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The effect of surface/ground water interactions on wetland sites with different characteristics

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Abstract

Wetlands have gained greater attention in the last two decades, since they have an important impact on water supply and water quality control. Treatment wetlands have recently been used as a best management practice to decrease the storm water runoff peaks and to improve storm water runoff water quality. Therefore, efforts have been made toward a better understanding of both wetland hydrology and wetland water quality. Wetlands are located between uplands and downstream flooded systems and surface/ground water interactions are usually observed in these critical transitional zones. Surface and ground water are mixed and the quality of both sources is affected by each other due to this interaction. Therefore, it is important to understand the role of surface/ground water interactions on wetland sites to develop accurate wetland models. In this study, the effect of surface/ground water interactions on wetland hydrology is investigated for different wetland conditions, such as vegetation, slope of the land site, and lateral and vertical hydraulic conductivities by using the wetland model WETland Solute TrANsport Dynamics (WETSAND). This wetland model has both surface flow and solute transport components, incorporates surface/ground water interactions and accounts for upstream contributions from urbanized areas. Simulations are conducted for the Duke University restored wetland site in the Sandy Creek watershed. It is observed that the effect of surface/ground water interaction on surface water depths becomes more dominant on wetland sites with high slopes and low vegetation.

Keywords: Wetland hydrology; Surface/ground water interaction; Wetland model; Water quality

1. Introduction

Wetlands have gained great attention recently, since they control surface water flow and downstream water quality [1,2]. The ability of decreasing the surface runoff peaks and improving the surface runoff water quality qualifies wetlands as a best management practice method [3–5]. Researchers have been challenged to

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develop sophisticated wetland models in order to be able to adequately model the wetland dynamics and nutrient transport at wetland sites. Moreover, surface/ground water interactions play an important role in wetlands. These processes affect the dynamics of wetland hydrology and solute transport significantly. Therefore, it is important to incorporate the effect of surface/ground water interactions into wetland models and understand its consequences for wetland sites with different characteristics.

There have been studies to understand the interaction mechanisms between wetland and ground water. The interactions between ground water and streams, lakes and wetlands are discussed by Winter et al. [6] in detail. Winter [7] discussed the role of topography, geologic framework, water table level and climate on ground water interaction with streams, lakes and wetlands. The importance of surface/ground water interactions in wetlands on wetland functions are discussed in a study by Price and Wadington [8]. Harvey et al. [9] tried to quantify recharge and discharge in the Water Conservation Area 2A in the Central Everglades by using the one-dimensional transport with inflow and storage model (OTIS). Restrepo et al. [10] developed a computer package for MODFLOW to simulate the interaction of wetlands with aquifers. Koreny et al. [11] investigated the hydrology of a created riparian wetland system and observed water seepage from the wetland into a subsurface environment which has local ground water flow system characteristics. Crowe et al. [12] developed a numerical model to simulate the ground water–wetland interactions and contaminant transport and applied their model to a wetland site at Point Pelee, Ontario, Canada. McHale et al. [13] investigated stream–wetland interactions by measuring nitrogen in stream and ground water at a riparian wetland site located in the Archer Creek watershed in the Adirondack Mountains of New York State.

These studies are examples of the efforts toward a better understanding of nonlinear wetland dynamics by incorporating surface/ground water interactions into wetland models. This study contributes to these research efforts by investigating the effect of surface/ground water interactions on wetland hydrology for different wetland characteristics. For this purpose, we analyze the change in surface water depth by using the WETSAND [14] model with different values of the wetland parameters, namely slope, vegetation density, and lateral and vertical hydraulic conductivity. We present the results for the Duke University restored wetland site in the Sandy Creek watershed.

2. Methodology

2.1. Wetland solute transport dynamics (WETSAND)

The WETSAND model has two main components: wetland water quantity and wetland water quality [14]. The wetland water quantity component analyzes the overland flow on a wetland site by using diffusion wave theory. The overland flow from upland areas is routed through the wetland areas into the stream as lateral inflow. The model takes into account rainfall, lateral inflow and ground water discharge as water sources; infiltration, evapotranspiration and ground water recharge as water sinks. Infiltration is calculated by the modified version of the Green-Ampt method during an unsteady rain [15], and evapotranspiration is calculated by the Thornthwaite Method [16]. The surface/ground water interaction is taken into account by ground water recharge/discharge terms and calculated by using Darcy's Law. The upstream surface runoff generated over urbanized areas is simulated by using the EPA Storm Water Management Model (SWMM5) [17] and it is incorporated into the wetland model as an inflow boundary condition at the stream. The diffusion wave equation is used to calculate the change in water depth as follows:

$$\frac{\partial y}{\partial t}+c\frac{\partial y}{\partial x}=K_1\frac{\partial^2 y}{\partial x^2}+\bar{q} \qquad (1)$$

where y is the surface water depth (L), t is time (T), x is the distance (L), c is the wave celerity (L/T), K_1 is the hydraulic diffusivity (L^2/T), and $\bar{q}$ is the water source/sink terms (L/T). The term $\bar{q}$ is the sum of the rainfall, ground water recharge and discharge, lateral inflow, infiltration, and evapotranspiration components. The flow rate over a wetland area is then calculated by the power law given by Kadlec and Knight [18] which takes into account the effect of vegetation density on the flow at wetlands:

$$Q=K\ Wy^3S_0$$
$$K=\begin{Bmatrix}1\times 10^7\ \text{m}^{-1}\ \text{day}^{-1}\ \text{dense vegetation}\\ 5\times 10^7\ \text{m}^{-1}\ \text{day}^{-1}\ \text{sparse vegetation}\end{Bmatrix} \qquad (2)$$

where Q is the flow rate in (L^3/T), W is the wetland width (L), and K is the coefficient which reflects the vegetation density ($L^{-1}T^{-1}$).

The wetland water quality component analyzes the concentration of total phosphorus and total nitrogen or each compound of the nitrogen cycle (organic nitrogen, ammonium nitrogen and nitrate nitrogen) on wetland areas by using the one-dimensional advection–dispersion–reaction equation. The velocity calculated by water quantity component is used as input in the water quality component. The nitrogen and phosphorus concentration generated over urban areas are calculated by using SWMM5 and used as boundary condition at upstream point of the wetland site. The surface/ground water interaction is taken into account by including the mass term due to the ground water recharge/discharge into the advection–dispersion–reaction equation. The formulations for phosphorus and nitrogen concentrations are given as follows:

- **Total phosphorus (TP):**

$$\frac{\partial C_{\text{TP}}}{\partial t}=-V\frac{\partial C_{\text{TP}}}{\partial x}+\frac{1}{A_x}\frac{\partial}{\partial x}\left(A_xD_x\frac{\partial C_{\text{TP}}}{\partial x}\right)+\frac{q_{\text{Lin}}}{A_x}\left(C_{\text{TP}}^{\text{L}}-C_{\text{TP}}\right)+\frac{q_{\text{gwd}}}{A_x}\left(C_{\text{TP}}^{\text{gw}}-C_{\text{TP}}\right)-K_{\text{TP}}C_{\text{TP}} \qquad (3)$$

- **Total nitrogen (TN):**

$$\frac{\partial C_{\text{TN}}}{\partial t}=-V\frac{\partial C_{\text{TN}}}{\partial x}+\frac{1}{A_x}\frac{\partial}{\partial x}\left(A_xD_x\frac{\partial C_{\text{TN}}}{\partial x}\right)+\frac{q_{\text{Lin}}}{A_x}\left(C_{\text{TN}}^{\text{L}}-C_{\text{TN}}\right)+\frac{q_{\text{gwd}}}{A_x}\left(C_{\text{TN}}^{\text{gw}}-C_{\text{TN}}\right)-K_{\text{TN}}C_{\text{TN}} \qquad (4)$$

where C_{TP} is the total phosphorus concentration (M/L^3), C_{TN} is the total nitrogen concentration (M/L^3), A_x is the cross-sectional area in x-direction (L^2), D_x is the dispersion coefficient (L^2/T), q_{Lin} is the lateral inflow (L^2/T), C_{TP}^{L} is the lateral total phosphorus concentration (M/L^3), C_{TN}^{L} is the lateral total nitrogen concentration (M/L^3), q_{gwd} is the ground water discharge (L^2/T), $C_{\text{TP}}^{\text{gw}}$ is the total phosphorus concentration in ground water (M/L^3), $C_{\text{TN}}^{\text{gw}}$ is the total nitrogen concentration in ground water (M/L^3), K_{TP} is the first order loss rate constant for total phosphorus reduction ($1/T$), and K_{TN} is the first order loss rate constant for total nitrogen reduction ($1/T$).

2.2. Application site: Duke University restored wetland site

The application site is located in Durham, North Carolina, USA (Fig. 1(a)), which is in the southern section of Durham County and covers 554.41 ha (1370 acres). It is a wetland system that has recently undergone restoration within the Sandy Creek watershed. Urban runoff from

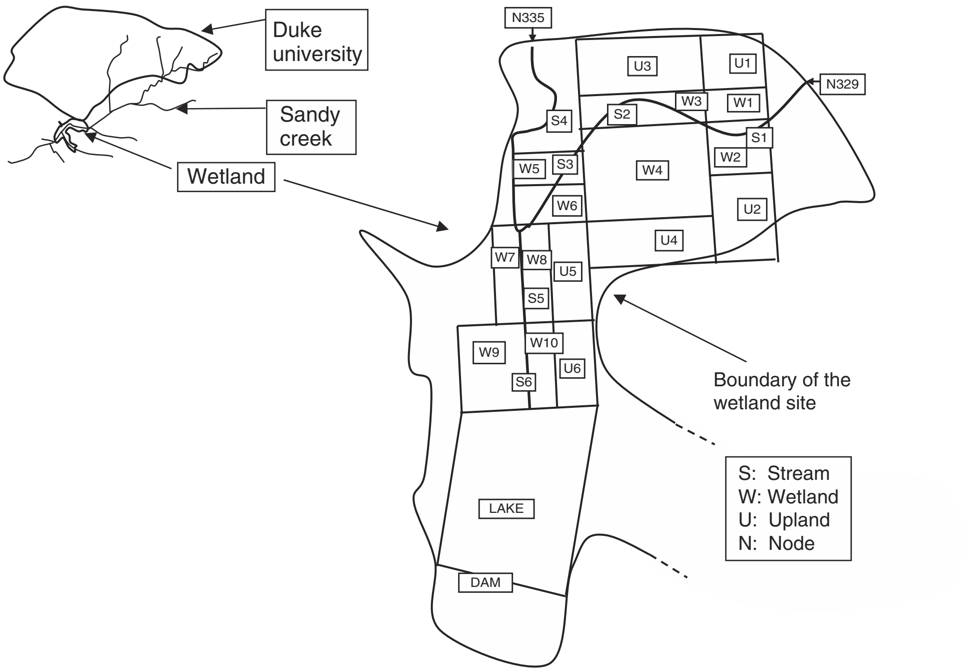

Fig. 1. (a) Duke University and wetland site watersheds, in Durham, North Carolina, United States; (b) Discretization of the Duke University wetland site.

parts of the Duke University campus and parts of the City of Durham flows into the restored wetland area. The runoff reaches the Jordan Reservoir and Cape Fear River through New Hope Creek of which Sandy Creek is a tributary. The drinking water of Durham and Orange counties in the state of North Carolina is supplied from the Jordan Reservoir and Cape Fear River.

The wetland stream restoration project is designed to transform the degraded portion of Sandy Creek into 2 ha (5 acres) of wetland by re-contouring and raising the water table of the creek. Over 579 m (1900 ft) of Sandy Creek has been restored by closing part of the original streambed and opening a new streambed with more meanders, in order to enhance the water flow over the floodplain and aid in the removal of nutrients and sediments. In addition to this, there is a constructed dam which creates additional wetland sites upstream. The artificial lake behind the dam will have a surface water level at 89.92 m (295 ft) above mean sea level. Investigators from the Duke University Nicholas School of the Environment and Earth Sciences have been measuring ground water levels from 20 sampling wells located throughout the wetland site and water quality data from Sandy Creek Tributary D at the wetland site. The ground water level measurements are taken once every two weeks and water quality measurements for major nutrients (N, P and cations) are taken monthly at the wetland and lake site as well as in all tributaries [19].

In order to apply the WETSAND model to this site, the Duke University wetland site was discretized into six upland (U) and ten wetland (W) sections and six stream (S) segments (Fig. 1(b)). The upstream surface runoff flows into the wetland area through the nodes N329 and N335. The analyses were conducted on different wetland sections and these sections were selected according to the different ground water levels observed at these sections. Modeling the Duke University wetland site by using the WETSAND and collected data used in modeling is presented in detail by Kazezyılmaz-Alhan et al. [14]. In this paper, the WETSAND model is used to predict the effect of surface/ground water interactions for different wetland characteristics, i.e., vegetation, slope of the land site, and lateral and vertical hydraulic conductivity at Duke University restored wetland site.

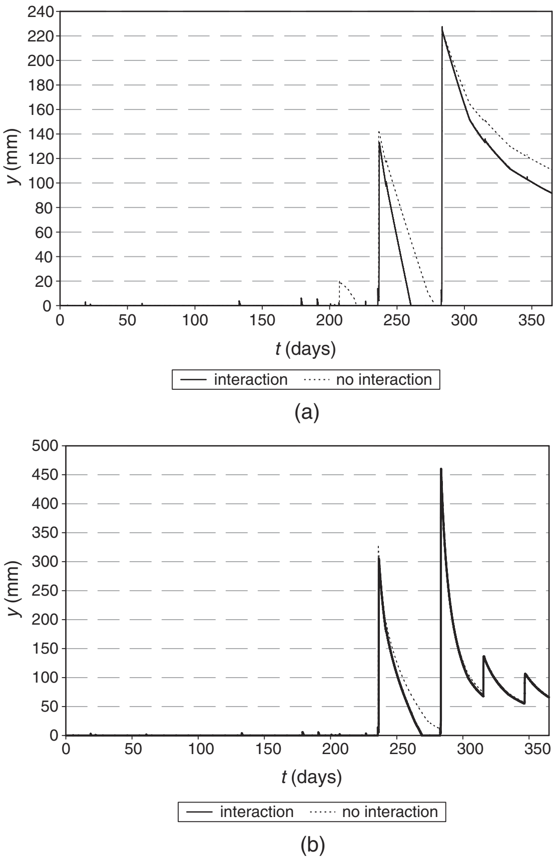

Fig. 2. Change of water depth on wetland section four (W4) for (a) $S_0 = 0.001$ and (b) $S_0 = 0.0001$.

3. Results and discussion

Here, we present the results obtained on wetland section four where we mostly observe ground water recharge. Similar results are obtained for wetland section eight where we mostly observe ground water discharge. The results show clearly that the effects of surface/ground water interactions in general play a significant role on wetland dynamics and therefore should be taken into account when modeling wetland hydrology and solute transport.

Fig. 2(a) and (b) show the change of water depth on wetland section four (W4) with slopes $S_0 = 0.001$ and $S_0 = 0.0001$. These figures show that the effect of the interaction on water depth decreases as the slope of the terrain decreases. The difference between the water depth calculated with the interaction effect included and the water depth calculated with no interaction effect included is larger for the wetland section with high slope than the wetland section with mild slope.

The change in water depth on wetland section four is plotted for vertical hydraulic conductivities $K_z = 0.001$ m/h and $K_z = 0.002$ m/h in Fig. 3(a) and (b), respectively. We observe that the difference between the water depth calculated with the interaction effect included and the water depth calculated with no interaction effect included is not significant for different vertical hydraulic conductivities. Therefore, we conclude that the vertical hydraulic conductivity does not play a major role in determining the effect of surface/ground water interaction on water depth.

Next, the effect of surface/ground water interaction on wetlands with different vegetation characteristics is investigated. The change in water depth on wetland section four (W4) is plotted for $K = 0.1 \times 10^7$ m^{-1}/h and $K = 0.5 \times 10^7$ m^{-1}/h in Fig. 4(a) and (b), respectively. Large K values represent low vegetation density whereas small K values represent high vegetation density. As can be seen from these figures, the effect of surface/ground water interaction on wetland water depth decreases as the vegetation density increases at a wetland site.

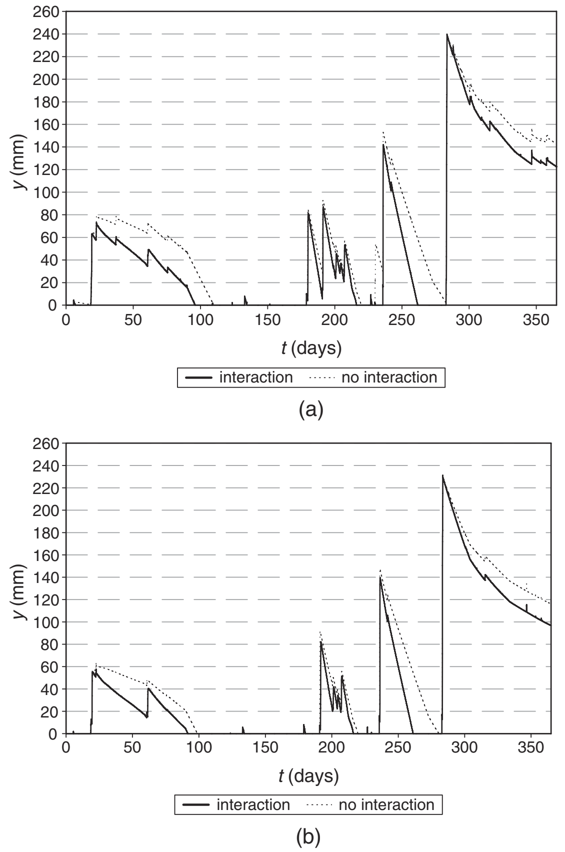

Fig. 3. Change of water depth on wetland section four (W4) for (a) $K_z = 0.001$ m/h and (b) $K_z = 0.002$ m/h.

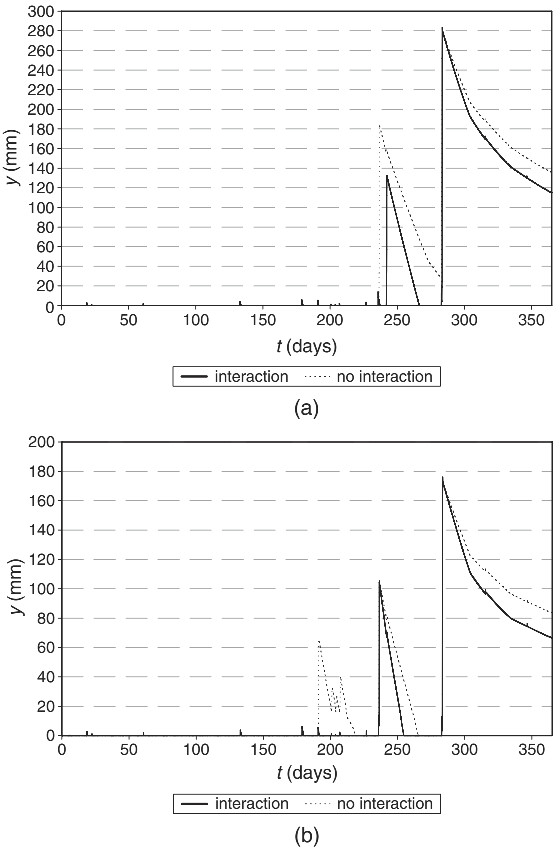

Fig. 4. Change of water depth on wetland section four (W4) for (a) $K = 0.1 \times 10^7\,m^{-1}/h$ and (b) $K = 0.5 \times 10^7\,m^{-1}/h$.

Finally, the role of lateral hydraulic conductivity is investigated for an anisotropy ratio of one. Fig. 5(a) and (b) show the change in water depth on wetland section four (W4) with lateral and vertical hydraulic conductivity values $K_x = K_z = 0.001$ m/h and $K_x = K_z = 0.002$ m/h, respectively. It is observed that the interaction effect on change of water depth increases as the lateral and vertical hydraulic conductivity increases. Since we determined from the previous analyses that the vertical hydraulic conductivity does not change the interaction effect on water depth significantly, we conclude that the increase in lateral hydraulic conductivity causes an increase in the interaction effect on water depth.

4. Conclusions

In this study, the effect of surface/ground water interactions on wetland hydrology is investigated. Particularly, the effect of the exchange of water between surface and subsurface phases on surface water depths is analyzed for different wetland characteristics such as vegetation, slope of the terrain, and lateral and vertical hydraulic conductivities. The simulations are made by using the WETSAND model which has both water quantity and water quality module and incorporates surface/ground water interactions. The results are presented for the Duke University restored wetland site in the Sandy Creek watershed. It is observed that the effect of

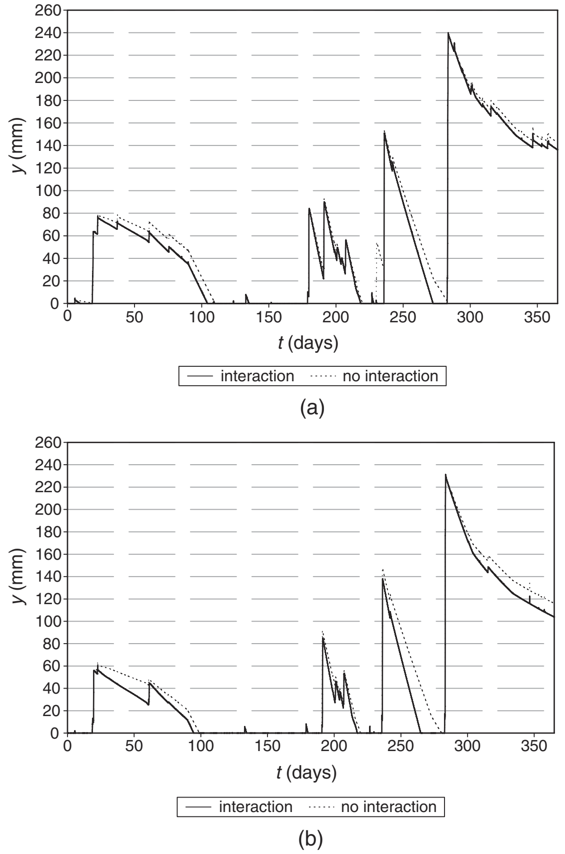

Fig. 5. Change of water depth on wetland section four (W4) for (a) $K_x = K_z = 0.001$ m/h and (b) $K_x = K_z = 0.002$ m/h.

surface/ground water interactions is significant at wetland sites with low density vegetation or with high terrain slope. The lateral conductivity of the wetland soil is also important in determining the effect of interaction on surface water; however, the role of vertical hydraulic conductivity is found to be negligible. The change of water depth due to the effect of surface/ground water interactions results in change of water velocity which consequently affects the advection term in the concentration equations. Therefore, the effect of surface/ground water interactions at wetland sites with low density vegetation or with high terrain slope also plays an important role on nutrients. This subject will be investigated in more detail as a future study.

Nomenclature

A_x	cross-sectional area in x-direction
C_{TN}	total nitrogen concentration
C_{TN}^{gw}	total nitrogen concentration in ground water
C_{TN}^{L}	lateral total nitrogen concentration
C_{TP}	total phosphorus concentration
C_{TP}^{gw}	total phosphorus concentration in ground water
C_{TP}^{L}	lateral total phosphorus concentration
c	wave celerity
D_x	dispersion coefficient
K	coefficient which reflects the vegetation density
K_{TN}	first order loss rate constant for total nitrogen reduction
K_{TP}	first order loss rate constant for total phosphorus reduction
K_1	hydraulic diffusivity
Q	flow rate
$\bar{q}$	water source/sink terms
q_{gwd}	ground water discharge
q_{Lin}	lateral inflow
t	time
W	wetland width
x	distance
y	surface water depth

References

[1] C.J. Richardson, Wetlands ecology, Encyclopedia Environ. Biol., 3 (1995) 535–550.
[2] W.J. Mitsch and J.G. Gosselink, Wetlands, third edn., John Wiley, New York, 2000.
[3] M. Borin, G. Bonaiti and L. Giardini, A constructed surface flow wetland for treating agricultural waste waters, Water Sci. Technol., 44 (11–12) (2001) 523–530.
[4] M.T. Moore, R. Schulz, C.M. Cooper and J.H. Rodgers, Mitigation of chlorpyrifos runoff using constructed wetlands, Chemosphere, 46 (6) (2002) 827–835.

[5] G.F. Mitchell, C.L. Hunt and Y.M. Su, Mitigating highway runoff constituents via a wetland, Soil Mech. 2002 Transport. Res. Rec., 1808 (2002) 127–133.
[6] T.C. Winter, J.W. Harvey, O.L. Franke and W.M. Alley, Ground Water and Surface Water A Single Resource, US Geological Survey Circular 1139, 1998.
[7] T.C. Winter, Relation of streams, lakes, and wetlands to groundwater flow systems, Hydrogeol. J., 7 (1999) 28–45.
[8] J.S. Price and J.M. Wadington, Advances in Canadian wetland hydrology and biochemistry, Hydrol. Process., 14 (9) (2000) 1579–1589.
[9] J.W. Harvey, J.T. Newlin and S.L. Krupa, Modeling decadal timescale interactions between surface water and ground water in the central Everglades, Florida, USA, J. Hydrol., 320 (2006) 400–420.
[10] J.I. Restrepo, A.M. Montoya and J. Obevsekera, A wetland simulation module for the MODFLOW ground water model, Ground Water, 36 (5) (1998) 764–770.
[11] J.S. Koreny, W.J. Mitsch, E.S. Bari and X.Y. Wu, Regional and local hydrology of a created wetland system, Wetlands, 19 (1) (1999) 182–193.
[12] A.S. Crowe, S.G. Shikaze and C.J. Ptacek, Numerical modeling of groundwater flow and contaminant transport to Point Pelee marsh, Ontario, Canada, Hydrol. Process., 18 (2004) 293–314.
[13] M.R. McHale, C.P. Cirmo, M.J. Mitchell and J.J. McDonnell, Wetland nitrogen dynamics in an Adirondack forested watershed, Hydrol. Process., 18 (2004) 1853–1870.
[14] C.M. Kazezyılmaz-Alhan, M.A. Medina Jr. and C.J. Richardson, A wetland hydrology and water quality model incorporating surface water/groundwater interactions, Water Resour. Res., 43 (4) (2007).
[15] S.T. Chu, Infiltration during an unsteady rain, Water Resour. Res., 14 (3) (1978) 461–466.
[16] C.W. Thornthwaite, An approach toward a rational classification of climate, Am. Geogr. Rev., 38 (1948) 55–94.
[17] L.A. Rossman, Storm Water Management Model, User's Manual, Version 5, Water Supply and Water Resources Division National Risk Management Research Laboratory, Cincinnati, OH, US Environmental Protection Agency, EPA/600/R-05/040, 2005.
[18] R.H. Kadlec and R.L. Knight, Treatment Wetlands, CRC Press, Inc., 1996.
[19] C.J. Richardson, R. Elting, J. Pahl and G. Katul, Restoration of hydrologic and biogeochemical functions in bottomland hardwoods, in: Hydrology and management of forested wetlands: proceedings of the international conference. American society of agricultural and biological engineers, St. Joseph, Michigan, USA, 2006, pp. 50–57.