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Sensitivity analysis of the DRAINWAT model applied to an agricultural watershed in the lower coastal plain, North Carolina, USA

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Abstract

The DRAINWAT, DRAINmod for WATershed model, was selected for hydrological modelling to obtain water table depths and drainage outflows at Open Grounds Farm in Carteret County, North Carolina, USA. Six simulated storm events from the study period were compared with the measured data and analysed. Simulation results from the whole study period and selected rainfall events assured that the DRAINWAT model reasonably predicted the water table depths and drainage outflow events even though it underestimated outflows in very dry period after 24 April, 2001. The potential evapotranspiration by various calculation methods was found to be the most sensitive parameter in this study. The other three parameters (maximum surface depressional storage, Manning's channel roughness coefficient, and channel bedslope) were not significantly ($\alpha = 0.05$) sensitive to the cumulative outflow as expected. The DRAINWAT model may be a useful tool for water management in flat agricultural areas with high water table if it can be calibrated properly with reliable measurements.

Introduction

Eastern North Carolina in the United States has suffered from a decline in water quality over the past 20 years mainly because of excessive nutrients from non-point sources (Poe *et al*. 2003). Especially runoff carrying sediments from non-point sources has been considered as the major pollutant of surface water (Muñoz-Carpena *et al*. 1999), and occurs in a large portion of agricultural watersheds. Previous studies have been conducted in recent years to evaluate and reduce nutrient loadings (Stow *et al*. 2001), and various models have been developed and applied to explain these phenomena (Muñoz-Carpena *et al*. 1999; Amatya *et al*. 2004; Fernandez *et al*. 2007; Gollamudi *et al*. 2007). Many comprehensive models such as ANSWERS (Beasley *et al*. 1980), AGNPS (Young *et al*. 1987), SWAT (Arnold *et al*. 1998) and DUFLOW (Aalderink *et al*. 1995) have been developed and applied in different spatial and temporal scales. As decision tools, however, these types of model are difficult to use for assessing water quality because of their high data input requirements, problems in calibration and parameterisation in large watersheds, and underlying uncertainties in the formulation processes and parameterisation (Fernandez *et al*. 2002). Most decision makers working with watershed level management may only need planning level information that is obtained easily from the use of simpler models. For this reason, coupling with lumped parameter water quality models and comprehensive hydrological models may be an alternative as lumped parameter models require minimal input data for simulation and are capable of accurate predictions on long temporal scales (Haith & Shoemaker 1987; Cooper & Bottcher 1993; Johnes 1996; Fernandez *et al*. 2002; Wickham & Wade 2002; Shrestha *et al*. 2008). In addition, lumped parameter models require less time and effort than comprehensive models. (Fernandez *et al*. 2002).

DRAINMOD, DRAINage MODel, is an agricultural water management model that was originally developed to simulate the performance of drainage and related water management systems at a field scale on poorly drained soils with flat topography (Skaggs 1978; Skaggs *et al*. 1991; Skaggs & Chescheir 1999). Even though this is a hydrological model, many modellers have recently used it for water quality assessment by linking it with process-based (Youssef *et al*. 2005; Tian *et al*., in press) or simple lumped parameter water quality models in poorly drained coastal plain watersheds (Fernandez *et al*. 2002, 2003, 2005, 2006, 2007; Amatya *et al*. 2003, 2001, 2004; Skaggs *et al*. 2003). As an example, DRAINWAT, DRAINmod for WATershed hydrology model, was linked with a lumped parameter nitrogen (N) model for the purpose of N transport assessment (Amatya *et al*. 2003, 2004). The key point of the linking approach is the accuracy of hydrological simulations, especially drainage outflows, which is a main factor driving the nutrient loading. In order to accurately predict outflow, we first need to know which parameters are more sensitive to outflow predictions. Sensitivity analysis of input parameters of DRAINMOD field-scale model has been conducted earlier (Haan & Skaggs 2003; Wang *et al*. 2005). However, the number of studies on sensitivity analysis of input parameters of DRAINMOD-based watershed-scale models is relatively small (Konyha & Skaggs 1992; Fernandez *et al*. 2006) compared with other type of studies such as impacts of management practices on watershed hydrology (Amatya *et al*. 1997, 2004; Fernandez *et al*. 2007), land use conversion (Kim *et al*., in press; Skaggs *et al*., in press) and climate change (Amatya *et al*. 2006).

The objectives of this study were: **(1)** to use the DRAINWAT model to investigate the hydrology, primarily the drainage outflows for specific storm events, of the 1037 ha, poorly drained agricultural watershed in the North Carolina coastal plain that drains into a constructed wetland system; and **(2)** to analyse the sensitivity of outflow to the model input parameters. The simulation model was tested with 30 months (1 July 1999–31 December 2001) of outflow data collected by the UNC Institute of Marine Science on the study watershed located at Open Grounds Farm, Carteret County, North Carolina.

Materials and methods

Site description

The DRAINWAT model was evaluated on a 1037 ha agricultural watershed, which is a part of the Open Grounds Farm in eastern Carteret County in the lower coastal plain of North Carolina, USA (Fig. 1). The farm, located adjacent to the Albermarle-Pamlico Estuarine System, is an important habitat for many species of birds and animals (Fig. 1) (Anderson & Onorato 1994). Marshes next to this farm at the headwaters of the South River accommodate a food chain that maintains both shellfish and finfish. Estuarine creeks on Open Grounds Farm (OGF) serve as nurseries for commercially important species (Anderson & Onorato 1994; Kim 2009).

The farm is an 18 220-ha row-crop operation including corn, soybean and cotton (Poe *et al*. 2003). Fertilisers applied to these fields contain urea, ammonium and nitrate nitrogen (Poe *et al*. 2003; Kim 2009). The drainage system of the watershed is made up of field ditches and collector canals. The depth of field ditches is generally 90 cm and the ditches are spaced 100 m apart. The depth of collector canals is 180 cm, and they are spaced 1610 m apart (Fig. 2). The slope of this watershed is less than 0.1%. It is poorly drained and the water table is shallow (Soil Survey of Carteret County, North Carolina 2010).

The average daily maximum temperature is less than 31.6°C during the summer, and the average daytime winter temperature is around 20°C (State Climate Office of North Carolina 2009). The average annual rainfall of the coastal plain ranges from 1200 to 1370 mm (Skaggs *et al*. 1991; Amatya *et al*. 2002, 2006; State Climate Office of North Carolina 2009). Details of the general climate of the study site are described in Kim (2009).

Model description

DRAINWAT is a watershed-scale version of DRAINMOD (Skaggs 1978) developed for drained agricultural and forest lands. It has been tested and modified to simulate the hydrological balance and nutrient loading from agricultural watersheds over 10 000 ha (Amatya *et al*. 2003, 2004). DRAINMOD simulates the hydrology of poorly drained, high water table soils on an hour-by-hour, day-by-day basis for long periods of time. This model uses a combination of methods such as the Hooghoudt equations for modelling subsurface drainage, Kirkham equation for subsurface drainage during ponded conditions, the Green-Ampt method for infiltration and other approximate methods for quantifying processes including runoff, evapotranspiration and depression storage. The usage of the original field-scale model, DRAINMOD (Skaggs 1978; Skaggs *et al*. 1994), has been extended to analyse the hydrology of certain types of wetlands to determine whether the wetland hydrological criterion is satisfied for drained or partially drained sites, and to determine the hydraulic capacity of systems for land treatment of wastewater (Skaggs & Chescheir 1999). DRAINWAT was developed by coupling two DRAINMOD-based models: a field scale forestry version DRAINLOB (McCarthy *et al*. 1992) and an agricultural watershed-scale version FLD&STRM (Konyha & Skaggs 1992).

By combining DRAINLOB and FLD&STRM models, DRAINWAT is capable of modelling agricultural, forested and mixed land use watersheds of medium scale, and also was successfully tested with large-scale watersheds (Amatya *et al*. 2003). DRAINWAT was developed as a

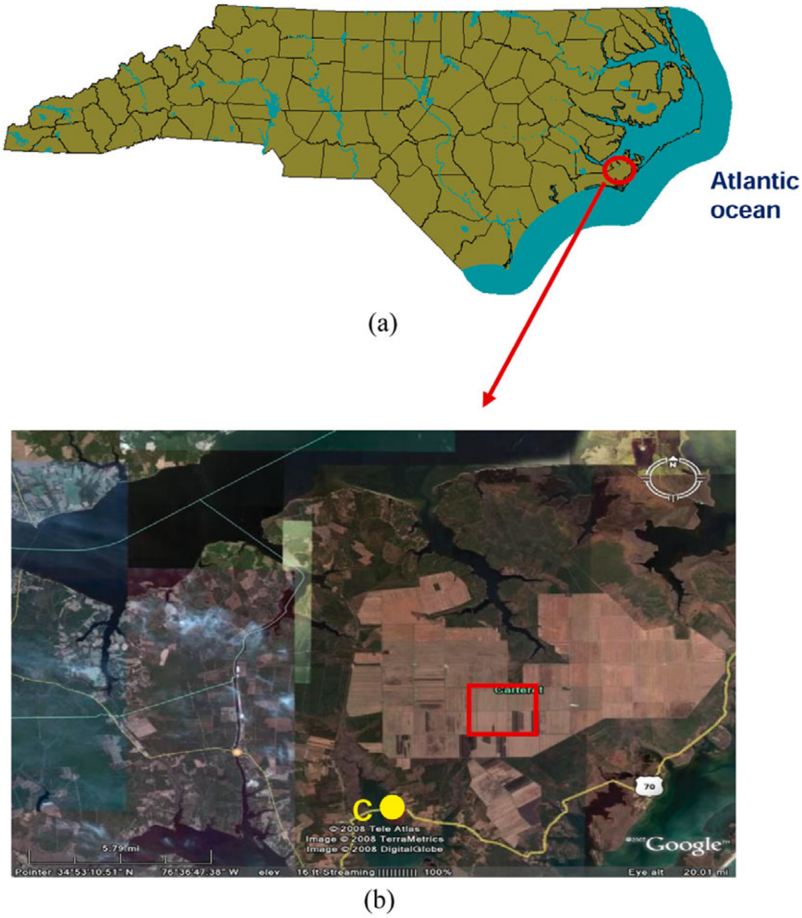

Fig. 1. Location map of the study watershed at Open Grounds Farm in the Carteret County near the coast of North Carolina along with a satellite image. (a) Location of Open Grounds Farm. (b) Satellite image showing the layout of the study site. C indicates the location of raingauge at the Weyerhaeuser's Carteret study site, and red box is the watershed studied (satellite image is from Google Earth 2010).

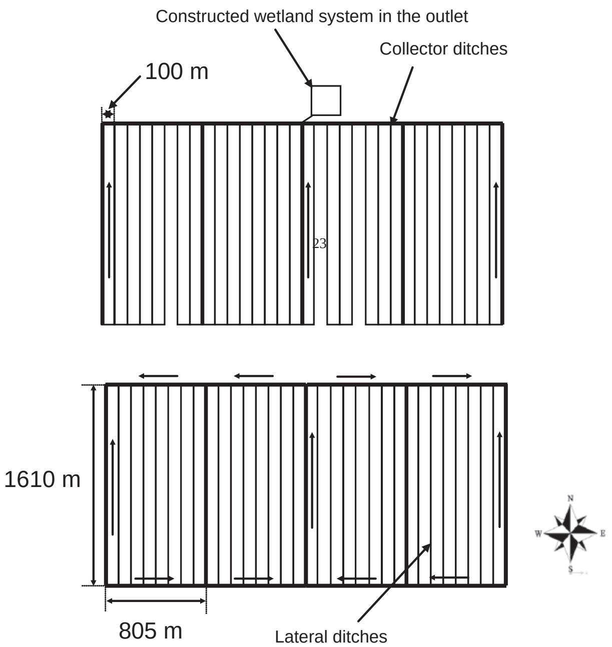

Fig. 2. Dimension of each field in the watersheds.

sequenced set of simulations to first combine outflow from each field with that of other fields that drain into the collector ditch of the subcatchment. The field can be defined as the smallest area with relatively uniform soil and land use conditions. The same model parameters can be applied in each field. An instantaneous unit hydrograph with a time of concentration concept is used to route the overland flow and ditch flow to the subcatchment outlet (Amatya *et al*. 1997; 2003).

The simulated outflow from all subcatchments provides lateral inflow to the main channel network. The lateral inflow is then routed through the channel system to the watershed outlet using numerical solutions of one dimensional St. Venant equations for mass conservation and momentum (Amatya *et al*. 2003). Details of the modelling procedure are described elsewhere (Konyha & Skaggs 1992; Amatya 1993; Amatya *et al*. 1997; Kim 2009).

Evaluation of model performance

Six storm events from our most reliable measured flow data were analysed to evaluate DRAINWAT performance

Table 1 Monthly measured rainfall and potential evapotranspiration (PET) data for the Carteret site compared with long term (1951–2000) data from Morehead city, NC (after Amatya *et al*. 2006)

	Rainfall for each year (mm)			PET for each year (mm)			50 Year average rainfall
Month	1999	2000	2001	1999	2000	2001	in Morehead City (mm)
Jan	78	123	33	46	36	38	114
Feb	64	62	67	65	54	43	101
Mar	40	45	90	79	87	65	101
Apr	88	214	64	107	89	106	75
May	78	78	55	128	135	125	109
Jun	120	187	140	124	139	137	109
Jul	138	288	137	152	117	119	159
Aug	371	212	101	109	127	124	175
Sep	164	253	50	74	93	93	148
Oct	98	19	14	75	76	85	104
Nov	88	155	42	65	35	51	95
Dec	50	82	59	48	35	38	101
Total:	1377	1718	852	1072	1023	1024	1391

in predicting the outflows on daily basis. All events were defined to start at the time of the initial rise of the hydrograph and extend until at least 5 days to include subsurface drainage part of the storms (Amatya *et al*. 1997). Model sensitivity analysis was conducted to identify the parameters that have the greatest effect on the simulation results. Several researchers of DRAINMOD and DRAINMOD-based models in the past have examined which parameters have the greatest effect on the model output (Skaggs *et al*. 1991; Konyha & Skaggs 1992; Fernandez *et al*. 2002; Amatya *et al*. 2003; Haan & Skaggs 2003; Wang *et al*. 2005). Kim (2009) suggested four input parameters that have the potential to influence the outflow simulation but not yet extensively studied in previous studies. Those parameters are: maximum surface depressional storage, Manning's channel roughness coefficient, channel bedslope and potential evapotranspiration (PET) by three methods. Detailed descriptions can be found in Kim (2009).

Soil hydraulic conductivity and initial water table depth are also sensitive parameters to the outflow. However, the sensitivity of soil hydraulic conductivity was already extensively tested in other studies (i.e. Konyha & Skaggs 1992; Haan & Skaggs 2003). Initial water table depth is important at the initial stage of simulation only, but generally it is not sensitive after ~2–3 months as the initial soil moisture conditions stabilise. Statistical significance of linear regression analysis of simulated versus measured outflows was evaluated from the coefficient of determination (r^2) for each of the six storm events. Student *t*-tests at $\alpha = 0.05$ significance level were conducted to determine whether the simulated outflow values are statistically different. Details of the evaluation of model performance can be found in Kim (2009).

Hydrometeorological measurements

All daily hydrometeorological parameters including daily rainfall, radiation and PET for a grass reference measured at a nearby weather station at the Carteret site, North Carolina, USA were processed and integrated to obtain the annual totals as shown in Tables 1 and 2 (Amatya *et al*. 2006). Air temperature, relative humidity, wind speed and water table depth were obtained as the total average. Procedures for estimating daily PET using these parameters have been described in detail by Amatya *et al*. 1995, 1996, 2006). Measured daily outflow data from the OGF site were not adequate to compare with the simulated daily values for the whole 2.5-year period, mainly because of physical problems with the flow meter at the site during the study period (Kim 2009). For this reason, only simulated daily outflows were presented in Fig. 3, and six rainfall events were selected and compared with the simulation results. Daily stream flow at the outlet of the 1037 ha study watershed was calculated by Poe *et al*. (2003) using measured values of stage and velocity of an automatic flow meter in an open channel (ISCO 750 area velocity flow module). Only the reliable measured flow data for some periods were used to calibrate the model with the predicted outflow. Details of the collection of stream flow data are described in Kim (2009).

Results and discussion

Simulation results

Simulated water table depths and daily/cumulative outflows for 30 months (1999–2001) period of baseline simulation of the study site as a response of rainfall and weather data measured at the nearest gauge (Carteret site, Tables 1 and 2) from the outlet of the Open Grounds

Table 2 Measured annual hydrometeorological parameters for Carteret weather station (After Amatya *et al*. 2006)

Year	Rain mm	Average temp. (°C)	Net rad. (Mm)	PET (mm)	Flow (mm)	Runoff coeff., %	WTD, (cm)	AET (mm)
1999	1377	16.7	1438	1072	614	0.45	86	763
2000	1718	15.6	1434	1023	857	0.50	79	861
2001	852	16.3	1121	1024	45	0.05	148	807
[a]Mean	1538	16.4	1282	970	541	0.33	95	997
[a]SD	310	0.6	142	94	286	0.13	22	143

[a]The values of mean and standard deviation (SD) for each column are the averages and standard deviations from 1988 to 2004 (Amatya *et al*. 2006).
AET: Actual evapotranspiration; PET, potential evapotranspiration; WTD: Water table depth.

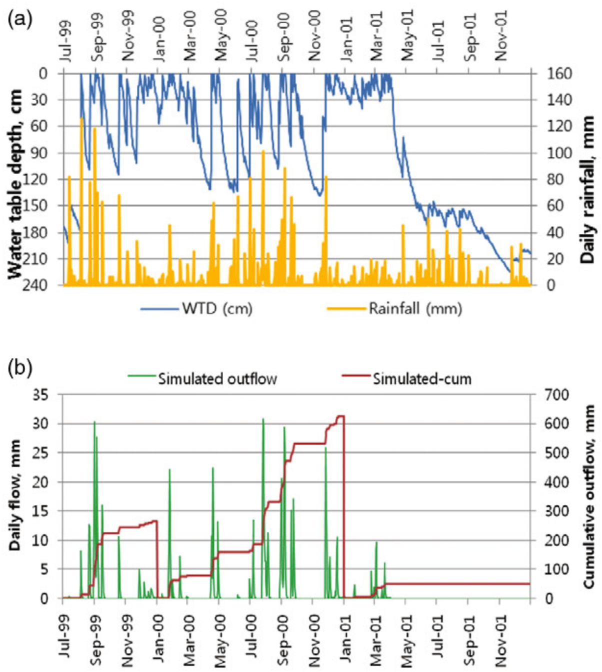

Fig. 3. Preliminary simulation results of hydrological components. (a) Water table depths (WTD) and daily rainfall of study watershed from July 1999 to December 2001. (b) Simulated daily outflow (Simulated outflow) and cumulative outflow (Simulated-cum) in the outlet of study watershed.

Farm are summarised and presented in Fig. 3. The direct response of rainfall to drainage outflows is indicated by the rise in water table depths in this system as drainage rate is a function of water table depth (Skaggs 1978; Skaggs *et al*., in press) (Fig. 3b). For 1999, only fall and winter (from 1 July to 31 December) data were presented as the first 6 months (1 January to 30 June) of simulation was used as the 'warm-up' period. Simulated annual average daily water table depths were 65, 55 and 128 cm in 1999, 2000 and 2001, respectively. The simulated average water table depth for the study period for 2.5 years together was 85 cm.

Based on the simulation results, in 1999, the water table never rose above 1.5 m until 4 August when the biggest rainfall event of the study period occurred. Then the simulated water table depth remained shallow and did not drop below 1.2 m. The water table rose to near the ground surface when three hurricanes hit this area in September and October 1999 (Shelby *et al*. 2005). In the wet year of 2000, the simulated water table was so shallow that it never dropped under 1.4 m during the year. It was dry in 2001 with only 852 mm rain and water table depths were below 1.5 m for 249 days afterwards (Table 2) as the rainfall was consistently below normal during the August–November period (Table 1). As reported in the previous studies (Amatya *et al*. 1996; Amatya *et al*. 2006), the simulated deep water table in 2001 was mainly due to the lower than 50-year average rainfall observed at a nearby weather station in Morehead City, NC (Table 1) and higher ET rates.

Simulated annual outflow by the DRAINWAT model was 264 mm from 1 July to 31 December in 1999, 625 mm from 1 January to 31 December in 2000, and 50 mm from 1 January to 31 December in 2001, respectively (Table 3). Based on the rainfall and water table depth, the outflows in 1999 and in 2000 were reasonable, and similar to other results observed at nearby coastal plain sites (Amatya *et al*. 2002; Shelby *et al*. 2005). Simulated daily outflow was 0 mm after the water table dropped to 117 cm on 24 April 2001, and subsequent precipitation from small rainfall events was not sufficient to fill up the unsaturated soil depth.

Storm event analysis

Reliable measured outflow data for six storm events were used for the analysis. Results in Fig. 4 show measured and simulated event hydrographs for those six events. Underestimation of events 3 and 6 may be caused by very dry antecedent conditions of soil. These simulation results of DRAINWAT under the dry conditions with deep water tables were also consistent with other study results (Amatya *et al*. 1997, 2004, 2006), which attributed such a discrepancy to the possible violence of model's 'drained to equilibrium' condition (Skaggs 1978) and modelling

Table 3 Simulated annual outflow at Open Grounds Farm (OGF) and measured outflows in other nearby study sites, Carteret and Plymouth (mm). Carteret and Plymouth data are from Amatya *et al*. (2006) and Amatya *et al*., 2002), respectively

	OGF			Carteret			Plymouth		
	Sim. outflow	Rain	R/O ratio	Outflow	Rain	R/O ratio	Outflow	Rain	R/O ratio
1999 (Jun. 1–Dec. 31)	264[a]	909[b]	0.29	453	909	0.50	339	875	0.39
2000 (Jan. 1–Dec. 31)	625[a]	1719[b]	0.36	857	1719	0.50	494	1275	0.39
2001 (Jan. 1–Dec. 31)	50[a]	852[b]	0.06	45	852	0.05	245	806	0.21

[a]Simulated outflows were presented for comparison as the number of reliable measured data was limited.
[b]Because no rainfall data were available in OGF site, precipitation data from Carteret site were used for comparison.

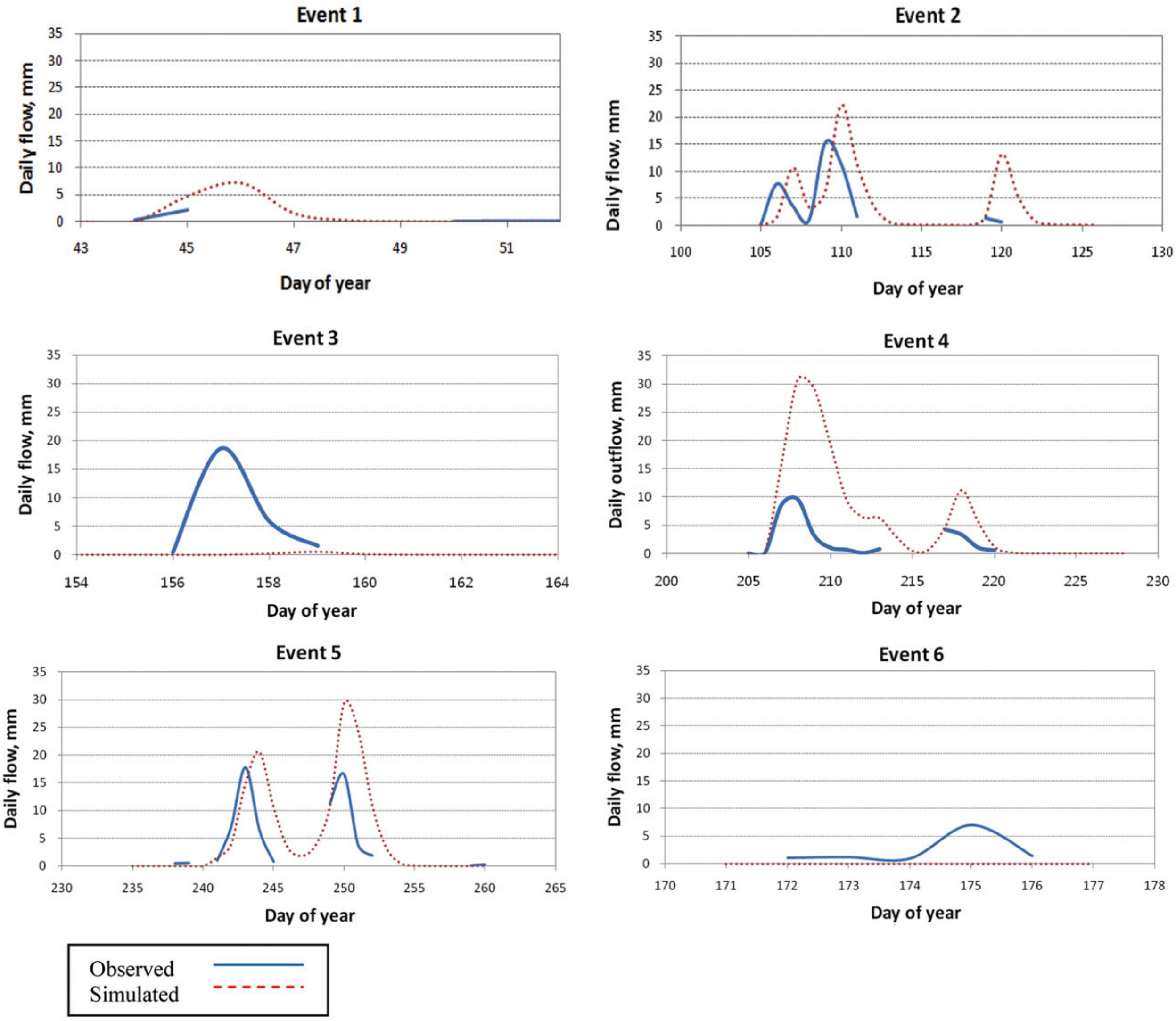

Fig. 4. Storm event analysis in selected period.

ET. DRAINWAT overestimated daily outflows in events 1(not complete data), 4 and 5. The model was able to simulate daily outflows but were somewhat overestimated and delayed ~1–2 days in events 2 and 5.

These simulation results were compared with selected measured data and summarised in Table 4 with statistical parameters. The r^2 values varied from 0.20 for event 3 and event 6 to 0.79 for event 1. Based on r^2 values, simulation results were not found to be significant at $\alpha = 0.05$. Highest r^2 value of event 1 resulted from a small sample size of 4 for the rising part of the hydrograph only. As almost all of the simulated outflows were 0 during selected period in event 3 and event 6, the r^2 value was only 0.20 (undefined). These results clearly indicate the inadequacy of the simulated hydrology to be linked with lumped parameter water quality models. However, several other studies using DRAINMOD-based watershed scale models (Konyha & Skaggs 1992; Amatya *et al*. 1997; 2003, 2004; Fernandez *et al*. 2002, 2005; Chescheir *et al*. 2004) in eastern North Carolina and Italian coastal plain (Bisol 2006) have shown greater predictability (higher r^2 and smaller errors) as documented by Kim (2009). The limitation of the measured data is one of the reasons for poor model performance.

Table 4 Summary of statistical analysis for estimating simulation results in selected period

		Average daily outflow, mm		
Event no.	Dates	Observed	Predicted	r^2
1	Feb. 13–20, 2000	0.64	1.19	0.79
2	April 15–May 5, 2000	5.27	8.76	0.34
3	June 4–7, 2000	6.58	0.20	0.20
4	July 24–Aug. 11, 2000	3.31	13.37	0.33
5	Aug. 25–Sept. 15, 2000	6.09	11.54	0.43
6	Jun. 21–25, 2001	2.55	0.00	0.20

To evaluate reasons for our less accurate model predictions compared with findings of others, our second objective was to evaluate the sensitivity of various model input parameters or relevance to our field site. Although we tailored the sensitivity analysis to data for actual events at our field site, the analysis does not require that the model accurately simulates the measured data. The sensitivity analysis itself identifies the important parameters to be considered for the model calibration with the measured outflow data in this case.

Sensitivity analyses

Four parameters including surface depressional storage, Manning's coefficient of channel roughness (n), channel bed slope and methods of PET were used for sensitivity analysis of the simulated drainage outflow. Earlier sensitivity analyses did not extensively evaluate these effects on storm event outflows yet.

Cumulative daily outflows for all cases

Cumulative daily outflows for four parameters, including surface depressional storage, Manning's roughness coefficient, channel bedslope and the methods of PET estimation are compared in Fig. 5. Cumulative outflows were only sensitive to PET methods, but found to be very insensitive to the other three parameters. The value of maximum surface depressional storage (STMAX) used in

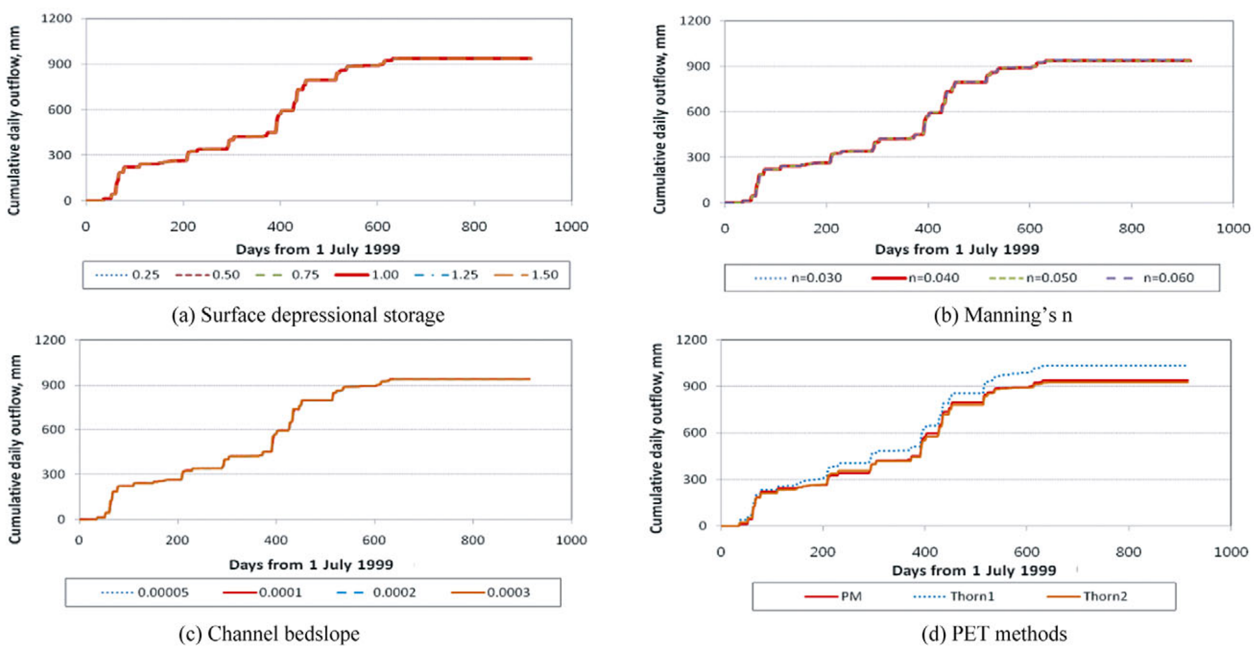

Fig. 5. Comparison of cumulative outflows for selected parameters. (a) Surface depressional storage, (b) Manning's roughness coefficient n, (c) Channel bedslope, (d) PET methods.

the baseline simulation was 1.0 cm for agricultural land with good surface drainage (Chescheir *et al.* 1990). Predicted cumulative daily outflows were compared for six different values of depressional storage of 0.25, 0.50, 0.75, 1.00, 1.25 and 1.50 and the results are presented in Fig. 5(a). The Manning's channel roughness coefficient (n) for the base simulation in this study was 0.04 for an earthen channel with vegetation on the side slopes (McCuen 1989). In the case of Manning's n (Fig. 5b), three *n*-values including 0.03, 0.05 and 0.06 were used. The changes in daily cumulative flow caused by the variation in channel bed slope are summarised and presented in Fig. 5(c). The number of channel bed slope in baseline simulation was 0.0001. There were no unique trends, and no substantial changes over 10% in simulated cumulative outflows were observed as these three parameters were changed individually.

Konyha & Skaggs (1992) observed similar results. They found that total outflow volume was changed only from 226.0 mm to 224.3 mm in simulations with FLDNSTRM with +150% and −150% change of Manning's n. They also reported that channel bed slope was more sensitive than the Manning's roughness, but the simulated outflow during the 60-day period used in their simulation was not significantly affected by increasing channel bed slope.

Cumulative daily outflows obtained by using three different PET calculation methods in the model were compared (Fig. 5d). Those three methods were Penman-Monteith (PM), Thornthwaite 1 (Thorn1) and Thornthwaite 2 (Thorn2). The PET method for the base simulation was PM. Based on Student's *t*-test, significant differences in outflows were found between Thorn1 and other two methods ($\alpha < 0.05$), but the difference between PM and Thorn2 was not significant ($\alpha > 0.05$). These discrepancies may be mainly caused by the different magnitudes of ET estimated by each method (Amatya *et al.* 1997), and may be considered as reasonable. The ET in a forested watershed is generally greater than that of an agricultural watershed (Skaggs *et al.*, in press) or a clear-cut watershed (Sun *et al.* 2005, 2010). The monthly correction factors calculated for Thorn1 were average values with one set of correction factors from forested watershed in Carteret County and with two sets from agricultural watersheds in Washington and Edgecombe County, North Carolina (Amatya *et al.* 1995). On the contrary, the set of monthly correction factors developed for Thorn2 was solely from the agricultural research site.

Surface depressional storage

There were no significant differences in cumulative daily outflows obtained by using those values ($\alpha = 0.05$) indicating that cumulative outflow was also not sensitive to depressional storage. No substantial variations in cumulative outflows were found (< 5%) caused by the change in STMAX values in each year of the study period (Fig. 6). Based on other studies conducted at nearby sites (Amatya *et al.* 2003; Shelby *et al.* 2005), July–December in 1999 included an extremely wet period preceded by a very dry period of July; mid-August 2000 was very wet; and 2001 was very dry in terms of rainfall compared with the 50-year average (Table 1). These results can be explained two ways as Skaggs *et al.* (1991) suggested. Surface depressions might have remained nearly full during most of the year and did not substantially affect outflow during a very wet period such as July 1999–December 2000. On the contrary, in a dry period like 2001, there were no substantial runoff events over 5%. Skaggs *et al.* (1991) conducted a simulation study to determine the effects of natural factors including STMAX on hydrology of a natural pocosin near Wilmington, North Carolina. They reported that simulated annual average outflow increased only from 365 to 384 mm as the STMAX storage decreased from 2.5 to 0.5 cm. They also mentioned that the year-to-year variation in annual outflow caused by STMAX change was much greater than the effects of all other factors used in their study.

Results in Fig. 6 present the patterns of daily outflows based on different STMAX values for four storm events. Rainfall and the fluctuations in predicted water table depths of the corresponding events are also presented. In simulated event 1, daily outflow decreased as the depressional storage increased. This event was characterised as one big rainfall event of 131.0 mm at August 3–4, 1999. The soil was very dry and the simulated water table depth was 175 cm at the first day of event. On the contrary, the water table was at the ground surface caused by previous rainfall events when event 4 began at the day of 62 (March 3, 2001) with the rainfall of 28.2 mm at March 3–5, 2001. Therefore, even though there were substantial differences between the rainfall amounts in events 1 and 4, the peak flow rates of events 1 and 4 were similar to each other because of the differences in initial soil moisture conditions affecting the surface storage.

The volume of outflow in event 2 ranged only 0.4 to 1.0 mm (Table 5), but the respective rainfall of 73.9 mm between June 4 and 7, 2000 was more than double the amount of event 4. This result can be explained by the simulated water table depth of 133 cm on the initial day of the event. Initial water table depth of event 3 was 43 cm, and related rainfall amount was 160.3 mm on 23–26 July 2000. Water table depth was not shown to be substantially sensitive to the change in STMAX.

The sensitivity analyses of event outflow characteristics in relation to the STMAX are summarised in Table 5. In event 1 peak flow rate decreased from 8.9 to 7.4 mm/day

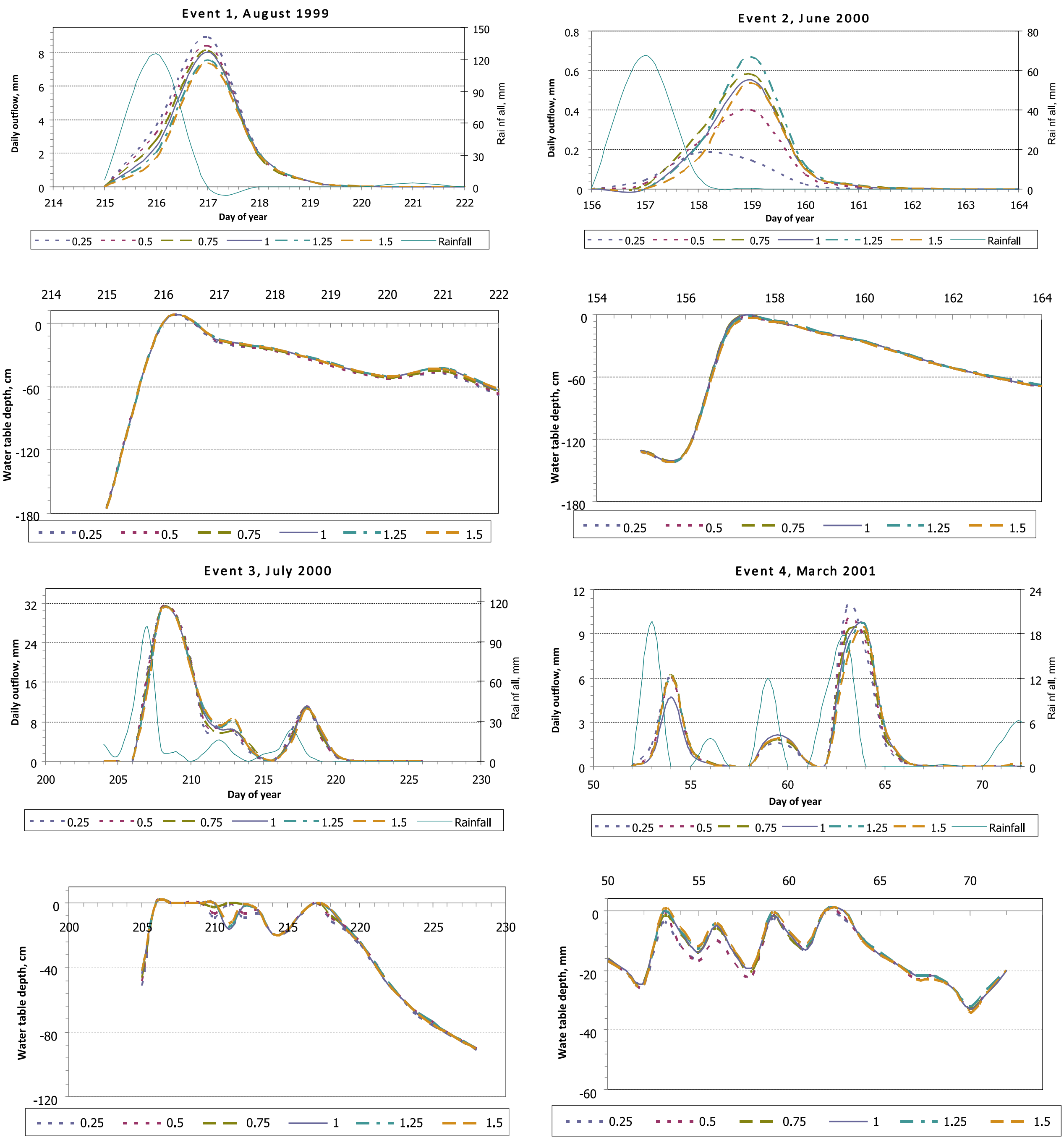

Fig. 6. Sensitivity of daily flows and simulated water table depth to the surface depressional storage (STMAX).

as STMAX increased from 0.25 to 1.5 cm, as expected. There was a slight decrease from 31.1 to 30.7 mm/day, but it was not substantial in event 3. However, peak flow rate unexpectedly increased from 0.19 to 0.67 mm/day as STMAX increase from 0.25 to 1.25 cm, and then decreased by 20% from 0.67 to 0.54 mm/day as STMAX increase by 20% from 1.25 to 1.50 cm for the event 2. We found that in small rainfall events like this, the flow rate can unexpectedly increase as STMAX increases, even though the amount of flow change is small. No unique trends were found in the results for event 4. Time to peak outflow was predicted to be 2 days for events 1 and 3, and 2 to 3 days for events 2 and 4. In event 1, the volume of outflow slightly decreased as STMAX increased, but no

Table 5 Effects of maximum surface depressional storage (STMAX) on predicted storm event hydrograph characteristics

Dates	STMAX (cm)	Peak flow rate (mm/day)	Time to peak (days)	Volume of event outflow (mm)
Event 1	0.25	8.9	2	14.9
Aug. 4–14, 1999	0.50	8.4	2	13.9
	0.75	8.1	2	13.1
	<u>1.00</u>	**<u>8.1</u>**	**<u>2</u>**	**<u>12.9</u>**
	1.25	7.6	2	11.9
	1.50	7.4	2	11.4
Event 2	0.25	0.19	2	0.41
June 1–11, 2000	0.50	0.40	3	0.751
	0.75	0.58	3	1.007
	<u>1.00</u>	**<u>0.55</u>**	**<u>3</u>**	**<u>0.902</u>**
	1.25	0.67	3	1.037
	1.50	0.54	3	0.811
Event 3	0.25	31.1	2	121.2
Jul.23–Aug.2, 2000	0.50	31.0	2	121.4
	0.75	31.0	2	121.6
	<u>1.00</u>	**<u>31.0</u>**	**<u>2</u>**	**<u>121.1</u>**
	1.25	30.8	2	122.5
	1.50	30.7	2	122.8
Event 4	0.25	10.7	2	20.7
March 3–14, 2001	0.50	9.8	2	20.7
	0.75	9.0	2	20.7
	<u>1.00</u>	**<u>9.7</u>**	**<u>3</u>**	**<u>21.3</u>**
	1.25	9.6	3	20.6
	1.50	9.4	3	20.0

STMAX for baseline simulation: 1 cm (in bold with underline).

unique patterns were found in events 2, 3 and 4, and the changes were very small.

We concluded that the watershed outflow was not sensitive to STMAX over the range from 0.25 to 1.5 cm. Jurek (2001) also found similar results in his study on pine forests in eastern North Carolina. He used three values of STMAX including 3, 7.5 and 10 cm based on field conditions for baseline simulation for his study. Then he tested the sensitivity of peak flow rates and outflow by changing these values from −50% to +25%. His baseline simulation results of peak flow rate and total annual outflow were 11.1 mm/day and 296.4 mm, respectively. Peak flow rate did not change at all with different STMAX values. Slight reduction (3%) in annual outflow was observed with a 50% reduction in STMAX, but he concluded that this was not substantial (Jurek 2001).

Manning's roughness coefficient (n)

The change in peak flow rate, time to peak and the volume of event outflows because of the increase of Manning's roughness (n) are given in Table 6. The *n*-value for the ditch and channel depends upon the type of vegetation on the bank and floodplain. On a daily basis, variations of simulated outflows were found for specific rainfall events as *n*-value increased. Simulated daily outflow decreased gradually as n increased in moderate (event 1 of day 215 in 1999 and event 4 of day 52 in 2001) and big (event 3 of day 206 in 2000) storm event (Fig. 7). Interestingly, in a small outflow event (event 2), a fivefold decrease in flow was found when n increased from 0.04 to 0.05.

Table 6 Effects of Manning's roughness in predicted specific storm event hydrographs

Storm event date	Manning's roughness	Peak flow rate (mm/day)	Vol. of event outflow, mm	Time to peak (days)
1. Aug. 3–14, 1999	0.030	7.9	12.7	2
	<u>0.040</u>	**<u>8.1</u>**	**<u>12.9</u>**	**<u>2</u>**
	0.050	7.7	13.3	2
	0.060	6.9	12.9	2
2. June 1–11, 2000	0.030	0.6	0.9	3
	<u>0.040</u>	**<u>0.6</u>**	**<u>0.9</u>**	**<u>3</u>**
	0.050	0.1	0.2	3
	0.060	0.1	0.2	3
3. July 23–Aug. 2, 2000	0.030	40.7	117.9	2
	<u>0.040</u>	**<u>30.8</u>**	**<u>121.1</u>**	**<u>2</u>**
	0.050	24.5	121.8	2
	0.060	20.6	121.4	2
4. Mar. 3–14, 2001	0.030	10.0	20.1	2
	0.040	**9.7**	**21.3**	**3**
	0.050	9.1	21.7	3
	0.060	8.4	21.7	3

Manning's n for baseline simulation: 0.040 (in bold with underline).

Peak flow rate decreased with increasing n for events 3 and 4, as expected, but there were no distinct trends shown for events 1 and 2. For event 2, abrupt decrease in peak outflow rate was observed as was the case with the outflow when n increased from 0.04 to 0.05 as shown in Fig. 7 (Table 6). We argued that for some small events like those evaluated, there may be some threshold value of n where infiltration into soil is enough to prevent runoff.

As the Manning's roughness increases, outflow rate generally decreases because of decrease in velocity. However, the volume of event outflow increased as n increased only from 0.03 to 0.05 for event 1, and then decreased after that. The volume of event outflows even increased in the events 3 and 4. Although these increases were not substantial (< 5%), this may also be caused by the extended period of flow (event duration) when velocity decreases with an increase in n.

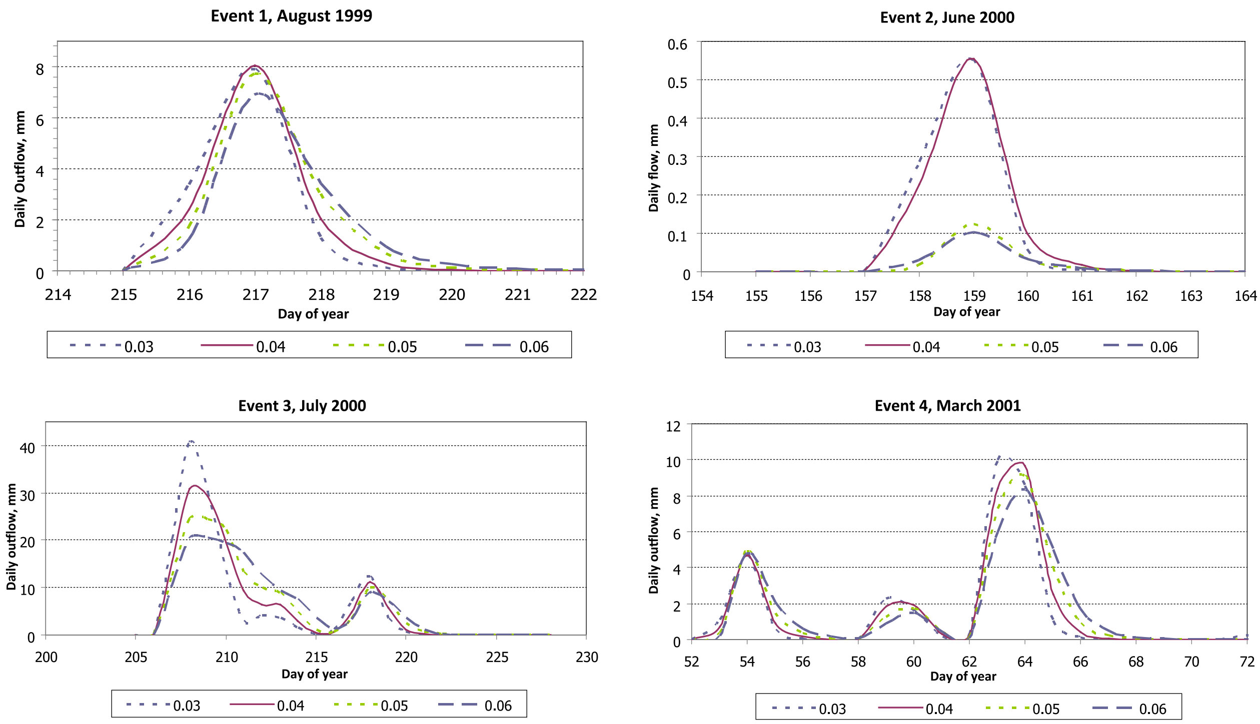

Fig. 7. Sensitivity analyses for Manning's roughness (n).

The size of peak flow rate was similar for the events 1 and 4, but outflow volume of event 4 was somewhat greater than that for event 1 for every n-value. In the case of event 1, it was a single rainfall event, and there were no previous, large rainfall events to saturate the soils for 20 days. Simulated water table depth on August 3 was 177 cm, and initial outflow rate was 0 mm. A large amount of rainfall was needed to fill the pore space of the unsaturated soil before the flow started. In the case of event 4, however, two small rainfall events occurred right before this event (Fig. 7), and consequently the amount of outflow on the first day was not zero (0.22 mm, not shown). The simulated water table depth on the first day of the event 4 was already at the surface.

Time to peak remained the same without change (i.e. 2 days for events 1 and 3, 3 days for event 2), except for event 4 in which case it increased from 2 to 3 with an increase in n, as expected. Because these simulations were based on a daily time step, changes of time to peak occurring in less than one day cannot be observed as the Manning's roughness increased. In general, time to peak is expected to increase with the increase in channel roughness because of the decrease in velocity. Differences possibly would have been noticed for simulation results with an hourly time steps.

Even though small variations of peak flow rate, time to peak and the volume of event outflows caused by the increase of Manning's roughness were found, the change of those parameters were generally not substantial (< 5%). Similar results were found from other studies. For example, Konyha & Skaggs (1992) reported that channel roughness was the least sensitive parameter among the five that includes time of concentration, channel bottom slope, hydraulic conductivity, drainage spacing and channel roughness.

Channel bed slope

In the case of event outflows (Fig. 8), as the channel bed slope increased, peak flow rate increased, but time to peak decreased in all events except for event 1. Decreased peak flow rates for increased bed slopes can be caused by the dry soil conditions right before the rainfall events.

The peak flow rate, time to peak, and volume of event of four rainfall events are summarised in Table 7. The peak flow rates of events 1 and event 4, were, respectively, 8.2 and 8.9 mm/day for the bed slope of 0.00005. As the slope increased, however, peak flow rate decreased in event 1, and increased in event 4. This result may be caused by the initial soil moisture condition. In the case of event 1, the water table was deep on the first day of the event, and a large amount of rainfall was used to fill the pore space of the dry soil. In event 4, the soil was already saturated when rainfall began. Only in big

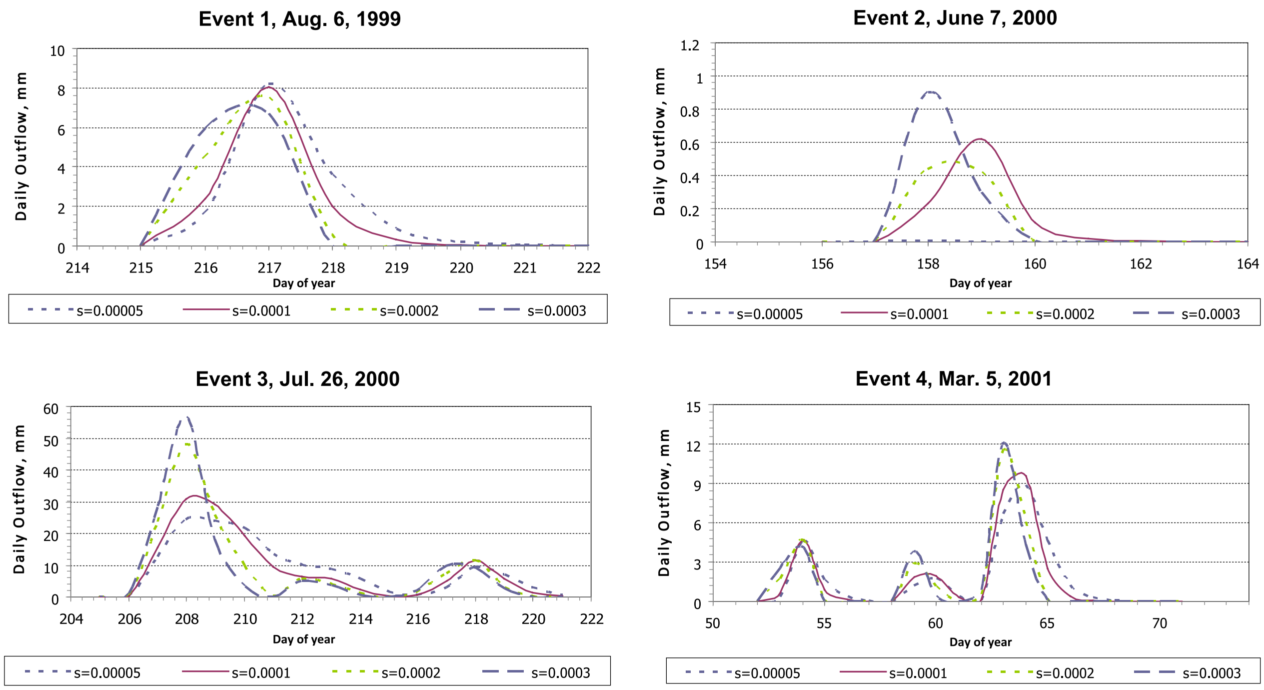

Fig. 8. Sensitivity of event flow rates to different values of channel bed slope.

Table 7 Effects of channel bedslope on predicted storm event hydrograph characteristics

Dates of events	Channel slope	Peak flow rate (mm/day)	Time to peak (days)	Volume of event outflow (mm)
1. Aug. 4–14, 1999	s = 0.00005	8.2	2	14.7
	s = 0.0001	**8.1**	**2**	**12.9**
	s = 0.0002	7.5	2	12.5
	s = 0.0003	6.7	2	12.6
2. June 01–11, 2000	s = 0.00005	0.0	3	0.01
	s = 0.0001	**0.6**	**3**	**0.99**
	s = 0.0002	0.4	3	0.86
	s = 0.0003	0.9	3	1.21
3. July 23–Aug. 2, 2000	s = 0.00005	24.3	2	122.8
	s = 0.0001	**30.8**	**2**	**120.0**
	s = 0.0002	48.1	2	120.0
	s = 0.0003	56.7	2	117.5
4. Mar. 3–14, 2001	s = 0.00005	8.9	3	21.9
	s = 0.0001	**9.5**	**3**	**21.3**
	s = 0.0002	11.5	3	19.2
	s = 0.0003	12.1	3	18.8

s in baseline simulation : 0.0001 (in bold with underline).

storm event (event 3) we could clearly observe that the peak flow rate significantly increased from 24.3 to 56.7 mm/day as the channel slope increased from 0.00005 to 0.0003.

There were no changes of daily time to peak in every event, as such changes, if any, may be noticed for time periods less than a day. No unique trends were observed in the volume of events as slope increased. However, for event 2, substantially low peak flow rate and volume of event were observed when slope was very low (slope = 0.00005). Similar results were observed by Konyha & Skaggs (1992). This low outflow rate caused by the very low channel slopes can result in delaying peak flows, and finally increased flooding at each field in the watershed as water level in the channel builds up. As slope increased, the channel did not hamper flow and field hydrology dominates watershed behavior (Konyha & Skaggs 1992).

Konyha & Skaggs (1992) reported that channel bed slope was the second most important parameter affecting outflows in their sensitivity test. They also mentioned that channel bed slope was one of the important factors influencing the channel carrying capacity, and then outflow. As channel slope increases, generally carrying capacity of the channel increases, and then outflow rates also increase. However, the hydrology of their study was not significantly affected by the increased channel carrying capacity resulting from increased bottom slope and changes of other parameters.

Methods of calculating PET

The effects of PET obtained by three different methods on simulated storm events are presented and summarised in Table 8 and Fig. 9. In the case of event 2 with peak flow of 0.5 mm/day, significant differences were observed with different PET methods based on Student's *t*-test ($\alpha < 0.05$). On the contrary, there were no significant differences in event 3 ($\alpha > 0.05$), a very wet event in which ET was not limited by soil moisture, water tables were near the surface, and the peak flow rate was 31 mm/day.

In events 1 and 4 where the peak flows rates were intermediate (8.1 and 9.7 mm/day, respectively), simulated hydrology varied, depending on the initial soil moisture condition. When soil was dry at the first day of flow as in event 1, the peak flow rate and total volume of outflow events were significantly different ($\alpha < 0.05$). However, no significant differences ($\alpha > 0.05$) were observed among different PET methods when the soil was already saturated at the first day of event because of rainfall events of the previous day.

Table 8 Effects of potential evapotranspiration (PET) methods on predicted storm event hydrograph characteristics

Dates	PET methods	Peak flow rate (mm/day)	Time to peak (days)	Volume of event outflow (mm)
Aug. 4–14, 1999	**PM**	**8.1**	**2**	**12.9**
	Thorn1	21.3	2	40.4
	Thorn2	14.0	2	24.7
June 1–11, 2000	**PM**	**0.6**	**2**	**0.9**
	Thorn1	1.1	3	1.8
	Thorn2	0.0	3	0.0
July 23–Aug. 2, 2000	**PM**	**30.8**	**2**	**121.1**
	Thorn1	30.6	2	112.7
	Thorn2	30.5	2	107.2
Mar. 3–14, 2001	**PM**	**9.7**	**3**	**21.3**
	Thorn1	8.6	3	20.6
	Thorn2	8.2	3	18.2

PM, PET methods in baseline simulation: PM (in bold with underline). PM-Penmann-Monteith; Thorn1-Thornthwaith with first correction factor; Thorn2-Thornthwaith with second correction factor.

The Thornthwaite method generally overestimated outflows as a result of underestimating PET. The monthly correction factors for the Thornthwaite method were originally developed to mitigate the PET prediction errors in outflows that resulted from substantially underestimated evaporation losses of intercepted water from pine stands in North Carolina (Helvey 1967; cited by Amatya *et al.* 1997). Even though these prediction errors are reduced by the use of average correction factors with the PET in DRAINMOD (T2), the Thornthwaite method may still underpredict ET and then overpredict outflows. Correction factors for T1 method with Thornthwaite were developed by Amatya *et al.* (1995). Our sensitivity analysis indicates that simulated outflows in agricultural watersheds are overestimated if Thornthwaite PET is calculated using T1 correction factors.

Conclusions

Based on our DRAINWAT model simulations of water outflow from a 1037 ha agricultural subwatershed

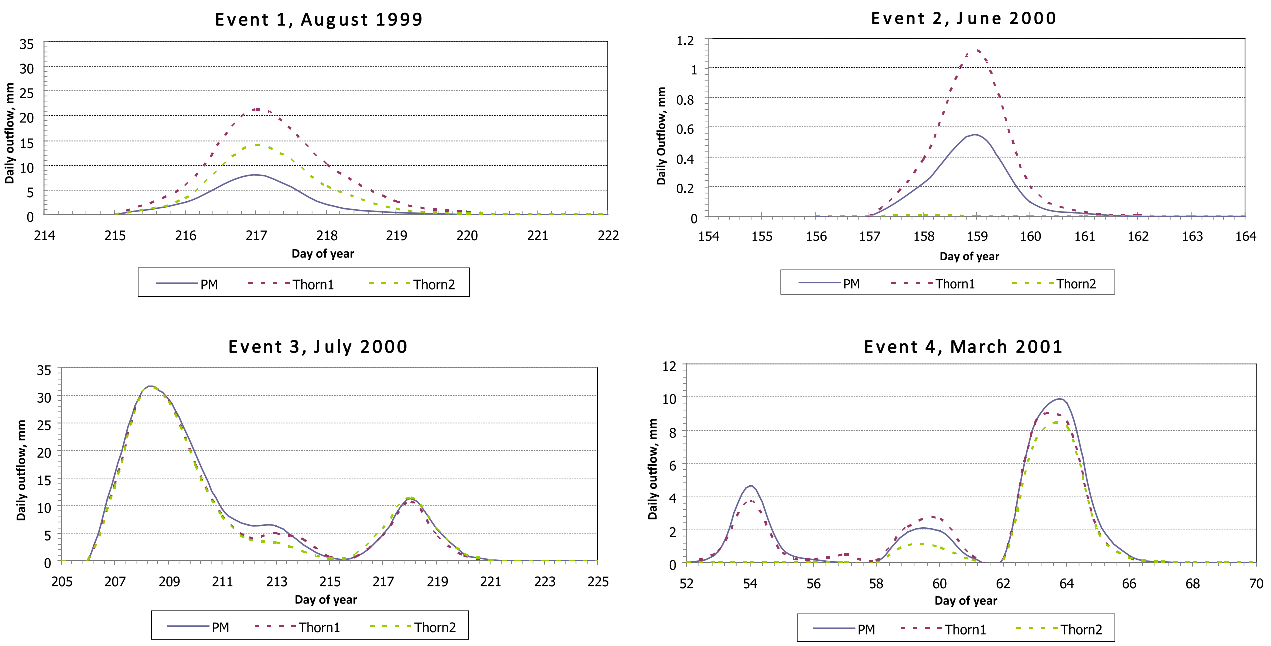

Fig. 9. Sensitivity of event flow rates to potential evapotranspiration by different calculation methods.

following six rainfall events that occurred during a 30-month period, deviations between simulated and measured outflows were most likely effected by the method of ET calculation used. Sensitivity analyses for different antecedent moisture conditions and magnitudes of outflow showed that simulated outflow was most sensitive to the ET calculation method used in the model, while maximum depressional storage (STMAX), Manning's channel roughness coefficient and channel bed slope had less effect. However, the sensitivity of simulated daily outflows to the latter three parameters depended on antecedent soil moisture conditions and the magnitude of the rainfall event (and consequent outflow rates). For PET, simulation results using the Thornthwaite method with correction factors that were specifically collected and estimated only from agricultural watersheds (Thorn 2 factors) like our study site were more consistent with baseline simulation, in contrast to correction factors that are based on average data from agricultural and forested watersheds (Thorn 1 factors). With proper calibration of the DRAINWAT model and judicious selection of the PET method with respect to the watershed being simulated, this model can be a useful tool to evaluate hydrological cycles in both agricultural and forested areas with flat topography (i.e. western coastal area in South Korea; coastal plain of Northern Italy) as was shown in several other studies.

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