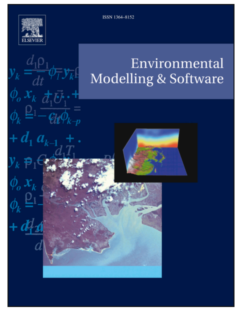

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Hyunwoo Kang, Venkataramana Sridhar

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Drought assessment with a surface-groundwater coupled model in the Chesapeake Bay watershed

Hyunwoo Kang[1], Venkataramana Sridhar[1]*,
1 Department of Biological Systems Engineering
Virginia Polytechnic Institute and State University, Virginia, USA, 24061

Email: vsri@vt.edu
*Corresponding Author

Abstract

An integrated framework of surface and groundwater models is essential for the comprehensive understanding of impacts of droughts due to surface water and subsurface exchanges. We evaluate the response of soil moisture and groundwater dynamics during drought in the Northern Atlantic Coastal Plain in the Chesapeake Bay Watershed. The Variable Infiltration Capacity model coupled with MODFLOW (VICMF) was implemented and several variables were used in the Multivariate Standardized Drought Index (MSDI) that consider multivariate perspectives of droughts. Three drought indices were derived (MSDI_PSV, MSDI_PSM, MSDI_PWM) (PSV: Precipitation and Soil moisture from VIC; PSM: Precipitation and Soil moisture from VICMF, PWM: Precipitation and WTE from VICMF), and the accuracy of the results was verified using a performance measure (Drought area Agreement (%); DA) and a statistical test to evaluate spatial extent of the drought areas. The MSDI_PWM showed better results for predicting drought events as it captured overall drought conditions.

1. Introduction

A comprehensive understanding of the hydrologic cycle and watershed processes in the terrestrial environment is essential for water budget estimation and sustainable water management under changing weather and climate extremes. Specifically, interactions between surface water and groundwater in the watersheds where the exchanges are dominant can have significant impacts on water resources, watershed management and nutrient loadings (Bailey et al., 2016). However, the exchanges between these systems have been analyzed without coupling, and many models have considered improving the exchanges in a vertical direction (Niu et al., 2007; Liang et al., 2003). To give more accurate evaluations of these interactions, a fully coupled model is necessary to provide a better understanding of both surface and groundwater conditions across multiple spatial and temporal scales.

Numerous techniques and different approaches are available to investigate the patterns of groundwater and surface water interactions at various spatiotemporal scales (Panday and Huyakorn, 2004; Bailey et al., 2016; Sridhar et al., 2017). These techniques and advanced tools provide opportunities to explain the effects of these interactions on water availability, hydrologic processes and drought conditions including the rates of evapotranspiration, surface runoff, soil moisture and groundwater level. Sridhar et al. (2017) developed a new coupled framework using Variable Infiltration Capacity (VIC) (Liang et al., 1994) and MODFLOW models, referred to as VICMF hereafter, to investigate the influence of groundwater dynamics on water balance components and assess how changing hydrology alters recharge and thus groundwater levels. The VIC model can provide downward flux generated from the precipitation events and estimates surface atmospheric fluxes using atmospheric forcing, soil and vegetation data over the land surface. Under certain conditions where the contribution of groundwater is adding moisture in the vadose zone, the subsurface water movement can be significant as there is upward flux from below; this can be useful for estimating the soil moisture. In addition, the VIC model includes multiple soil layers with variable infiltration rates, and a routing module that uses the linear-transfer-function model is available to simulate the streamflow in the river network system. However, the VIC model does not estimate hydrologic dynamics related to groundwater or groundwater–surface water interactions because it is applied in an uncoupled surface hydrologic model framework. Thus, the coupled VICMF model was developed for a more accurate understanding of the physical processes in surface–groundwater interactions.

Hydrologic models have applied water and energy balance approaches, and they are beneficial for addressing spatial distributions of water resources and drought conditions. However, an application of only surface hydrologic model does not capture integrated drought conditions of surface and groundwater dynamics at once (Oki and Kanae, 2006). The integrated framework somewhat complements these shortcomings of drought evaluations. In addition, drought indices are used for evaluating drought severity, frequency and impact (Niemeyer, 2008), as well as for improved drought prediction (Kang and Sridhar, 2018; Sehgal and Sridhar, 2018). Numerous drought indices have been applied to assess drought conditions, and the Multivariate Standardized Drought Index (MSDI), which is calculated using multiple hydrometeorological variables such as precipitation, soil moisture and runoff, is used to identify retrospective droughts in the United States (US) (Hao and AghaKouchak, 2013; Hao and AghaKouchak, 2014). Since the MSDI can consider multiple hydrometeorological variables, MSDI applications enable us to analyze various aspects of droughts integrating surface and groundwater dynamics. In this study, the MSDI was applied to represent multivariate perspectives on drought conditions with various combinations of variables (e.g., soil moisture, precipitation, water table elevation (WTE)).

The Northern Atlantic Coastal Plain (NACP) aquifer system is ranked the 13^{th} in total groundwater withdrawals in the US (Reilly and others, 2008). The supply of surface water in this region is limited because of numerous sources of the surface waters are brackish estuaries, despite sufficient precipitation (more than 1,100 mm/year). Besides, many populations in the NACP rely heavily on groundwater to satisfy their water demand, but water availabilities in the NACP region have been threatened by droughts, available drawdowns, agricultural demands, and industrial contaminations (Masterson et al., 2013). Thus, an accurate drought assessment that considers both surface and groundwater conditions would be useful for the NACP region.

The objectives of this study are 1) to identify the physical relationship between surface and groundwater variables, such as soil moisture and WTE, during drought events using the coupled VICMF model and 2) to evaluate the drought conditions using various drought indices in the Chesapeake Bay Watershed, including the Northern Atlantic Coastal Plain (NACP) aquifer system. Since the MSDI calculation with groundwater condition is the first attempted approach, the results of this study would contribute to generating valuable information on surface and groundwater drought conditions with a dynamically coupled model. Integrated surface and groundwater systems provide new insights into soil moisture, water table elevation, baseflows, and evapotranspiration (Gosselin et al., 2006; Jaksa and Sridhar, 2015; Sridhar et al., 2018).

2. Methods

2.1. Study Area and descriptions of groundwater model

The NACP aquifer system in the Chesapeake Bay Watershed occupies an area of approximately 28,200 km^2 between latitude 36°40' and 39°45' N and longitude 77°30' and 79°15' W (Figure 1). The climate is temperate and humid with annual precipitation of 1,020 mm, and large metropolitan areas are included along with coastal areas such as Washington D.C. and Richmond. In addition, the NACP aquifer provides a widely used groundwater supply due to its thickness and large areal extents (Masterson et al., 2016a).

The US Geological Survey (USGS) developed a groundwater flow model (MODFLOW-NWT) for the NACP aquifer system (Masterson et al., 2016a; Masterson et al., 2016b). This model provides a detailed evaluation of the groundwater availability of the NACP aquifer system. The NACP aquifer system is hundreds of meters thick along the coastline with a maximum thickness of about 3,000 m. The aquifer system includes nine confined aquifers and nine confining units. Population and changes in land use during the last few decades have led to various increased freshwater demands for the 20 million people in the region. Water table elevations are decreasing by about 0.6 m/year that results in large changes and difficult in water use and management of aquifer resources. Total groundwater withdrawal in 2013 was computed to be about 4.9 million cubic meters per day (Mm^3/day) and it provides 40 percent of the drinking water supply in highly populated regions. Precipitation amount for 2005 to 2009 is about 234.8 Mm^3/day, but almost 70 percent is lost by evapotranspiration that led to 74.5 Mm^3/day entering the groundwater system as aquifer recharge (Masterson et al., 2016a; Masterson et al., 2016b).

In this study, only some parts of the NACP area (Chesapeake Bay region) will be considered for the coupled model as it is important to include the effect of upward flux and recharge estimates (Figure 1). Masterson et al. (2016a) and Masterson et al. (2016b) provide some packages and input parameters for the MODFLOW simulation (McDonald and Harbaugh, 1988) in the NACP region. Since the original spatial resolution of MODFLOW was 1 mile (1.6 km), a spatial downscale method (Kriging) was applied for the coupled model (1 km). The required parameters and packages for the VICMF model were the horizontal and vertical hydraulic conductivities, specific storage, specific yield, General-Head Boundary (GHB) package, Recharge (RCH) package, River (RIV) package, and Well (WEL) package. The Drain (DRN) package is also required to simulate the VICMF model, and the drain elevation and conductance for the DRN package are calculated based on Equation (1) and (2).

$$C = \frac{KA}{X_1 - X_0} \quad \text{--} \quad (1)$$

$$D_e = S_e - SL \quad \text{--} \quad (2)$$

where C is conductance (L^2/T), K is hydraulic conductivity (L/T), A is the area (L^2), X is the position (L) when head is measured, D_e is the drain elevation (L), S_e is the surface elevation (L) and SL is the depth of the soil layers (L) from the VIC model (Hildreth, 2013; Sridhar et al., 2018).

2.2. VIC and MODFLOW model

The VIC model is a physically based macroscale hydrologic model that includes a water and energy balance framework (Liang et al., 1994). The model estimates several hydrologic and atmospheric variables such as soil moisture, surface runoff, baseflow, and evapotranspiration, and applies a conceptual system to demonstrate water and surface energy budgets. Furthermore, the VIC model includes multiple soil layers with variable infiltration rates, and a routing module that uses the linear-transfer-function model is available to simulate the streamflow in the river network system. These essential characteristics of the VIC model provide an opportunity to couple the land surface scheme with a groundwater model for accurate descriptions of the entire hydrologic budgets. However, the model is applied as a land surface hydrologic model that does not estimate hydrologic dynamics with groundwater or groundwater–surface water interactions. Thus, a coupled framework is required to provide an understanding of the physical mechanisms of droughts considering both surface and groundwater conditions simultaneously.

The Modular Three-Dimensional Finite-Difference Ground-Water Flow model (MODFLOW-2005) is a physically based, three-dimensional, and distributed finite-difference groundwater model that considers aquifer groundwater levels and routes groundwater flow in the system (Harbaugh, 2005). Also, the coupled VICMF model is another variant of MODFLOW that is used for this study. With the MODFLOW model, estimations of groundwater recharge, pumping, vadose zone percolation, discharge to subsurface drains, and river–aquifer interactions are available. However, MODFLOW does not estimate the surface water budget components, such as soil moisture and surface runoff (Bailey et al., 2016).

The VICMF coupled model was developed for a more accurate understanding of physical processes with surface–groundwater interactions, and the coupled model was successfully applied to the Eastern Snake Plain Aquifer (ESPA) region of Snake River Basin (SRB) (Sridhar et al., 2017).

2.3. VIC-MODFLOW (VICMF) coupled model

The coupled VICMF model (Hildreth, 2013; Sridhar et al., 2017) is integrated with surface and groundwater inputs in the NACP Aquifer System region, where the Chesapeake Bay is located (Figure 1). The VICMF model is based on the interdependent equations that estimate the flow of water in a surface and groundwater hydrologic system (Figure 2). The groundwater area includes the MODFLOW applications in the NACP region, and it estimates upward flux to surface zones (soil layer). The drainage package is used to calculate upward flux (discharge) from the MODFLOW grid cells for the daily stress period, which are integrated into a corresponding grid of the VIC model for the daily simulation. The amount of discharge (U_f) into the unsaturated VIC soil layers that are generated by the drain package is represented by Equation (3.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} + U_f \text{ --- } (3)$$

where θ is the soil moisture content (L^3/L^3), D(θ) is the hydraulic diffusivity (L^2/T), K(θ) is the hydraulic conductivity (L/T), and z is the soil depth (L).

The surface area consists of vegetation and soil layers (VIC model), which combines the upward flux from the groundwater area. In addition, the VIC model simulates infiltration that is recharged to groundwater zones. Finally, the MODFLOW model combines the recharge to simulate groundwater dynamic for the following day (Figure 2). The whole process of the coupled model generates WTE, soil moisture and energy fluxes. The horizontal discretization of the groundwater model is designed to be consistent with the surface discretization, and the discharges of the groundwater model improve the estimation of soil moisture by the surface model. MODFLOW packages such as the recharge, drain, well, river, and GHB (General-Head Boundary) enable to drive the coupled model with the meteorological forcings.

The VIC model was applied at a 1/16th-degree resolution (0.0625°, 5 km) with atmospheric forcing data (daily precipitation, maximum and minimum temperatures and wind speed), and there were 50 rows and 38 columns. The grid cells for the groundwater model downscaled as 250 rows and 190 columns, and each cell is uniformly spaced at 1 km, which is five times finer than the resolution of a VIC grid cell. Thus, the 25 grid cells (5 × 5) of the groundwater model were aggregated as a mean value for dynamic exchanges of the coupled model (Figure 2). In addition, the NACP grid cells were realigned to match the VIC model grid cells since the grid cells in the NACP model are aligned and not geographically directed north to south (50.727° from horizontal). Finally, since the groundwater model was created as a daily basis, a specific work for the temporal aggregation for the coupling was not required. The daily outputs (e.g., soil moisture, WTE) were aggregated on a weekly time step for computations of drought indices.

Other VIC inputs, such as soil and vegetation data, were obtained from the LDAS (http://ldas.gsfc.nasa.gov/) at the same spatial resolution as the meteorological data. Moreover, this study utilized the MODFLOW parameters from the NACP groundwater model (Masterson et al., 2016), including the hydraulic conductivity. The groundwater model was calibrated using the parameter estimation processes and by comparing with observations (e.g., water table elevation) of transient and steady-state conditions (Masterson et al., 2016a). Besides, the drain package was applied to each MODLFOW grid cell to interact with VIC grid cell. The coupled model computed daily estimates of the WTE, soil moisture and other fluxes for the period from 1987 to 2016.

2.4. Drought indices and overall descriptions of analysis

In this study, the VIC and VICMF models were used to compute the input variables required for computing the MSDI and to evaluate the multivariate drought conditions in the NACP region. The calculation of multivariate drought indices was based on the joint probability and distribution models (Hao and AghaKouchak, 2013; Hao and AghaKouchak, 2014).

This method is an extension of the generally used SPI computation proposed by McKee et al. (1993), extended to a bivariate model of precipitation, soil moisture and other variables. Indicating two variables (e.g., precipitation and soil moisture) at a specific time scale (e.g., 25 weeks) as random variables X and Y, respectively, the joint distribution of two variables (X and Y) can be represented as

$$P(X \leq x, Y \leq y) = p \text{ ------------------------------------ } (4)$$

where p is the joint probability of the two variables. The MSDI was then computed as follows (Hao and AghaKouchak, 2014):

$$\text{MSDI} = \emptyset^{-1}(p) \text{ -- } (5)$$

where $\emptyset$ is the standard normal distribution function.

Hao and AghaKouchak (2014) used a nonparametric joint distribution method to avoid computational difficulty in fitting parametric distributions. An empirical joint probability in the bivariate variables is calculated by the Gringorten plotting position formula (Gringorten 1963; Yue et al. 1999; Benestad and Haugen 2007)

$$P(X_k, Y_k) = \frac{m_k - 0.44}{n + 0.12} \text{ -- } (6)$$

where n is the number of the observation and m_k is the number of occurrences of the pair (x_i, y_i) for $x_i \leq x_k$ and $y_i \leq y_k$. After the joint probability is derived from Equation (6), it is used as an input variable to Equation (5) to calculate the MSDI.

In this study, the MSDI approach was mainly used for the estimation of drought indices, but combinations of variables differed between the two models. For example, precipitation and soil moisture were used to compute MSDI for the VIC model, but other combinations were available for the VICMF model, such as precipitation, soil moisture and WTE. For the VIC model, MSDI with precipitation (P) and soil moisture (S) was computed and it was MSDI_PSV.

For the VICMF model, a drought index was computed in addition to the MSDI with P and S (MSDI_PSM), and it was the MSDI with P and WTE (MSDI_PWM). Each drought index was computed from the simulated results of the VIC and VICMF models, and they were subsequently used to evaluate drought events in the NACP regions during the period of 2000 to 2016 because the US Drought Monitor (USDM) was only available from January 2000.

The USDM is the most widely used drought product in the US, and it provides a weekly drought map in collaboration with the National Drought Mitigation Center (NDMC), the U.S. Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) (Svoboda et al., 2002). In this study, weekly drought maps from the USDM were used to verify the drought areas of each drought index from the models in the NACP region. The performances of the drought indices were evaluated by the Drought area Agreement (DA) statistics, which was calculated as the rate of intersected areas where drought areas were correctly captured per total area of the USDM.

Figure 3 shows the time series plots of drought areas in the NACP regions from the USDM (http://droughtmonitor.unl.edu/; Svoboda et al., 2002), and there were four representative drought events in the periods of 2002, 2008, 2011, and 2012. All drought events were defined when more than 20% of areas were affected, and they lasted longer than 40 weeks. Each drought event is highlighted with black and dashed boxes, and they are named E1 to E4, respectively.

A statistical test was performed to check the significant differences in the performances of the drought indices (e.g., MSDI_PSV, MSDI_PSM and MSDI_PWM). A one-way analysis of variance (ANOVA) method was applied to reject the null as the mean value of DA from the same drought indices ($\alpha = 0.05$). For the multiple comparisons of two drought indices, Tukey's Honest Significant Difference (HDS) test was also carried out. If zero was included within the

95% confidence interval and the p-value was higher than 0.05, there was no significant difference between the drought indices.

3. Results and discussion

3.1. Soil moisture estimation of the VIC and VICMF models

In this study, soil moisture from the VIC and VICMF models was compared to analyze the impacts of groundwater dynamics. Figure 4(a) shows the seasonal comparison of total soil moisture during the study period, and the red and blue lines represent the results of the VIC and VICMF models. Each line was calculated by the mean value of soil moisture for each week during the study period (1987-2016). Overall, the mean value of soil moisture from the VIC model was higher than that of the VICMF (209.4 mm and 206.7 mm, respectively). The red line in Figure 4(b) shows the difference in weekly soil moisture between the two models, and a positive number means that soil moisture from the VIC model was greater than that of the VICMF. The soil moisture from the VICMF was slightly higher from January to April (1–16 weeks), and the VIC was higher for the rest of the period (May to December). The blue line represents the total upward flux produced by the VICMF model, and the difference in soil moisture was higher when the upward flux was relatively low (31–45 weeks). Additionally, there was a significant linear correlation between the soil moisture difference and upward flux (Figure 4(c)). In other words, the upward flux calculated by the groundwater model was closely related to the soil moisture estimation (VICMF), which would affect the drought assessment.

Soil moisture is one of the most appropriate variables to monitor and assess the impact of water shortage on vegetated land due to its effects on atmospheric dynamics (Cammalleri et al., 2016). In addition, augmenting soil moisture via irrigation to increase plant-available water for root extraction when there is a precipitation deficit is required for crop growth and agricultural production (Bolten et al., 2010; Sánchez et al., 2016). Therefore, an estimation of reliable soil moisture using surface–groundwater dynamics is essential for the computation of drought indices.

3.2. Drought area agreement and WTE

The drought maps of the drought indices from the VIC and VICMF models were compared with the USDM drought maps to assess the accuracy of the drought indices. Figure 5 provides the DA derived from the drought indices for each drought event, which were MSDI_PSV from the VIC model and MSDI_PSM and MSDI_PWM from the VICMF model. DA was calculated as the rate of intersected areas where drought areas were correctly captured per total area of the USDM. The drought indices were computed at the same temporal scale with corresponding dates with USDM (weekly). Four representative drought events lasted more than six months (Figure 3). The longest (63 weeks) and most serious droughts occurred in 2002, which caused the greatest decrease in WTE computed from the VICMF model.

Overall, the performances of the MSDI_PWM were higher than those of other indices for all drought events, and it was affected by the different combinations of drought indices. The DA values of MSDI_PS from the VIC (MSDI_PSV), MSDI_PSM and MSDI_PWM from the VICMF model (MSDI_PSM and MSDI_PWM) were 97.5%, 97.7% and 99.9% for the first event (E1) and 97.5%, 97.6% and 98.1%, for E2, respectively. The DA values were 68.3%, 70.6% and 75.7% for E3 and 91.3%, 91.7% and 96.4% for the E4 (Figure 5). For all the drought events, the mean values of MSDI_PWM were the highest. In addition, Figure 6 presents the spatial comparisons of the representative drought conditions for each period and the MSDI_PWM showed higher DA values. However, there are some poor agreements during the beginning of the drought period (e.g., E1 and E3). The sources of the poor agreements are 1) The MSDIs used in this study only consider precipitation, soil moisture, and WTE conditions, while the USDM is a composite index that consider multiple drought indices (e.g., PDSI, SPI, SWSI), climate indices (e.g., ENSO), USDA/NASS Topsoil Moisture, NOAA/NESDIS satellite Vegetation Health Indices, and local reports from more than 450 expert observers across the U.S., and 2) the spatial resolution of USDM (< 1km) is smaller than the outputs of the VIC and VICMF models (Svoboda et al., 2002).

Figure 7 represents the comparisons of the USDM drought areas, MSDI_PSM and MSDI_PWM. Drought severities for each event were represented by the mean values of MSDI_PWM, and they were -1.83 for E1, -1.41 for E2, -0.82 for E3, and -1.05 for E4. Based on the results, the E1 period was the most severe drought in the last twenty years in the NACP region, and MSDI_PSM and MSDI_PWM accurately captured the drought conditions. However, the performances of MSDI_PSM and MSDI_PWM differed during the drought termination period. As shown in Figure 10(b)), the green line represents the severe drought of MSDI (<-1.5), and the black and blue lines indicate the MSDI_PSM and MSDI_PWM, respectively. After October 2002, there was a drought recovery, but the slope of MSDI_PSM was much steeper than that of MSDI_PWM. Thus, some of the drought areas after October 2002 were not adequately captured by MSDI_PSM. The DA values of MSDI_PSM were rapidly decreased at the end of the E1 period (Figure 5(a)). In addition, Figure 7(c) represents the drought areas, MSDI_PSM and MSDI_PWM for the E4 period. Similar to the results of the E1 period, the slope of MSDI_PSM was slightly steeper than that of MSDI_PWM during the drought termination period, which also affected the decrease in the DA values at the end of the E4 period (Figure 5(d)). Droughts have an enormous impact on hydrologic variables, such as runoff, soil moisture, and groundwater, but their responses vary. The drought response of groundwater is slower than soil moisture regarding both drought onset and recovery (Van Loon, 2015), which shows that the drought assessment capability of MSDI_PWM was better during the drought recovery period. For the other drought events, such as the E3 period, similar results were shown (Figure 5(c)). These results imply that a drought index that considers both meteorological and groundwater conditions are better suited to capture overall drought conditions, specifically for the coastal estuaries. It is evident that there is a time lag between groundwater and surface water systems in capturing drought conditions. However, it depends on the type of the groundwater systems, shallow or deep, soil moisture conditions and how fast the recovery happens (Sridhar et al., 2006; Sridhar and Hubbard, 2010). In the NACP region, the fall line and geology determine the relatively short time of response. Also, as a first attempt to integrate the groundwater system in the drought assessment, our hypothesis is that groundwater integration for drought extent mapping is essential.

Groundwater is generally viewed as a buffer resource, and the groundwater use increased during drought periods (Uddameri et al., 2017). Besides, a groundwater drought is defined by the periods of decreased groundwater recharge and groundwater levels (Van Lanen and Peters, 2000; Mishra and Singh, 2010). Thus, an analysis of WTE during drought periods is essential because it presents a scenario of groundwater availability during droughts in the areas where the various land covers exist like the NACP region. In this study, we analyzed the effect of droughts on WTE in selected urban and rural areas, and compared the wet, normal, and drought conditions and analyzed the significance of the data through a statistical analysis. Since SPI is the most commonly used drought index for the drought assessment (Guenang and Kamga, 2014), it is considered to be suitable for distinguishing between drought, normal and wet conditions.

Figure 8(a) and (b) were developed using long-term WTE with the VICMF model, and wet, normal and drought conditions were divided based on the results of MSDI_PWM that showed the highest DA. The wet, normal, and drought conditions were defined by the ranges of the Standardized Precipitation Index (SPI) at the corresponding areas, and they are based on the SPI classification (McKee et al., 1993). If the SPI values are less than -0.5, it is considered as drought. If the SPI values are between -0.5 to 0.5, it is a normal condition. Finally, if the SPI values are greater than 0.5, it is wet and hence no drought. Figure 8(a) shows the urban area results (Washington DC), and Figure 8(b) represents the rural area results (downstream areas of the Potomac River and the Rappahannock River). The locations and land use for the urban and rural areas are shown in Figure 1. For both urban and rural areas, WTE decreases tended to be greater during drought (SPI < -0.5), which was more than during normal (-0.5 < SPI < 0.5) and wet conditions (SPI > 0.5). The mean values of the urban area were 32.8 m, 33.2 m and 33.3 m for the drought, normal and wet conditions, respectively. For the rural area, the mean values were 10.3 m, 10.5 m and 10.6 m, respectively. Furthermore, a statistical test was performed to check the significant differences in each condition. A one-way method was used to compare three conditions (drought, normal and wet) (α = 0.05). For the multiple comparisons of conditions, Tukey's HDS test was also carried out. If zero was included within the 95% confidence interval and the p-value was higher than 0.05, there was no significant difference between the conditions.

For the urban area, there was a significant difference between the conditions, which were determined by one-way ANOVA (p-value < 2e-16), and the Tukey's HSD test indicated that there were significant differences among the three conditions (Figure 8(c)). For the rural area, the differences were significant for the three conditions (p-value = 5.3e-14), and the Tukey's HSD test showed that there were significant differences between drought and normal (p-value < 2e-16) and drought and wet conditions (p-value < 2e-16) (Figure 8(d)). However, there was no significant difference between normal and wet conditions. Overall, the results imply that the WTE was significantly influenced by the drought conditions in both urban and rural areas, but the magnitude of differences between drought and normal conditions for the urban area was higher (0.4 m) than for the rural area (0.2 m).

3.3. Statistical test for the DA and WTE

To evaluate the performances of the drought indices from the VIC and VICMF models, a statistical test was carried out for the drought events and DA values. Table 1 shows the ANOVA results for each drought event; the p-values of E1 and E4 were less than 0.05 (rejecting the null hypothesis), which can imply that there was a significant difference in the mean values of DA for E1 and E4. However, the p-values of E2 and E3 were 0.648 and 0.551, which did not reject the null hypothesis, and there was no significant difference between the DA values. Table 1 and Figure 9 show the results of Tukey's HSD test, which confirm where the differences occurred between groups. For the E1 period, there was a significant difference between groups as determined by one-way ANOVA (p-value = 0.0036), and the Tukey's HSD test also revealed that there were significant differences between MSDI_PSV and MSDI_PWM (p-value = 0.007) and MSDI_PSM and MSDI_PWM (p-value = 0.014). For the E4 period, the Tukey's HSD test also revealed that there were significant differences between MSDI_PSV and MSDI_PWM (p-value = 0.004) and MSDI_PSM and MSDI_PWM (p-value = 0.08). The results of the E1 and E4 periods statistically prove that the performances of MSDI_PWM (MSDI with precipitation and WTE) showed better DA compared to the USDM. However, no significant differences were found for E2 and E3, but the mean values of DA from the MSDI_PWM were slightly better. In addition, even if not statistically significant, the result of MSDI_PSM from VICMF was slightly higher than that of MSDI_PSM from the MSDI_PSV, and it can be inferred that the effect of surface–groundwater dynamics can be important for drought assessment.

4. Conclusion

The coupled framework including surface and groundwater conditions is useful for considering surface and groundwater dynamics while assessing the impact of changing hydrology on drought predictions. The coupled VICMF model was applied to the NACP region in the Chesapeake Bay, one of the largest and the most productive estuary at present. Additionally, surface hydrologic simulations using the VIC model were performed, and the results of the VIC and VICMF models were used to compute the drought indices and assess the drought conditions. The critical findings of this study are as follows:

1) The mean soil moisture values from the VIC model were higher than those of VICMF, and the soil moisture differences were greater when the upward fluxes were relatively low. The soil moisture data from the two models implies that the upward flux was linearly related to the soil moisture estimation and therefore drought assessments.

2) The performance of the MSDI_PWM was better than that of the other indices for all drought events. For all events (E1 to E4), the DA values of MSDI_PWM were 99.9%, 98.1%, 75.7% and 96.4%, respectively, which were reliable results for the drought assessment. Since the drought evaluation capability of MSDI_PWM was better during the drought recovery period, the DA values from MSDI_PWM were better.

3) The significance of the DA values was verified by the statistical test (one-way ANOVA), and the E1 and E4 results showed that there were significant differences in the mean values of DA. In addition, the results of Tukey's HSD test revealed that there were significant differences between MSDI_PWM and the other drought indices for the E1 and E4 periods.

4) In both urban and rural areas, there were WTE decreases during drought periods, which were more than during normal and wet conditions. However, the difference between drought and normal conditions for the urban area was higher (0.4 m) than that for the rural area (0.2 m).

5) For drought assessment, an integrated modeling framework that considers climate–hydrologic–human interactions, including the groundwater condition (Uddameri et al., 2017), is recommended. Thus, the coupled approach investigated in this study may be useful to better characterize and simulate drought assessment that considers the surface–groundwater dynamic, which in turn can serve as an effective tool for decision-making, drought mitigation and risk management.

6) The WTE derived from the VICMF model is coupled with the surface water model (VIC), and MSDI calculated with this analysis is also the first attempted method in a region where groundwater dynamics is quite varied and insufficiently addressed. It is considered to be somewhat novel since it can generate the information on surface water and groundwater drought conditions with a dynamically coupled model.

7) The results of this study emphasize the need for an integrated framework with surface and groundwater models to assess more accurate drought conditions for the estuary regions in the globe.

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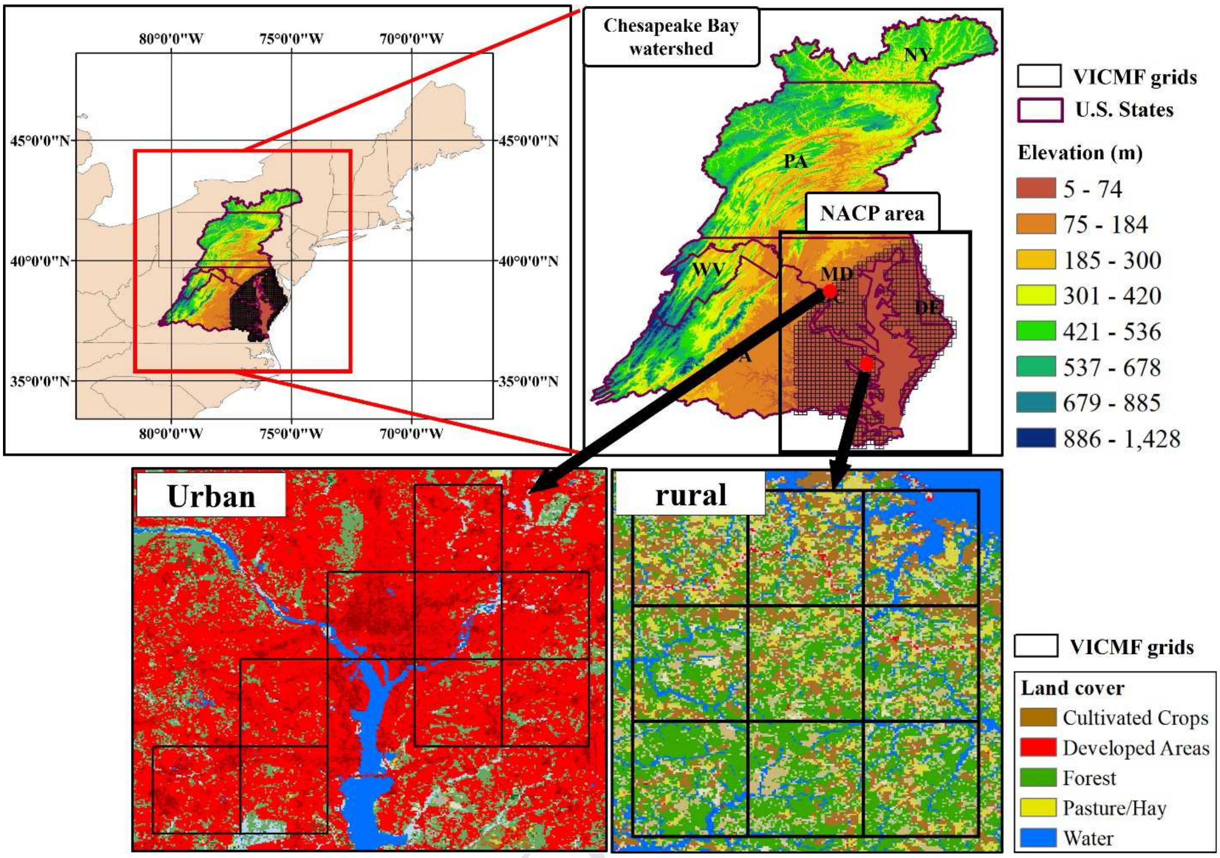


Figure 1. Location map of the study region. The upper-left figure highlights the location of the North Eastern US and the Chesapeake Bay Watershed with a red box. The upper-right figure represents the Chesapeake Bay Watershed and the NACP aquifer system (black box). The red circles represent the locations of urban and rural areas. The figures in the bottom show the land-use maps from the National Land Cover Database (NLCD-2011) (https://www.mrlc.gov).

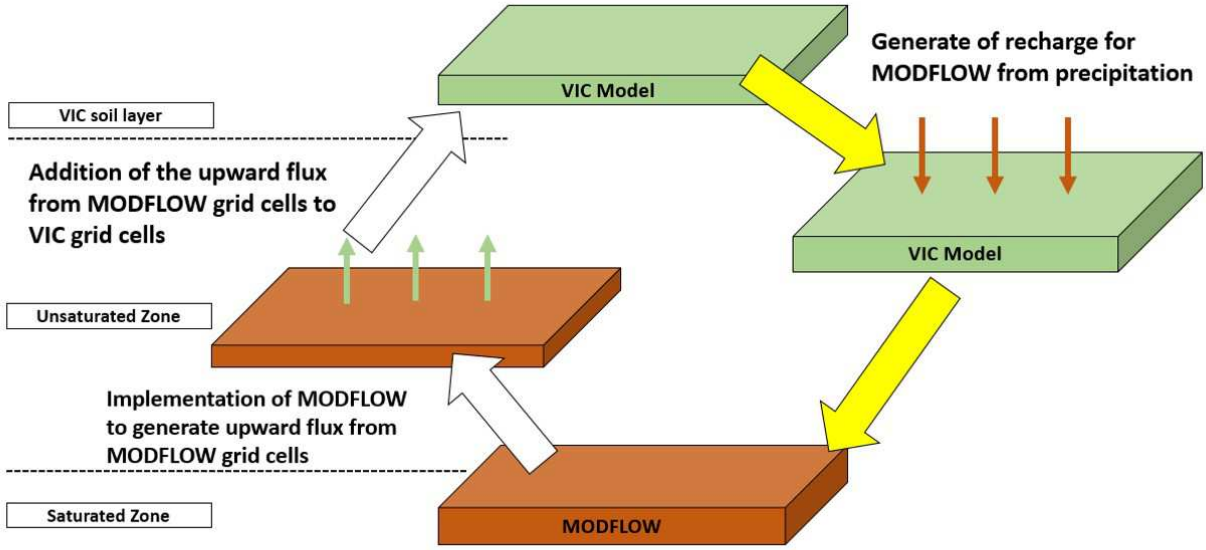


Figure 2. Overall diagram of the coupled model. MODFLOW generates the upward flux (left). The VIC model generates the infiltration, which will recharge the unsaturated and saturated areas. MODFLOW applies the recharge to estimate the upward flux for the following day (Sridhar et al., 2017).

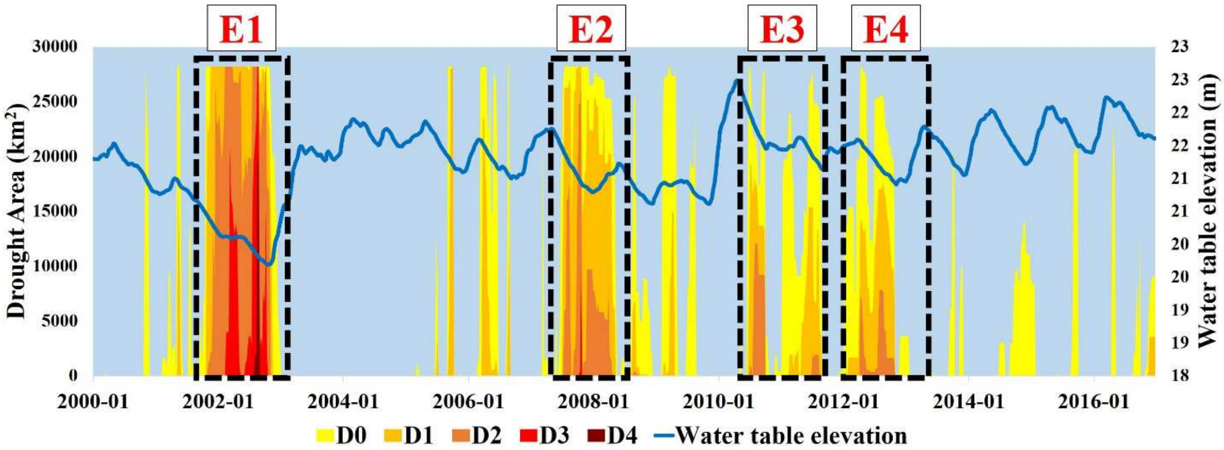


Figure 3. Drought area maps for the NACP region from the United States Drought Monitor (USDM) from January 2000 to December 2016. Each color represents a different drought condition category. Yellow indicates the D0 category (Abnormal drought), orange indicates the D1 category (Moderate drought), darker orange indicates the D2 category (Severe drought), red indicates the D3 category (Extreme drought), and dark brown indicates the D4 category (Exceptional drought). Black and dashed boxes represent the drought events (E1 to E4). The blue line indicates the average WTE in the NACP region.

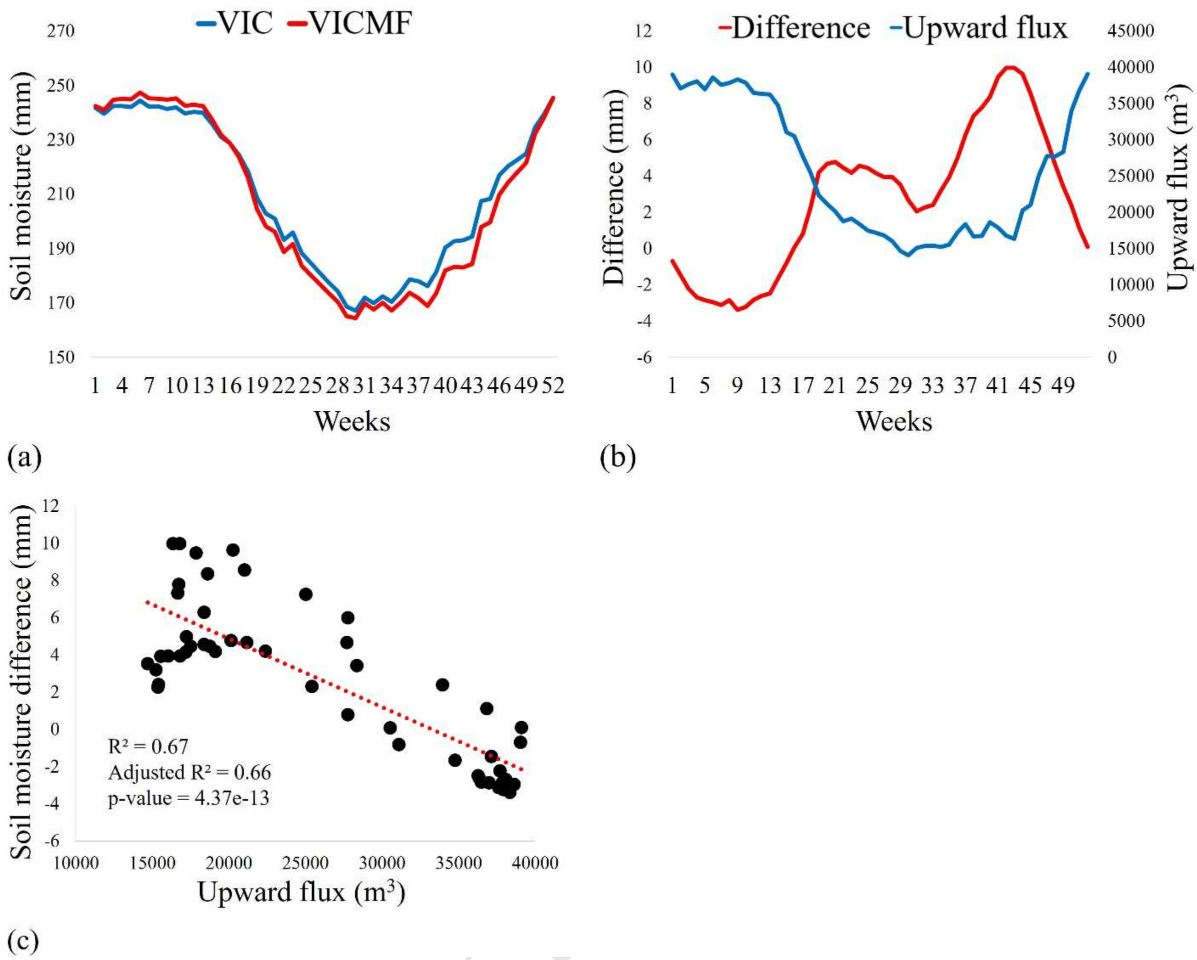


Figure 4. The results of soil moisture comparison from the VIC and VICMF models. (a) Seasonal soil moisture comparison of the VIC and VICMF models. Blue line represents the VIC, and Red line indicates the VICMF. (b) Soil moisture difference between the VIC and VICMF models and upward flux. Blue line represents the difference, and Red line indicates the upward flux. (c) Linear regression of the soil moisture difference and upward flux

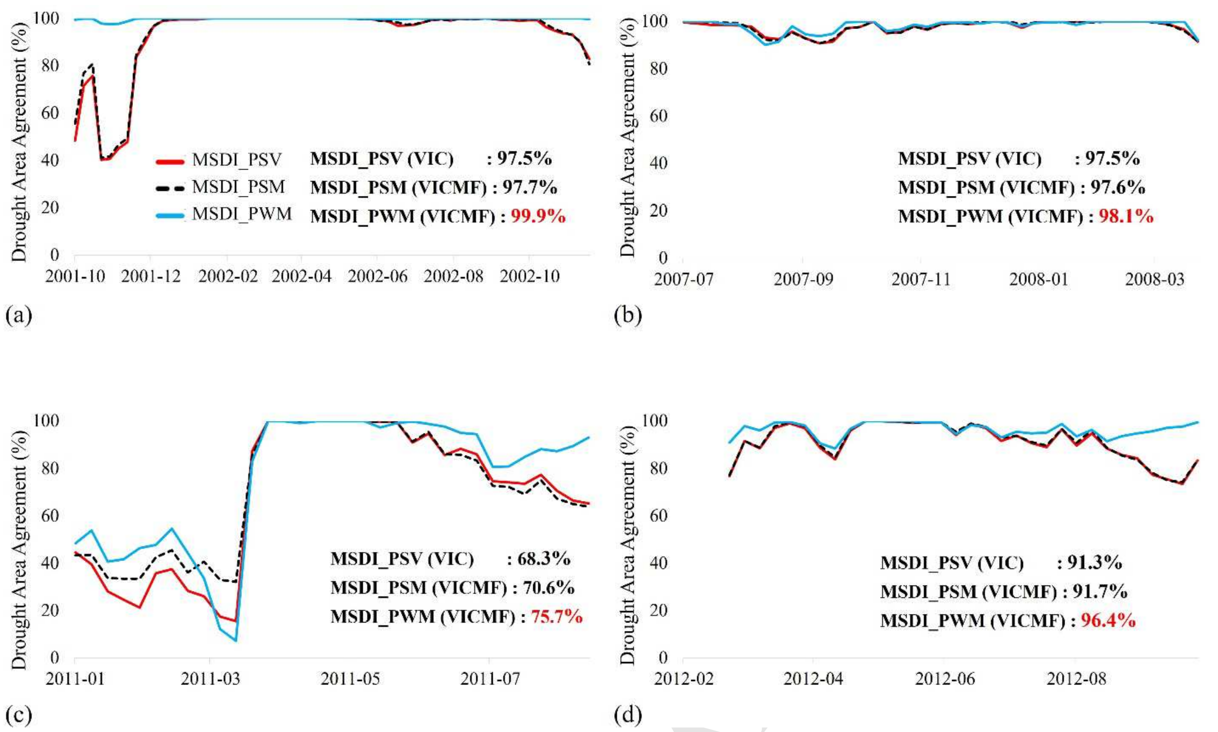


Figure 5. The Drought Area Agreement (DA) values for each drought event. The red line shows the DA values for the MSDI_PSV, the black and dashed line represents the results for MSDI_PSM, and the blue line indicates the results for MSDI_PWM. (a) E1 period (October 2001–October 2002). (b) E2 period (July 2007–November 2008). (c) E3 period (January 2011–August 2011). (d) E4 period (February 2012–September 2012).

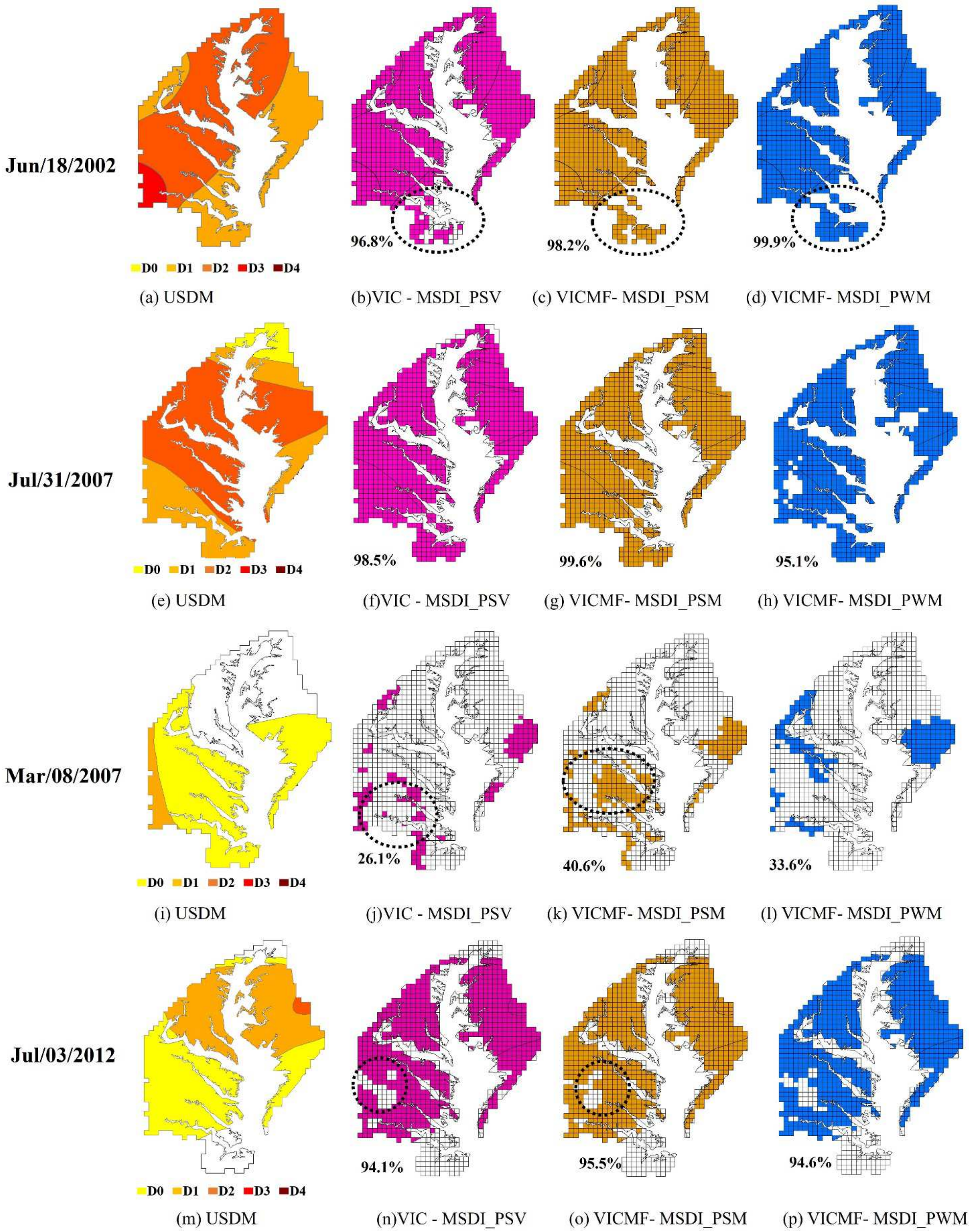


Figure 6. The comparison of drought areas from the USDM, MSDI_PSM, MSDI_PSV, and MSDI_PWM on June-18-2002 (a to d), July-31-2007 (e to h), March-08-2011 (i to l) and July-03-2012 (m to p).

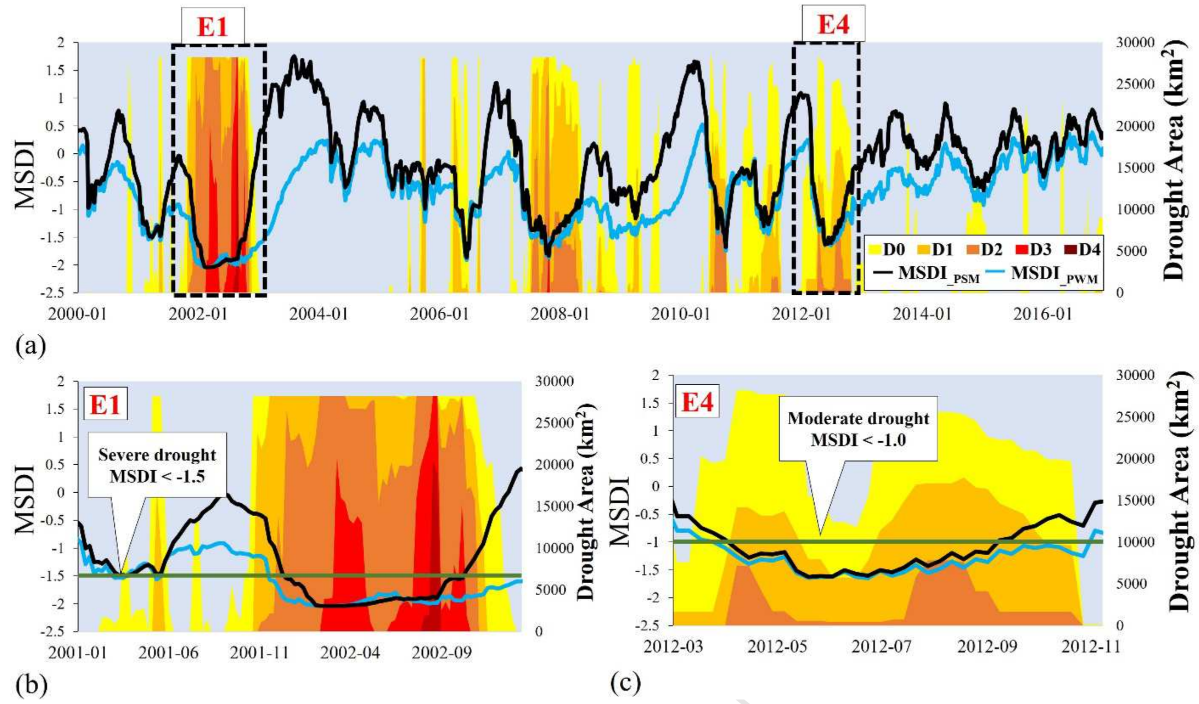
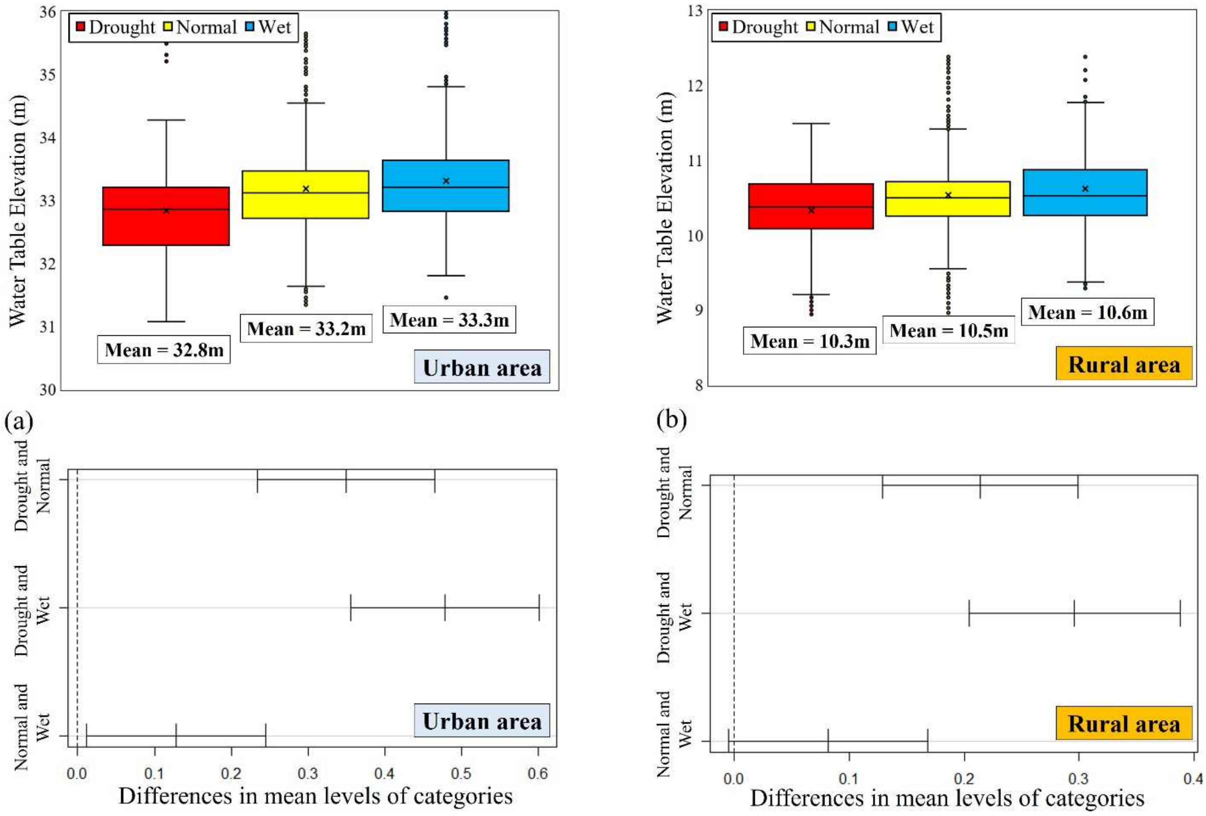


Figure 7. Drought area maps for the NACP region from the USDM, and time series of MSDI_PSM and MSDI_PWM. The black line represents the MSDI_PSM, and the blue line indicates the MSDI_PWM. (a) Drought maps and drought indices from 2000 to 2016. (b) E1 period. (c) E4 period.



(c) (d)

Figure 8. The results of WTE for the urban and rural areas. (a) and (b) are the box and whisker charts for the drought, normal, and wet conditions. The red box represents the drought, the yellow box represents the normal condition, and the blue box indicates the wet condition. The upper and lower whiskers represent maximum and minimum values, the first quartile represents 25%, the median represents 50%, and the third quartile represents 75% of the values. (c) and (d) are the results of Tukey's HSD test, and they show differences in the mean levels of WTE values based on a 95% confidence interval. The Y-axis represents the groups of categories for the comparisons. Each line in the figures indicates the 95% confidence interval for the comparisons.

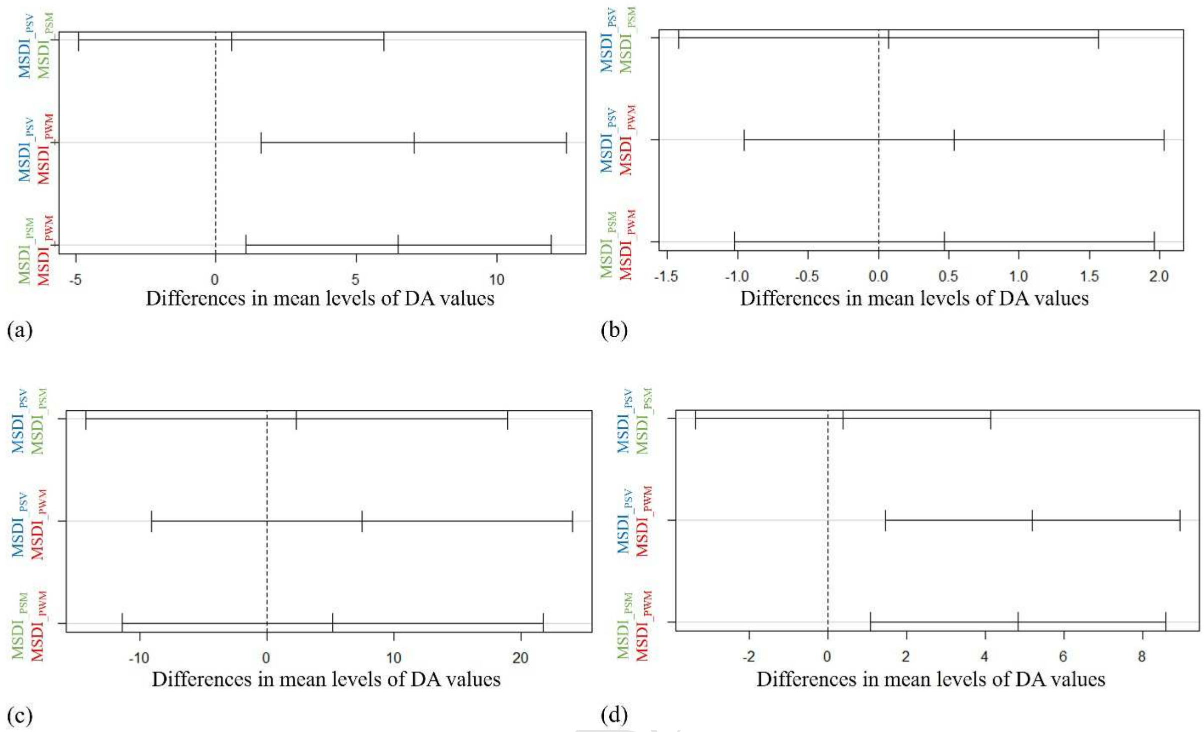


Figure 9. The results of Tukey's HSD test show differences in drought indices based on a 95% confidence interval. The Y-axis represents the groups of the drought indices for the comparisons. Each line in the figures indicates the 95% confidence interval for the comparisons. (a) E1 period. (b) E2 period. (c) E3 period. (d) E4 period.

Table 1. ANOVA results for each drought event

	Degree of freedom	Sum of Squares	Mean Square	F	p-value
E1	2	1849	924.6	5.824	0.004
E2	2	6.7	3.4	0.435	0.648
E3	2	963	481.6	0.600	0.551
E4	2	572	286.1	6.765	0.002

Highlights

Coupled surface water- groundwater modeling is performed.

Evaluation of soil moisture and upward flux is critical for drought assessment.

Better results for 2002 and 2012 drought conditions during the drought recovery period.

Integrated modeling is required for precise drought predictions.