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A COMPARISON OF MIKE SHE AND DRAINMOD FOR MODELING FORESTED WETLAND HYDROLOGY IN COASTAL SOUTH CAROLINA, USA

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ABSTRACT Models are widely used to assess hydrologic impacts of land-management, land-use change and climate change. Two hydrologic models with different spatial scales, MIKE SHE (spatially distributed, watershed-scale) and DRAINMOD (lumped, field-scale), were compared in terms of their performance in predicting stream flow and water table depth in a first-order forested watershed in coastal South Carolina. The model performance was evaluated using the coefficient of determination (R^2) and Nash-Sutcliffe's model efficiency (E). Although both models performed reasonably well in predicting monthly and annual average water table depths and stream flow with acceptable E values (0.55-0.99) for the five-year period (2003-2007), MIKE SHE yielded better results than DRAINMOD for daily hydrologic dynamics. Both models, however, showed relatively large uncertainty in simulating stream flow for dry years. The subsurface drainage predicted by MIKE SHE was lower than simulated by DRAINMOD for dry years, higher for extremely wet years and similar for normal climate years. The differences were likely that MIKE SHE employed distributed physical characteristics of the watershed, especially of soil and topography which can substantially affect the subsurface flow, but the spatial average condition was only used by DRAINMOD; the results from both models were, thus, similar for those average (e.g., normal climate) conditions, and different for varying conditions. This study suggests a lumped parameter model could perform equally well at the monthly temporal scale for modeling stream flow under average climatic conditions; however a distributed hydrological model provides more accurate prediction of daily stream flow and water table depth across varying climatic conditions.

Keywords: stream flow, water table depth, actual evapotranspiration, subsurface drainage, surface runoff

INTRODUCTION Models are effective tools to examine hydrologic conditions governing wetland ecology and assess ramifications of water management, land use change and climate change in terms of the functions and services of the wetland ecosystems (Skaggs et al., 1991; Martinez et al., 2008; Lu et al., 2009). However, successful applications of hydrologic models depend on selection of the most appropriate models for the purposes of particular studies and, thus, require our understanding of the usefulness, advantages and limitations of different models.

Hydrological models can be classified into three categories, lumped, distributed, and semi-distributed (Refsgaard, 1996). The lumped models are parameterized by the average characteristics of study watersheds (e.g., DRAINMOD, Skaggs et al., 1991; SAC-SMA, Carpenter and Georakakos, 2006). The distributed models (which are most likely process-based) can consider spatial and temporal variability in physical characteristics of the watersheds (e.g., MIKE SHE, Graham and Butts, 2005; WetSpa, Shafii and Smedt, 2009). The semi-distributed models are hybrids of lumped and distributed models with spatial representations of some of the system characteristics (e.g., semi-distributed version of SAC-SMA, Ajami et al., 2004). Therefore, even though the lumped and semi-distributed models may have the advantage of being easy to apply because of the small number of input parameters required, they may be subject to large errors when applied to catchments or watersheds with high spatial heterogeneity in hydro-geological characteristics. On the other hand, the distributed models may provide accurate representation of hydrological variability in study sites because of their capability of characterizing physical conditions in space, but are often limited by uncertainty in the large number of associated input parameters, which in turn may increase uncertainty in model outputs (Miller et al., 2007; Haydon and Deletic, 2009), difficulty in model calibration (Boyle et al., 2000), and “cost” in collecting and preparing the input data and in model calibration and validation (Freer et al., 2003). Therefore, each type of hydrologic models has its own merits and limitations.

The objective of this study was to evaluate the performance of two models, MIKE SHE and DRAINMOD, for estimating stream flow (as a sum of subsurface drainage and surface runoff) and water table depth in a first-order forested watershed in Coastal South Carolina. Both models are often used to assess hydrological processes in poorly drained, low-gradient watersheds in coastal areas. Therefore, this comparison provides much needed information about the potential use of these two specific models particularly, in predicting stream flow and water table dynamics.

METHODS

Study Site Description A first-order watershed (WS80) on the Santee Experimental Forest (33.15ºN, 79.8º W) in South Carolina was chosen for this work because it is a control watershed in a paired watershed system with gauging records since 1967 (Fig. 1). The 160 ha watershed is characteristic of the subtropical monsoon region of the Atlantic Coast with short, warm and humid winters and long and hot summers; the long term average annual temperature is 18.7°C, and average precipitation is 1350 mm (Amatya et al., 2003). The topography is planar with slope of less than 4%. The elevation is between 4-10 m above sea level. The soils are characterized by loam surface and clayey subsoil, drained moderately well in uplands and poorly in riparian zones. The forest cover consists of naturally regenerated bottomland hardwoods in riparian zones and mixed pine-hardwoods in uplands (Hook et al., 1991). Detailed site descriptions can be found in Harder et al. (2006, 2007).

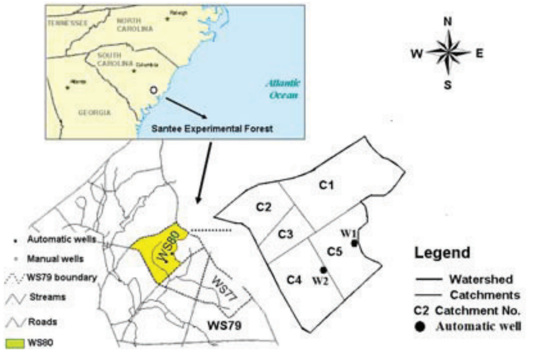

Figure 1. Watershed 80 on Santee Experimental Forest, South Carolina, USA (C1 - C5 are the divided catchment numbers. W1 and W2 are the automatic wells.)

Field Measurements and Data Collections Precipitation and air temperature were measured at WS80 at hourly intervals. To estimate Penman-Monteith based potential evapotranspiration (PET), additional meteorological measurements including solar and net radiations, wind speed and direction, vapor pressure, and relative humidity were collected at 30-minute intervals at the Santee Experimental Forest Headquarters about 3 km away from the study sit. Flow measurements taken at 10-minute intervals at the outlet of the watershed were integrated to obtain daily flows. Water table depth was recorded at 4- hour intervals by two shallow automatic recording wells installed in upland and lowland locations. Details of these measurements are given in Dai et al. (2010).

Hydrologic Models and Parameterization MIKE SHE is a distributed hydrological model with full mechanistic representation of hydrological processes (process-based), and can simulate watershed hydrology under complicated conditions with different types of soils, vegetation and topography (DHI, 2005; Zhang et al., 2008; Lu et al. 2009). In this study, MIKE SHE was coupled with a one-dimensional river/channel water movement and routing model MIKE 11 (DHI, 2005) to simulate the full hydrological cycle, including evapotranspiration, infiltration, unsaturated flow, saturated flow, overland flow and stream flow. The main inputs for the model include spatial data on topography, soil, vegetation and drainage network, and temporal data on precipitation and PET based on Penman-Monteith (Xu and Singh, 2005). The watershed was divided into 675 (50 by 50 m) cells for MIKE SHE simulations.

DRAINMOD is a field scale hydrological model with partial mechanistic representation and some empirical relationships, and is designed to simulate the water balance for areas with parallel ditches on poorly drained soil, especially for agricultural water management in coastal plains (Skaggs, 1999). The simulated processes include evapotranspiration, infiltration, water table, subsurface drainage, surface runoff, sub-irrigation, and controlled drainage. In this study, DRAINMOD was used to predict water table and stream flow dynamics on WS80 watershed that was divided into five sub-catchments (C1- C5; Fig. 1) based on topography. The main parameters of DRAINMOD were defined based on a study of monthly water balance in WS80 by Harder et al. (2006), some of which were modified to reflect the spatial variability in the sub-catchments. For example, surface detention storage was allowed to vary from 10-80 mm (Table 1) in

Table 1 Key input parameters for MIKE SHE and DRAINMOD *

Parameter	MIKE SHE	DRAINMOD
Drainage depth (cm)	5-95(35)	20-60 (40)
Ditch Spacing (m)	n/a	350-600 (500)
Depth to impervious layer (m)	0.6-2.2 (1.6)	1.5
Surface detention storage (mm)	11-180 (36)	10-80 (40)
Rooting depth (forest/crop) (mm)	500/300	500/300
Leaf area index (LAI)	0.2-6.6(2.8)	n/a
Saturated hydraulic conductivity ($\cdot 10^{-6}$ m/s)	0.1-100 (9.5)	0.78-13.9 (7.1)
Potential evapotranspiration(P-M method)(mm d^{-1})#	0-7.5	0-7.5

*: The values in brakes are mean; #: P-M = Penman-Monteith

different sub-catchments because this was the range of variability identified (Dai et al., 2010). Same was the case with ditch depth which also varied. The drainage spacing was estimated based on the sub-catchment size. However, the number and layers of soil types (for that matter their properties) used by DRAINMOD were somewhat different from those used in MIKE SHE (Table 1). Similarly, canopy interception is not simulated in DRAINMOD. Same rainfall and daily P-M PET data as in MIKE SHE were used. The overall predicted stream flow of the whole watershed was determined as the area-weighted average of flows predicted in each of the five sub-catchments, to which DRAINMOD was applied individually. The key input parameters for both models were presented in Table 1.

Model Performance Evaluation Both models have been calibrated and validated for WS80 (Harder et al., 2006; Dai et al., 2010). However, those calibrations and validations were performed with relatively short-term (2-3 years) datasets. In order to compare the two models appropriately, model performance in this study was tested with a dataset comprising a 5-year period of observation.

The hydrologic (stream flow and water table) and climatic (temperature and rainfall) data measured in 2003-2007 were used for evaluating model performance in terms of predicted stream flow (which was divided into surface runoff and subsurface drainage (SSD) for detailed examination), water table depth, and actual evapotranspiration (AET). Precipitation was 1671, 962, 1540, 1255 and 923 mm for the five years, respectively. With hurricane Isabelle in September, precipitation of the wet year of 2003 was 320 mm higher than the long term annual average (i.e., 1350 mm). The two dry years of 2004 and 2007 had precipitation about 400 mm below the average. These large climatologic variations within these years, which in turn led to large temporal variations in stream flow and to temporal and spatial variations in water table depth, presented desirable conditions for model testing because examining model responses to those variations may ensure an unbiased model evaluation. The 5-year observed dataset was used to evaluate the performance of the two models using the coefficient of determination (R^2) and the model efficiency (E) (Nash and Sutcliffe, 1970) statistics.

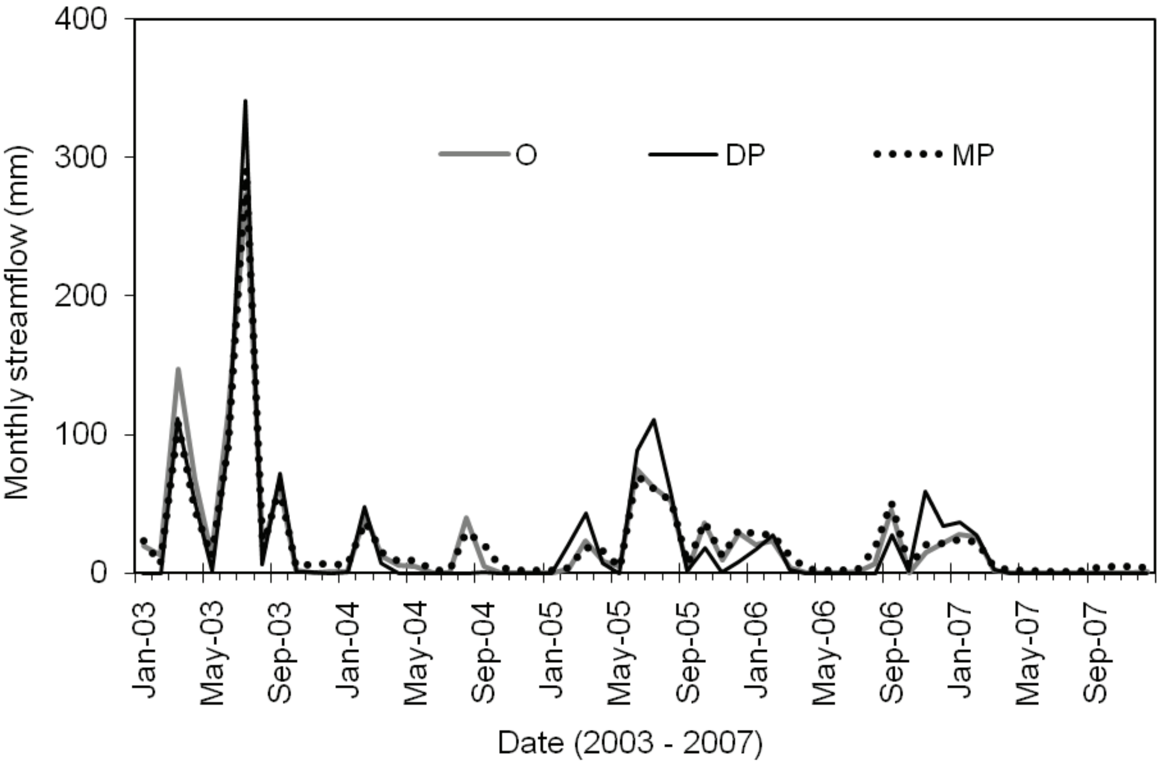

Fig. 2: Observed vs. predicted monthly stream flows during the calibration and validation periods (DP represents the results predicted by DRAINMOD, MP the results predicted by MIKE SHE, and O the observations.)

RESULT AND DISCUSSION

Model Performance The observed and simulated stream flow for 2003-2007 is presented in Figure 2. MIKE SHE over-predicted the flow during dry periods, such as the periods from October of 2003 to January of 2004, and from May to December of 2007. In contrast, DRAINMOD over-predicted the flow in some wet periods, such as July of 2003 and July of 2005, and in the periods of low temperature and rainy springs of 2005 and 2007.

The over-prediction of stream flow during dry periods by MIKE SHE is an artifact of the model which does not allow a river/stream to dry out (Lu et al., 2006). In fact, the stream in WS80 usually has no-flow during the dry periods. It is, however, required that MIKE SHE maintains a very low flow on the stream bed for no-flow periods. As a result, the total stream flow predicted by MIKE SHE for dry periods was generally higher than the measurement. Unlike MIKE SHE, DRAINMOD employed averaged spatial characteristics of the study area (e.g., surface detention storage, evapotranspiration parameters like upward flux in soils), leading to the over-prediction of stream flow for some days with high stream flow during wet periods and the under-prediction for low flow days during dry periods. Because PET based on a grass reference was used the predicted ET by the both models may be somewhat lower (Sun et al., 2009) resulting in some increased stream flow. DRAINMOD's over-prediction of flow may also be due to under-prediction of ET that did not account for interception.

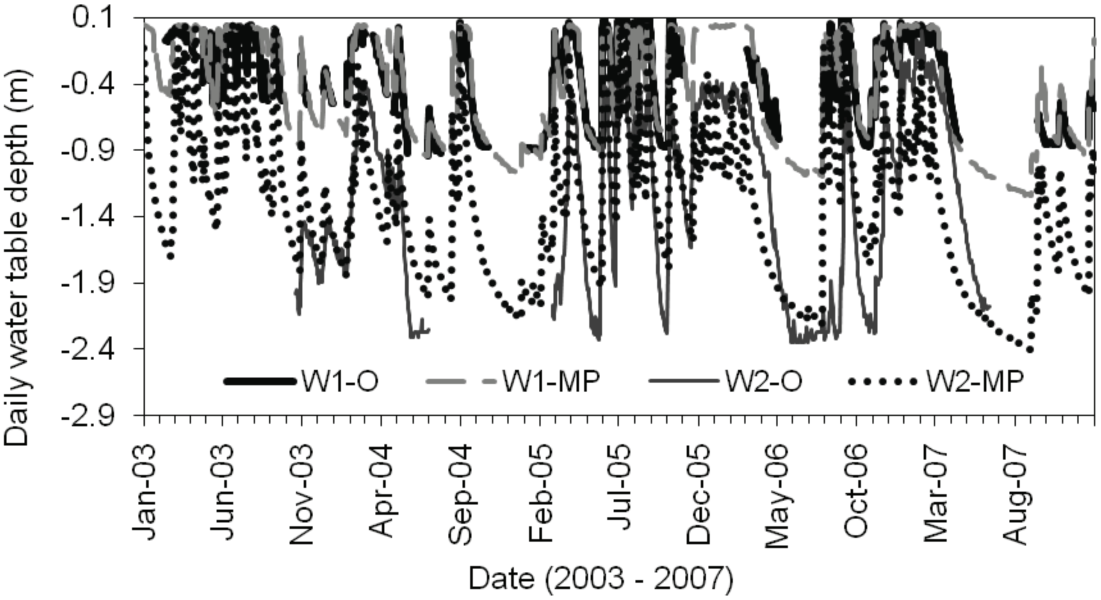

Fig. 3a: Observed vs. simulated daily water table by MIKE SHE during the calibration and validation periods (MP represents the results predicted by MIKE SHE, and O the observations. W1 and W2 are the automatic wells)

The measured and predicted water table depth is presented in Figure 3a and 3b, respectively. MIKE SHE captured the water table dynamics at this site (Fig. 3a), even though it showed small under-prediction of the water table at well W2 during the period from December of 2005 to March of 2006 and the period from January to February of2007. DRAINMOD under-estimated the water table at well W1 during the low

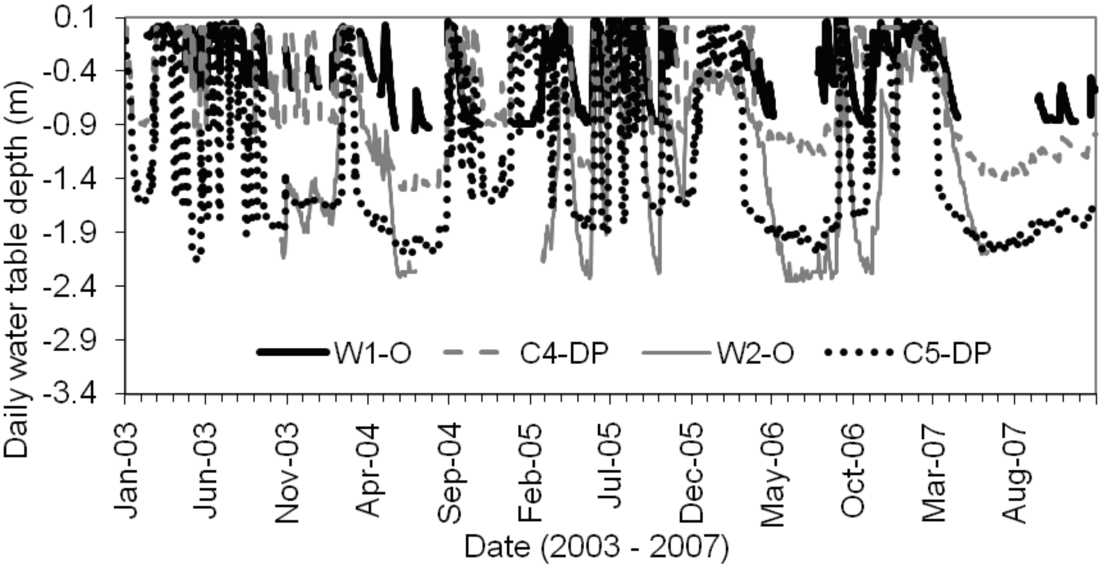

Fig. 3b: Observed vs. simulated daily water table by DRAINMOD during the calibration and validation periods (DP represents the results predicted by DRAINMOD. C4 and C5 are the catchment numbers where the automatic wells 2 and 1 were located. See Fig. 1)

precipitation periods (e.g., dry summers of 2004, 2006 and 2007) and over-predicted at W2 during the period from December of 2005 to March of 2006 (Fig. 3b).

The water table level under-predicted by MIKE SHE and over-predicted by DRAINMOD for well W2 during the period from December of 2005 to March of 2006 were mainly due to the stream flow over-predicted by MIKE SHE and under-predicted by DRAINMOD. However, the water table level under-predicted by DRAINMOD for low precipitation periods may be due to over-predictions of AET.

The results of model evaluation based on the statistics suggested that MIKE SHE generally performed better than DRAINMOD. For predicting monthly and/or long-term stream flow, MIKE SHE and DRAINMOD performed equally well with an R^2 of 0.96 and 0.90, and E of 0.96 and 0.85, respectively. An E value larger than 0.75 for estimating monthly flow should be considered as “very good” as suggested by Moriasi et al. (2007). For daily stream flow, however, MIKE SHE (R^2=0.64, E=0.57) showed better performance than DRAINMOD (R^2=0.53, E=-0.25), even though the average daily stream flow predicted by DRAINMOD (0.75 mm/day during this five-year period) displayed strong agreement with the observation (0.74 mm/day). For daily water table dynamics at W1 and W2, MIKE SHE (R^2=0.80 and E=0.79 for W1, 0.47 and 0.46 for W2) also performed better than DRAINMOD (R^2=0.33 and E=-0.6 for W1, 0.50 and 0.32 for W2). These differences in water table prediction may be due to the differences in model parameterization as water table related parameters, especially the soil hydraulic properties, were spatially distributed for MIKE SHE, but lumped for DRAINMOD.

The results (Fig. 4) of the actual evapotranspiration (AET) predicted by both MIKE SHE and DRAINMOD followed the pattern of the potential evapotranspiration (PET) calculated by the Penman-Monteith method (Xu and Singh, 2005; Harder et al, 2007).

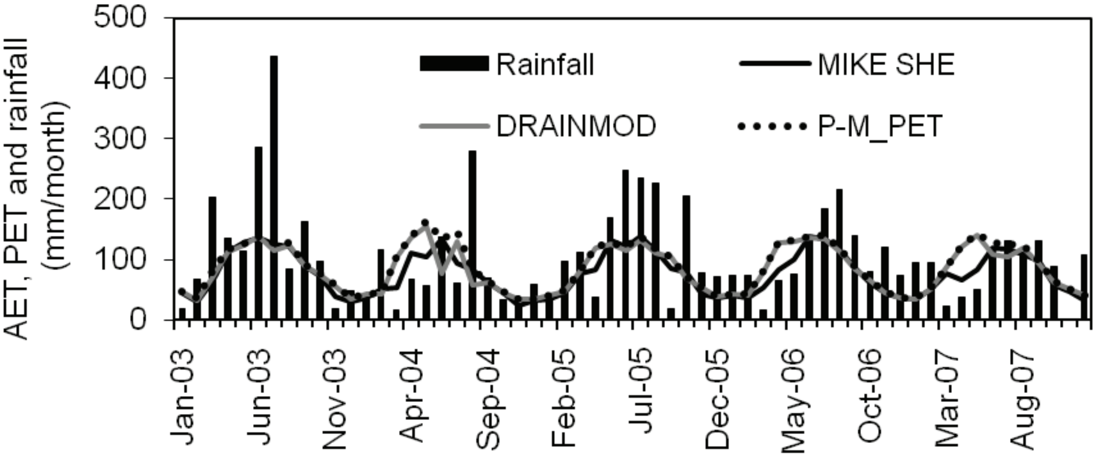

Fig. 4: Observed monthly rainfall, and calculated monthly PET by Penman-Monteith (P-M) and predicted AET by DRAINMOD and MIKE SHE during the calibration and validation periods

Table 2 The simulated rates of the contribution of surface runoff and subsurface drainage to stream flow *

Year	Rainfall (mm)	Flow (mm)	M-RD (%)	D-RD (%)	M-RF (%)	D-RF (%)
2003	1671	733.7	18.2	9.7	81.8	90.3
2004	962	109.5	36.3	59.6	63.7	40.4
2005	1540	306.6	30.0	21.2	70.0	78.8
2006	1255	138.7	39.8	37.0	60.2	63.0
2007	923	58.4	42.9	63.8	57.1	36.2

*: M-RF and D-RF are the surface runoff rates simulated by MIKE SHE and DRAINMOD, respectively; M-RD and D-RD are the subsurface drainage rates.

AET is modeled in DRAINMOD as a function of PET, the soil moisture in the root zone, and soil-water upflux as a result of water table depth without a consideration of evaporation from vegetation canopy interception in forested watersheds. The model assumes AET equal to PET for unlimited soil moisture for high water tables when it is on or near the surface with saturated soils like in 2003 and 2005. For other dry conditions like in early-mid 2004, 2006 and 2007 summer, AET was still nearly equal to PET most likely due to higher upflux of the clayey soils with a larger water holding capacity. However, the AET predicted by MIKE SHE for dry periods was lower than simulated by DRAINMOD. This was likely related to the differences in AET modeling between the models.

The results also showed that the two models successfully simulated surface runoff and subsurface drainage during average climatic years but differed in varying dry or wet years (Table 2). For example, in dry years DRAINMOD produced a higher estimation of the contribution rate of subsurface drainage (SSD) (≈60%) than MIKE SHE (≈40%); the pattern was reversed for wet years. The higher SSD by DRAINMOD in dry years may be potentially due to somewhat higher (on average) surface storage used in it than in MIKE SHE (Table 1) that prevented the surface runoff even though the water table was near the surface soon after the precipitation event. This apparently yielded rather very high subsurface drainage only as was the case in the large precipitation event of August 28, 2004 when there was a very large subsurface drainage but no surface runoff. Other factors that affect SSD during dry conditions in these two models may be the use of different conductivity in soil layers and depth to the impervious layers. However, the mean contribution rate of subsurface drainage for DRAINMOD showed close agreement to that from MIKE SHE in this 5-year period from 2003-2007. This difference may be due to MIKE SHE utilizing spatial difference in topography (slope) of the study site that dictates the micro-topography (e.g. the surface detention storage) affecting the surface runoff rates. However, DRAINMOD does not utilize this spatial variability and rather uses an average value (Table 1). During normal to wet years, when soil is saturated with high near surface water tables, all excess rainfall in DRAINMOD becomes runoff instantly without being routed like in MIKE SHE, which may result in slightly higher surface runoff like in 2003 and 2005. Although DRAINMOD had a slightly higher surface storage, on average, than MIKE SHE, the lower conductivity assumed in the top soil layer (Table 1) might have also resulted in slight over-prediction.

SUMMARY AND CONCLUSIONS The model testing and evaluation in this study demonstrated that both MIKE SHE and DRAINMOD can be reliably used for monthly and/or long-term estimate of stream flow and water table dynamics for average climatic periods. MIKE SHE is more robust, providing better predictions across varying climatic conditions and it provided more accurate daily predictions, which was attributed to MIKE SHE's consideration of the spatially distributed physical characteristics of the watershed. The model comparison showed that there are differences in predicting other hydrological components such as AET, surface runoff, and subsurface drainage. These prediction differences between the models are related to the different modeling methods and (spatial or lumped) parameterization used by the models. Although MIKE SHE performed better than DRAINMOD to simulate hydrology of this watershed, DRAINMOD needs less input information. Therefore, users should evaluate whether the effort needed to parameterize MIKE SHE, which requires extensive calibration due to the large number of input parameters, especially for those with considerable spatial variation, (e.g., topography and soils), is warranted based on the assessment objectives. Also, it is important to acknowledge (1) the limitation of MIKE SHE in over-predicting stream flow during dry periods for such a watershed with an ephemeral stream, and (2) the limitation of DRAINMOD as a field-scale model in applying on large watersheds. This is because a lumped parameterization based on average values for DRAINMOD is bound to err in extreme conditions, especially very dry period when water table is deep in this type of study sites with low-relief topography and complicated distributions of soils and vegetation and without a regulated drainage system.

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