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HYDROLOGIC RESPONSE OF A FORESTED SINKHOLE WETLAND TO DIFFERENT LAND MANAGEMENT SCENARIOS

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This study employed the SPAW (Soil-Plant-Atmosphere-Water) model to simulate the hydrology of a forested sinkhole wetland on the Tennessee Highland Rim. Recent development activities have increased awareness of the potential adverse impacts of continued watershed development on the wetland plant community. The SPAW model was used to simulate hydrologic conditions over a 50 year period for two future land management scenarios (LMS's) with 19.7 % (LMS 2) and 37.9 % (LMS 3) of the watershed converted to impervious surfaces. Published flooding tolerances, reported as an upper limit on growing season inundation, for individual tree species were used to assess the likely response of the existing plant community for each scenario. Dominant tree species at the site are sweetgum (Liquidambar styraciflua), red maple (Acer rubrum), willow oak (Quercus phellos), blackgum (Nyssa sylvatica), and green ash (Fraxinus pennsylvanica). Seepage rates during the growing season had a more dominant influence on growing season inundation than increased surface runoff from the future developments. The forested buffer is responsible for maintaining large seepage rates during the growing season and appears to be the most important aspect of future land management. Overall, development with impervious surfaces in the range of 20-25 % is unlikely to appreciably influence the existing plant community. This study demonstrates a simple modeling framework for addressing land management decisions in zero-order watersheds containing depression wetlands. Recommendations for improving performance of the SPAW model are provided.

INTRODUCTION

Wetlands perform many important hydrologic, biogeochemical, and habitat-related functions. Performance of these functions is strongly influenced by site hydrologic conditions. Hydrology is known to influence plant community establishment and persistence and chemical transport and transformation in wetland ecosystems (Mitsch and Gosselink, 2000). Development activities that alter site hydrology, therefore, can have tremendous detrimental effects on the overall health of the wetland ecosystem.

Watershed development, urbanization in particular, increases the volume, frequency, and rapidity of surface runoff reaching wetlands (Azous and Horner, 2000). The result is an increased frequency and duration of surface flooding that can decrease the diversity of the existing plant community due to the increased mortality of individual species. It is difficult to predict how individual species will respond to hydrologic alteration due to large within species variation and varying response to other site factors such as soil type (Hook, 1984). As a result, careful management is required to protect wetland ecosystems from adverse effects.

This paper addresses the impact of existing and projected land management scenarios on the hydrologic response of a sinkhole wetland and the subsequent response of the forested plant community. The sinkhole wetland is located on the Tennessee Highland Rim (THR) and is typical of other sinkhole wetlands found throughout the THR (Wolfe, 1996). Recent development activities within the watershed have increased awareness of the potential effects of these activities on the overall health of the wetland ecosystem. A hydrologic model is used to simulate 50 years of hydrology for the existing and projected land management scenarios. Published flooding tolerances for individual tree species are used to assess the likely response of the existing plant community.

STUDY SITE

The Tennessee Highland Rim (THR) is a division of the larger Interior Low Plateau physiographic province. Sinkhole wetlands are common along the central and southern portions of the Eastern Highland Rim and the northwest portion of the Western Highland Rim (Figure 1). Most of the THR is underlain by Mississippian age limestone with interbedded cherts and shales.

The wetland selected for this study is located at N36º10’53” and W85º27’21” in Algood, Tennessee near the Eastern Highland Rim escarpment (Figure 1). The Algood wetland is located in Burtons Branch watershed and has an area of 11.6 km^2 and an elevation drop of 12 m from the watershed divide to the outlet. Surface runoff from the Algood wetland enters Burtons Branch and travels 3.5 km before emptying into a sinkhole (Figure 1).

The Algood wetland was initially selected for detailed study due in part to its pristine condition. However, during the summer of 2003, approximately 13 % of the watershed was converted to commercial land use, increasing the surface runoff contribution to the water budget of the site. Following construction activities that altered site topography, a detailed topographic survey was conducted to precisely define the watershed area. In Figure 2, a topographic map of the Algood wetland and surrounding area is shown with the watershed boundary indicated.

A comprehensive monitoring program was initiated for the Algood wetland in 2003. The wetland and watershed were instrumented with a weather station, water level sensors, groundwater wells and piezometers, and a network of tipping –bucket rain gages (Figure 2). A comprehensive description and analysis of this hydrologic dataset is provided by Hill (2007). Hill and Neary

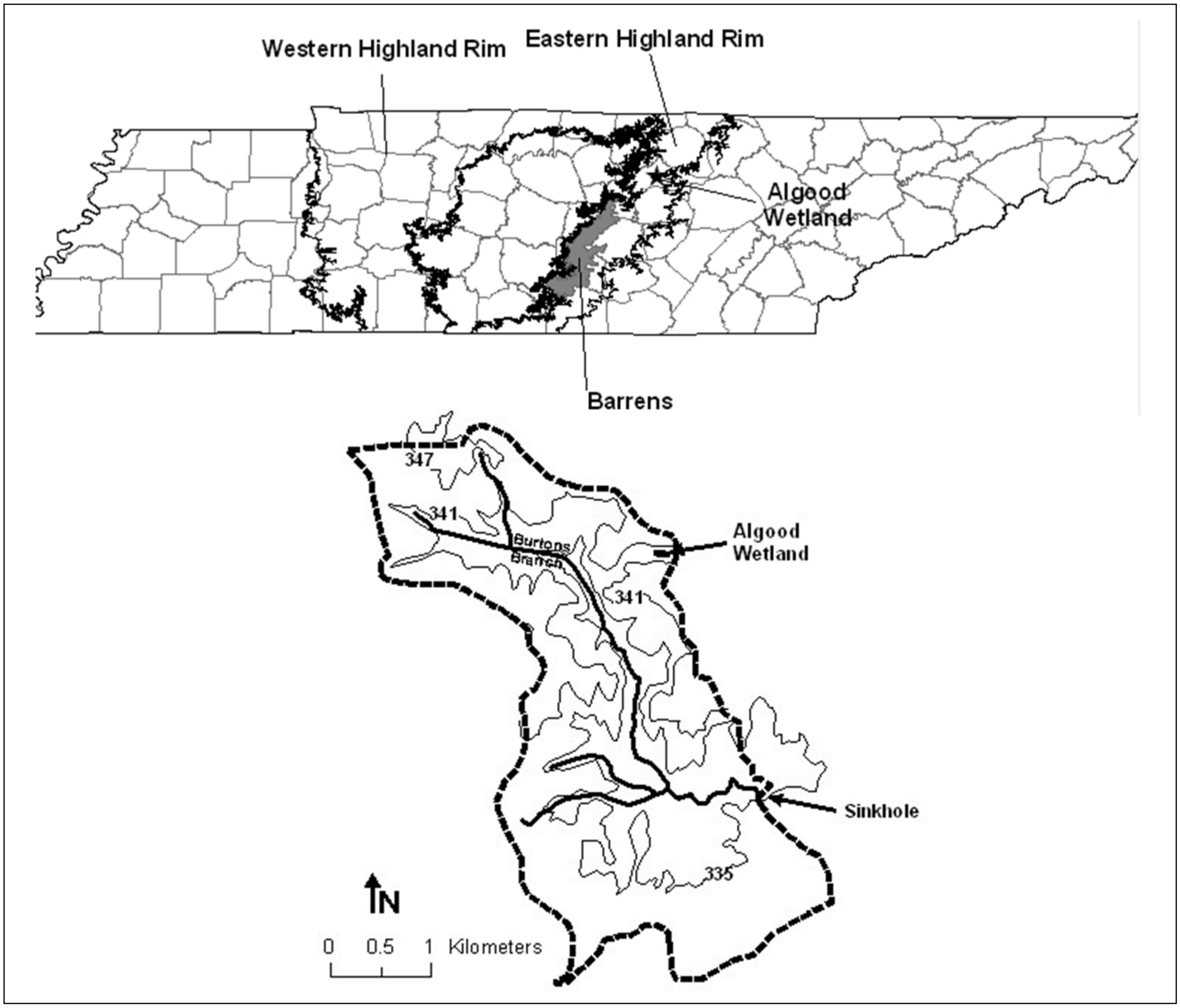


Figure 1. Location of Algood wetland in Burton's Branch watershed.

(2007) report ET rates approaching 19 mm/day for the Algood wetland and attribute these large rates to contrasting roughness and moisture conditions at the site (commonly referred to as clothesline and oasis effects). Despite these large ET rates, seepage (recharge) was found to be the dominant water loss mechanism for the wetland. On an annual basis, canopy interception averaged 18.8% of gross precipitation for 2004 and 2005 (Hill, 2007).

Subsurface conditions strongly influence the hydrology of the Algood wetland. The soil profile above limestone bedrock is shallow (~2m) and contains a fragipan horizon at an approximate depth of 1 m that creates perched water table conditions during portions of the year. The higher hydraulic conductivity in the upper soil horizons promotes horizontal groundwater flow. As a result, much of the infiltrated water from the surface body is transpired by perimeter trees without recharging the deep groundwater system.

MODEL DESCRIPTION

The SPAW (Soil-Plant-Atmosphere-Water) hydrologic model (Saxton, 2004) was selected to simulate the hydrologic processes occurring in the Algood wetland. An earlier study by Hill et al. (2006) successfully used the SPAW model to develop functional assessment models for use in

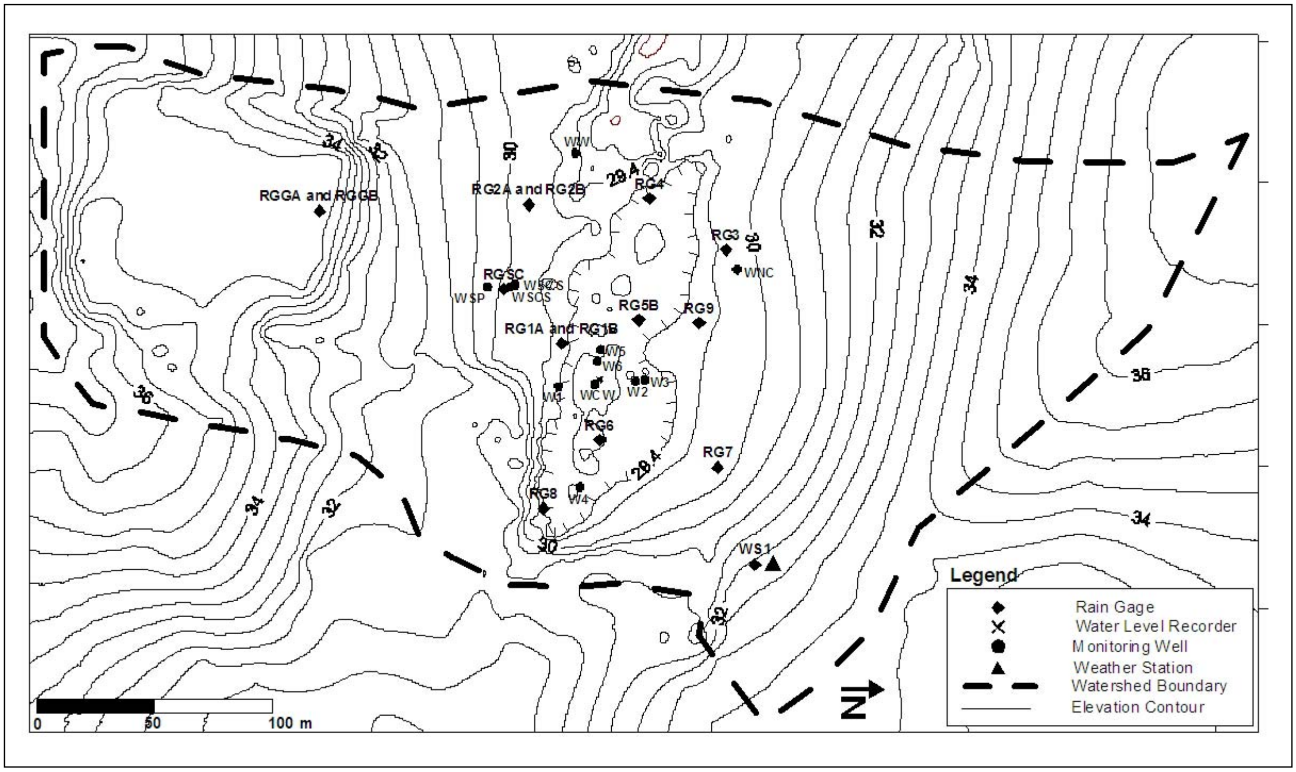


Figure 2. Topographic map of Algood wetland showing locations of monitoring equipment and watershed boundary.

wetland regulation. The current modeling study uses an expanded dataset and more detailed process descriptions to improve model performance.

SPAW uses two model elements, fields and ponds, to represent a hydrologic system. Field elements are used to model homogenous hydrologic response units (areas with homogenous land use and soil type). Required inputs to each field element include a soil profile description, climatic data (precipitation and potential evapotranspiration), crop curves describing annual distributions of plant canopy, greenness and root depth, and a runoff curve number. Event curves numbers are adjusted up or down depending on the available soil storage.

Pond elements are used to model ponds and wetlands that receive surface water inputs from one or more fields. Required inputs to each pond element include pond geometry (area-stage relationship), seepage (either constant or time dependent), outlet crest elevation and a stage-discharge relationship, and a pond infiltration depth.

SPAW lacks the capability to directly simulate canopy interception and evaporation for pond elements. Canopy interception and evaporation are significant to the water budget of the Algood wetland (Hill, 2007) and were modeled indirectly as described in the next section.

Seepage and evapotranspiration

Seepage from pond elements is modeled in SPAW with the seasonal time-dependent step function shown in Figure 3. Independent estimates reported by Hill and Neary (2007) based on observations of diurnal surface water cycles are shown for comparison. The same annual distribution of seepage is repeated for each year of the simulation period. This is supported by the relatively small variability displayed for the estimated seepage rates shown in Figure 3, which span several years.

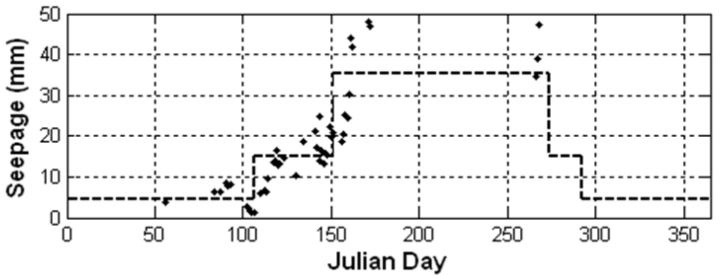


Figure 3. Temporal distribution of daily seepage used in SPAW (dashed line). The solid points are estimates from observations of diurnal surface water cycles (Hill and Neary 2007).

Measured meteorological data were averaged on a daily time step and used to estimate reference crop ET (ET_o) using the FAO Penman-Monteith equation (Allen et al., 1998). The temporal distribution of $\mathrm{ET_o}$ for 2004 and 2005 is shown in Figure 4. Potential evapotranspiration (PET) was computed by multiplying ET_o by a crop coefficient. Crop coefficients were computed from independent estimates of ET reported by Hill and Neary (2007). The temporal distribution of crop coefficients is shown in Figure 5. The computed crop coefficients fall well outside the typical range (Allen et al., 1998). These abnormalities are due to contrasting roughness and moisture conditions at the site as described by Hill and Neary (2007).

The regression relationships developed by Hill (2007) were used to estimate throughfall from gross precipitation. Precipitation retained on the canopy was subtracted from the daily potential ET. This reduced PET rate was supplied to SPAW for allocation to open water and bare soil evaporation.

Equations were calibrated to estimate ET_o during periods with missing meteorological data and for application in long-term hydrologic simulations outside the monitoring period. The Hargreaves equation for ET_o (Allen et al., 1998) given by

$$ET_o = 0.0023(T_{mean}+17.8)(T_{\max}-T_{\min})^{0.5}R_a \tag{1}$$

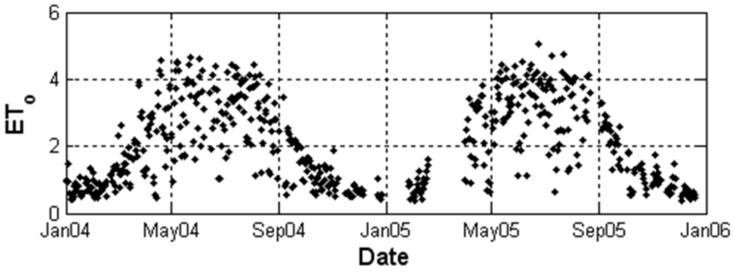


Figure 4. Temporal distribution of reference crop evapotranspiration ($\mathrm{ET_o}$) for 2004 and 2005.

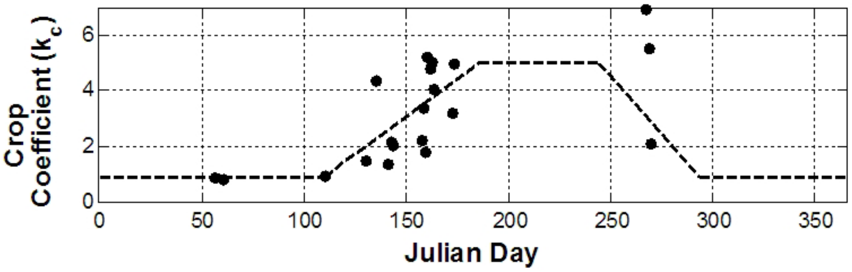


Figure 5. Temporal distribution of crop coefficient (k_c) used to compute potential evapotranspiration from reference evapotranspiration ($\mathrm{ET_o}$) and supplied to SPAW (dashed line). The solid points are estimates from observations of diurnal surface water cycles (Hill and Neary, 2007).

was recalibrated using measured meteorological data at the Algood wetland during 2004 and 2005. In Equation 1, R_a is the extraterrestrial radiation (mm/day) and T is temperature (^{o}C). The recalibrated equations for the nongrowing and growing seasons, respectively, are

$$ET_o = 0.025 + 0.507\, ET_{oEq.1} \tag{2}$$

$$ET_o = -1.061 + 0.685\, ET_{oEq.1} \tag{3}$$

where $ET_{oEq.\ 1}$ is the ET_o estimate based on Equation 1. Figure 6 shows a comparison of ET_o estimates based on the recalibrated Hargreaves Equations and the FAO Penman Monteith Equation.

Model setup

Figure 7 shows the land use distributions for the Algood wetland watershed. Three field elements were used to represent the three land use classes (forest, grass/pasture, and impervious surfaces) shown. A single pond element was used to represent the wetland. The pond element represents the area of maximum flooding extent shown in Figure 7 and has a total area of 0.93 ha. At maximum stage, the pasture north of the wetland forest becomes inundated. Outflow through a small drainage ditch occurs when the wetland stage exceeds approximately 40 cm. A stage-outflow relationship was developed using Manning's equation, which assumes uniform flow, and field measurements of channel dimension and slope.

Soil properties in the Algood wetland watershed were obtained from the Putnam county soil survey (USDA 1992). Surface textures for all soil series are silt loam, followed by a silt clay loam texture in the subsoil. The fragipan horizon is also a prominent profile feature in the watershed. A soil profile description for the Monongahela soil series was used for all three field elements representing forest, grass/pasture, and impervious land uses. The Monongahela series occupies the majority of the grass/pasture land use as indicated by Figures 7 and 8. Figure 8 shows the Monongahela series with a hydrologic soil group designation of C.

As noted by Hill et al. (2006), additional seepage occurs following precipitation events that is not represented by the temporal rates in Figure 3. This effect was modeled indirectly using a drawdown pump. A removal rate of 0.004 m^3/s was specified and verified with the analysis of measured hydrograph recessions.

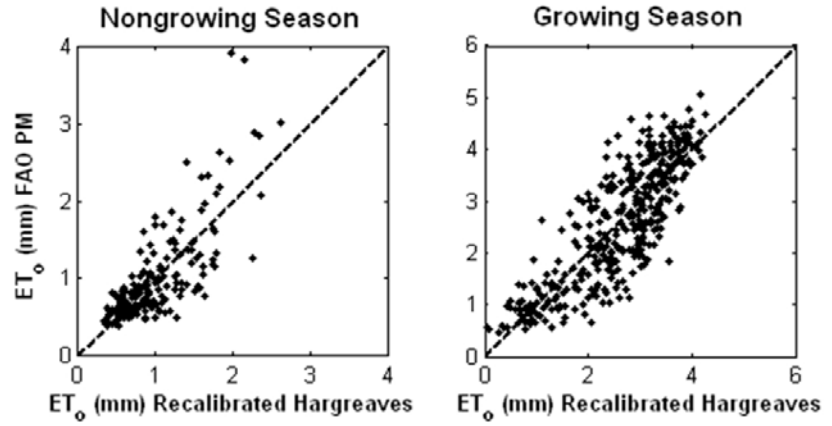


Figure 6. Comparison of reference evapotranspiration (ET$_o$) estimates based on the recalibrated Hargreaves equation and the FAO Penman Monteith equation.

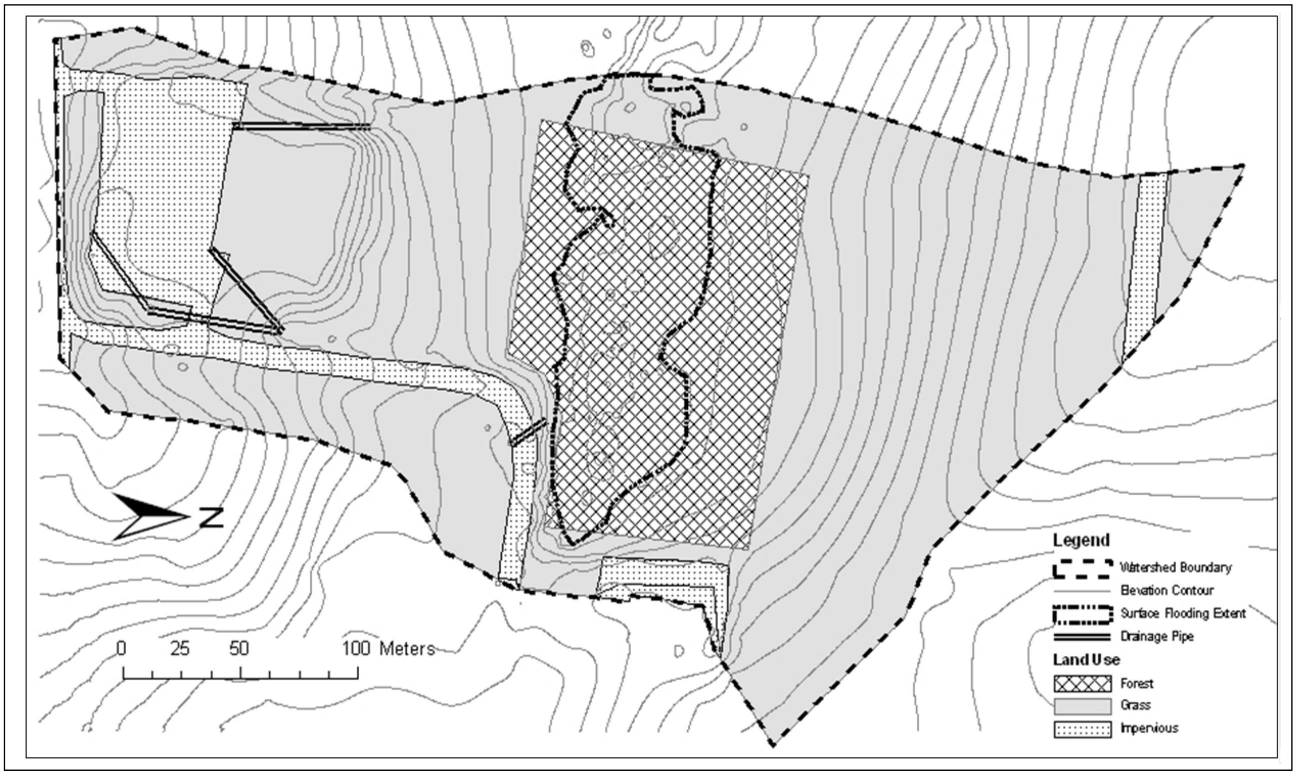


Figure 7. Land use distribution for the Algood wetland and watershed.

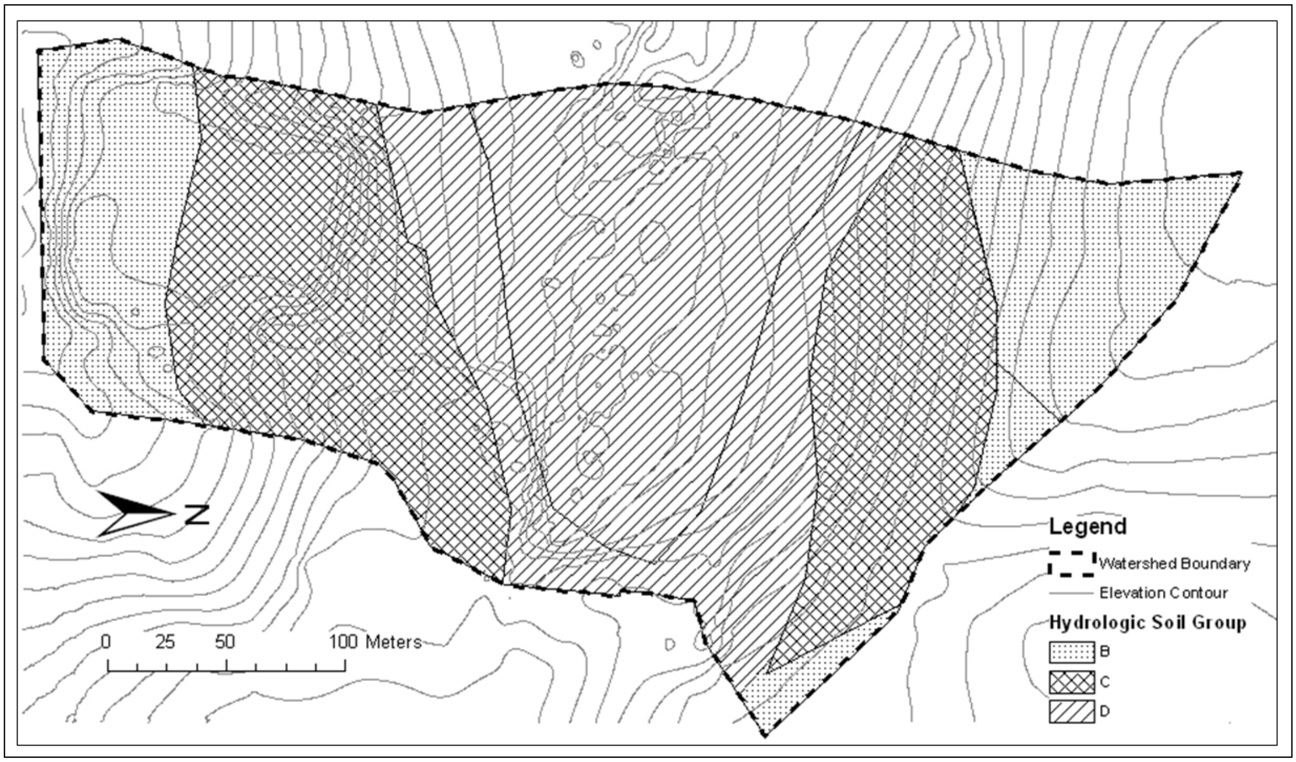


Figure 8. Mapped soil series for Algood wetland with hydrologic soil group designation (B, C, or D).

Model calibration and validation

The first year of measured wetland stage (2004) was used for model calibration and the second year (2005) was used for model validation. During model calibration, the runoff curve number for each field element and the infiltration depth required for the initiation of ponding (a pond element parameter), denoted by I_D, were varied. Both runoff curve number and I_D strongly influenced the simulated hydroperiod, which are the most important performance measure for this study. Seepage rates also strongly influence hydroperiod, but were not varied during model calibration.

Pond Infiltration depth (I_D). The I_D parameter can be computed by

$$I_D = (\theta_s - \theta_r)d_e \tag{4}$$

where θ_s is the saturated water content (i.e., porosity), θ_r is the residual water content, and d_e is an effective depth.

Assuming the depth of the fragipan horizon to be the effective depth and using typical values for the water contents in Equation 4 gives a value of 45.7 cm for I_D. This assumes that no surface ponding occurs until the wetting front reaches the fragipan soil horizon. Ponding is likely to occur much earlier due to significant clay accumulation above the fragipan horizon (Hill 2007). Additionally, ponding could occur immediately if the rainfall intensity exceeds the infiltration capacity at the soil surface, although canopy storage could attenuate this effect.

A calibrated value of 11.3 cm was adopted for I_D. Despite the limitations of the simplified modeling framework, Figures 9 and 10 indicate that the simulated hydroperiod compares favorably with the measured. During the calibration period, the measured hydroperiod was 255 days, compared to a simulated value of 262 days (2.7 % difference). During the validation period, the measured hydroperiod decreased to 145 days, compared to a simulated value of 135 days (6.9 % difference). If only the growing season is considered, the percent difference between the measured and simulated hydroperiod was 2.4 % during 2004 but increased to 40.6 % (a difference of 13 days) during 2005.

The poor performance during the growing season of 2005 is due to the inundation period lasting 6 days during May of 2005 that was not predicted by the hydrologic model. The model under predicted the drawdown date in May by 4 days, which resulted in over depletion of the subsurface storage of 11.3 cm. At the start of the rainfall event on May 19, 2005, the simulated subsurface storage was depleted to nearly 4 cm, which exceeded net precipitation and watershed runoff. As a result, the model did not predict the reemergence of ponded conditions. After the drawdown following this event, the reemergence of ponded surface water did not occur until mid-January in 2006, which the model accurately predicted (Figure 10).

Runoff Curve Numbers. Following the procedures outlined by USDA (1986) and using the hydrologic soil group distribution shown in Figure 8, a composite curve number of 74 was computed for the Algood wetland watershed. Independent curve numbers were computed for 23 rainfall events occurring in 2004 and 2005. Precipitation events were selected that were short duration and high-intensity, which produced single peaked hydrographs. Runoff volumes were computed directly for each event using water budget considerations (see Hill, 2007 for details). Computed curve numbers ranged from 57 to 84 with an average of 72, which is only 2.8 % less than the value of 74 computed from established protocols. Runoff from the largest development in the southwest corner of the watershed does not discharge directly into the wetland. As a result, additional reductions were applied following USDA (1986) to produce a composite curve number of 72.

Simulations during the calibration period using these curve number values were poor, particularly during the growing season. Simply increasing the individual curve numbers did not improve model performance during the growing season and led to frequent surface water outflows during the dormant season. Surface outflow through the drainage ditch on the west side was observed only 6 times throughout 2004 and 2005 and only for short durations. Closer inspection of internal model

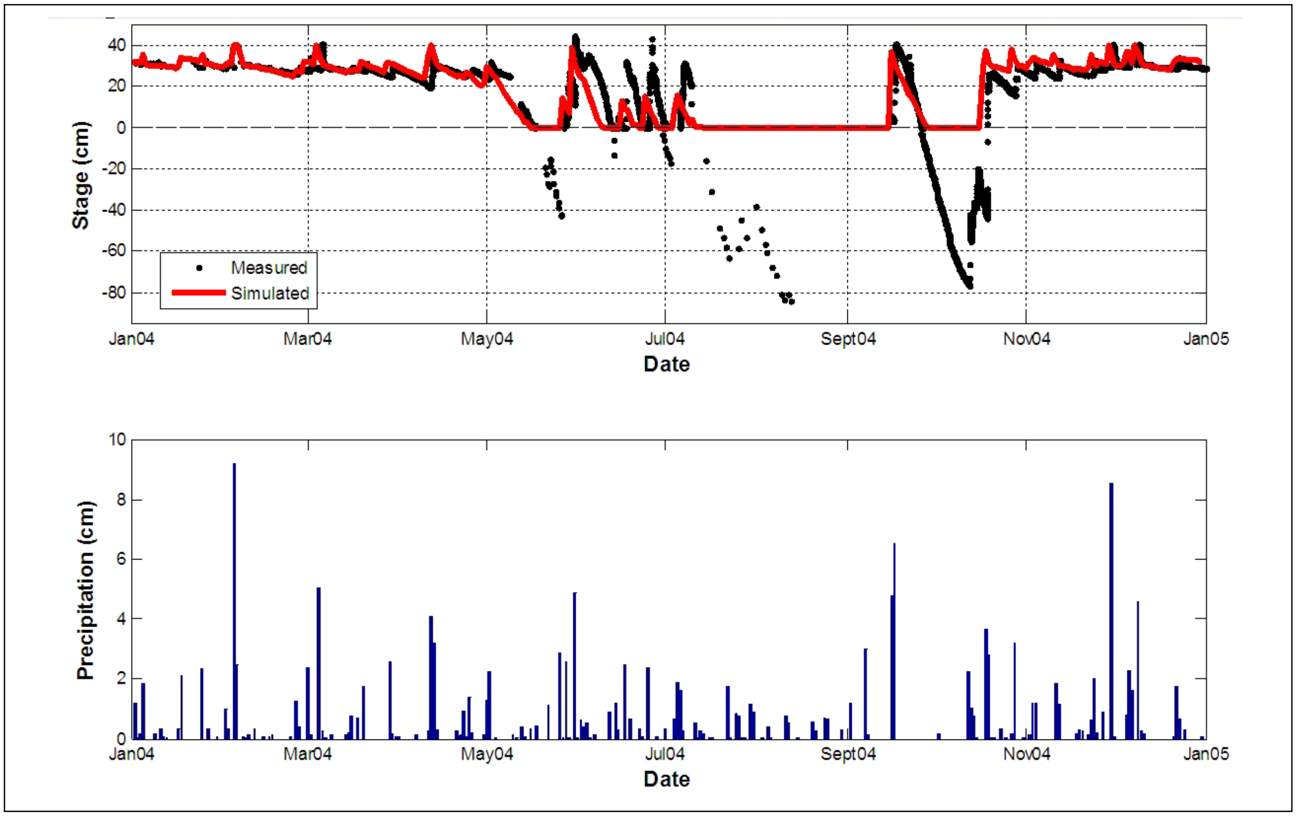


Figure 9. Comparison of observed wetland stage to values simulated by the SPAW hydrologic model during calibration period.

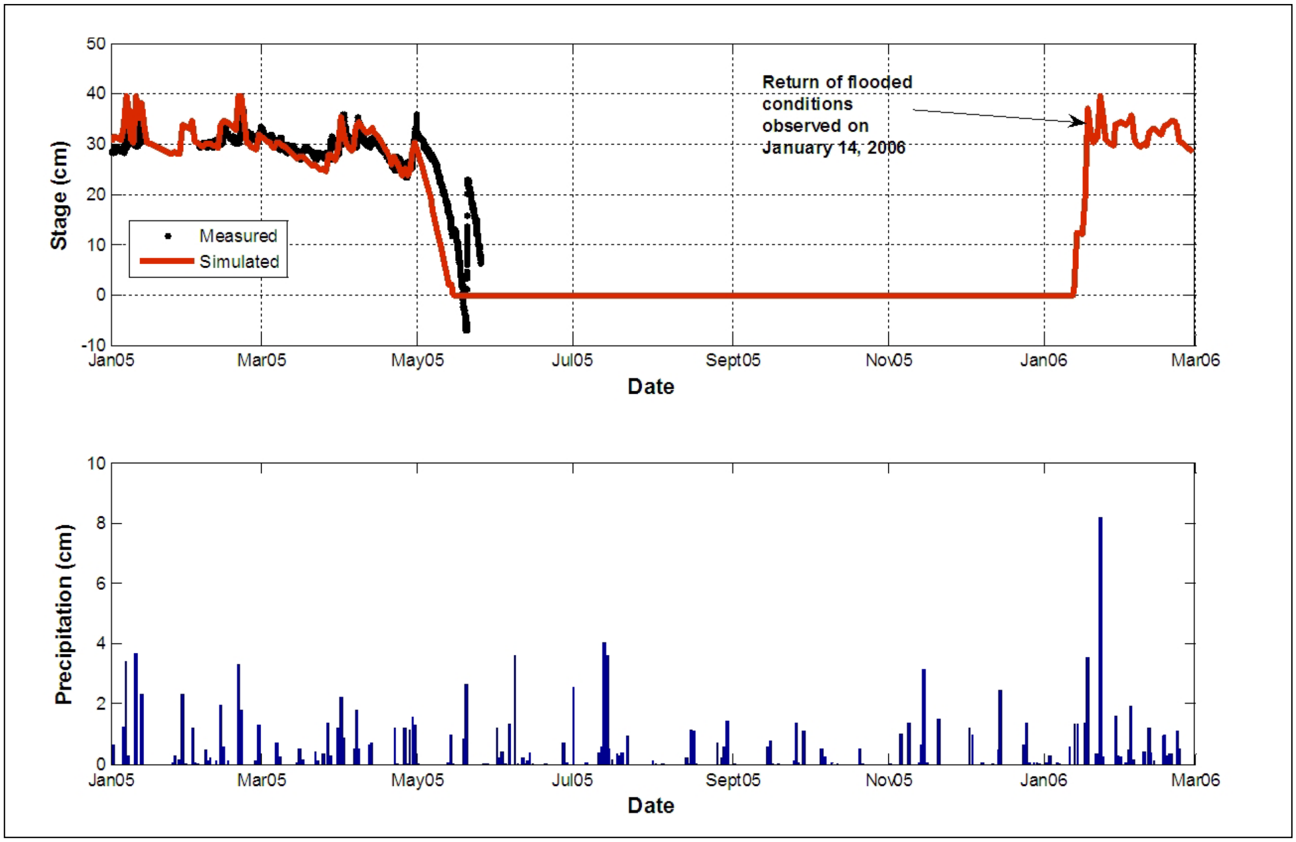


Figure 10. Comparison of observed wetland stage to values simulated by the SPAW hydrologic model during validation period.

variables indicated that the large PET rates supplied to SPAW during the growing season (Figure 5) were quickly depleting the subsurface storage volume.

A limitation of the SPAW pond model is it does not distinguish between open-water evaporation and bare soil evaporation. More rigorous descriptions include a two-stage description of bare soil evaporation (e.g., Snyder et al., 2000) which predict reduced rates as the depth to water table increases. This effect was simulated indirectly by reducing the maximum crop coefficient which approaches 5 (Figure 5) during the growing season. A value of 1.1 was adopted and greatly improved model performance during the growing season. Although this invariably led to reduced rates of open water evaporation, the simulated drawdown times were not affected appreciably since seepage is the dominant water loss mechanism.

During the calibration period, the model under predicted wetland stage by an average of 1.88 cm (25 events). During the validation period, the model under predicted wetland stage by an average of 1.61 cm (12 events). Overall, the simulation results compare well with the observed. Of particular importance to this study is the models ability to reproduce the observed hydroperiod. It is also important to note that since the SPAW hydrologic model will be used to simulate future land management scenarios, the uncertainty in runoff volume predictions will decrease as the percentage of impervious surfaces increases. This is due to decreased dependence of the runoff curve number on antecedent moisture conditions.

Long-Term Simulations

The simulation period was extended to include a 50-year period beginning in 1956 and ending in February of 2006. A long-term record of precipitation and average daily temperatures was obtained from the nearest meteorological station (National Climatic Data Center, COOP ID 402009). The recalibrated Hargreaves equations given by Equations 1-3 were used to estimate ET_o. Daily net precipitation was estimated from daily gross precipitation using the regression relationships reported by Hill (2007). All other model parameters were unchanged from the simulations during 2004 and 2005.

The simulated hydroperiod from 1956 to 2005 is shown in Figure 11. Values ranged from 171 to 343 days with an average of 230 days. The average value under existing land use conditions was 8.5 % greater than the long-term average hydroperiod of 212 days estimated by Hill et al. (2006) for the unimpacted condition (i.e., watershed completely forested).

Simulated hydroperiods for 2004 and 2005 were 277 and 177 days, respectively; measured values were 255 and 145 days for 2004 and 2005, respectively. Closer inspection of precipitation records indicated significant differences between measured precipitation at the site and the values reported at the nearest meteorological station. The long-term simulations were repeated with site measured precipitation for 2004 and 2005, but with throughfall and ET_o still computed with regression relationships developed from measured data. The results improved with simulated hydroperiods of 266 and 170 days for 2004 and 2005, respectively. This is only a 4.3 % difference for 2004, a year with normal precipitation (Figure 11) and a 17.2 % difference for 2005, a year with below normal precipitation (Figure 11).

SIMULATION OF LAND MANAGEMENT SCENARIOS (LMS)

Two future land management scenarios (LMS 2 and LMS 3) were identified for consideration and are shown in Figure 12. Both are considered likely development scenarios based on site

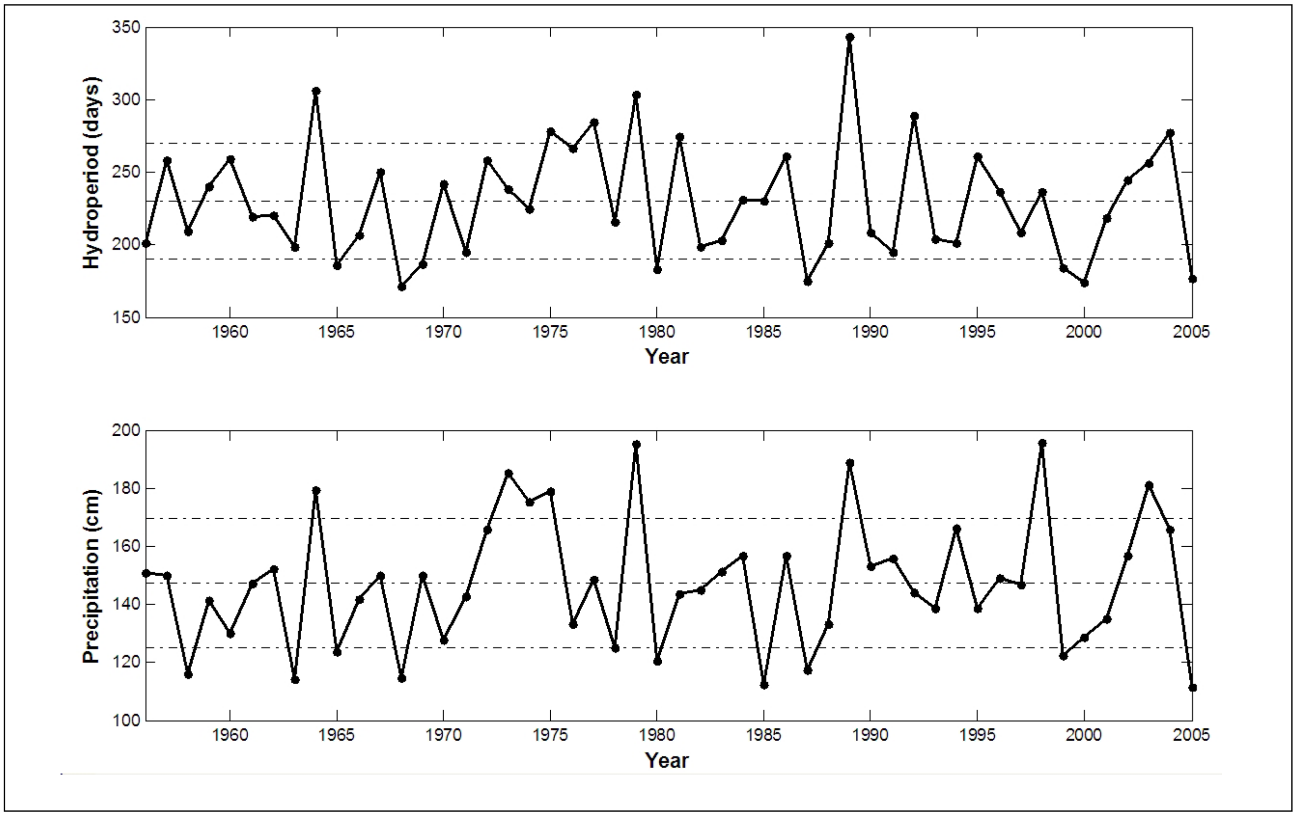


Figure 11. Results of long-term hydrologic simulation for (a) hydroperiod (days) and (b) annual precipitation (cm), from 1956-2005. The dashed horizontal lines indicate the mean +/- one standard deviation.

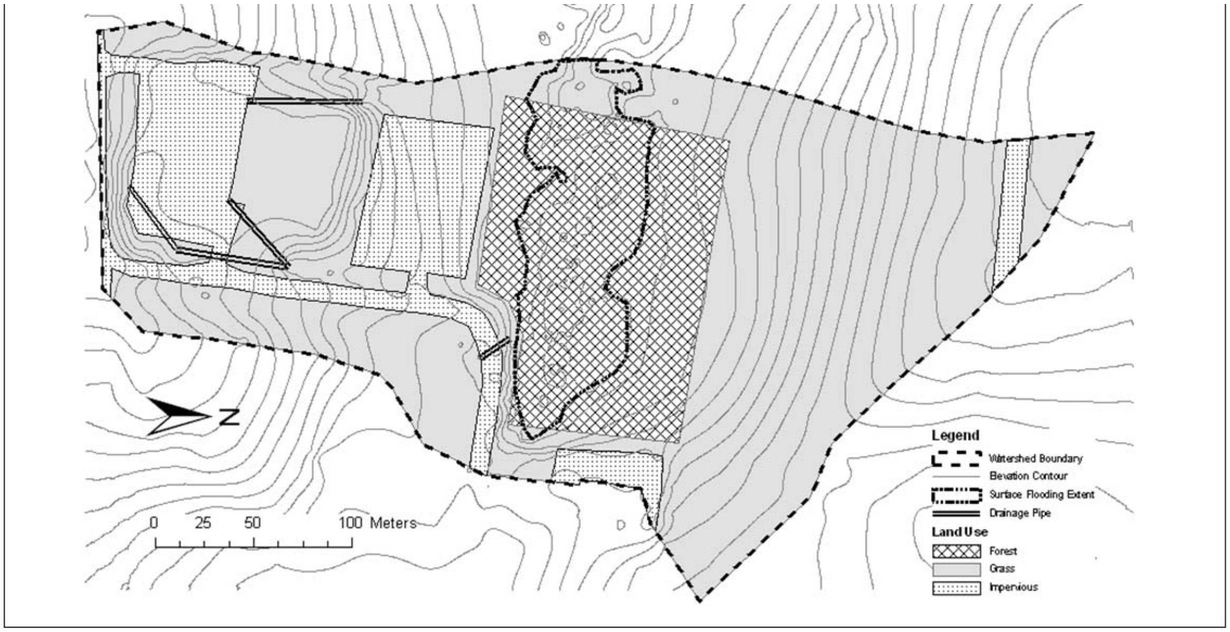
considerations (e.g., property lines, topography, etc.) and regional experience. LMS 2 includes the addition of a 0.5 ha development in the south pasture. LMS 3 includes the addition of developments in both the north and south pastures with a total area of 1.8 ha. Table 1 summarizes the land use distribution and composite curve number for the existing LMS (LMS 1) and the two future LMS's.

Long-term hydrologic simulations were completed for each LMS with appropriate parameter adjustments as summarized in Table 1. It was assumed that all runoff from the future developments is directed to the wetland without additional on-site detention. This is consistent with both existing developments, which direct runoff directly to the Algood wetland. This type of variation on these two generic development scenarios will be considered in a later section.

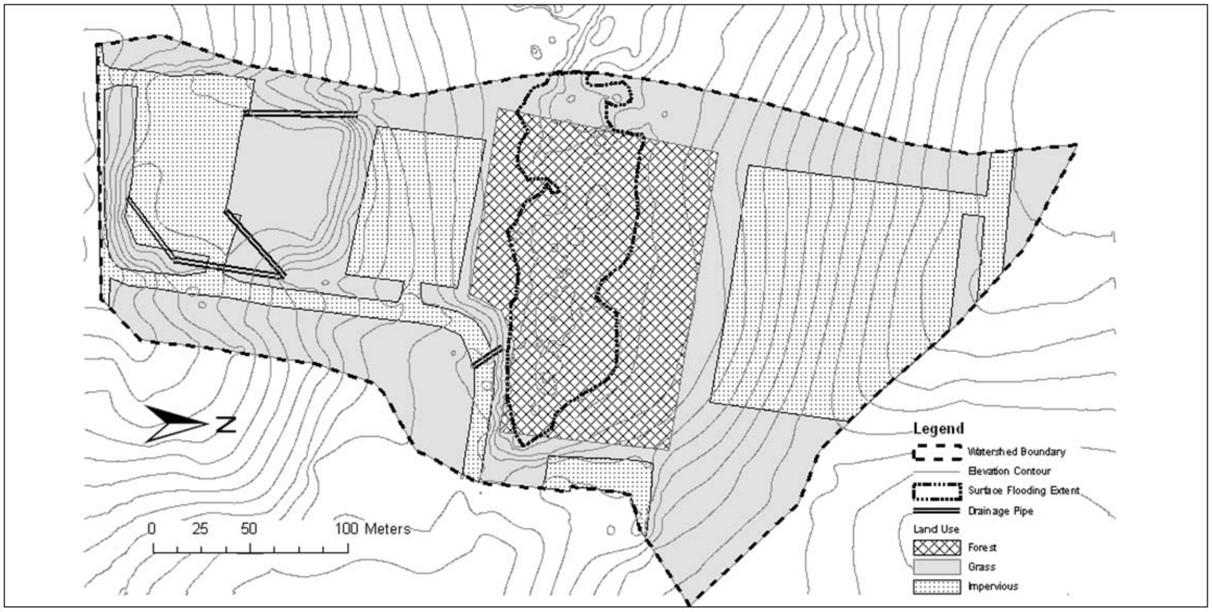
Assessment models have been developed previously by Hill et al. (2006) to rapidly assess how impacts of this type influence wetland hydrologic regimes. Model output is a functional capacity index (FCI) that ranges from 0.0 to 1.0 and represents the capacity of a given wetland to perform a specific function (i.e., provide acceptable hydrologic regime) relative to unimpacted wetlands

Table 1. Land use distribution for each land management scenario and corresponding composite curve numbers.

Land Management Scenario (LMS)	Land Use			Composite Curve Number
	Forest (%)	Impervious (%)	Short Grass/Pasture (%)	
LMS1	11.6	13.1	75.3	72
LMS2	11.6	19.7	68.7	76
LMS3	11.7	37.9	50.4	82



(a) Land Management Scenario 2 (LMS 2)



(b) Land Management Scenario 3 (LMS3)

Figure 12. Future land management scenarios simulated with the SPAW hydrologic model: (a) LMS 2 – Addition of urban development in south pasture, (b) LMS 3 – Addition of urban developments in both north and south pastures. See Figure 7 for existing land use distribution.

in a region. For reference, LMS 1 results in an FCI of 0.90. The FCI decreases to 0.84 under LMS 2 and 0.76 under LMS 3. These values will be reconsidered following assessment of the plant community.

PLANT COMMUNITY ASSESSMENT

Dominant tree species were identified through standard vegetation sampling protocols as detailed by Roberts et al. (2006) and are listed in Table 2. The waterlogging tolerances reported by Hook (1984) are also included in Table 2 and are based on a review of the pertinent literature on the tolerance of various lowland tree species to waterlogging (used synonymously with flooding). Although an individual species' response to waterlogging may vary significantly from the flooding tolerances reported in Table 2, they were used in this study to formulate a range of likely plant community responses to the future LMS's.

Flooding tolerance is reported in terms of inundation during the growing season in Table 2. The growing season was defined as the interval between the last temperature of 0 ^{o}C in the spring and the first in the fall. Growing season lengths were computed for 1956-2005 using average daily maximum temperatures and ranged from 160 to 214 days with an average of 187 days. Over the long term, the average start date for the growing season was April 16th and the average end date was October 20th.

Figure 13 shows the percent of the growing season inundated over the simulation period for each LMS. For comparison, the flooding tolerances from Table 2 are shown for three of the dominant tree species (sweetgum, red maple, and black gum). Under LMS 1 (existing conditions), the site was flooded an average of 28.5 % of the growing season, which increased to 31.4 % and 35.7 % for LMS 2 and LMS 3, respectively.

The least water tolerant of the five dominant tree species listed in Table 2 is black gum, followed by green ash, red maple, willow oak, and sweet gum. The results indicate that under existing

Table 2. Waterlogging –tolerance ratings adapted from Hook (1984) for dominant tree species found in the Algood wetland.

Species	Wetland Indicator Status of Dominant Woody Vegetation	Final water-logging-tolerance rating group[1]	Comments[2]
Liquidambar styraciflua (sweetgum)	FAC+	Moderately tolerant	Mature trees died if flooding occurred 44% of growing season. May have large variation in tolerance to flooding
Acer rubrum (red maple)	FAC	Moderately tolerant	Varies considerably in tolerances over its range. Remained healthy with flooding less than 37% of growing season. Develops adventitious water roots.
Q. phellos (willow oak)	FACW-	Moderately tolerant	Mature trees all died first year of partial inundation.
Nyssa sylvatica (blackgum)	FAC	Weakly tolerant	Healthy if flooded less than 17% of growing season.
Fraxinus pennsylvanica (green ash)	FACW	Moderately Tolerant	Prefers very wet soils but not fully saturated or flooded. Mature trees died after 3-4 years flooding.

[1] Moderately tolerant – Those species capable of living from seedling to maturity in soils waterlogged about 50% of the time. Waterlogging typically occurs in portions of the winter, spring, and early summer.

Weakly tolerant – Those species that are capable of living from seedling through maturity in soils that are temporarily waterlogged for durations of 1-4 weeks and usually accounting for 10% of the growing season.

[2] Refer to Hook (1984) for references to support these comments

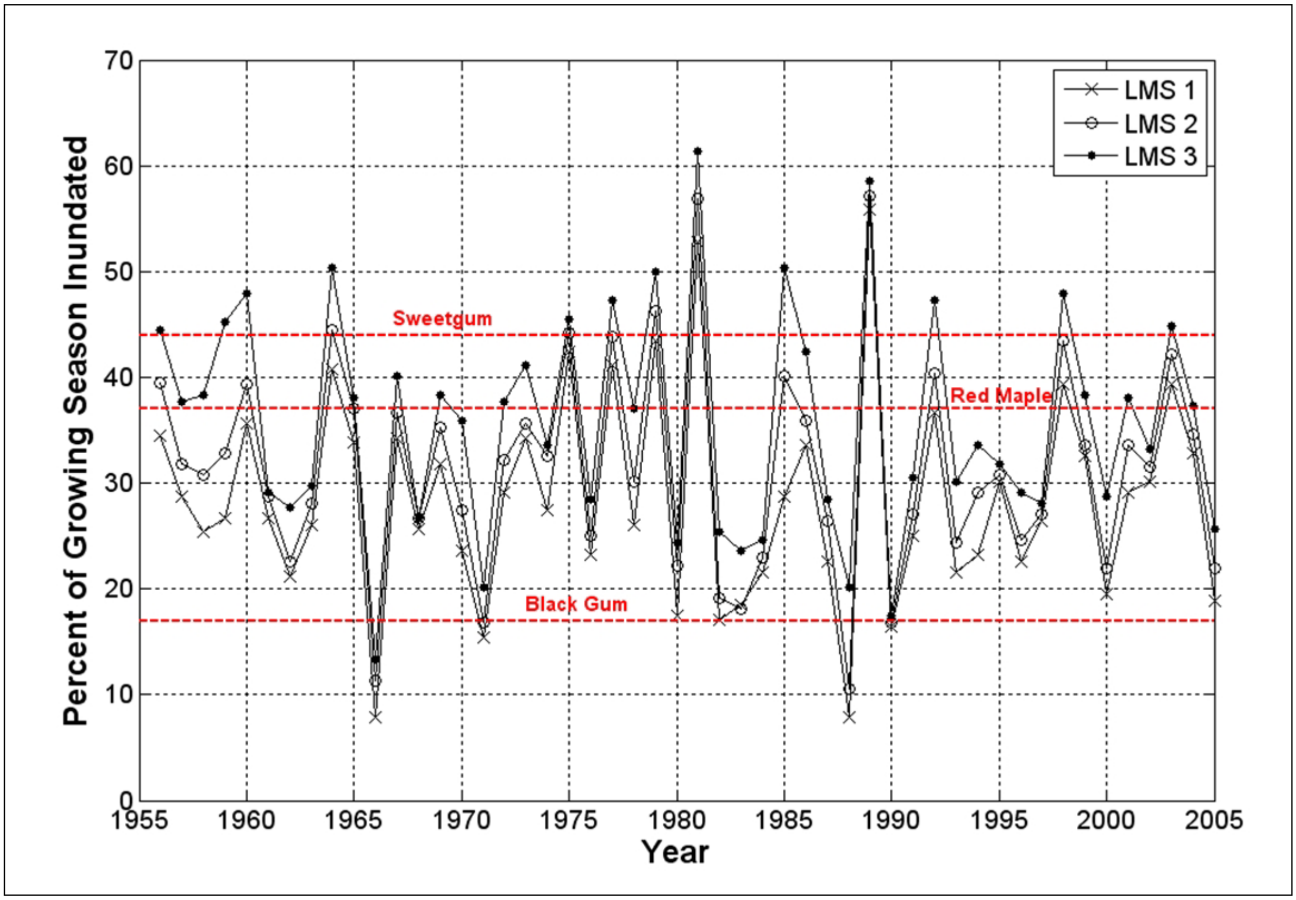


Figure 13. Percent of growing season with surface inundation for different land management scenarios. (LMS).

conditions (LMS 1, 13.1 % impervious surfaces), the two least water tolerant species (black gum and green ash) as a community are unlikely to survive. For the remaining species, the flooding tolerances are only exceeded 8 times during the 50 years of simulated hydrology.

Under LMS 2 (19.7 % impervious surfaces), the flooding tolerance of red maple (37 %) is exceeded 12 of the 50 years, with only one occurrence of two consecutive years with inundation above the tolerance. Under LMS 3 (37.9 % impervious surfaces), the flooding tolerance of red maple is exceeded 24 of the 50 years, with six consecutive multi-year (2-5 years) periods where the flooding tolerance is exceeded. This suggests the threshold development scenario is intermediate between LMS 2 and LMS 3.

Depth of water is also an important factor to consider, since larger depths greatly reduce the diffusion of atmospheric oxygen into the soil and interferes with oxygen transport from the atmosphere to the roots (Hook, 1984). The depth-duration curves shown in Figure 14 for each LMS indicate little effect on the exceedance probability of water depths greater than 28-30 cm. It is possible that this may be a modeling artifact due primarily to the models tendency to under predict wetland stage during the growing season for high-intensity, short duration events that initiate ponding prior to the subsurface becoming saturated.

Inundation periods occurring late in the growing season are more detrimental to tree species due to the development of highly reduced soil conditions (Hook, 1984). After the initial drawdown of surface water in late May and early June, inundation periods are brief for all LMS's due to greater seepage rates (Figure 3). For LMS 1, the initial inundation period ranged from 6 % to 54 % of the

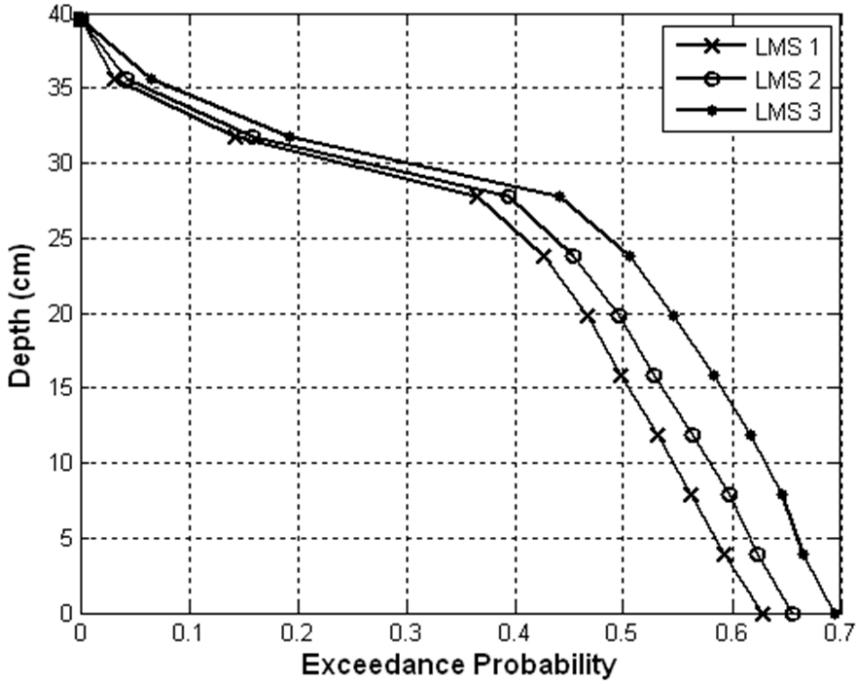


Figure 14. Comparison of depth duration curves for each land management scenario (LMS).

growing season, with an average of 22 %. Since this feature of the hydrologic regime remains relatively unchanged for either LMS, the results in Figure 13 may be misleading. If the existing plant community has historically been exposed to one significant inundation period during the early growing season, followed by brief inundation periods during the middle and late growing season, the simulated hydrologic regimes for LMS 2 and 3 may be less detrimental to the plant community than the results of Figure 13 suggest. This is supported by the current success of black gum and green ash tree species under existing land use conditions. Continued success under LMS 2 and 3 would then depend on the ability to maintain brief inundation periods during the middle and late growing season.

An important feature of the existing hydrologic regime is the rapid drawdown following inundation events in the growing season. This is particularly evident during June and July of 2004 where four complete drawdowns occur. The rapid drawdown is a direct consequence of the annual seepage pattern shown in Figure 3, which shows larger seepage rates occurring during the growing season. Increased seepage during the growing season is attributed to transpiration of infiltrated water around the perimeter of the wetland. Removal of infiltrated water by transpiration increases the hydraulic gradient that controls the rate of pond seepage. Perimeter trees intercept advected energy and utilize it to sustain high rates of transpiration. This type of removal mechanism has been previously suggested by Meyboom (1966), Millar (1971), and more recently by Parsons et al. (2004) for a seasonal prairie wetland surrounded by a ring of willow trees.

As indicated in Figure 12, a forested buffer was preserved for both future LMS's. The buffer has an approximate width of 40 m on the north side of the wetland and 30 m on the south side. In an urban setting, where perimeter trees intercept warm and dry air, the influence on pond seepage is expected to increase. Additional long-term simulations were completed using reduced seepage rates during the growing season, which might be expected if future LMS's include removal of the forested buffer around the perimeter of the wetland. A reduction of 10 % resulted in an increase in growing season inundation of 18.7 %, relative to existing conditions (LMS 1). Reductions of 25 % and 50 % increased the growing season inundation by 22.6 % and 32 %, respectively. These results indicate that only a moderate decrease in growing season seepage rates, due to removal of the forested buffer, is more disruptive to the hydrologic regime than either future LMS considered.

CONCLUSIONS

This study employed the SPAW (Soil-Plant-Atmosphere-Water) model to simulate the hydrology of a forested sinkhole wetland on the Tennessee Highland Rim. Recent development activities have increased awareness of the potential adverse impacts of continued watershed development on the wetland plant community. The SPAW model was used to simulate hydrologic conditions over a 50 year period for two future land management scenarios (LMS's) with 19.7 % (LMS 2) and 37.9 % (LMS 3) of the watershed converted to impervious surfaces.

Plant community success was assessed by comparing simulation results to published flooding tolerances of individual tree species, reported as an upper limit on growing season inundation. These tolerances provide a means to predict in general how a population of species may respond to an altered flooding regime. The results indicate unfavorable hydrologic conditions under existing conditions (13.1 % impervious surfaces) for the two least water tolerant species (black gum and green ash). This is inconsistent with the observed plant community response to development activities that occurred late in 2003 and is an indication that the flooding tolerance may be significantly greater. The longest inundation period occurred between the start of the growing season and the first drawdown date. Inundation periods occurring later in the growing season were brief due to large seepage rates. A stand of mature trees is more apt to survive extended inundation if it occurs early in the growing season.

Seepage rates during the growing season had a more dominant influence on growing season inundation than increased surface runoff from the future developments. A forested buffer was preserved in both future LMS's and is responsible for maintaining large seepage rates during the growing season. Preservation of the forested buffer appears to be the most important aspect of future land management.

A particularly valuable extension of this work is continued documentation of site hydrology and plant community response as development inevitably continues in the Algood wetland watershed. Some variation of LMS 2 is likely to occur in the near future (< 2 years). The analysis indicates favorable hydrologic conditions for this scenario, although a change in plant community composition is expected, specifically a decrease in diversity with a greater abundance of the moderately tolerant species listed in Table 1 (sweetgum, red maple, and willow oak). The simulation results indicate unfavorable hydrologic conditions under LMS 3. This scenario is less likely to occur since the north pasture is not currently zoned for commercial development. Overall, development with impervious surfaces in the range of 20-25 % is unlikely to appreciably influence the existing plant community.

Measures to mitigate the effects of future development should be explored, particularly if signs of plant community stress are observed following additional development. The existing developments currently direct all runoff to the wetland. Detention basins alone are inadequate as mitigation measures since the volume of runoff is not reduced significantly. Potential strategies include runoff diversion to existing storm sewer systems, implementation of low impact development technologies, and modification of the outlet structure to decrease drainage time.

The results of this study also have implications for the rapid hydrologic assessment models previously developed for sinkhole wetlands on the Tennessee Highland Rim (Hill et al., 2006). Given the importance of the forested buffer to hydrologic function, the models should include an additional variable to characterize buffer width and location around the perimeter. Additionally, the relationship between wetland hydroperiod and functional capacity index (FCI) should be reconsidered. Figure 15 shows the original relationship proposed by Hill et al. (2006) and corresponding FCI scores for each LMS. The relationship decreases linearly from the unimpacted condition (FCI = 1.0) at a hydroperiod of 212 days to a minimum of 0.1 at a hydroperiod of 365 days. An FCI score of 0.76 for LMS 3 inadequately reflects the expected site level response of the plant community. As a result, a revised relationship is also shown in Figure 15 that shows a greater decrease in functional capacity as the hydroperiod increases. The revised relationship decreases to a value of 0.3 (instead of 0.1) then remains constant as the hydroperiod increases. Sites in this region are expected to retain wetland hydrologic conditions, but transition to a more water tolerant herbaceous plant community.

More generally, this study demonstrates a simple modeling framework for addressing land management decisions in zero-order watersheds containing depression wetlands. The SPAW model performed reasonably well for hydroperiod prediction in this study, despite its simple treatment of surface runoff and pond seepage. Model improvements recommended to extend the capabilities of SPAW are: (1) extend canopy process descriptions (i.e., canopy interception and evaporation) to pond elements, (2) improve pond element evapotranspiration model to distinguish between open water evaporation and bare soil evaporation, (3) improve surface runoff process descriptions to include advances in daily flow simulation models based on the NRCS curve number (Mishra and Singh, 2004), and (4) improve process description of pond seepage.

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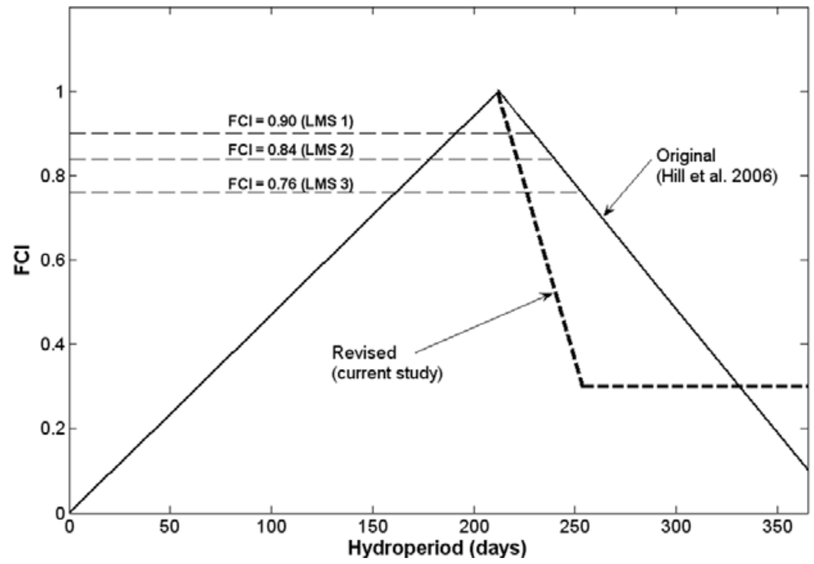

Figure 15. Revised relationship between wetland hydroperiod and functional capacity index (FCI) originally proposed by Hill et al. (2006).

2007). Critical reviews by the dissertation advisory committee led to significant improvements in the manuscript.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration guidelines for computing crop water requirements. Land and Water Development Division, Food and Agricultural Organization of the United Nations, Rome, Italy.

Azous, A.L., and R.R. Horner. 2001. Wetlands and urbanization: implications for the future. CRC Press, Boca Raton, FL, USA.

Hill, A.J., and V.S. Neary. 2007. Estimating evapotranspiration and seepage for a sinkhole wetland from diurnal surface water cycles. Journal of the American Water Resources Association, Vol. 43(6), pp. 1359-1619.

Hill, A.J. 2007. Monitoring and modeling the hydrology of a forested sinkhole wetland on the Tennessee Highland Rim. Ph.D. Dissertation, Tennessee Technological University, Cookeville, TN, USA.

Hill, A.J., V.S. Neary, and K.L. Morgan. 2006. Hydrologic modeling as a development tool for HGM functional assessment models. Wetlands, Vol. 26(1), pp. 161-180.

Hook, D.D. 1984. Waterlogging tolerance of lowland tree species of the south. Southern Journal of Applied Forestry, Vol. 8(3), pp. 136-147.

Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. Journal of Hydrology, Vol. 4, pp. 38-61.

Millar, J.B. 1971. Shoreline-area ratio as a factor in rate of water loss from small sloughs. Journal of Hydrology, Vol. 14, pp. 259-284.

Mishra, S.K., and V.P. Singh. 2004. Long-term hydrological simulation based on the Soil Conservation Service curve number. Hydrological Processes, Vol. 18(7), pp. 1291-1313.

Mitsch, W.J., and J.G. Gosselink. 2000. Wetlands, third edition. John Wiley and Sons, New York, NY, USA.

Parsons, D.F., M. Hayashi, and G. van der Kamp. 2004. Infiltration and solute transport under a seasonal wetland: bromide tracer experiments in Saskatoon, Canada. Hydrological Processes, Vol. 18(11), pp. 1011-2027.

Roberts, T.H., K.L. Morgan, A.J. Hill, R. Cripps, and V.S. Neary. 2006. Hydrogeomorphic Classification and Assessment of Depression and Flat Wetlands on the Tennessee Highland Rim. In Review, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

USDA. 1992. U.S. Department of Agriculture. Soil survey for Putnam County, Tennessee. Soil Conservation Service, TN, USA.

USDA. 1986. U.S. Department of Agriculture. Urban hydrology for small watersheds. Natural Resources Conservation Service, Conservation Engineering Division. Washington, DC, USA.

Saxton, K.E., 2004. Documentation for the soil plant atmosphere water (SPAW) model. U.S. Department of Agriculture Argricultural Research Service. Web Address <http://hydrolab.arsusda.gov/SPAW/Index.htm>.

Snyder, R.L., K. Bali, F. Ventura, and H. Gomez-MacPherson. 2000. Estimating evaporation from bare or nearly bare soil. Journal of Irrigation and Drainage Engineering, Vol. 126(6), pp. 399-403.

Wolfe, W.J. 1996. Karst wetlands on the barrens, geomorphic control of wetland hydrology and plant distribution on the highland rim of Tennessee. Ph.D. Dissertation, Clark University, Worchester, MA, USA

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