture must be proposed. A van Genuchten type (van Genuchten, 1978) mathematical model is proposed for this purpose.

For the van Genuchten type model, the dimensionless water retention function S_e , is given by

$$S_e = (\theta - \theta_r) / (\theta_s - \theta_r) = \left(\frac{1}{1 + (\alpha d_{WT})^N} \right)^M \quad (4.1)$$

And, solving for θ ;

$$\theta = \left[\left(\frac{1}{1 + (\alpha d_{WT})^N} \right)^M * (\theta_s - \theta_r) + \theta_r \right] \quad (4.2)$$

Where θ is volumetric moisture content [L/L]; θ_r is residual volumetric moisture content [L/L]; θ_s is volumetric moisture content at saturation [L/L]; d_{WT} is the depth to water table [L]; α is a dimensional parameter [1/L]; N and M are dimensionless curve fitting parameters and $M = 1 - 1/N$ ($N > 1$). This equation contains four independent parameters (θ_s , θ_r , α and N), which have to be estimated to represent the observed soil-moisture retention behavior.

From the field site, soil moisture profiles were monitored continuously, averaged for the day for each level (i.e., 10, 20, 30 cm etc.) and integrated over the soil column to yield the total moisture content in the top 150 cm (limit of the probe depth). For any given day and depth to water table value, there is total soil moisture value which varies over a limited range. All the data points are from field observations. Plotting the daily average, vertically integrated soil moisture vs. depth to water table, the considerable variability displayed by each station was explored. First, the mean value for every range of depth to water table (i.e., ranges like 0-0.5 cm, 0.5-1 cm, 1-1.5 cm ...etc.) was calculated. The corresponding mean of total soil moisture for water table range is shown in the plotted *mean_PS42* points in Figure 4.5. A similar approach was used to get the

minimum points (shown as *min_PS42* in Figure 4.5). Next, van Genuchten type mathematical functions were fitted to the mean and minimum values (shown as *Fit_mean* and *Fit_min* in Figure 4.5). The best fit equation was used to find the relative moisture condition described below.

In this approach, van Genuchten parameters were fitted to match the mean soil moisture behavior and another set to the minimum soil moisture behavior for every station using Equation (4.2). Two examples are shown in Figure 4.5 for the fitted mean and minimum van Genuchten curves. An example of fitted mean and minimum curve to daily observation of upper zone total soil moisture for PS42 is shown in Figure 4.5a. Figure 4.5b shows another example of fitted mean and minimum curves to daily observations of lower zone total soil moisture for PS41. It should be noted by the reader that this is not a standard application of the van-Genuchten moisture retention curves for Equation (4.2). Instead, the use was a matter of convenience (i.e., a reasonable mathematical relationship) to fit the observed behaviors to explore the concept of relative moisture. Other mathematical models could have been used to fit the data as well but were not explored in this study.

It is proposed that describing relative moisture condition based on the actual condition relative to the minimum and mean soil moisture behavior will better represent antecedent moisture condition, available “free moisture” for any water table depth, and reduce field-scale variability in moisture observations at multiple stations. “Free moisture”, or free vadose zone storage, is herein defined as the variable moisture that can exist for any water table depth. Thus, the moisture condition could change from the maximum to the minimum content with negligible water table fluctuation. For more

details of the physics and mechanics of this moisture variability, the reader is directed to Shah and Ross (2006). The foundation for the relative moisture condition is the

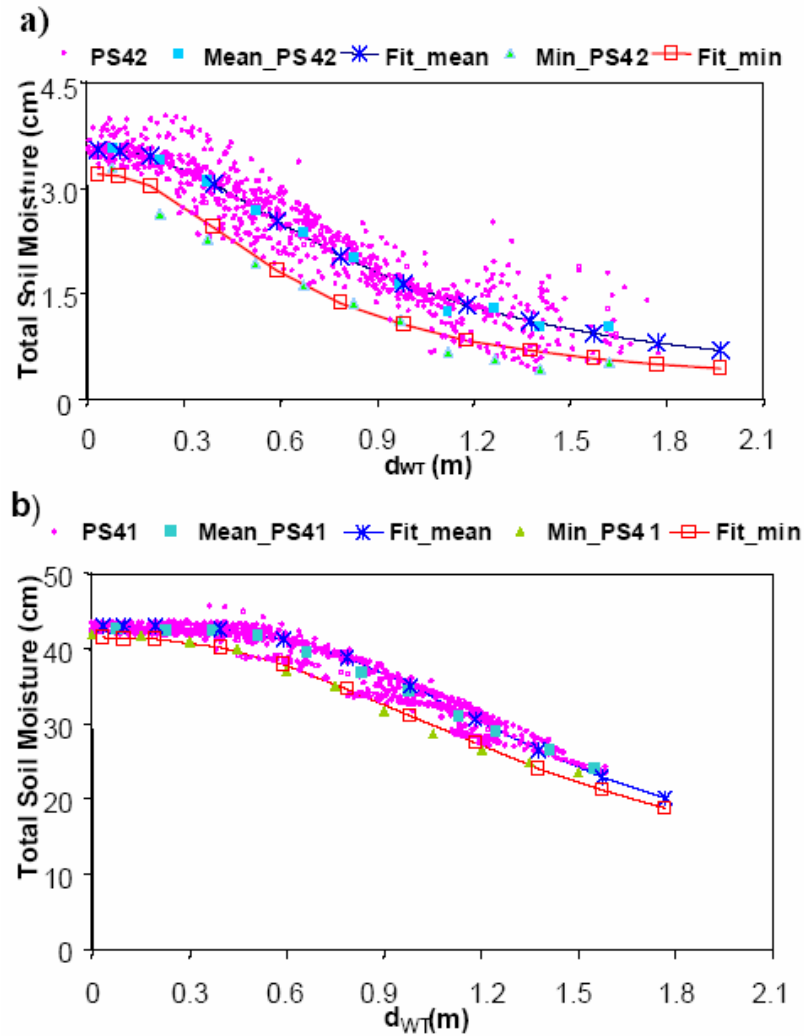


Figure 4.5. Examples of Fitted Mean and Minimum Curves to Daily Observations of Total Soil Moisture vs. Depth to Water Table in (a) Upper Zone for PS42; (b) Lower Zone for PS41

following. At any stable water table depth there is limited minimum, mean (normal) and maximum total soil moisture. Thus, the available vadose zone moisture at that water table elevation (for negligible water table change) is the excess moisture above the minimum. Moisture conditions declining beyond this threshold results in significant water table decline (i.e., ET stress to the water table). Total soil moisture below the mean represents

relative dry antecedent condition and above the mean, relative wet condition (for that corresponding water table depth). The quantitative relative moisture condition is therefore the actual content minus the minimum divided by the mean minus the minimum for both zones, upper and lower (both also specific to that water table depth).

The upper zone relative moisture condition, Equation (4.8) can be described as the ratio of the difference between the current total soil moisture, Equation (4.3), and the minimum total soil moisture, Equation (4.4), the definition of minimum total soil moisture, to the difference between the mean total soil moisture, Equation (4.5), the definition of mean total soil moisture, and the minimum total soil moisture at the same depth to water table.

In this way, each station, strongly exhibiting field-scale variability, can be normalized to a more consistent quantitative relative moisture condition. The model formulation can then be based on relative moisture condition instead of actual moisture content. For example, during shallow water table conditions with high moisture content, the soil moisture condition can vary from relatively wet to dry very quickly and with very little volume change. The representative definition equations for the upper zone are:

$$\Theta_{UZ}(d_{WT}) = \int_0^{\xi_{UZ}} \theta(z, d_{WT}) dz \quad (4.3)$$

$$\Theta_{UZ,\min}(d_{WT}) \equiv \int_0^{\xi_{UZ}} \theta_{\min}(z, d_{WT}) dz \quad (4.4)$$

$$\Theta_{UZ,\text{mean}}(d_{WT}) \equiv \int_0^{\xi_{UZ}} \theta_{\text{mean}}(z, d_{WT}) dz \quad (4.5)$$

$$D_{UZS} = \Theta_{UZ} - \Theta_{UZ,\min} \quad (4.6)$$

$$D_{UZSN} = \Theta_{UZ,\text{mean}} - \Theta_{UZ,\min} \quad (4.7)$$

$$\mathfrak{R}_{UZ} = \frac{D_{UZS}}{D_{UZSN}} = \frac{\Theta_{UZ}(d_{WT}) - \Theta_{UZ,\min}(d_{WT})}{\Theta_{UZ,\text{mean}}(d_{WT}) - \Theta_{UZ,\min}(d_{WT})} \quad (4.8)$$

The denominator of Equation (4.8) could be considered the “nominal” upper zone storage, D_{UZSN} in the IHM documentation consistent with terminology used for the HSPF model (Bicknell *et al.*, 2001). The numerator of Equation (4.8) then represents the available storage in the upper zone, D_{UZS} .

Where D_{UZS} = upper zone storage. [L];

D_{UZSN} = upper zone nominal storage. [L];

\mathfrak{R}_{UZ} = upper zone relative moisture condition. [Dimensionless];

\mathfrak{R}_{LZ} = lower zone relative moisture condition. [Dimensionless];

$\theta(z, d_{WT})$ = the actual volumetric moisture content of the soil, [L/L];

$\Theta_{UZ}(d_{WT})$ = upper zone total soil moisture influenced by depth to water table, d_{WT} .
[L];

$\Theta_{UZ,\text{mean}}(d_{WT})$ = upper zone total soil moisture from the corresponding fitted mean curve
for the given depth to water table, d_{WT} . [L];

$\Theta_{UZ,\min}(d_{WT})$ = upper zone total soil moisture corresponding to the fitted minimum curve
for the given depth to water table, d_{WT} . [L];

ξ_{UZ} = the fixed thickness of the upper zone layer (e.g. soil A horizon). [L]

Similar equations are applied to the lower zone as well, exception being that the lower zone comprises the soil zone below the A horizon down to the minimum of either the water table or the groundwater extinction depth, ξ_X . The ground water extinction

depth is defined herein as the depth below which the vegetation can no longer effectively derive ET from the water table. This depth has been mathematically shown to be the sum of the soil capillary zone thickness, ξ_{CZ} , plus the plant root zone thickness, ξ_{RZ} (Ross *et al.*, 2005a) as

$$\xi_X = \xi_{CZ} + \xi_{RZ} \quad (4.9)$$

4.2 Air Entrapment/pressurization

4.2.1 Background

The role of air entrapment in inhibiting infiltration has long been recognized (e.g., Adrian and Franzini, 1966; Morel-Seytoux and Khanji, 1974; Vachaud *et al.*, 1974; Parlange and Hill, 1979). Several theoretical and experimental studies, e.g., Youngs and Peck (1964) and McWhorter (1971), have quantitatively defined the impact of air compression on infiltration. These studies found that, air compression ahead of a wetting front, in some water table conditions, brings about a sharp decrease in the infiltration rate. However, as pointed out by Parlange and Hill (1979) and observed by Wang *et al.* (1998), air compressibility has been generally found negligible, when the air is free to move ahead of the wetting front. Hence, the importance of air compression in an unconfined aquifer with deep water table is generally considered negligible. However, for shallow water table environments ($d_{WT} < 2$ m) air compression plays a significant role in determining infiltration in many soils (Touma *et al.*, 1984).

Because air entrapment in shallow water table environments reduces infiltration and causes artificial rise in the water table, it has significant implications for estimating and modeling ground water recharge. Healy and Cook (2002) presented a thorough

review of methodologies to estimate recharge using groundwater levels, but commented that one of the major limitations of any method for shallow unconfined aquifer was the Lisse effect. As the artificial rise in the water table is difficult to identify it can easily be mistaken for recharge (Healy and Cook, 2002).

Accurate estimation of soil air pressure is thus of great importance for modeling runoff and water table recharge. Mathematical solutions derived from laboratory studies e.g., Wang *et al.*, (1997, 1998) provide very useful insight into the process of air entrapment, however the use of the laboratory derived equations have not been adequately tested against field conditions. Latifi *et al.*, (1994) concluded that air pressure buildup was more pronounced in soil columns of two layers than in a monolithic soil. Zhang and Ross (2006) discuss the importance and prevalence of soil layering in most coastal plane soils. Natural soil layering introduces uncertainty in the applicability of laboratory results, derived under homogenous soil conditions.

Another important aspect to note is that most of the theoretical, experimental work or field observations have been limited to an event based approach wherein the effects of single rainfall event on air pressurization/ water table fluctuation are noted and analyzed any for only short duration. For the purpose of long term modeling of stream flow and aquifer recharge a continuous monitoring and analysis is needed. For field conditions subjected to multiple events and varying antecedent conditions, air effects may become compounded and/or prolonged. Recently, Crosbie *et al.*, (2005) proposed a time series approach to infer ground water recharge using a water table fluctuation method. The approach tried to overcome the limitations mentioned in Healy and Cook (2002) and was reported to be applicable to long-term records of precipitation and water table

elevation. Even though the proposed model by Crosbie *et al.*, (2005) was innovative in its accounting for air pressurization, the model eliminated all water level rise, if the assumed criteria for Lisse effect (see Crosbie *et al.*, 2005, Equation 2) was satisfied. This may, during long continual rainfall events, neglect the actual water table rise due to wetting fronts reaching the water table.

The above discussion clearly illustrates the need for a more physically- based analysis of air entrapment over long- term (multi-event) records. The current study attempts to address this need by using shallow water table elevation records in conjunction with observed soil water content profiles that were measured during a field study. The specific objective of the investigation was to: (1) detect the presence of Lisse effect, (2) quantify the air pressurization values in field data, and (3) use quantified air pressurization values to determine the location of true elevation of the water table.

The approach used in the study was to calibrate a Richards' equation model to the observed water content profile and derive depth to water table from resultant pore water tension pressure, as it is unaffected by air pressurization. The soil moisture behavior can then be used to determine the true depth to water table. The difference between the observed and the true depth to water table will hence give the value of air pressurization (Shah *et al.*, 2006). Also a simple analysis based on ideal gas law was also done to help understand air pressurization effects.

4.2.2 Theoretical and Model Testing of Excess Pressure

Due to air entrapment, traditional rainfall infiltration models such as Green and Ampt (1911), tend to over predict infiltration with physical soil parameters in shallow

water table environments. For the current study, infiltration can be derived directly from integrated volume changes since soil water content was explicitly measured. Assuming a one dimensional soil column, integration of the soil water content values gives the total water content (TWC) per unit area of soil column at any instant in time. Subtraction of two consecutive values will, hence, give an estimate of net infiltration or net ET (depending on the algebraic sign of the difference) in the units of length. For the purposes of this study, net infiltration or net ET refers to all inflow and outflow respectively (including lateral flows) for details of the approach one is directed to Rahgozar *et al.*, (2005). Nachabe *et al.*, (2005) and Rahgozar (2006) used a similar approach to determine ET and found the methodology to give a very good match with calculated values from other methods. For this particular study, given the spatial distribution of the soil moisture sensors, a simple numerical integration was done to calculate TWC for the soil column of length 1.5 m. The mathematical equation used is

$$TWC = \sum_1^8 z_i \theta_i \quad (4.10)$$

where z_i [L] is the depth associated with each sensors, and θ_i [L^3L^{-3}] is the water content values observed at the corresponding sensor.

4.2.2.1 Numerical Model

Soil water content profiles were modeled using a single-phase, one-dimensional Richards' equation simulation model known as HYDRUS -1D (version 3) (Simunek *et*

al., 2005). Calibrated versions of this model have been used and verified in a number of studies (e.g., Hernandez *et al.*, 2003; Simunek and van Genuchten, 1999). Also, an independent team of hydrologists scrutinized HYDRUS and found the model reliable and highly capable (Software Spotlight, 2000). The model uses the Galerkin type linear finite element method for space discretization and a finite difference method for temporal discretization of the Richards (1931) equation. This equation for a one dimensional vertical column can be written as:

$$\frac{\partial \theta(z,t)}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \left(\frac{\partial h(\theta)}{\partial z} + 1 \right) \right] - S \quad (4.11)$$

where h [L] is the water pressure head, θ [L^3L^{-3}] is the volumetric water content, t [T] is time, z [L] is the spatial coordinate (positive upwards), K [LT^{-1}] is the unsaturated hydraulic conductivity, and S [$L^3L^{-3}T^{-1}$] represents the sink term. HYDRUS was previously used by Hammecker *et al.* (2003) to try and quantify the effect of air compression. The approach they used was to apply Dirichlet conditions, namely the upper boundary given by the ponding water level in the plot and the lower boundary given by the depth of the water table, as the two boundary conditions. The lack of match with the observed data was attributed to the air compression, as all the other processes were assumed to be accounted for in HYDRUS. No further analysis was done to quantify the air entrapment from the numerical solution. And limited comparisons to observed soil moisture profiles were made.

As described in Hillel (1998), due to air entrapment, the soil-water content does not attain total saturation but some maximal value lower than saturation, which he called satiation. Satiation can be taken into account by considering that the maximum water content in a soil only reaches to a value smaller than porosity, more commonly referred to as natural saturation or effective porosity (Charbeneau, 2000). Hence, laboratory determination of soil saturation water content normally overestimates the values found in the field. This phenomenon was considered in the calibration of soil parameters.

For the current investigation, data for two months (May and June) in 2002 and another two months (April and May) in 2003 were analyzed, and modeled numerically using HYDRUS. This period of record was selected because it represented the transitional months when conditions changed from very dry to very wet. Hence, a good contrast between the conditions with and without air pressurization can be expected. Due to hysteresis, the effective porosity shows a long term seasonal behavior. Hence, for calibration purposes, saturated water content values that are used correspond to the maximum water content values observed during the period of record. As expected, the values were found to be less than the laboratory determined porosity, by as much as 7-8%. Additional details and findings from this numerical model can be found in Shah *et al.*, (2006).

4.2.2.2 Calculation of Excess Pressurization using Ideal Gas Law

The difference between the d_{wT} obtained from theoretical solution (HYDRUS-1D) and field observations, gives a quantitative estimate of air pressurization. If the pressure of the entrapped air is atmospheric then the observed and the actual d_{wT} will be

at the same location, void pressures above atmospheric pressure will cause well water levels to increase because the well is only screened below the water table. The pressure of the compressed air in excess of atmospheric, herein denoted as “excess pressure”, is defined as the difference between the observed d_{WT} and the HYDRUS-1D generated d_{WT} (elevation of zero tension). It is expressed in terms of depth of water column.

In an attempt to quantify the amount of excess pressure and, potential thresholds for air eruption, a simple spreadsheet-air-excess-pressure-analysis was set up. The maximum saturated water content for every sensor from the entire period of data collection was found. To this value 7.5 % (Nachabe *et al.*, 2004) was added to account for the residual air, crudely representing the actual total soil porosity at each sensor. Multiplication of porosity by the depth associated with each sensor gives the available pore space in the soil column (per unit cross sectional area). Subtracting total soil water content obtained by integrating water content values along the soil profile (like in Equation 4.9) from the porosity gives the amount of pores filled with air in the soil column.

It is important to know the inherent assumptions involved in the spreadsheet calculation of excess pressure. The first and possibly most important assumption is that all the entrapped air present between the wetting front and the water table has the same pressure. This significant limitation will be discussed later. The second assumption is that continuous counter flow of air during an event is neglected prior to eruption. Therefore, the only way the soil air can leave the soil column is via air eruption. Finally, the temperature is assumed to be constant and the ideal gas behavior is assumed under adiabatic conditions.

Morel-Seytoux and Khanji (1975) proposed a model for quantifying air compression using Boyle's law. As Boyle's law assumes the mass of the gas to be constant, this methodology becomes invalid in case of air eruption. It is for this reason the ideal gas law is used for the spreadsheet analysis, with the underlying assumption that void air behaves like an ideal gas. Consistent with the HYDRUS solution, hourly time steps were used for pressure calculations. Thus, hourly values of total soil water content were used to determine the changes in the volume from which the void air pressure is derived.

Mathematically the ideal gas law can be defined as

$$PV = nRT \quad (4.12)$$

where P is the absolute pressure (N/cm^2), T is absolute temperature (K) assumed constant at 298K, V is volume of the void air (cm^3), n is the number of moles, and R is the gas constant [= 831.41 N-cm / (mol/ K)].

As mentioned earlier, both the simulation periods were preceded by dry conditions. Therefore, the initial pressure of the entrapped air is assumed to be atmospheric, P_0 , i.e. $10.13 \text{ N}/\text{cm}^2$. The initial volume V_0 of entrapped air was determined by subtraction of observed total soil water content (initial value) from the total pore space (constant = 68.92 cm^3) of the soil column. At the next hour the new volume of air (V_1) is similarly calculated, using the corresponding observed total soil water content. Assuming a constant temperature T , Equation 4.12, is used to determine the initial number of moles (n_0). Using n_0 and the volume at the next hour V_1 , the pressure P_1 was found again using Equation 4.12.

From this approach, excess pressure (expressed as centimeters of an equivalent water column) is determined as follows:

$$\Delta P = \frac{P_1 - P_0}{\rho g} \quad (4.13)$$

Where ΔP is the excess pressure (cm), ρ is the density of water, and g is the acceleration due to gravity, and ρg is assumed as 0.00981 N/cm^3 . Between consecutive time steps two processes are possible. First, due to net ET, the new volume of air is greater than the previous volume or secondly, due to net infiltration, voids are reduced and excess pressure ensues. It is important to note that at an hourly time step, sufficient infiltration can occur to cause the excess pressure to become quite large. Therefore, excess pressure may reach an upper limit where by rapid air eruption occurs. This breaking value, as defined in Wang *et al.* (1997), results in eruption and a lowering of air pressure values.

Consider the ET case where the volume of air increases. In this case the new value of air pressure will decrease, except that there is no wetting front to preclude air uptake by the soil from the atmospheric boundary. As a result the pressure cannot significantly decrease below atmospheric. Thus, during the spreadsheet analysis the new pressure value is made atmospheric if the solution of the Equation 4.12 results in sub atmospheric pressure during drying conditions. However, no adjustment is made if the new pressure comes out to be greater than atmospheric. One problem that remains is that the ideal gas law cannot be used to determine the air eruption thresholds. Also, as a consequence of air eruption, an undeterminable number of moles of air is lost. Hence, for the infiltration case, to incorporate air breaking value thresholds, pressures must be set through observation of the data to constrain the maximum pressure.

In the absence of any other indicators, excess pressure determined from comparison of the HYDRUS solution with the field observation, was used to limit the excess pressure values calculated in the spreadsheet. Air eruption was evident in several events in both periods, requiring constraining the maximum pressure. Thus, if the excess pressure calculated from Equation 4.13 exceeded the thresholds for air breaking derived by HYDRUS, the excess pressure was set at the threshold and the numbers of moles lost were calculated using the ideal gas law.

As will be seen later in the results section, the excess pressures calculated using HYDRUS show large variations depending on the infiltration magnitude and the antecedent conditions. However, critical thresholds were more consistent. This implies that, in order to determine air eruption for each event, different thresholds have to be set. To avoid this cumbersome approach, the analysis was done only on the events occurring in the month of May of 2002 and 2003.

4.3 IHM Testing

These last two sections investigated the methodology for soil zonation and air entrapment affects which are important factors for modeling vadose zone behavior. This section focuses on testing and model application. Limited previous work has been done to improve the concept basis of the IHM. Ross *et al.*, (2005a) made improvements to provide a smooth transition to satisfy ET demand between the vadose zone and deeper saturated ground water. While the IHM approach provides a more sound representation of the actual soil profile than original FIPR hydrologic model (FHM). Shah and Ross

(2006) explored the criteria and behavior of free vadose zone storage used in IHM and the physics and mechanics of this moisture variability. Zhang and Ross (2006) differentiated upper and lower regions of the unsaturated zone (vadose zone). Field soil moisture observations and soil characterization data were used to formulate a new basis for the upper zone and lower zone in IHM. And they developed a new methodology to describe relative moisture condition in both zones for modeling soil hydrologic response.

Within the IHM, consistent with the physical processes, the water table fluctuation, infiltration, and ET fluxes control vadose zone moisture response. With a very shallow groundwater table, the interaction between unsaturated and saturated zone becomes very strong. The groundwater table strongly influences the water content in the unsaturated part of the root zone and the groundwater table represents a moving boundary between saturated and unsaturated conditions. In testing the model behavior, questions are offered such as is the distribution of ET from interception, upper zone, lower zone and groundwater distribution reasonably simulated; are the water table fluctuations comparable, and is the infiltration to recharge behavior adequate. Aly (2005) applied a preliminary version of IHM to a small basin in West-central Florida. But, more extensive investigation of theoretical basis of the simulated vertical processes and longer-term application were still needed.

The behavior of the IHM is examined through comparisons with collected data at a study site in West-Central Florida. The objectives of this exploration were to (1) test the model of the vertical processes controlling water table behavior, ET distribution and infiltration, (2) investigate the sensitivity of model parameters, and (3) offer recommendations for improvements and parameterization for regional model application.

Rigorous testing was done to better understand the robustness and/or limitations of the methodology of the IHM for upper and lower vadose zones.

4.3.1 Site Description

The application site is shown in Figure 4.6. More information about the field study can be found in Trout and Ross (2005) and Ross *et al.*, (2005b). This watershed encompasses an area of 450 acres and is located in a shallow surficial aquifer setting within a small catchment of Long Flat Creek, a tributary of the Alafia River in West-Central Florida. The site is characterized by a shallow water table ($0 < d_{WT} < 2$ m), a thin surficial aquifer (1 to 5 meters thick) underlain by a competent clay confining unit. The site is a grassed upland area sloping at a characteristic 1-2 percent grade toward a small stream that is surrounded by a riparian forested wetland (slash pine and water oak). Average annual rainfall in this setting is approximately 140 cm. The boundaries of the watershed were defined by highly resolved topography, via 1/3 m (1ft) contour interval stereographic interpreted aerials. The basin includes isolated pothole wetlands and alluvial wetlands with some stage monitoring.

Long Flat Creek is a stream that flows from the southeast to the north-northwest through the study basin and is visible by the riparian forest that surrounds it. Two major wetlands, probably remnant sinkhole features, are present within the study area, one in the southwestern and one in the southern sub-basins (Figure 4.6). The northwest corner of the watershed contains an orange grove but otherwise it is mostly grassland with alluvial forested and marsh isolated type wetland.

4.3.2 Model Setup

For the surface water system, the watershed was subdivided into six sub-basins. Each sub-basin was further divided into land segments based on land use categories (Figure 4.6). The surface hydrology of each land segment is simulated separately as HSPF PERLND (pervious land) units. Sub-basins 1-4 include one PERLND. Sub basin 5 includes a grass (landuse ID 2 in Figure 4.6) and a citrus land segment (landuse ID 3 in Figure 4.6) and sub-basin 6 includes a grass and a mined land segment (landuse ID 4 in Figure 4.6), that is, the surface hydrology of sub-basins 5 and 6 are simulated with two PERLNDs for each sub-basin.

The groundwater system was conceptualized as a single-layer, unconfined surficial system with no-flow boundaries coincident with the topographic divides that form the boundaries of the surface basin (Aly, 2005). Greater than 12 m (40 ft) of head difference exists between the water table and the underlying confined aquifer. This head difference has been sustained over the available groundwater record (multiple decades). Therefore, the lower boundary of the single-layer system is reasonably assumed to be a no-flow boundary. Then, recharge to the water table is discharged laterally to the stream or is transported vertically to support ET demand.

4.3.3 Data Collection

Field data were collected at five-minute intervals from September 2001 until June 2004 including: soil moisture at 10 cm depth intervals, stream flow into and out of the basin, precipitation, potential ET, runoff rates from a controlled plot and complete

meteorological conditions. Also included were daily water table heads for all observation wells.

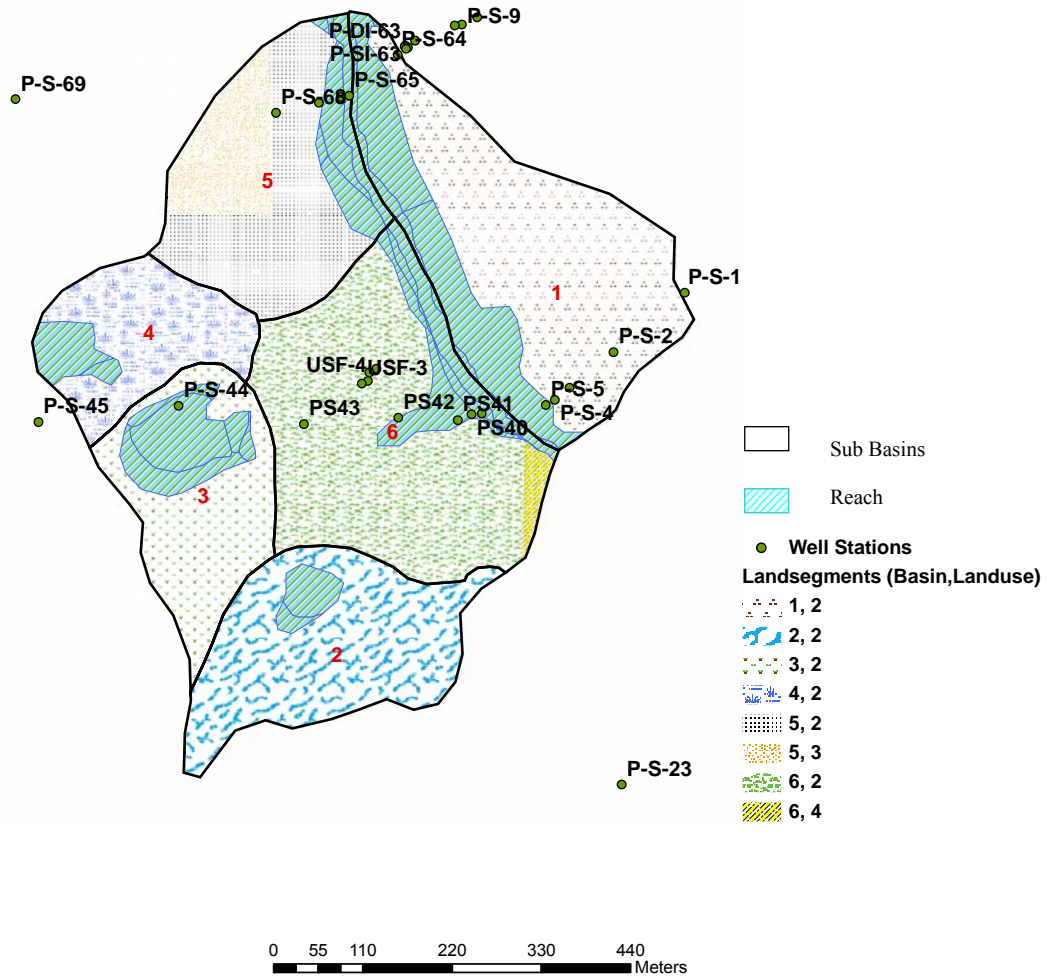


Figure 4.6. Sub-Basins, Landsegments and Observation Wells at the Long Flat Creek Study Site

4.3.3.1 Basin Landuse

The 1999 land-use map was obtained from the SWFWMD online GIS database (SWFWMD online resources). The land use and land cover features were categorized according to the Florida Land Use and Cover Forms Classification System (FLUCCS).

Each FLUCCS code was assigned to one of five general land-use categories (PERLNDs): grass or pasture, forested, irrigated agriculture, urban, and mined or disturbed.

4.3.3.2 Soil Moisture

Capacitance shift type (Sentek Model Enviro SMART) soil moisture probes were installed adjacent to monitoring wells PS43, PS42, PS41, PS40, USF1 and USF3 with manufacturer reported accuracies to $\pm 0.1\%$, and laboratory verified to 0.05% to gravimetric moisture content using specific calibration curves. Vertical resolution was achieved with sensor placement at 10, 20, 30, 50, 70, 90, 110 and 150 cm below land surface. The moisture probes from PS43 to PS40 were along a downhill transect from the upland grassed area at PS43 to the riparian forest near the stream at PS40.

4.3.3.3 Water Table

The study location was instrumented with several water table observation wells. Vented water table observation wells housed submersible pressure transducers (Northwest Inc.). The transducers were calibrated to measure pressure from 0-34 KPa (5 psi) with an accuracy of 0.034 KPa (0.005 psi).

4.3.3.4 Rainfall

Rainfall data were collected from January 2002 to July, 2004 with tipping bucket rain gauges, first laboratory calibrated and continually verified with manual (NWS type) rain gages. Five minute precipitation records were collected through the period with only minimal data gaps.

4.3.3.5 Stream Flow

Stream gages were installed near upstream, mid-stream and downstream of the basin along Long Flat Creek using installed multi-section calibrated weirs. Five minute flow records were obtained from upstream and downstream gages as inflow and outflow of the watershed with considerable data gaps due to frequent weir failures.

4.3.3.6 Potential Evapotranspiration

Potential ET (*PET*) was estimated from several sources including onsite using open pan evaporation measurements multiplied by a constant pan coefficient (0.7) and/or onsite or offsite meteorological data. More reliable PET estimates (based on comparison to open water evaporation rates) were calculated based on the empirical equation of Jensen and Haise, J & H (1963) using temperature and solar radiation records.

$$ETP_{J\&H} = \left[\frac{R_s}{2450} * ((0.025 * T_{ave}) + 0.08) \right] \quad (4.14)$$

The input parameters for the J & H equation were: instantaneous solar radiation, R [Wh/m² per hour] and daily average temperature, T_{ave} [°C]. Solar radiation and temperature data were obtained from the onsite measurements and were supplemented with Florida Automated Weather Network (FAWN) ONA (URC) data. The FAWN ONA site was selected due to the close proximity to the research site. Details of data collection can be found in Rahgozar *et al* (2005), Trout *et al.* (2005) and Ross *et al.*, (2006).

4.3.4 Model Calibration

Model calibration was used to establish the most suitable values for several key model parameters. The objective of calibration was to compare model performance to observations and to test the robustness of the model conceptual framework. Calibration was carried out for two distinct land cover types, grassed and forested land cover in the study area for the years January 1, 2002 through June 30, 2004. Parameters found by calibration included soil infiltration index (*INFILT*) and upper zone (depression) storage capacity (*UZSN*). Other parameters were found through soil analyses or published characterization data (Carlisle *et al.* 1989) pertinent calibration data are summarized in Table 4.1. The two land cover types differed greatly in ET, resistance to surface runoff and interception (i.e., vegetative parameters differed greatly), however soil properties were similar. Thus, very different plant coefficient, root zones, upper zone storage and interception parameters were used for these two land cover types (Figure 4.7a and b). In Figure 4.8a, the modified plant coefficient for grassed and forested land cover was only adjusted slightly from values derived by independent measurement of Rahgozar *et al.*, (2005).

This analysis focused on the comparison of flux rates and cumulative fluxes of ET components: interception ET (ICET), upper zone ET (UZET), lower zone ET (LZET), groundwater ET (GWET) and total ET (TAET). Also, infiltration and depth to water table (DTWT) were compared to observations.

Table 4.1. Derived Calibration Parameters for Forested and Grassed Land Cover

Parameter	Calibration Value	
	Forest	Grass
INFILT (cm/hr)	4.32	2.29
UZSN(cm)	0.05	4.06
Saturation	0.37	0.34
Field Capacity (cm/cm)	0.13	0.16
Root Zone Thickness (cm)	100	50
Capillary Fringe Thickness (cm)	30.48	30.48
Capillary Zone Thickness (cm)	100	100
Wilting Point	0.05	0.05
Hydraulic Conductivity (cm/day)	30.48	30.48

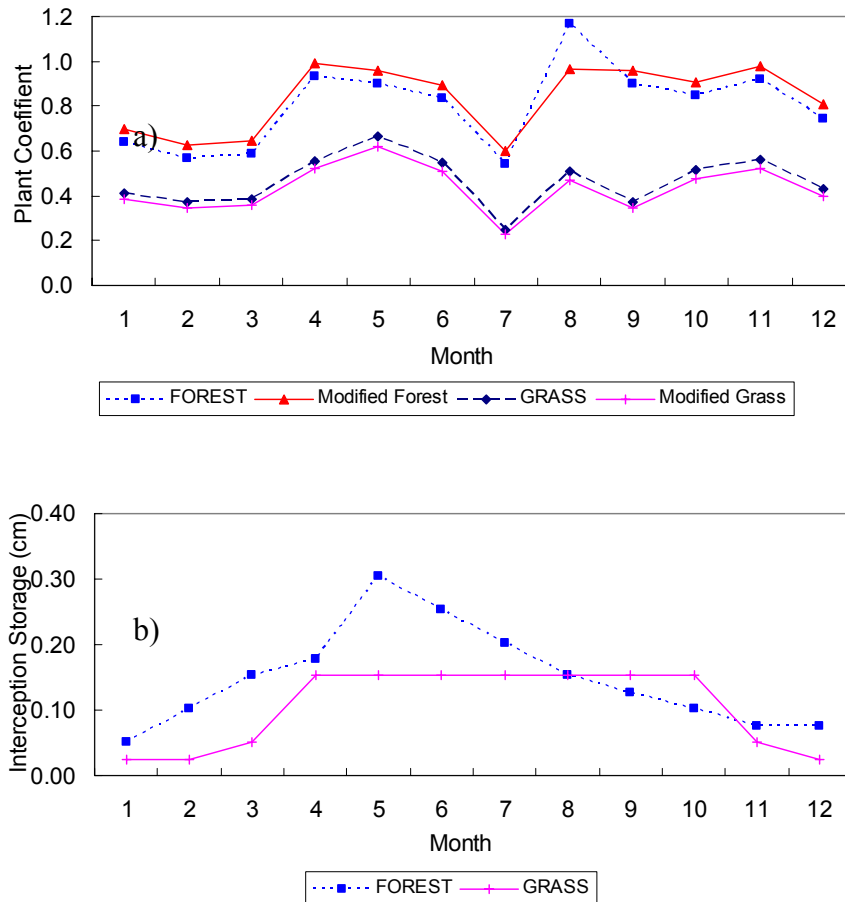


Figure 4.7. Calibration Values Used for (a) Plant Coefficient and (b) Interception Storage for Grassed and Forested Land Cover

So that appropriate processes were compared, the observed upper zone ET and lower zone ET from Rahgozar *et al.*, (2005), were plotted against lower zone ET adjusted to LZET plus GWET when the depth to water table was deeper than 30 cm (1 ft). Similarly, for the upper zone ET, UZET was added to GWET when the depth to water table was less than 30cm (1 ft) (corresponding to capillary fringe at land surface).

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results and discussion of soil zonation analysis, air entrapment analysis and IHM testing.

5.1 Soil Zonation

In West-Central Florida, a cool, dry and low ET winter season and a warm, rainy summer season constitute a typical annual climatic cycle. The seven to eight months of the dry season (usually from October to March) show rapidly changing but generally milder average temperatures and lower monthly rainfall. Rainfall in the winter is usually associated with frontal passage and with the infrequent low pressure systems that form in the Gulf of Mexico close to the Florida coast (Myers and Ewel, 1991). Winter in Florida is typically dry when there is not an El Niño effect in the Pacific. The mean monthly rainfall varies from 70 to 110 mm in North Florida, 50 to 90 mm in Central Florida, and 40 to 50 mm in South Florida (MacVicar, 1981) during this period, contrasting values two or three times that in the peak of the summer rainy season.

In general, the period March to April, in West-Central Florida, represents the driest soil moisture conditions with low rainfall and high springtime ET stress. This

combination results in the deepest water table conditions. While from June to September, West-Central Florida experiences high rainfall, high ET, and shallow but rapidly fluctuating water table. Referring to Figure 5.1, the broad summer rainfall peak from June through September was slightly wetter than normal for the period. Typically, rainfall accounts for 50-60 percent of the annual total during the 3-month period.

5.1.1 Moisture Conditions for the High ET Period

For the high ET period analysis, the four months that make up the wet season (June through September, 2003) were chosen this period usually shows relatively uniform high temperatures, high solar radiation, and high monthly rainfall. In 2003, the period from April to Aug (4/1/2003-8/31/2003), an unusually high rainfall accumulation of 96.5 cm was observed at the site. Expected for high ET and frequent rainfall during this period, total soil moisture showed much temporal variability in both the upper and lower zone (Figure 5.1b, g, d and i) for both forested and grassed cover; while the resultant relative moisture, \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} (Figure 5.1c, h, e and j) for forested and grassed cover clearly showed more uniform response (little variability between similar stations) and thus reducing field-scale variability. Relative moisture also showed strong dynamic fluctuation early in this period. Interestingly and somewhat expected, relative moisture fluctuation was greatly dampened when water table was at land surface.

5.1.2 Moisture Conditions for the Low ET Period

Examining a low ET period (11/1/2003-12/31/2003), with an associated observed rainfall sum of 70 mm, the total soil moisture and corresponding upper zone

and lower zone relative moisture behavior were quite different. During the November to December period, a characteristic low ET rate and low rainfall accumulation followed a prolonged period of above average rainfall 30.48 cm (12 in) in the proceeding 15 months; yet, the water table became deeper during this period. Referring to Figure 5.2, comparing the distinct vegetative cover groups, the relative moisture in the upper and lower zone exhibited similar behavior within a group, but distinctly different behavior between groups (Figure 5.2c, h, e and j). It was also observed that the water table (Figure 5.2a, f) and the total soil moisture (Figure 5.2b, g, d and i) are on decline while relative moisture both in the upper and lower zone, showed variability and periodic increases. Again, similar to what was observed in the high ET period, relative moisture shows differences in upper and lower zone.

5.1.3 Statistical Summary and Discussion

Summaries of statistical analysis are provided in Table 5.1 and Table 5.2 to compare the relative moisture condition and actual total soil moisture mean and standard deviation for the different vegetative cover groups.

In Table 5.1, both high ET (a) and low ET (b) periods are compared. Relative moisture in both soil zones, \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} , show consistency with values around unity (1) for all wells (this is also consistent with observed rainfall being close to seasonal average most periods). Given the high water table fluctuation characteristic of this period, the mean of the total soil moisture shows much more variability (coefficient of variation, CV's 6-28% shown in Table 5.2). But for both upper and lower zone, the variability of

actual soil moisture exhibited from one site to another is very large while relative moisture condition, \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} , is more consistent. It was also observed that depth to

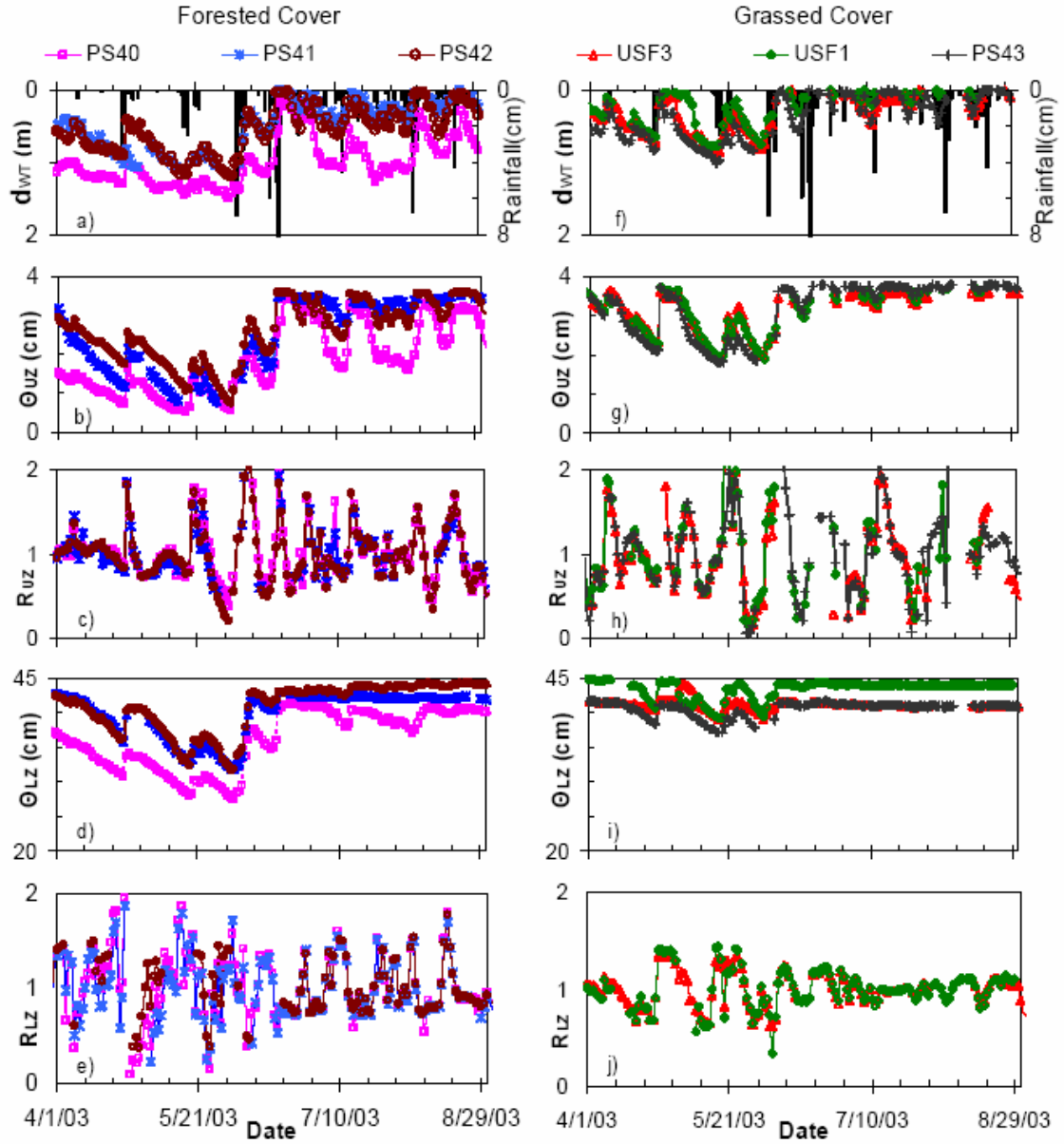


Figure 5.1. Upper and Lower Zone Total Soil Moisture vs. Relative Moisture for Representative High ET Period (Apr. - Aug. 2003) for Forested (a-e) and Grassed (f-j) Cover

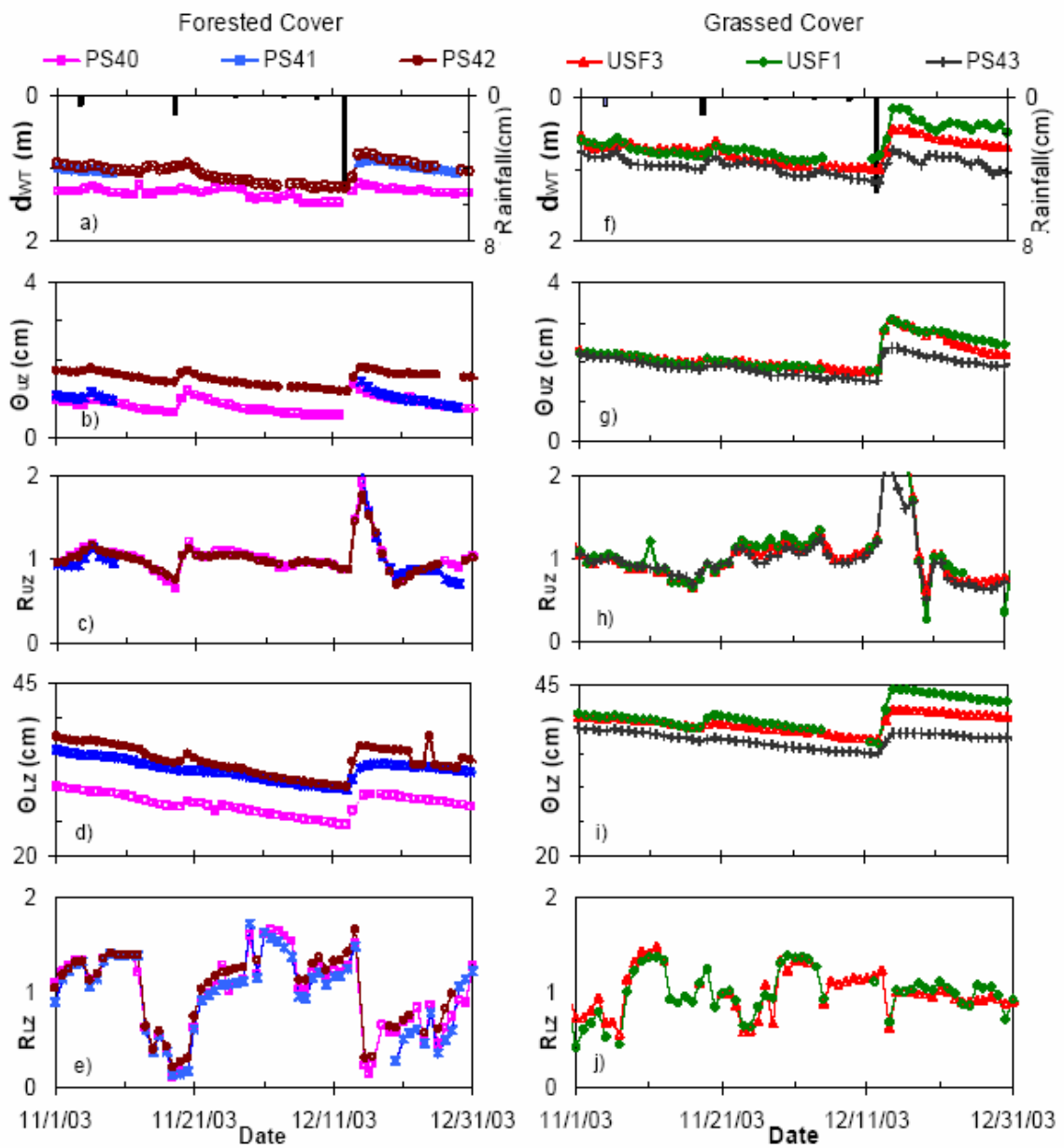


Figure 5.2. Upper and Lower Zone Total Soil Moisture vs. Relative Moisture for Representative Low ET Period (Nov. - Dec. 2003) for Forested (a-e) and Grassed (f-j) Cover

Table 5.1. Statistical Results for Relative Moisture Condition, \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} and Total Soil Moisture, Θ_{UZ} and Θ_{LZ} for both Upper and Lower Unsaturated Zone by Landuse Group in Selected a) High ET (4/1/2003-8/31/2003) and b) Low ET (11/1/2003-12/31/2003) Periods

a)

High ET Period	Grassed Land Cover			Forested Land Cover		
	USF3	USF1	PS43	PS40	PS41	PS42
\mathfrak{R}_{UZ}	0.990	0.983	1.016	1.003	1.017	1.005
\mathfrak{R}_{LZ}	0.999	0.999	0.999	1.009	1.016	1.009
Θ_{UZ} (cm)	3.08	2.95	3.18	1.85	2.48	2.59
Θ_{LZ} (cm)	41.22	43.47	40.61	36.09	39.96	40.83
Depth to Water Table (m)	0.360	0.311	0.376	0.994	0.494	0.550

b)

Low ET Period	Grassed Land Cover			Forested Land Cover		
	USF3	USF1	PS43	PS40	PS41	PS42
\mathfrak{R}_{UZ}	0.994	1.018	0.995	1.007	0.995	1.005
\mathfrak{R}_{LZ}	1.004	0.994	1.008	0.984	0.967	1.002
Θ_{UZ} (cm)	2.18	2.23	1.90	0.84	1.02	1.52
Θ_{LZ} (cm)	39.44	40.71	36.97	27.53	32.48	33.83
Depth to Water Table (m)	0.744	0.629	0.950	1.340	0.993	1.056

water table in grassed cover averaged shallower for both periods than forested cover considering both the observed behavior (Figs. 5.1 and 5.2) and the summary statistics (Table 5.1 and 5.2), even though the forested cover is considered a “wetland” and the grassed cover was further up the hillslope and considered an “upland” community. Relative moisture was also much more dynamic than total moisture or moisture concentrations reflecting variability in antecedent condition. But, relative moisture was much more consistent between stations indicating that the stations were all in similar antecedent condition at any time.

Table 5.2. Statistical Results for Relative Moisture Condition, \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} and Total Soil Moisture, Θ_{UZ} and Θ_{LZ} in Upper and Lower Unsaturated Zone by Landuse Groups for All Data Periods (1/1/2002-6/27/2004), (a) Forested Cover; (b) Grassed Cover

a)						
Comparison	Forested Land Cover	\mathfrak{R}_{UZ}	\mathfrak{R}_{LZ}	Θ_{UZ} (cm)	Θ_{LZ} (cm)	Depth to Water Table (m)
Individual	PS40	0.999	0.999	1.53	32.16	1.141
Station	PS41	1.001	0.998	2.39	37.45	0.735
Means	PS42	1.001	0.998	2.36	37.46	0.727
Mean Daily Comparison*	Mean	1.008	1.015	1.99	35.72	
	Standard Deviation	0.055	0.057	0.51	3.41	
	Coefficient of Variation (%)	5.7	4.9	28.2	9.7	
b)						
Comparison	Grassed Land Cover	\mathfrak{R}_{UZ}	\mathfrak{R}_{LZ}	Θ_{UZ} (cm)	Θ_{LZ} (cm)	Depth to Water Table (m)
Individual	USF3	1.004	1.022	2.8	39.59	0.548
Station	USF1	0.995	1.02	2.79	42.76	0.51
Means	PS43	1.000	1.009	2.76	39.02	0.625
Mean Daily Comparison*	Mean	1.026	1.022	2.84	40.43	
	Standard Deviation	0.0598	0.044	0.226	2.598	
	Coefficient of Variation (%)	6.4	4.2	11.3	6.6	

*statistically summaries are means of the daily comparisons with respect to average daily moisture conditions for stations with similar vegetative cover.

One final point is that the method for expressing relative moisture presented herein does not dampen the overall description of antecedent moisture condition. In fact, it accentuates the quantification of relative moisture state: wet or dry. An analysis of the relative moisture, overall coefficient of variability ($CV = \text{overall standard deviation/overall mean}$), showed that for the upper zone CV was 50% and the lower zone CV was 40% compared to CV for the total moisture content values which was 30% and 20%, respectively. Further discussion of this significance can be found in Zhang and Ross (2005).

5.2 Air Entrapment

Figure 5.3 a and b shows the variation of excess pressure calculated from spreadsheet analysis of void air pressures using the ideal gas law along with the HYDRUS solution, and the observed d_{WT} . The number and variation of air moles are also included in the figure to demonstrate air eruption. A review of Figure 5.3 (a) and (b) shows that rate of pressure decline calculated from the spreadsheet was significantly more than the decline calculated from HYDRUS. The results from the spreadsheet analysis raise a big question: what is going on with air pressure in shallow d_{WT} environment and why are the air excess pressure periods so prolonged? Another observation might be that Richards' equation solution may not represent d_{WT} and infiltration behavior well enough in shallow water table settings to reasonably quantify runoff (Hortonian or saturation excess) and recharge processes. In an attempt to answer this question and investigate the profound observation, basic processes in porous gas behavior need further exploration.

Richards' equation as solved by HYDRUS ignores void air pressurization. Hence for all boundary conditions and soil moisture variation it solves for d_{WT} , as the elevation of atmospheric moisture pressure (zero suction). The spreadsheet solution discussed on the other hand is highly dependent on the soil air volume changes from which (uniform) excess pressure is calculated. The spreadsheet solution did not take any soil property, or variability in air pressurization into account. The only driving variable in the spreadsheet solution was the change in void air volume, which is inherently assumed to be occurring

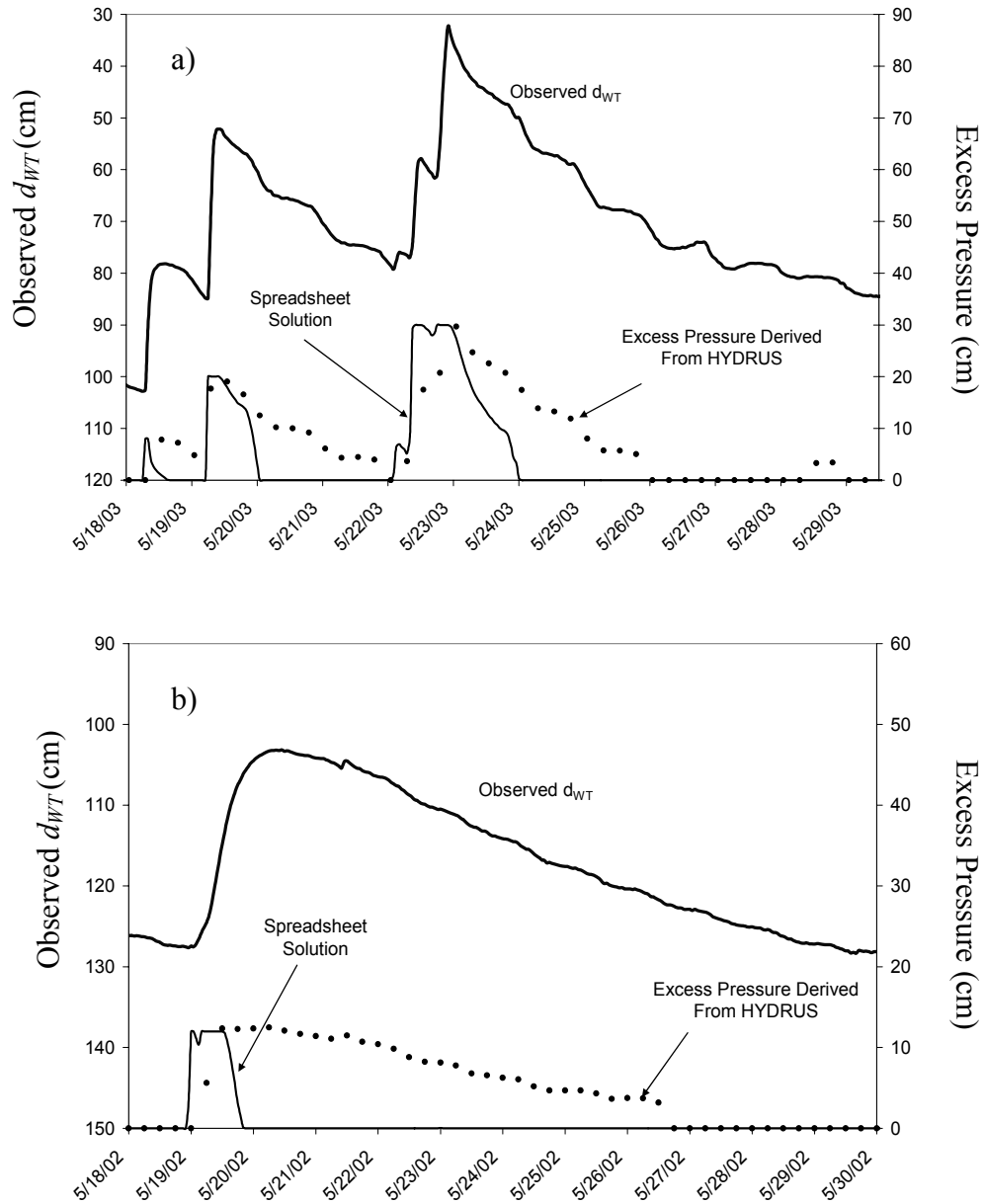


Figure 5.3. Excess Pressure as Calculated from a Spreadsheet Solution of the Ideal Gas Law and a HYDRUS Solution. Figures Show Pressure Variation for a) May 2003 b) May 2002

between the wetting front and the water table and was always assumed uniformly distributed. Further analysis of the physical process responsible for this curious behavior is strongly warranted. It would strongly warrant pore pressure and soil tension measurements in addition to water content and water elevation measurement.

5.3 IHM Testing

5.3.1 Sensitivity Analysis

Parameter sensitivity analysis yields an indication of the importance of a parameter on the model result. Small changes in the values of highly sensitive parameters produce large changes in model predictions and, conversely, large changes in insensitive parameters have little effect on the model results (Said *et al*, 2006; Doherty, 2001a).

The following parameters were tested in the IHM field-scale application: saturation (SA), field capacity (FC), upper zone nominal storage (*UZSN*), root zone thickness (RZ), capillary fringe thickness (CF), index of mean soil infiltration rate (*INFILT*) and plant coefficient (PC). The results of sensitivity analysis for process responses of: total ET, upper zone ET, lower zone ET, groundwater ET, recharge, runoff, infiltration and depth to water table, are listed for each of the estimated parameters in Table 5.3. Parameters were varied within reasonable physical ranges, resultant model response was compared to the original calibration response and results presented in Table 5.3 for grassed land cover and Table 5.4 for forested land cover. Table 5.3 a) lists the respective parameter setting and process relative change (%) and b) averaged sensitivity (process change / % parameter change for the range) for grassed land cover. Similar results are shown in Table 5.4a) and b) for forested land cover.

Of special interest for ET was the sensitivity results for seasonal plant coefficient variability carried out using three shape functions designated as: PC1, PC2 and PC3 for forested land cover. Forested land cover was used because it has a deeper root zone, therefore, it was believed that the plant coefficient would be considered to have more effect on lower zone and water table ET. Distribution PC2 is constant representing the averaged 12 month value from PC1 (found through measurements by Rahgozar *et al.*, (2005) which is used in Figure 4.8 (a) for forested land cover. PC3 is adjusted to the values and distribution reported by Aly (2005).

5.3.2 Results and Statistics Analysis

The cumulative ET flux (total ET, lower zone ET, upper zone ET and interception ET) comparisons to observations are shown in Figure 5.4 (a) for grassed and (b) for forested land cover. Model calibration statistics are presented in Table 5.5 for daily time scale and two different land covers: (a) grassed and (b) forested. Widely used error statistics are reported including: mean error (ME), root mean square error (RMSE) and mean absolute error (MAE). Scrutiny of error results indicates that model simulated results for ET fluxes compared reasonably well for all processes. For example, daily UZET for grassed land cover was 0.002 cm, 0.102 cm and 0.064 cm for ME, RMSE and MAE respectively and 0.002 cm, 0.065 cm and 0.028 cm for forested land cover for the calibration period.

In addition to comparing cumulative ET flux, the daily (temporally variable) ET flux performance is shown in Figure 5.5, 5.6 and 5.7 for total ET, lower zone ET and

Table 5.3. Model Sensitivity Analysis from Calibration Parameters for Grassed Land Cover

Tests	Parameters Settings					Parameter Relative Change (%)	Process Relative Change (%)							
	Saturation	Field Capacity	UZSN (cm)	CF (cm)	Root Zone (cm)		TAET	UZET	LZET	GWET	Recharge	Runoff	Infiltration	DTWT
1	0.35	0.15	0.38	30.48	50	Basis run	This is the basis run for comparison							
2	0.3	0.15	0.38	30.48	50	-14	-0.9	-0.4	-1.3	-1.1	-6.3	1.9	-0.5	1.6
3	0.47	0.15	0.38	30.48	50	34	2.2	-4.2	5.2	3.2	12	-4.5	2.4	-3.6
4	0.35	0.1	0.38	30.48	50	-33	-0.8	2.5	-2.3	5	19.7	2.9	-3.7	-1.4
5	0.35	0.2	0.38	30.48	50	33	0.1	-0.9	0.5	-3.5	-23.4	-1.6	3.2	2.5
6	0.35	0.15	0.18	30.48	50	-53	-2.5	-35.3	10.3	12.1	11.7	6.4	7.5	2.9
7	0.35	0.15	0.56	30.48	50	47	1.6	19	-5	-6.7	-8.3	-4.3	-3.7	-2.1
8	0.35	0.15	0.38	15.24	50	-50	0.9	21.8	-7.4	23.8	35.3	-10.5	23.7	-25.8
9	0.35	0.15	0.38	45.72	50	50	-0.3	-3.7	1	3.4	6	2.9	-2.2	12.7
10	0.35	0.15	0.38	30.48	25	-50	-4.6	7	-10.4	-6	-5.4	9.9	-8.5	-11.7
11	0.35	0.15	0.38	30.48	100	100	-1.2	1.6	-2.6	-1.8	-1.8	2.4	-2	-2.7

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a)

Parameter	Average Sensitivity							
	TAET	UZET	LZET	GWET	Recharge	Runoff	Infiltration	DTWT
Saturation	0.06	-0.05	0.12	0.08	0.39	-0.13	0.05	-0.11
Field Capacity	0.01	-0.05	0.04	-0.13	-0.65	-0.07	0.10	0.06
UZSN Capillary Fringe	0.04	0.53	-0.15	-0.19	-0.20	-0.11	-0.11	-0.05
Root Zone	-0.01	-0.23	0.08	-0.23	-0.33	0.11	-0.24	0.30
	0.01	-0.02	0.03	0.01	0.01	-0.03	0.02	0.03

b)

Table 5.4. Model Sensitivity Analysis from Calibration Parameters for Forested Land Cover

Tests	Parameters Settings			Parameter Relative Change (%)	Process Relative Change (%)							
	Plant Coefficient	INFILT (cm/hr)	Root Zone (cm)		TAET	UZET	LZET	GWET	Recharge	Runoff	Infiltration	DTWT
F1	PC1	2.54	100	Basis run	This is the basis run for comparison							
F2	PC2	2.54	100	See Fig 5.11	-0.14	0.32	-0.28	-4.09	-2.82	0.25	-0.5	-0.23
F3	PC3	2.54	100	See Fig 5.11	-0.39	68.76	16.31	27.77	1.8	1.48	15.57	-0.86
4	PC1	1.27	100	-50	-0.27	5.05	-1.63	-6.32	-9.22	5.57	-8.08	7
5	PC1	3.81	100	50	0.06	-2.87	0.79	4.64	3.83	-2.28	3.93	-3.32
6	PC1	2.54	50	-50	-4.21	6.89	-7.82	-5.09	-4.4	9.73	-6.03	-10.82
7	PC1	2.54	200	100	2.28	-3	4.05	4.45	3.87	-4.91	3.12	5.89

a)

Parameter	Average Sensitivity								
	TAET	UZET	LZET	GWET	Recharge	Runoff	Infiltration	DTWT	
PC1	See Figure 5.11								
PC2									
PC3									
INFILT	0.00	-0.08	0.02	0.11	0.13	-0.08	0.12	-0.10	
Root Zone	0.06	-0.10	0.12	0.10	0.08	-0.15	0.09	0.17	

b)

upper zone ET respectively. In Figure 5.5, the simulated TAET pattern (Figure 5.5 a, b) is generally similar to observed values with a good-to fair $R^2=0.59$ (Figure 5.5c) for grassed and 0.57 for forested (Figure 5.5d). Patterns also matched for lower zone ET for both land cover (Figure 5.6) with fair R^2 values of 0.55 and 0.52, respectively. From Figure 5.7, however, it seems the model always over-predicted the upper zone ET, especially during the months of July and August which is indicated by R^2 values lower than 0.4. One possible reason may be the upper zone in the model conceptually represents only depression storage (surface based ET) and the observed UZET represented an estimated for depression storage ET based on PET measurement only when water table is very close to land surface, primarily in the wet period (July and August). As pointed out in Rahgozar *et al.*, (2005), the measurement method of Rahgozar (2006) does not provide direct measurement of PET for water table elevations at or near land surface.

Table 5.5. Model Daily Performance Statistics for (a) Grassed and (b) Forested Land Cover

a)	Model Performance (Grassed Land Cover)	Statistics on Daily Values for All Periods		
		Mean Error (cm)	Root Square Mean Error (cm)	Mean Absolute Error (cm)
	UZET	0.002	0.102	0.064
	LZET	-0.002	0.085	0.064
	TAET	0.107	0.161	0.122
	ICET	-0.001	0.053	0.026
	INFILTRATION	-0.022	0.350	0.083
	DTWT	-1.194	1.949	1.537

b)	Model Performance (Forested Land Cover)	Statistics on Daily Values for All Periods		
		Mean Error (cm)	Root Square Mean Error (cm)	Mean Absolute Error (cm)
	UZET	0.002	0.065	0.028
	LZET	0.002	0.108	0.081
	TAET	0.004	0.146	0.089
	ICET	0.000	0.062	0.030
	INFILTRATION	-0.039	0.360	0.104
	DTWT	0.003	1.817	1.348

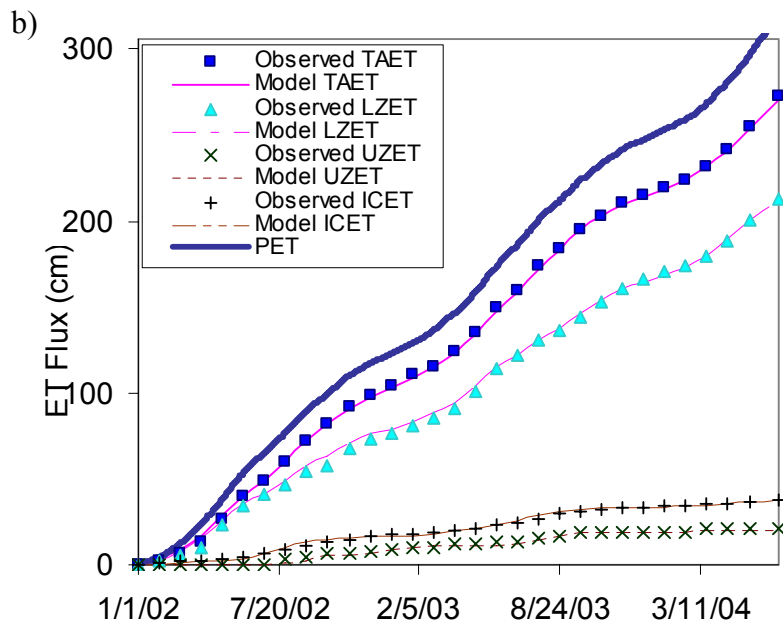
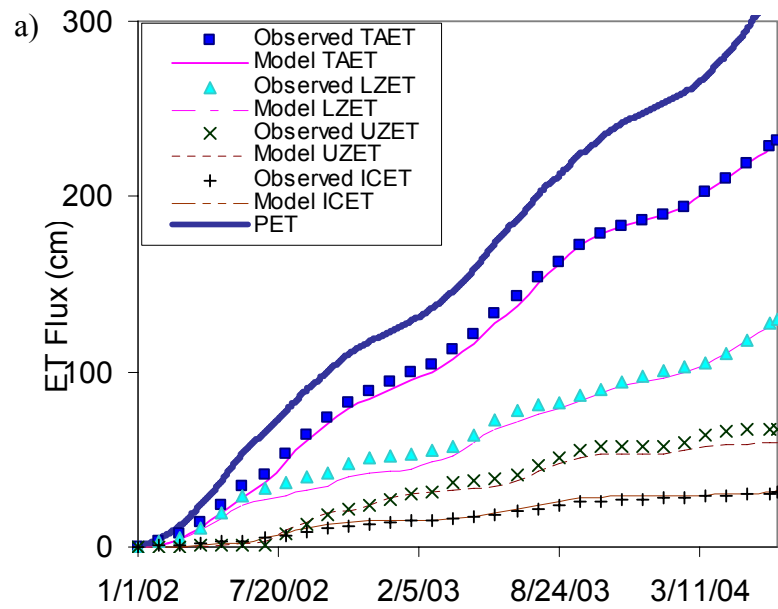


Figure 5.4. Calibration Results for Cumulative ET Fluxes for (a) Grassed and (b) Forested Land Cover

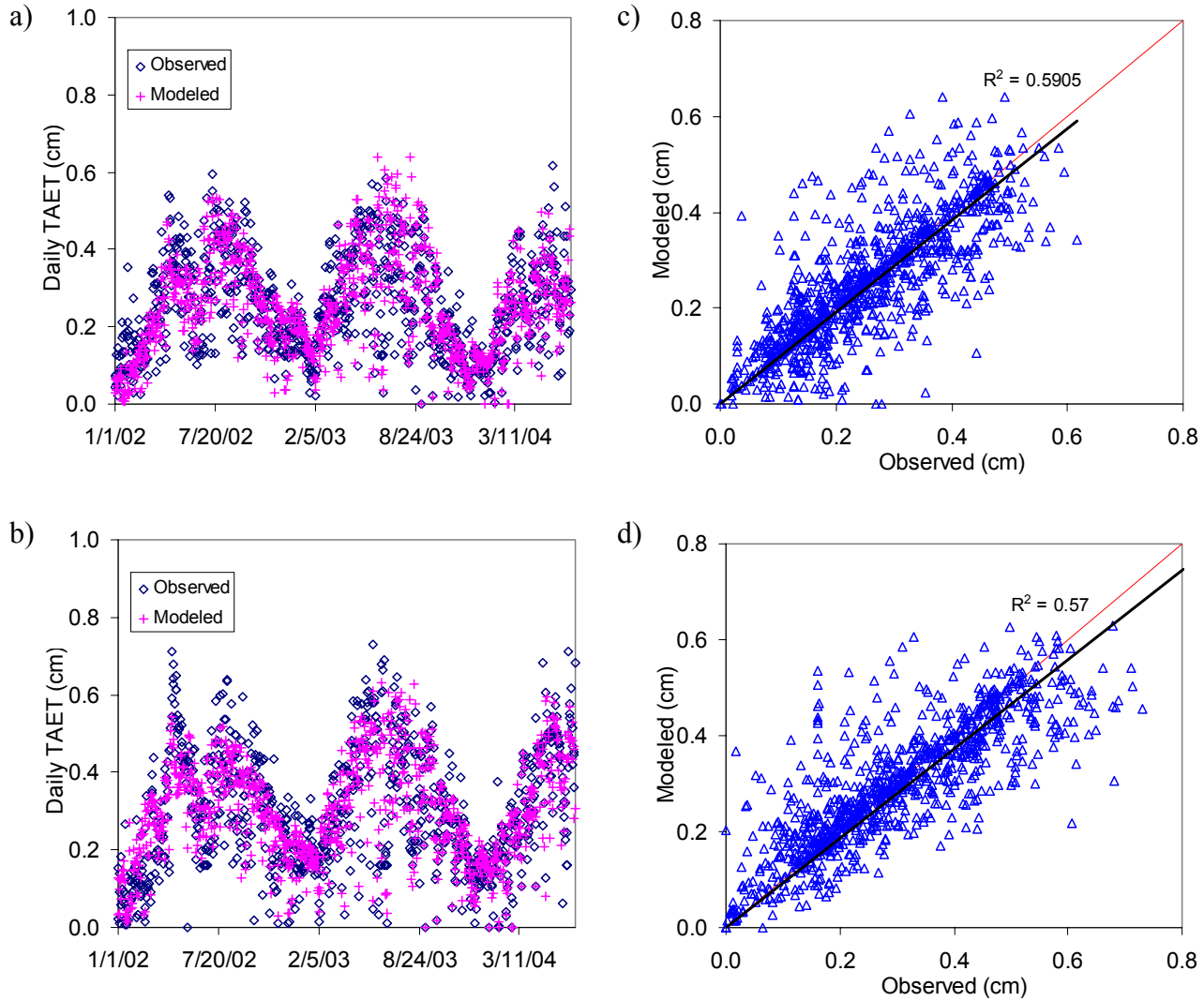


Figure 5.5. Calibration Results for Daily Total ET Flux for (a) & (c) Grassed and (b) & (d) Forested Land Cover

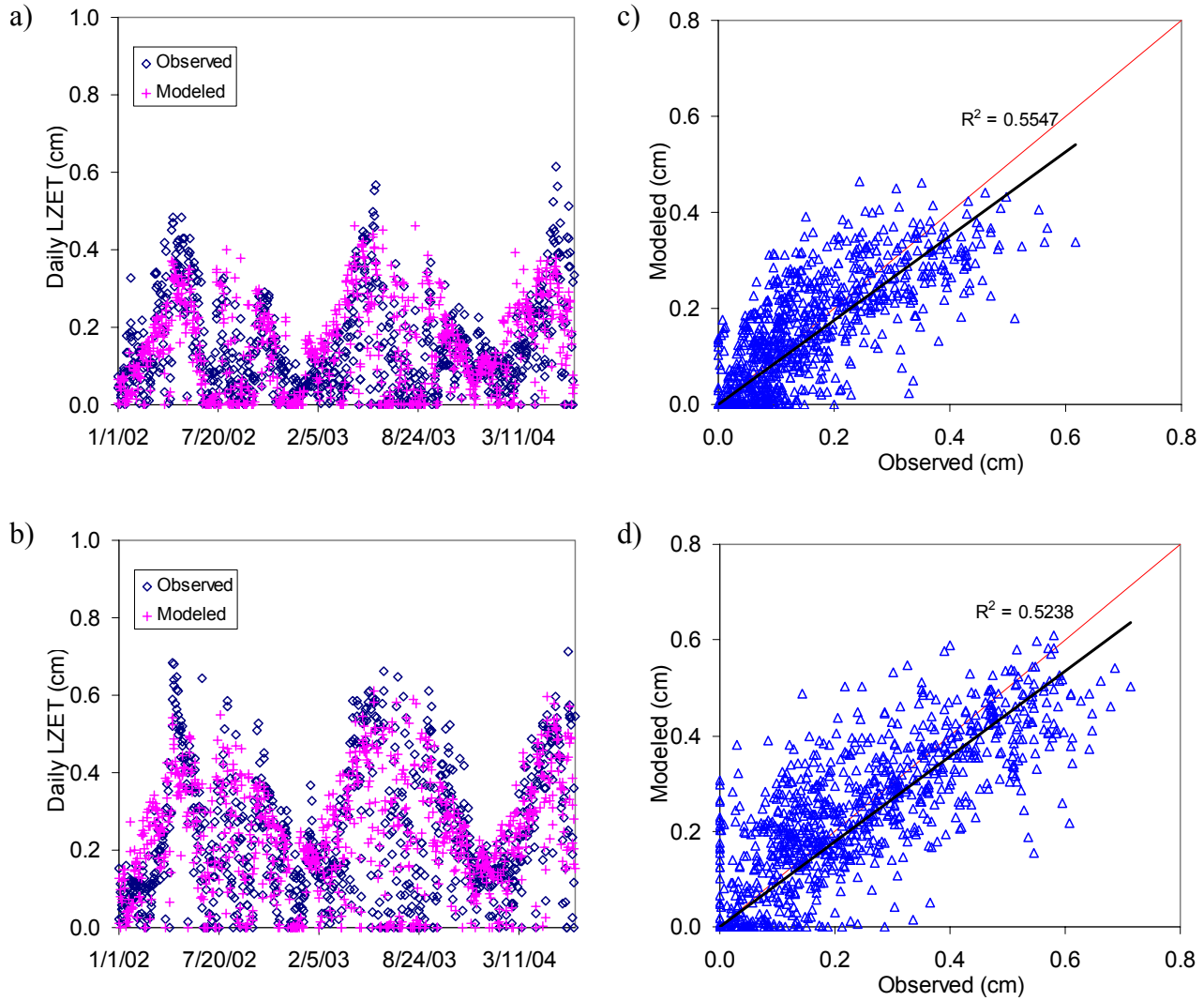


Figure 5.6. Calibration Results for Daily Lower Zone ET Flux for (a) & (c) Grassed and (b) & (d) Forested Land Cover

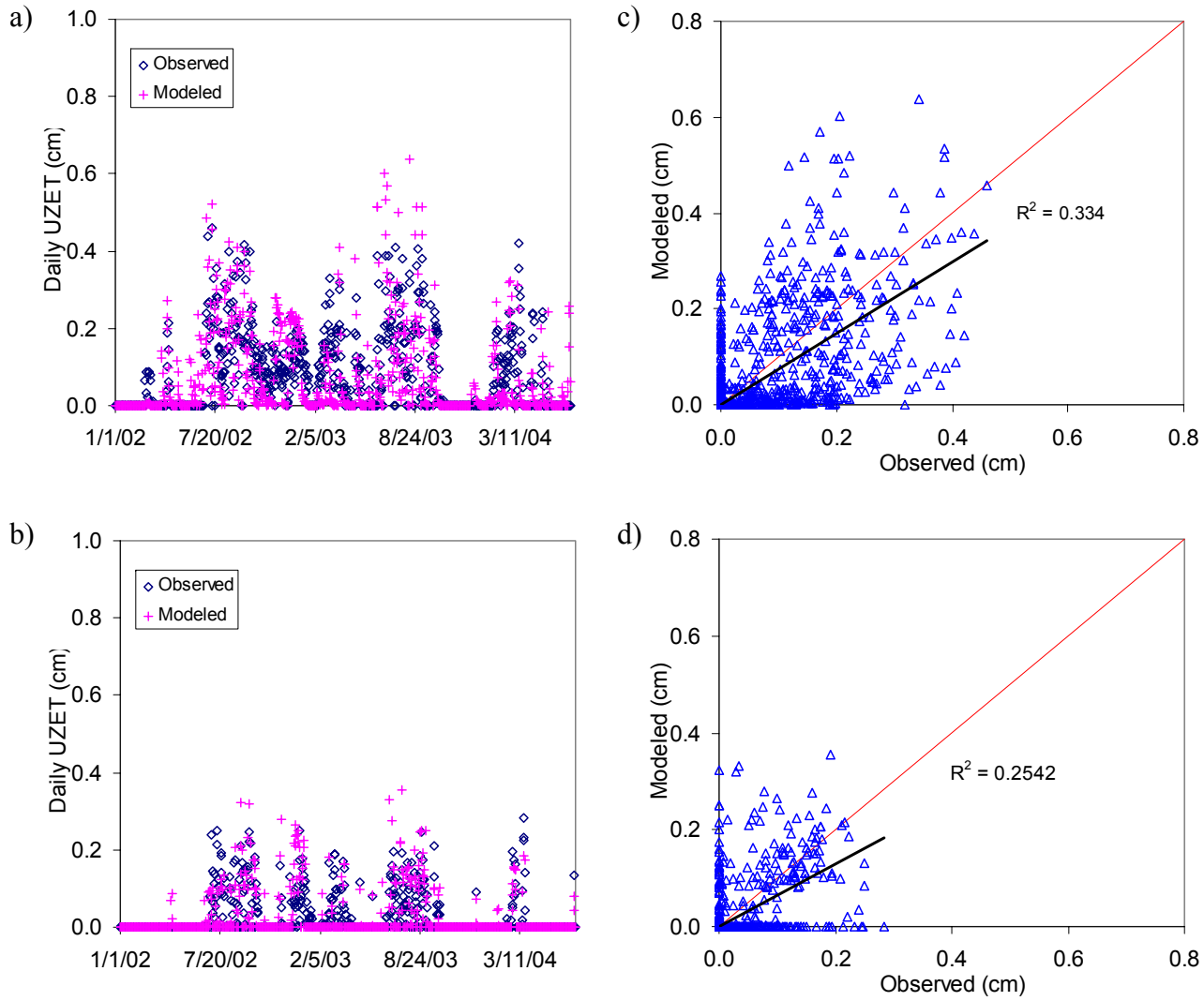


Figure 5.7. Calibration Results for Daily Upper Zone ET Flux for (a) & (c) Grassed and (b) & (d) Forested Land Cover

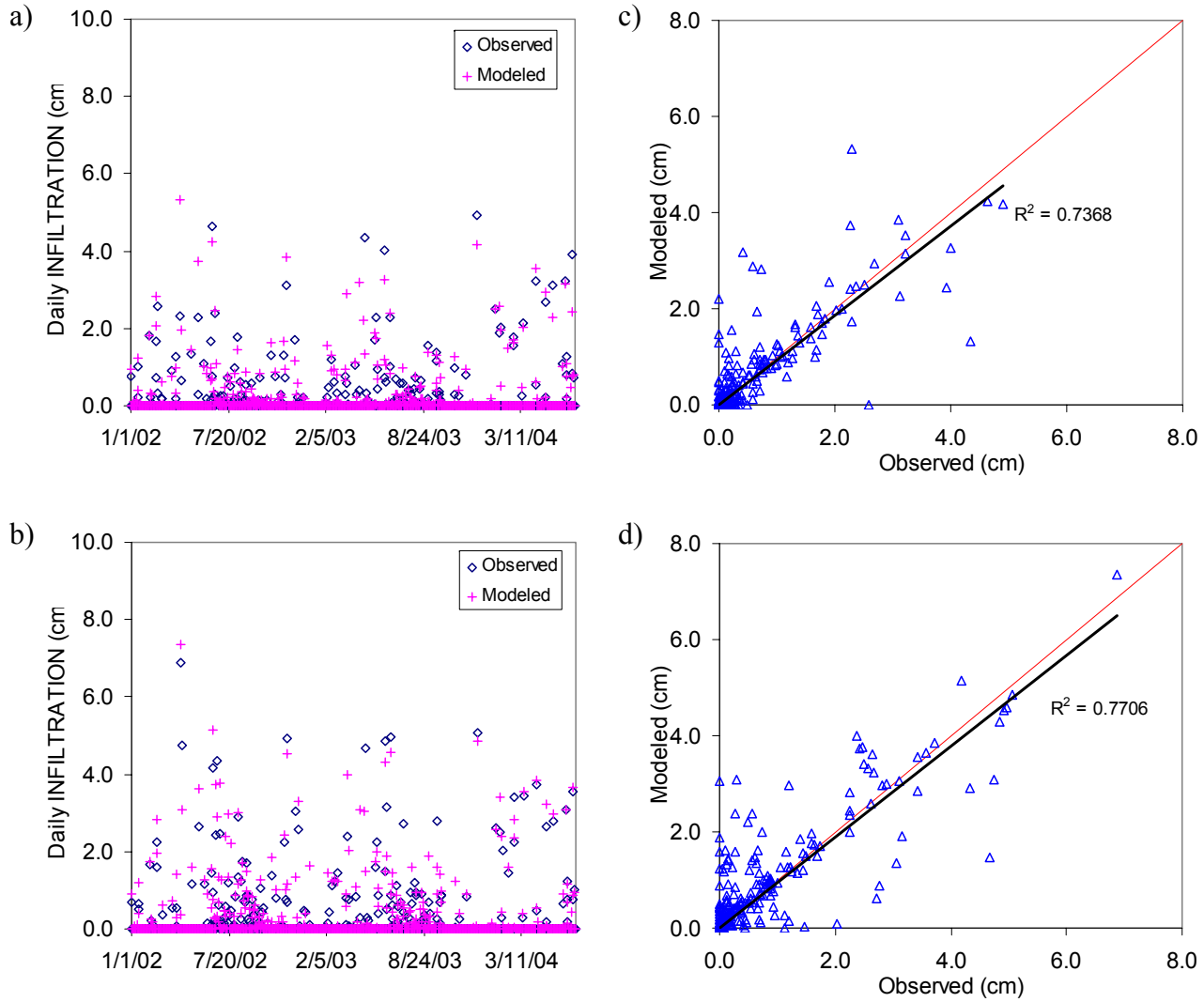


Figure 5.8. Calibration Results for Daily Infiltration for (a) & (c) Grassed and (b) & (d) Forested Land Cover

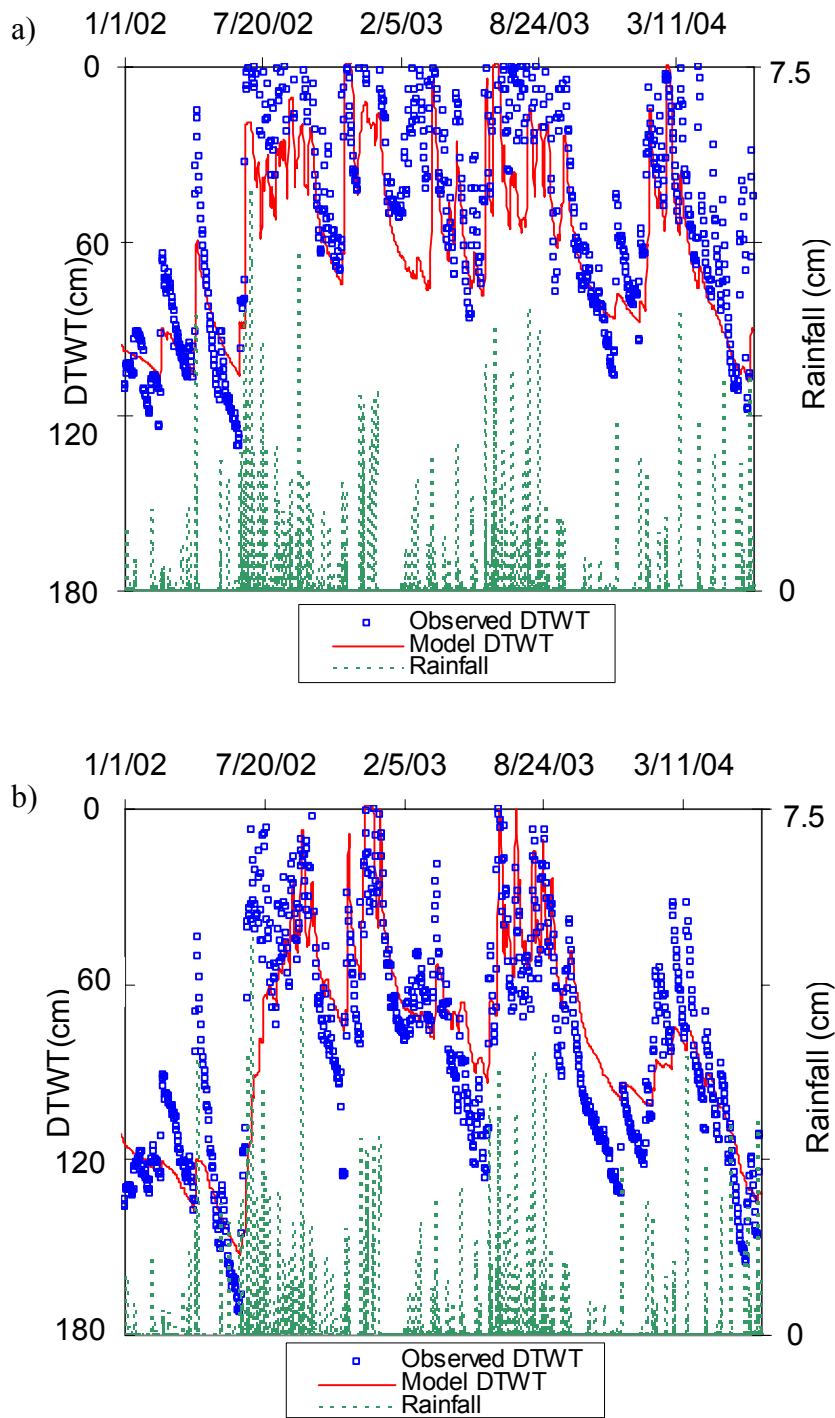


Figure 5.9. Calibration Results for Depth to Water Table for (a) Grassy and (b) Forested Land Cover

Comparing Figure 5.4 to Figures 5.5-5.7, the cumulative ET (total and all ET components in Figure 5.4) compares much better than the daily totals (Figures 5.5-5.7). The possible reason why the R^2 for daily rates are not very high even though the cumulative plots compare well may be from small differences in time scale between the observed data, derived by integrated soil moisture observations and the conceptualization of ET response in the model. A time scale example is shown in Figure 5.10, compared to Figure 5.5(d) with $R^2 = 0.57$, it is dramatically increased to 0.73 by plotting modeled and observed values using 3-day central averaging (Figure 5.10 a). Interesting only modest improvement is achieved with 5-day moving averages (Figure 5.10 b). For both observations and model behavior, daily comparisons were derived from midnight to midnight totals. It should be noted that, Rahgozar (2006) reported that soil moisture observations exhibit an inherent delay in moisture flux observations of several hours, also shown in Rahgozar *et al.*, (2005).

Infiltration values were also compared against observations as a de-facto test on model rainfall excess (runoff) prediction. Figure 5.8 shows that the model results compared to observations of daily infiltration volumes during the period with $R^2 = 0.74$ for grassed and 0.78 for forested land cover. One interesting note from the daily scatter plot in Figure 5.8a and b is that, there were periodically significantly “over-predicted” infiltration volumes during April to July, 2002 that occurred for both of these land covers. Further investigation of this observation will be discussed later.

Another observation was that the forested land cover with deep rooted vegetation and higher ET stress, exhibited profound difference in other fluxes (e.g., infiltration and runoff) when compared to grassed land cover even though the soils were similar. This is

attributed to higher ET demand whereby water table elevations average lower. The effects on the water table are illustrated in Figure 5.9 (a) for grassed and (b) for forested land cover. It can be noted that, contrary to typical hillslope models, the lower forested area exhibited frequently deeper water table than the upper grassed domain owing principally, it is believed, to the high ET demand of the forested land cover. It is noted that the model reasonably simulates fluctuation of depth to water table during deeper periods and more poorly during near-surface water table conditions. It was found that during July to September, 2002 at the site the water table was above the land surface about 75% of the time (Aly, 2005). From Figure 5.9, the simulated depth to water table for this period was consistently below the observed values. Aly (2005) also observed this behavior during earlier testing of the IHM. Reasons for the poorer performance for near-surface water table are unclear.

5.3.3 Discussion

The results described above for the daily observed and simulated component ET fluxes, depth to water table and infiltration indicated reasonably good calibration for the period. Most of the ET fluxes were reproduced by the IHM model either temporal (daily scale) or cumulative with small mean and absolute errors. The calibration sensitivity analysis suggests several issues warrant further discussion.

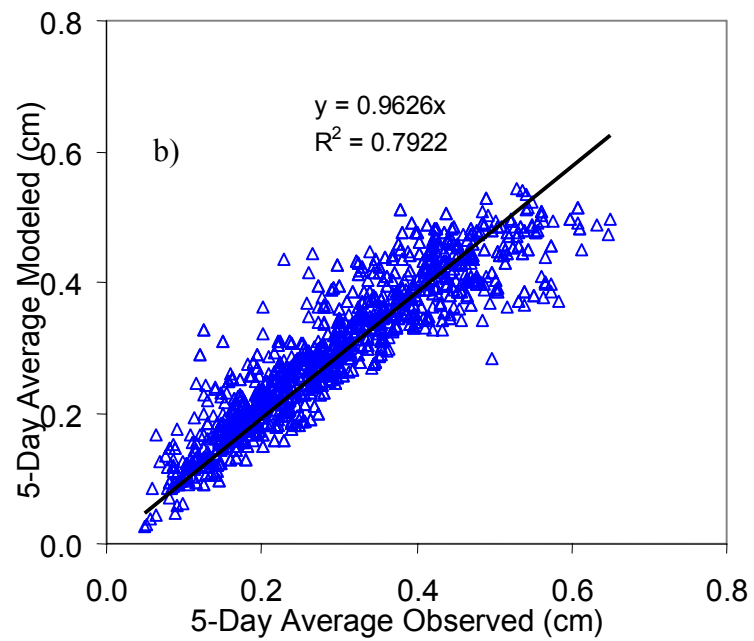
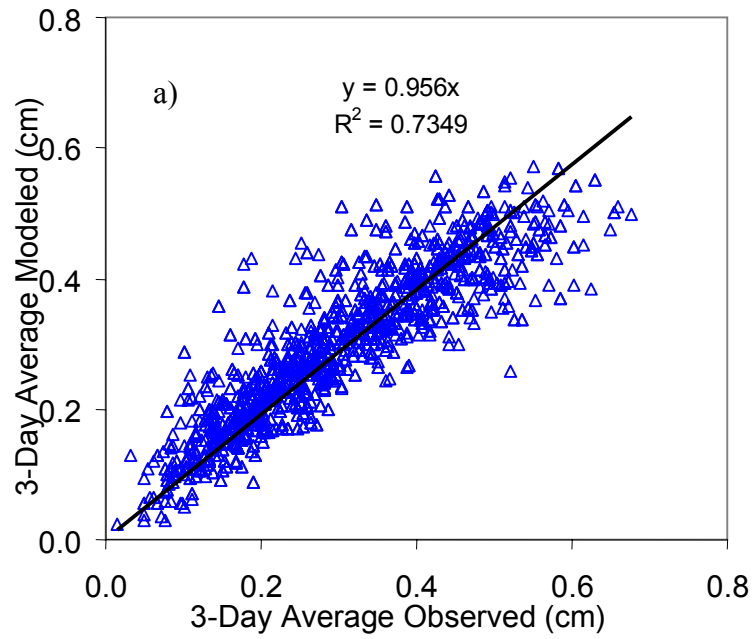


Figure 5.10. Time Scale Analysis on Daily TAET for Forested Land Cover
 (a) 3-Day Average (b) 5-Day Average

5.3.3.1 Calibration Parameters

5.3.3.1.1 UZSN and UZET

From the sensitivity analysis in Table 5.3 b, it was found that UZET is, not surprisingly, very sensitive to *UZSN* (sensitivity = 0.53). Increasing *UZSN* value increases the amount of water retained in the upper zone and available for ET, and thereby decreases the dynamic behavior of the surface and reduces direct overland flow. Zhang and Ross (2006) suggested that the upper zone thickness should be approximated as the soil A horizon (e.g., top 15 cm of upper soil), but during calibration it was realized that the present algorithms for upper zone in IHM (based purely on the conceptualization of HSPF) can only be considered as the depression storage. Therefore, in the present IHM model, there is no differentiation of the upper and lower vadose zone practically. The typical values of *UZSN* commonly used in HSPF range from 0.13 cm (0.05 in) to 12.7 cm (2.0 in) (EPA Technical Notes) which is broad, and at this point, poorly defined from site physical conditions. LaRoche *et al.*, (1996) reported values ranging from 0.04 cm (0.016 in) to 1.9 cm (0.75 in). The *UZSN* values found through calibration in this application were 4 cm (0.16 in) for grassed and 0.05 cm (0.02 in) for forested land cover and are within these published values but seem somewhat inconsistent. (i.e., lower for forested land cover).

5.3.3.1.2 Capillary Fringe/Root Zone and GWET

Ross *et al.*, (2005a) discussed that there are four threshold conditions in the transition of vadose zone to water table ET in shallow water table settings and considered in conceptualizing the IHM. The satisfaction of land cover ET demand from the vadose

zone or ground water (water table) can be (1) entirely by the vadose zone (deep water table condition) dictated by the plant potential, (2) partially from both vadose zone and ground water (roots in contact with capillary zone) also limited by the plant potential, (3) combined direct evaporation (augmentation) from the soil surface (capillary zone at land surface) and plant uptake, and (4) entirely by ground water at open water evaporation rates through direct evaporation from the soil (water table or capillary fringe at land surface). The moving boundary of the capillary fringe or the capillary zone above the water table transitioning particular thresholds seems to be reasonable conceptually but, the model sensitivity to these thresholds remains uncertain.

Decreasing capillary fringe thickness from 30 cm to 15 cm (-50% parameter change) significantly effects ET flux, increasing UZET by 22%, GWET 24%, recharge 7% and infiltration 24%, respectively. Also, LZET is decreased 7%, runoff 11% and DTWT 26%, respectively (in Table 5.3 a). For the forested land cover (Table 5.4 a), increasing root zone thickness from 100 cm (40 in) to 200 cm (79 in) causes negligible change in UZET (3%), slightly decrease runoff (5%), and only very slightly increases LZET (4%), GWET (4%) and infiltration (3%), respectively, indicating relative insensitivity to root zone depth for this set of calibration conditions or this hydrological setting. One reason may be that, for this case, the deeper root zone extends well into the water table thereby only slightly influencing uptake of GWET.

Capillary fringe and root zone thicknesses are physically-based but conceptual parameters derived from soil moisture retention data and/or expensive on-site analysis. In both observations and model behavior, under particular conditions, either can strongly influence ET processes in shallow water table settings indicated by the relatively high

sensitivity. For regional models, adequate characterization data are not always available. Therefore uncertainty in these parameters should be considered in models for calibration and predictions.

5.3.3.1.3 INFILT and Distribution of Available Moisture

From Table 5.4 b, it is shown that the total ET (TAET) is not very sensitive to soil infiltration rate (dictated by the *INFILT* parameter). While it is clear that the *INFILT* parameter effectively controls the overall division of the available moisture from precipitation (after interception) into surface and subsurface flow and storage components. Varying *INFILT* over a large range does not strongly influence TAET. However, the distribution of ET is somewhat more strongly sensitive to *INFILT*. High values of *INFILT* will produce more water in the lower zone and groundwater (leading to more LZET and GWET); low values of *INFILT* will produce more upper zone water (more UZET), also resulting in greater direct overland flow.

The *INFILT* parameter is primarily a function of soil characteristics and value ranges have been related to SCS hydrologic soil groups (Donigian and Davis, 1978) or soil characterization data (Fielland and Ross, 1991). Aly (2005) used exceptionally high *INFILT* values (15 cm/hr) for the same study site arguing that the West-Central Florida soils are mostly sandy. However, Aly (2005) did not examine the model for infiltration or ET distribution comparisons to observations. The *INFILT* values used in this study were 2 cm/hr for grassed and 4 cm/hr for forested land cover found through calibration comparisons to observed infiltration rates. For the soil type of the study site, Myakka

Fine Sand, the values used are reasonably close to hydraulic conductivities reported from soil tests (Carlisle *et al.*, 1989). Also the infiltration volumes and ET distributions observed through continuous soil moisture monitoring compared quite favorable to model results for the 3-year record examined.

5.3.3.1.4 Plant Coefficient and LZET

During the calibration and subsequent sensitivity testing of the plant coefficient parameter, it was found that the distribution of plant coefficient plays a critical role in describing LZET and GWET. Figure 5.11 shows the comparison of monthly averaged LZET between sensitivity test F1 with distribution PC1, F2 with the averaged monthly plant coefficient PC2 (constant values), and F3 with bell-shape plant coefficient PC3. PC1 was obtained from the analysis of data collected at the study site (Rahgozar *et al.*, 2005) and PC3 was an adjusted plant coefficient used by Aly (2005) (all the PCs are shown in Figure 5.11a). Figure 4.10b illustrated that the averaged monthly LZET with plant coefficient PC1 (used for calibration) has the best results when compared to the observed LZET. Poorer results are shown for PC2 or PC3. It also appears that seasonal variability in plant coefficient is strongly warranted as the constant value, PC2, exhibited both poor LZET and DTWT behavior.

At the field study site in West-Central Florida, it was observed that plant communities develop new growth peaking in April with maximum leaf area in August, and perhaps this is the underlying basis for the best performance exhibited by PC1. The interesting dip in plant coefficient in July appears to be an artifact of high rainfall, shallow water table and ET dominated by interception. The model was later found to be

relatively insensitive to the particular value of PC for this period as dominate water table at land surface resulted in soil evaporation at or near *PET* for the period. Plant

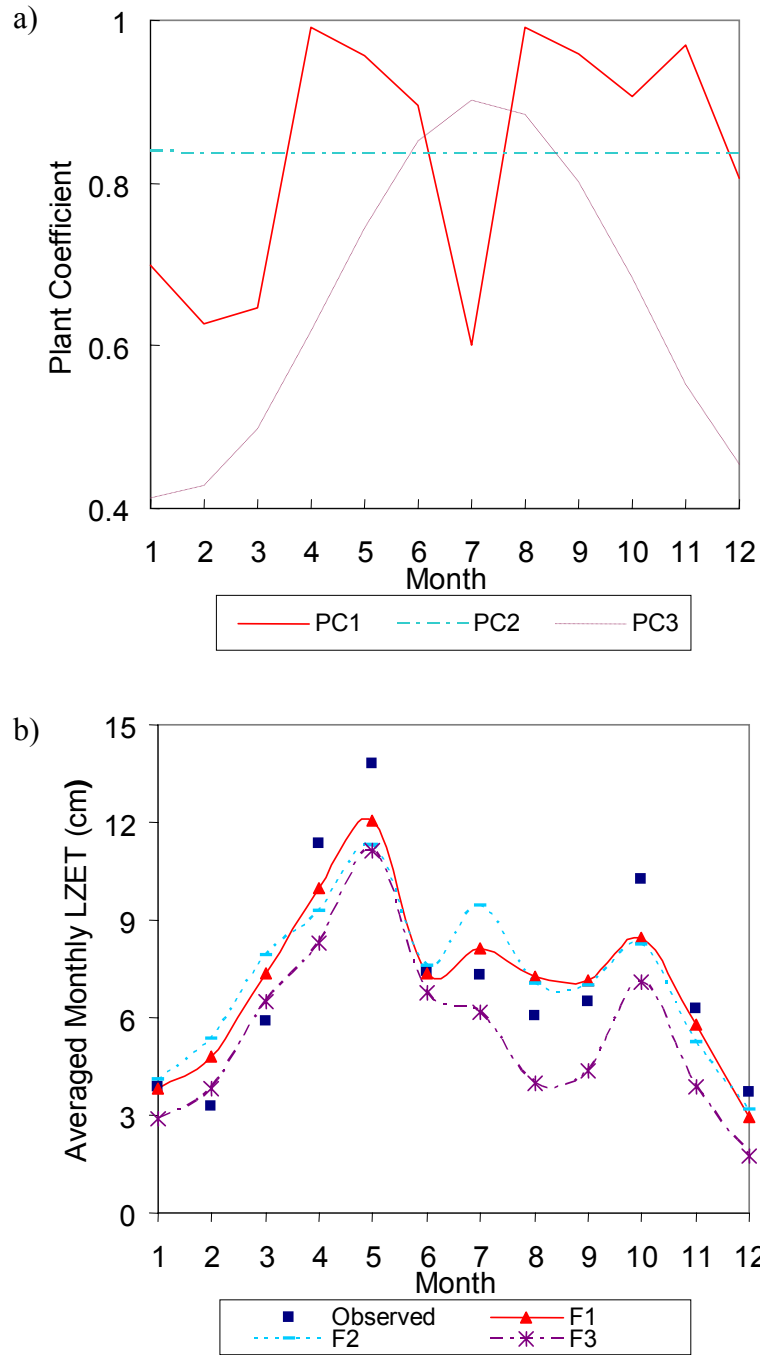


Figure 5.11. Sensitivity to Plant Coefficient Seasonal Variability for LZET (F1 with PC1, F2 with PC2, F3 with PC3)

coefficients obtained from field observations using the method of Rahgozar (2006) appear to be reasonable and directly applicable to simulation modeling.

5.3.3.2 Air Entrapment

Zhang and Ross (2006) and Shah, *et al.*, (2006) found significant Lisse effect evidence from field observations in the study site. Here, the IHM model application also illustrated these effects on infiltration and depth to water table as shown in Figure 4.10. Figure 4.10a and b are plots for the air entrapment periods (May to July, 2002 and April to May, 2003). From IHM model simulation compared to the observed DTWT for grassed land cover periodic differences are observed. The corresponding Figure 5.12c and d are the HYDRUS 1D (Simunek *et al.*, 2005) simulated solution during the same periods (Shah, *et al.*, 2006). Both the IHM and HYDRUS 1D model consistently showed the variations of the observed DTWT and the modeled DTWT with time. This was not surprising as both numerical models do not consider air entrapment effect and thus results of DTWT from these models neglect to observations for these particular periods. It is believed that periodic departures from the actual DTWT during large rainfall events are indicative of air entrapment and pressurization warranting future investigation. Figure 5.13 presents calibration results compared to the observed infiltration during periods (1) with or (2) and (3) without air entrapments conditions. During air entrapment periods, observed infiltration was decreased compared to simulated values. In contrast, the simulation results without air entrapment are reasonably good compared to observed data for infiltration.

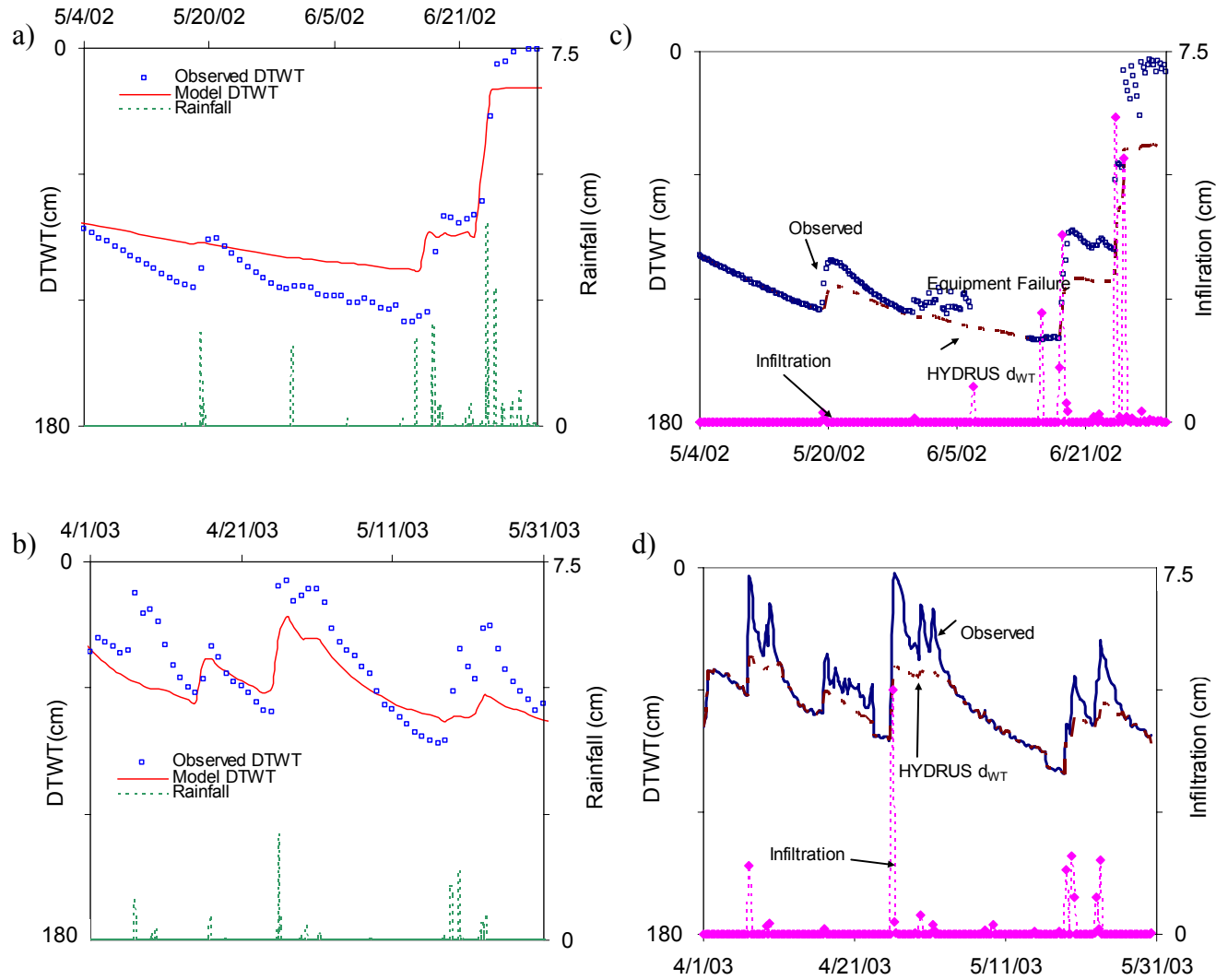


Figure 5.12. Air Entrapment Periods for Grassed Section (a) 5/4/02~7/1/02 and (b) 4/1/03~6/1/03 and Corresponding HYDRUS Solution (c) and (d)

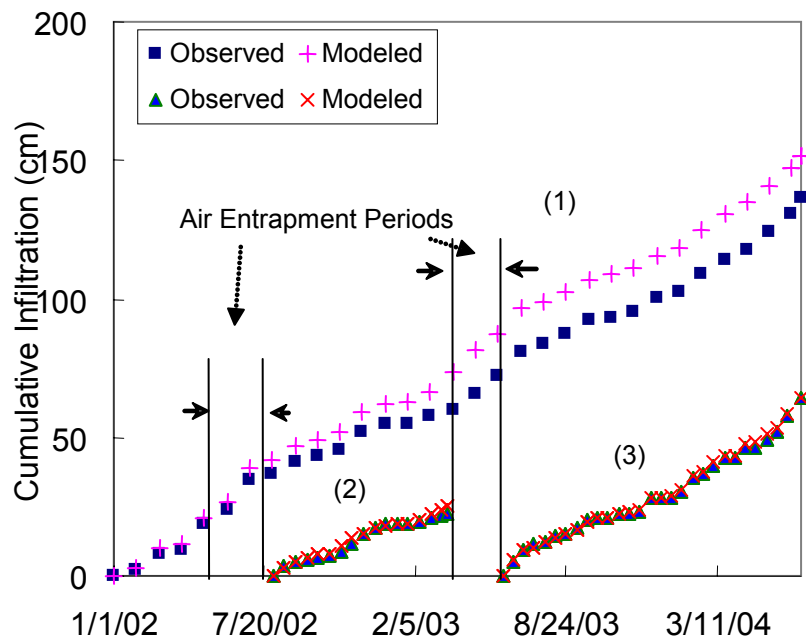


Figure 5.13. IHM Model Cumulative Infiltration Compared to Observations during Periods with or without Air Entrapment

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this study, model considerations for predicting vadose zone moisture dynamics, especially with respect to integrated surface and groundwater models, were investigated. The theoretical basis of vertical processes in IHM was discussed thoroughly and rigorous model sensitively and component performance testing was carried out to evaluate the robustness and limitation of the methodology of IHM. The conclusions and summary of the findings are organized as follows:

- 1) Several important modeling considerations were identified warranting additional investigation and model development:
 - a. Strong differential vadose zone retention and frequent variability in antecedent conditions exists between the upper and lower vadose zone in field observations.
 - b. Field-scale variability in moisture retention and depth to water table is prevalent throughout, at relatively small spatial scale of < 100 m.
 - c. Relative soil moisture appears to be a better indication of antecedent condition and tendency to support vadose zone *vs.* water table ET.
 - d. Air entrapment/pressurization affects the water table observation and thus infiltration, runoff and recharge. Also, air entrapment/pressurization appears to be relatively prolonged (several days) in some instances.

2) A new and useful relative storage condition and further discretization of the vadose zone was defined and advocated but was not fully tested within IHM.

In order to explore the new mathematical conceptualization of upper zone and lower zone behavior, analysis was made of daily average soil moisture obtained from field data. A formal definition for the upper soil zone was offered as the A horizon (top 10~20 cm) which, possibly, could also be included with surface depression storage.

Relative soil moisture condition was defined as the difference between the actual and the minimum, divided by the mean available (mean minus minimum) moisture for that water-table depth. A van Genuchten-type mathematical model was used to calculate the corresponding mean and minimum total moisture values at all water table depths. Further, because of the unique behavior of the two distinct soil zones, exhibited in shallow coastal plain soils, and the discovery that the two zones can be and frequently are in different relative states (wet or dry), further supports the contention that the vadose zone relative storage should be split into an upper and lower region.

For both the upper and lower zones, relative moisture is a function of water-table depth and stress history (wetting or drying). The lower zone extends from the upper zone (soil A horizon) down to the water table or the groundwater extinction depth, whichever is shallower. Moisture flux below this zone is only available to the saturated groundwater domain and, thus, only is available as recharge.

Because the upper and lower zone commonly exhibit different relative soil moisture conditions, the effects on infiltration, percolation and recharge will be significant. For example, a dry upper zone will yield higher infiltration when coupled

with a wet lower zone and may result in elevated recharge to the water table. Also, it is very apparent that the relative state of the lower zone will dictate the distribution of plant ET from the vadose zone vs. the water table in both the model and the physical domain.

3) The new relative soil moisture definition was tested considering field-scale variability. Several conclusions are offered from this testing.

Different land uses (vegetative covers) exhibit different relative soil moisture behavior, even in close proximity and even with the same hydrologic soil classifications and subjected to the same meteorological stresses. Thus infiltration, runoff and recharge behavior will be different. Therefore prediction by a model is strongly sensitive to and dependent on good ET performance, especially with regards to the distribution of ET from the various component storages. Comparison of ET performance by the IHM was made against field observations with generally good behavior shown, but further conclusions and observations are offered in item 5).

Comparisons of \mathfrak{R}_{UZ} and \mathfrak{R}_{LZ} against total soil moisture for both upper and lower zones for different vegetative cover types (grass and forest) in low and high ET periods yield some interesting observations. It was shown that expressing soil moisture in this manner eliminates field-scale variability due to difference in soil moisture retention and better represents the antecedent soil moisture condition.

4) The present version of IHM is not totally compatible with the new relative storage definition. The upper zone algorithms in HSPF appear to be suited only for describing depression storage effects.

5) Calibration testing of the IHM shows that the model, with parameter adjustments, can reproduce reasonable cumulative behavior including distribution of ET, but reproduction of daily behavior is somewhat poorer.

The testing and calibration of the IHM model for the vertical moisture retention and flux behavior was made for two land covers: grassed and forested, at a field site in West-Central Florida. The model was reasonably calibrated for a two-and-a-half-year simulation period (January, 2002 through July, 2004) to describe infiltration (and thus runoff), ET distribution and water-table fluctuation (and thus recharge). Calibration results compared reasonably well with observed processes with reasonable parameter estimates from physical soil measurements, reported characterization data and only limited parameter adjustment. However, results are much better for multi-day and cumulative behavior than daily.

6) Several key parameters were tested in the sensitivity analysis: saturation, field capacity, capillary fringe, root zone, soil infiltration index and nominal depression storage. The model shows strong sensitivity to soil properties and less sensitivity to plant properties (perhaps unique to this shallow-water-table-data setting). Thus, further testing in deeper water-table environments is strongly warranted.

7) Excess pressure was shown to be periodically important by greatly reducing infiltration (thereby increasing runoff) and water-table observations. The extent and perseverance of air pressurization appears to be greatest with deeper water tables and with more intense rainfall.

8) The time-scale of observed excess air pressure ranged over many days (not just hours) which has been previously shown. The ideal gas law approach, used to

understand the behavior, generally supports the magnitude of observed air pressurization differences but not the durations.

The current study employed field data and numerical modeling, using HYDRUS-1D to quantify the variation of air pressurization values. The observations of water table in the field data departed significantly on occasions from the theoretical values using a calibrated Richards' equation solution (and also IHM simulation results). Antecedent conditions were found to be very important in controlling air pressurization. Deeper water table and higher rainfall intensity seemed to be the most prevalent conditions generating excess air pressurization.

A simple analysis based on the ideal gas law was also done to help understand air pressurization effects. Interestingly, the duration of excess air pressures was inconsistent between observations and model predictions. Field observations of prolonged excess pressures (many days) can not be supported by ideal gas law analysis assuming uniform pressures in the vadose zone. This suggests that air pressures in the vadose zone may be strongly non-uniform but, this is only a hypothesis at this time. Further investigation is strongly warranted.

9) Investigation shows small variability in vadose zone moisture content dictates whether ET will affect the water table, even in shallow water table conditions. Moisture conditions for water-table depths less than 1/2 m appears to be near equilibrium consistent with the literature but below 1 m are highly variable.

10) The values of infiltration index, *INFILT*, used are reasonably close to reported values from soil tests (Carlisle *et al*, 1989), contrasting Aly (2005) exceptionally high values and traditional very low values used for regional HSPF only models.

11) Three plant coefficient distributions were investigated with findings suggesting that the plant coefficient distribution has a strong effect on lower zone and groundwater ET. The value obtained from the field observation in the manner of Rahgozar (2006) yielded the best performance for lower zone ET. The decline shown in July found through this method appears to be anomalous. The model artificially resets the plant coefficient to near 1 for this period to account for direct soil evaporation at near potential values because the water table was at or near land surface for most of this time.

It was also found that there is considerable benefit in deriving the plant coefficient from observed data in the method of Rahgozar (2006), at least for areas similar to the study area and periods when the water table is not at land surface.

12) Simulation results indicate comprehensive integrated hydrological models such as IHM can reproduce water-table behavior, soil moisture distribution incorporating field-scale variability and ET distribution and thus provide valuable predictive capability for continuous runoff or recharge studies. In this study, the applicability of IHM for two different land covers in shallow water table ($d_{WT} < 2$ m) settings were shown.

Reproducing ET: both total ET as well as ET distribution was very important for runoff and recharge predictions. The model performed reasonably well for vertical moisture distribution, water table and runoff prediction, especially with regard to multi-day and cumulative behavior.

Several limitations and recommendations are offered:

1) At present, IHM cannot be parameterized to represent the shallow vadose zone (A horizon soils) as the upper zone. Upper zone storage in HSPF appears to be only

conceptualized as depression storage (e.g., there is no direct infiltration to the upper zone, only initial abstraction capture). Further study, code enhancements and testing are warranted.

2) Conceptual changes are recommended to allow differentiation of the upper and lower soil zones. Perhaps changes to the infiltration model are also warranted so that infiltration is more a function of a shallow soil state as well as possible conceptual changes to ET behavior in a model with upper and lower vadose zone.

3) Actual and relative soil moisture storage was not compared to observations because of the problem with field measurements of the true elevation of saturation (periodic air entrapment deviations of observed water table). A strategy for addressing this occurrence needs to be derived and further investigation of the behavior and constraints of air pressurization in shallow water table hydrology needs to be made.

4) In shallow-water-table settings, brief periods of air entrapment play a role in controlling infiltration, runoff and observed depth to water table and are not adequately simulated by IHM, Richards' equation solution or any other known integrated surface-groundwater model.

5) There are still IHM model parameters with high uncertainties, especially under different calibration conditions (e.g., deep water table). Therefore further field-scale testing in different environments is strongly warranted, especially in deeper water table settings.

REFERENCES

- Abbott, M. B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986a). "An Introduction to the European Hydrological System – Systeme Hydrologique Europeen, SHE. 1 History and Philosophy of a Physically-based Distributed Modeling System." *J. Hydrol.*, 87, 45-59.
- Abbott, M. B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986b). "An Introduction to the European Hydrological System – System Hydrologique Europeen, SHE. 2 Structure of a Physically-based Distributed Modeling System." *J. Hydrol.*, 87, 61-77.
- Adrian, D.D and J.B.Franzini (1966). "Impedance to Infiltration by Pressure Build-Up Ahead of the Wetting Front." *Journal of Geophysical Research*, 71, 5857-5862.
- Aly, Alla (2005). "The Integrated Hydrologic Model: A Field-Scale Application." Reston, VA, *ASCE/EWRI*, 0-7844-0792-4.
- Bicknell, B.R., Imhoff, J.C., Kittle, J.L. Jr, Jobes, T. H., Donigian, A.S., Jr and Johanson, R.C. (2001). "Hydrological Simulation Program – FORTRAN (HSPF): User's Manual for Version 12." U.S. Environmental Protection Agency, Athens, GA. <<http://www.epa.gov/waterscience/basins/bsnsdocs.html>>.
- Bidlake, W.M., Woodham, W.M., Lopez, M.A. (1993). "Evapotranspiration from Areas of Native Vegetation in West-Central Florida." U. S. Geological Survey Open-File Report 93-415, U. S. Geological Survey, Tallahassee, FL.
- Carlisle, V.W., Sodek, F., Collins, M., Hammond, L.C. and Harris, W.G. (1989). "Characterization Data for Selected Florida Soils." Inst. of Food and Agric. Sci., Univ. of Florida, Gainesville.
- Crawford, N.H. and Linsley, R.K. (1966). "Digital Simulation in Hydrology – Stanford Watershed Model IV," Dept. of Civil Engineering, Stanford University, Stanford, Calif.
- Crosbie, R.S., P.Binning, and J.D.Kalma (2005). "A Time Series Approach to Inferring Groundwater Recharge Using the Water Table Fluctuation Method." *Water Resources Research*, 41 W01008, doi: 10.1029/2004WR003077.

- Donigian, A. S., Jr. and H. H. Davis, Jr. (1978). "User's Manual for Agricultural Runoff Management (ARM) Model". EPA-600/3-78-080. U.S. Environmental Protection Agency, Athens, GA. Donigian, A. S.
- Danish Hydraulic Institute (DHI). (1998). "MIKE SHE Water Movement - User Guide and Technical Reference Manual, Edition 1.1." <http://www.dhisoftware.com/mikeshe/>.
- Fielland, C. E., Ross, M. A. (1991) "Improved HSPF Infiltration Calibration Procedure with a Linked GIS", 1991 National Conference on Hydraulic Engineering and International Symposium on Groundwater, Nashville, Tennessee, July 1991.
- Garrote, L., and R. L. Bras. (1995). "A Distributed Model For Real-Time Flood Forecasting Using Digital Elevation Models." *Journal of Hydrology*. 167, 279-306.
- Geurink, Jeffrey S and Mark. A. Ross. (2006) "Time-Step Dependency of Infiltration Errors in the HSPF Model." *ASCE, J. Hydrologic Engrg.*, Vol. 11, No. 4.
- Green, W.H., and C.A. Ampt (1911). "Studies on Soil Physics, 1, Flow of Air and Water through Soils." *Journal of Agricultural Science*, 4, 1-24.
- Hammecker, C, A. C. D. Antonino, J. L. Maeght, and P. Boivin (2003). "Experimental And Numerical Study of Water Flow in Soil under Irrigation in Northern Senegal: Evidence of Air Entrapment." *European Journal of Soil Science*, 54, 491-503.
- Harbaugh, A.W., and McDonald, M.G. (1996). "Programmer's Documentation for MODFLOW-96, An Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model." U.S. Geological Survey Open-File Report 96-486, Reston, Va.
- Heliotis, F.D. and C.B. Dewitt (1987). "Rapid Water Table Response to Rainfall in a Northern Peatland Ecosystem." *Water Resource Bulletin*, 23(6), 1011- 1016.
- Healy, R.W., and P.G. Cook (2002). "Using Groundwater Levels to Estimate Recharge." *Hydrogeology Journal*, 10, 91-109.
- Hernandez, T, M. Nachabe, M. Ross, and J. Obeysekera (2003). "Modeling Runoff from Variable Source Areas in Humid, Shallow Water Table Environments." *Journal of the American Water Resources Association*, 39(1), 75-85.
- Heillel, D (1998). *Environmental Soil Physics*, Academic Press, San Diego, CA.

- Hooghoudt, S.B (1947). "Waaarnemingen van grondwaterstanden voor de landbouw. Commissie voor Hydrologisch TNO." Verlagen Technische Bijeenkomsten 1-6: 185-201.
- HydroGeoLogic Inc. (2003). "MODHMS: A Comprehensive MODFLOW-Based Hydrologic Modeling System, Version 2.1, Code Documentation and User's guide." HydroGeoLogic Inc., Herndon, Virginia.
<<http://www.modhms.com/software.htm>>.
- Ivanov, V.Y. (2002). "A continuous Real-time Interactive Basin Simulator." M.S. Thesis, Massachusetts Institute of Technology.
- Jensen, M.E. and Haise, H.R. (1963). "Estimating Evapotranspiration from Solar Radiation". *J. Irrig. Drainage Div. ASCE*, 89: 15-41.
- LaRoche J, van der Staay, GWM, Partensky F, Ducret A, Aebersold R, Li R, Golden SS, Hiller RG, Wrench PM, Larkum AWD and Green BR. (1996). "Independent Evolution of the Prochlorophyte and Green-plant Chlorophyll *a/b* Light-Harvesting Protein". *Proc Natl Acad Sci, USA* 93: 15244-15248.
- Latifi, H., S. N. Prasad, and O. J. Helweg (1994). "Air Entrapment and Water Infiltration in Two-Layered Soil Column." *J. Irrig. Drain. Eng.*, 120, 871-891.
- MacVicar, T.K. (1981). "Frequency Analysis of Rainfall Maximums for Central and South Florida." *South Fla. Water Manage. Dist. Tech. Publ. No. 81-3*.
- McWhorter, D.B. (1971). "Infiltration Affected by the Flow of Air." *Colorado State University Hydrological Paper*, 49, Fort Collins, CO.
- Meyboom, P (1967). "Groundwater Studies in the Assiniboine River Drainage: Part II, Hydrologic Characteristics of Phreatophytic Vegetation in South-central Saskatchewan." *Geological Survey of Canada Bulletin*, 139.
- Morel-Seytoux, H.J., and J.Khanji (1974). "Derivation of an Equation of Infiltration." *Water Resources Research*, 10, 795-800.
- Morel-Seytoux, H.J, and J.Khanji (1975). "Equation of Infiltration with Compression and Counter flow Effects." *Hydrological Science Journal*, 20, 505-517.
- Myers, R. L. and Ewel, J. J. (1991). *Ecosystems of Florida*. University of Central Florida Press, Orlando. FL.

- Nachabe, M., N. Shah, M.A Ross, and J.Vomacka (2005). "Evapotranspiration of Two Vegetation Covers in a Shallow Water Table Environment." *Soil Science Society of America Journal*, 69:492-499.
- Nachabe, M.H., C. Masek, J.Obeysekra (2004). "Observations and Modeling of Profile Soil Water Storage above a Shallow Water Table." *Soil Science Society of America Journal*, 68:719-724.
- Natural Resources Conservation Service (NRCS), "Lesson Plans: A Soil Profile." <http://soils.usda.gov/education/resources/k_12/lessons/profile/>.
- Panday, S. and Huyakorn, P.S. (2004). "A Fully Coupled Physically-Based Spatially-Distributed Model for Evaluating Surface/Subsurface Flow." *Advances in Water Resour.*, 27, 361–382.
- Parlange, J. Y., and D. E. Hill (1979). "Air and Water Movement in Porous Media: Compressibility Effects." *Soil Science*, 127, 257–263.
- Philip J.R. (1957). "The Theory of Infiltration, 4, Sorptivity and Algebraic Infiltration Equations," *Soil Science*, 84(3), 257-264.
- Powers, R.M., Davis, P.R., and Ross, M.A. (1989). "Modeling the Hydrologic Impacts of Phosphate Mining and Reclamation in Central Florida," *AWRA 25th Annual Conference on Water: Laws and Management*, Tampa, FL.
- Rahgozar, M., Ross, M., and Said, A. (2005). "Estimation of Evapotranspiration and Hydrologic Parameters Using Continuous Soil Moisture and Water Table Monitoring." *Hydrological Science and Technology*, 21(1-4), 119-142.
- Rahgozar (2006). "Estimation of Evapotranspiration using Continuous Soil Moisture Measurement." Dissertation, Department of Civil and Environmental Engineering, University of South Florida.
- Refsgaard, J.C. and Storm, B. (1995). "MIKE SHE in: Computer Models of Watershed Hydrology." V. P. Singh ed., Water Resources Publications, Colorado, USA, 809-846.
- Richards.L.A (1931). "Capillary Conduction of Liquids through Porous Mediums." *Journal of Applied Physics*, 1(5), 318-333.
- Ross, M., Geurink, J., Aly, Al, Tara, P., Trout, K and Jobes, T. (2004). "Integrated Hydrologic Model (IHM)-Volume I: Theory Manual." Water Resource Group, Dept. of Civil Engineering, University of South Florida, USA. <http://hspf.com/pub/him/IHM_Theory_Manual.pdf>.

- Ross, M., Geurink, J., Said, A., Aly, A and Tara, P. (2005a). "Evapotranspiration Conceptualization in the HSPF-MODFLOW Integrated Models." *JAWRA*, 41(5), 1013-1025.
- Ross, M., Trout, K., Tara, P., Said, A and Geurink, J. (2005b). "A New Discretization Scheme for Integrated Surface and Groundwater Modeling." *Hydrological Science and Technology*, 21(1-4), 143-156.
- Ross, M.A., Tara P.D., and Geurink J.S. (1998). "Review of the SDI Integrated Model ISGW," prepared for Southwest Florida Water Management District, University of South Florida, Tampa, FL.
- Ross, M., Tara, P., Geurink, J., and Stewart, M. (1997). "FIPR Hydrologic Model Users Manual and Technical Documentation." prepared for Florida Institute of Phosphate Research and Southwest Florida Water Management District, Center for Modeling Hydrologic and Aquatic Systems, CMHAS Water Resources Report, FIPR.97.03, University of South Florida, Tampa, FL.
- Ross, M., Geurink, J. and J. Zhang (2007). "Modeling Vadose Zone Moisture Dynamics with the Integrated Hydrologic Model (IHM), Part I: Theoretical Basis." ASCE, *J. Hydrologic Engrg.*, under review.
- Ross, M.A., and Tara, P.D. (1993). "Integrated Hydrologic Modeling with GIS," American Society of Civil Engineering," *Journal of Water Resources Planning and Management*, Vol. 119, No. 2.
- SDI Environmental Services Inc. (1999). "Update to Integrated Hydrologic Model of Central Northern Tampa Bay Area: ISGW/CNTB Model Run No. 121," prepared for Tampa Bay Water, 87 p. plus appendices.
- Shah, N., and M.Ross (2006). "Variability in Specific Yield for Different Wetting and Drying Conditions." *Vadose Zone Journal*, under review.
- Shah, N., Zhang, J. and M.Ross (2006). "Long Term Air Entrapment Affecting Runoff and Water Table Observations." *Water Resour. Res.*, under Review.
- Simunek, J., and M.Th. van Genuchten (1999). Manual of HYDRUS-2D Computer Program for Simulation Water Flow, Heat and Solute Transport in Variably Saturated Porous Media. U.S. Department of Agriculture, Riverside, CA.
- Simunek, J., M. Th. van Genuchten and M. Sejna (2005). "The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media." Version 3.0, HYDRUS Software Series 1, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 270 pp.

- Software Spotlight (2000). "Review of HYDRUS-2D." *Ground Water* 38(1), 10-11.
- Sophocleous, M.A., Koelliker, J.K., Govindaraju, R.S., Birdie, T., Ramireddygari, S.R. and Perkins, S.P. (1999). "Integrated Numerical Modeling for Basin-Wide Water Management: The Case of the Rattlesnake Creek Basin in South-Central Kansas." *J. Hydrol.*, 214, 179-196.
- Touma, J., G. Vachaud, and J.-Y. Parlange (1984). "Air and Water Flow in a Sealed, Pondered Vertical Soil Column: Experiment and Model." *Soil Science*, 137, 181–187.
- Trout, K and Ross, M. (2005). "Intensive Hydrologic Data collection in a Small Watershed in West-Central Florida." *Hydrological Science and Technology*, 21(1-4), 187-197.
- Tucker GE, Lancaster ST, Gasparini NM, Bras RL, Rybarczyk SM. (2001). "An Object-Oriented Framework for Distributed Hydrologic and Geomorphologic Modeling Using Triangulated Irregular Networks." *Computers & Geosciences*. 27(8): 959-973.
- Vachaud, G., J.P. Gaudet, and V.Kuraz (1974) "Air and Water Flow During Pondered Infiltration in a Vertical Bound Column of Soil." *Journal of Hydrology*, 22:89-108.
- van Genuchten, M.Th. (1978). "Calculating the Unsaturated Hydraulic Conductivity with a New Closed-Form Analytical Model." Research Report 78-WR-08, Water Research Program, Dept. of Civil Engineering, Princeton University, Princeton, New Jersey, USA.
- Vivoni, E.R., Ivanov, V.Y., Bras, R.L., Entekhabi, D. (2003). "Generation of Triangulated Irregular Networks Based on Hydrological Similarity." *J. Hydrologic Engrg.*, 9(4), 288-302.
- Wang, Z., J. Feyen, D. R. Nielsen, and M. T. van Genuchten (1997). "Two-Phase Flow Infiltration Equations Accounting for Air Entrapment Effects." *Water Resources Research*, 33(12), 2759-2767.
- Wang, Z., J. Feyen, D. R. Nielsen, and M. T. van Genuchten (1998). "Air Entrapment Effects on Infiltration Rate and Flow Instability." *Water Resources Research*, 34(2), 213-222.

- Waterstone Environmental Hydrology and Engineering, Aqua Terra Consultants, Richard Allen, and John Wilson (2001). "Uncertainty and Sensitivity Analysis for the Central Northern Tampa Bay Area Integrated Hydrologic Model: Phase II".
- Weeks, E.P (2002). "The Lisse Effect Revisited." *Ground Water*, 40(6), 652-656.
- WEST Consultants Inc., Gartner Lee Limited and Aqua Terra Consultants (2001). "Scientific Review of the Integrated Hydrologic Model ISGW/CNTB121".
- Yan, J.J. and Smith, K.R. (1994). "Simulation of Integrated Surface Water and Ground Water Systems - Model Formulation." *Water Resources Bulletin*, 30(5), 1-12.
- Youngs, E.G., and A.J. Peck (1964). "Moisture Profile Development and Air Compression during Water Uptake by Bounded Porous Bodies, 1, Theoretical Introduction." *Soil Science* 98, 290-294.
- Zhang, J. and M. A. Ross (2006), "A 2-Layer Vadose Zone Model for Surface-Groundwater Interactions." *J. Hydrologic Engrg.*, Accepted.

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