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Incorporating Influences of Shallow Groundwater Conditions in Curve Number-Based Runoff Estimation Methods

Ramesh S. V. Teegavarapu[1] (ID) · Singaiah Chinatalapudi[1]

Abstract Runoff generation process in any watershed is mainly affected by precipitation, land use and land cover, existing soil moisture conditions and losses. Shallow groundwater table conditions that occur in many regions are known to affect the soil moisture retention capacity, infiltration and ultimately the runoff. A methodology that links soil moisture capacity to the shallow groundwater table or High-Water Table (HWT) using a nonlinear functional relationship within a curve number (CN)-based runoff estimation method, is proposed and investigated using single and continuous event simulation models in this study. The relationship is used to obtain an adjusted CN that incorporates the effect of change in soil moisture conditions due to HWT. The CN defined for average conditions is replaced by this adjusted CN and is used for runoff estimation. A single event model that uses Soil Conservation Service (SCS) CN approach is used for evaluation of variations in runoff depths and peak discharges based on different HWT conditions. A real-life case study from central Florida region in the USA was adopted for application and evaluation of the proposed methodology. Results from the case study application of the models indicate that HWT conditions significantly influence the magnitudes of peak discharge by as much as 43% and runoff depth by 48% as the water table height reaches the land surface. The magnitudes of increases in peak discharges are specific to case study region and are dependent on the functional form of the relationship linking HWT and soil storage capacity. Also, for specific values of HWT, an equivalency between HWT-based CN and wet antecedent moisture condition (AMC)-based CN can be established.

✉ Ramesh S. V. Teegavarapu
rteegava@fau.edu

[1] Civil, Environmental and Geomatics Engineering, Florida Atlantic University, Boca Raton, FL 33431, USA

1 Introduction

Floods are among the costliest natural disasters in terms of human hardship and economic loss across the globe. Around 75% of natural disasters in the US are related to flooding (Perry 2000). Every year, the property damage in the USA due to flooding is noted to be over $5 billion (Pielke et al. 2002). Existing guidance on comprehensive flood management recommends the use of integrated modeling techniques to assess the flood risks with in a catchment. These techniques are based on the existing hydraulic models with broad-scale modeling of hydrologic processes. Literature is replete with several hydrologic simulation models that consider subsurface water interactions on surface or overland flooding or vice versa. However, in many studies, the focus has been on assessment of groundwater table variations due to overland flooding. While it is essential to assess those interactions or influences, the impact of high water tables on floods needs to be evaluated in many instances. In many situations, the peak flood discharges are a function of several factors that include: flat terrain, highly permeable soils, and high-water tables.

In many regions of the world, the groundwater table fluctuates between a shallow depth and land surface resulting in a period of ground surface saturation (Ewel 1990; Nachabe et al. 2004). The assessment of the saturation zones is important as these zones influence the saturation excess runoff mechanisms (VanderKwaak and Loague 2001). Also, this assessment can help in estimation of hydroperiod of wetlands (Arnold et al. 2001) and determine pollutant sources on overland flow planes (Yan and Kahawita 2000). Soil hydrological processes play an important role in land-atmosphere modeling. Chen and Hu (2004) indicate that in most climate models, these processes are understood by soil moisture variations in the first few meters of soil resulting from precipitation, evaporation, and transpiration. They also suggest that groundwater may have a small effect on soil moisture in areas with a deep groundwater table, but can act as a soil water source and have substantial effects in regions where the water table is near or within modeled soil column. Inundation of floodplain, or other flat areas occurs in conditions when already shallow water-table rises above the level of the land surface and this type of flooding is often an immediate precursor of overspill flooding from the stream channels (Smith and Ward 1998) and often referred to as water-table-flooding.

Groundwater influences on soil moisture variations and surface evaporation are either neglected or not explicitly treated in many modeling efforts (Chen and Hu 2004). Repeated flooding events are also partially caused by an unusually high groundwater table in many areas. Szilagyi et al. (2008) applied a 2-D finite element numerical model of the coupled system of vadose and saturated zones with diurnal fluctuations in evapotranspiration. The model successfully reproduced the reported phase-shift and produced diurnal groundwater and streamflow fluctuations. Gisbert et al. (2002) explained the importance of rising water table in the floods of Zafarraya Polje region. They emphasize that it is essential to examine the ground water table and water levels in the lakes or streams to determine the role played by surface water and ground water in the floods. Based on their study they concluded that groundwater plays a major role during the flooding events. Soil moisture is an important variable in the hydrologic cycle that is given its due importance in many hydrologic modeling studies. Improving the accuracy of initial soil moisture content is a crucial step in flood forecasting. The purpose of the Southern Great Plains (SGP) experiment (Mohanty et al. 1997) was to investigate and report findings concerning the spatio-temporal variability of soil moisture. The experiment considered different hydrologic conditions, different climate conditions, as well as different hierarchical time and space scales. The knowledge gained from the experiment may

assist in understanding soil moisture variances and allow for more accurate modeling of the soil moisture and flooding effects (Mohanty et al. 1997).

Integrated Catchment Approach (ICA) proposed by Schumann and Andreas (2002) is a most efficient conceptual tool for multi-lateral hydrological investigations on a small-scale basin. Excessive ground water contribution to flood flow generation is confirmed using ICA. Arbhabhirama and Chatchavalvong (1975) described how the ground water levels vary in relation to a flooding stream. In their study, they developed an analytical solution considering bank storages, flow rates, and ground water levels. Fleming and Neary (2004) developed model parameters and calibration methods that are used in Soil Moisture Accounting (SMA) algorithm. In the areas of high water tables, there is a limit to the soil storage capacity and infiltration cannot continue indefinitely without complete saturation of the soil. In such cases infiltration ceases, rainfall abstractions become zero, and rainfall-excess intensity equals rainfall intensity. In some areas, regional information on available soil storage (SFWMD 1994) can be used for modeling purposes.

Manivannan et al. (2001) used Green-Ampt infiltration model and Soil Conservation Service (SCS) curve number model to predict runoff from seven selected tank catchments in a southern region of India. The Green-Ampt model predicted runoff volume more accurately than the SCS curve number method. Gregory et al. (1999) used different methods to estimating soil storage capacity for stormwater modeling applications. Finally, they developed a relation between soil storage capacity and high-water table depth. Gregory et al. (1999) reported that for the sandy soils commonly found in the Southern region of Florida, USA, the Natural Resources Conservation Service (NRCS) developed standard profiles that relate soil storage capacity to the high-water table (HWT) depth (SFWMD 1994) can be used.

Bronstert et al. (1991) used a physically based distributed parameter watershed model to simulate the floods and flood protection measures in a flat area with the shallow groundwater table. In their study, they used the HYDRAIN, a hydrodynamic drainage model. This model consisted of two main components: the streamflow component for the runoff in the channel system, and the subsurface flow component for calculating the lateral ground water drainage as well as the interaction of ground water and channel water level. Jourde et al. (2007) used a hydrologic model integrating a digital terrain model to find the contribution of the karst groundwater to surface flow during Mediterranean flood near Montpellier, France. The model results demonstrated that karst system first absorbs part of the rainfall, which induces a general water table to rise within the aquifer, and then contributes to surface flow. Gurnell and Gregory (1986) explained the effect of ground water table levels on the generation of the runoff. They performed a few experiments to calculate the ground water levels and vegetation composition. The impact of water table levels on storm runoff has shown to be particularly significant under dry and moist conditions. Montaldo et al. (2007) explained the role of soil moisture conditions in the modeling of Alpine basin floods using three distributed hydrological models. Sade (2001) developed a parametric relationship between the available soil moisture and the depth of water table in the vadose zone to characterize the status of Soil-Plant-Atmosphere Continuum (SPAC) located in the flat terrains of Louisiana. Extensive soil water data, surface hydrology, and physiographical information were used for their study.

The Soil Conservation Service Curve Number (SCS CN) method (SCS 1972) is the most widely used method for runoff estimation and in flood modeling studies around the world. Several studies have documented numerous appplications and revisions of the method (e.g., Shaw and Walter 2009; Mishra and Singh 2003; Mishra et al. 2008; Suribabu and Bhaskar 2015; Hawkins et al. 2009). As a conceptually simple and single parameter method, the CN

method is used for design hydrology especially for basins with little or no streamflow records. The CN method addresses issues related to soil moisture conditions referred to as Antecedent Moisture Conditions (AMCs) or Antecedent Runoff Conditions (ARCs) mainly attributed to precipitation. Since the moisture conditions are also known to be influenced by shallow ground water table conditions, in this study a variant of the CN method that incorporates these influences is proposed and evaluated. The main focus is the development of a generic methodology to create such a variant and investigate the influences of the shallow ground water table or high-water table on runoff and peak discharge magnitudes. The variant developed in this study is evaluated based on its application to a case study region in the U.S.

2 Methodology for Linking Soil Moisture and Groundwater Level

Groundwater table levels can influence the amount of soil moisture and ultimately the soil storage capacity. Methodology for incorporating influences of shallow ground water level in CN-based runoff estimation method (SCS 1972) proposed in this study is explained through a series of steps in Fig. 1. The steps are described in this section. A relationship between groundwater table height or high-water table and the soil moisture retention capacity (or soil storage capacity) can be developed based on information from field studies (e.g., Gregory et al. 1999). The depth (H) of shallow groundwater table or HWT is measured from the surface of the soil downward. The functional relationship is expressed in Eq. (1) and H and HSG refer to the HWT depth (i.e., groundwater table depth below the surface) and hydrologic soil group respectively and S_k^o is the soil storage capacity at a level referred using index k. This relationship is used in Eq. (2) to obtain the curve number (CN_k') associated with each value of soil storage capacity. Constants (α, β) used in Eq. (3) change based on the unit system in
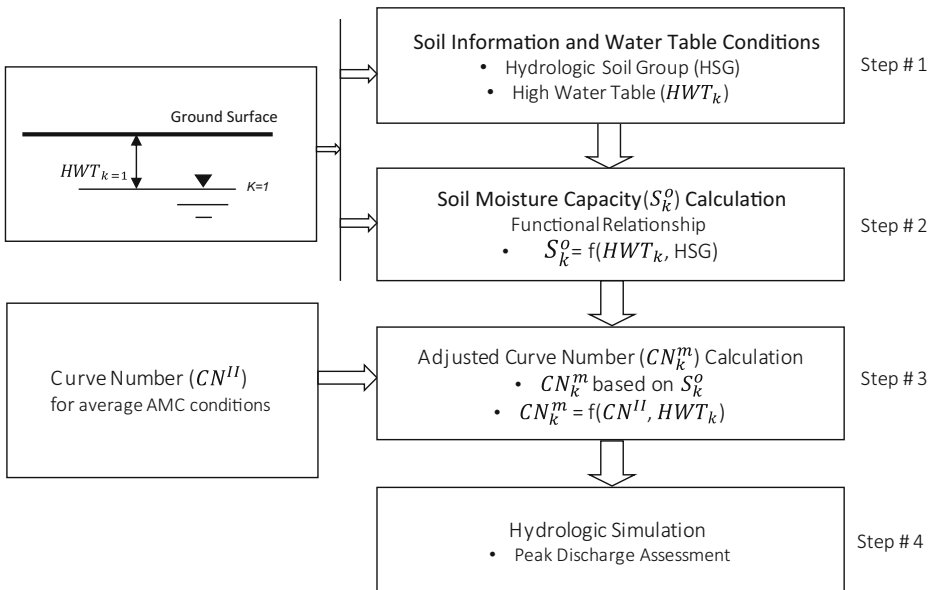

Fig. 1 Methodology for calculating adjusted curve numbers and peak discharges explained using a series of steps

which the runoff is calculated based on measure precipitation values. The relative increase (ϵ_k) in the curve number is calculated using Eq. (3). Equations (4) and (5) refer to the normal curve number (CN^{II}) based on existing conditions with HWT at the lowest level from the surface and adjusted curve number, CN_k^m, at different HWT levels respectively. The curve number CN^{II} refers to number associated with normal conditions (or average conditions) based on antecedent moisture condition (AMC) classification of SCS. The adjusted soil storage capacity S_k^m is calculated based on the adjusted curve number CN_k^m using Eq. (6) and runoff depth is estimated with the help the SCS runoff (R) calculation using the precipitation amount (P) in Eq. (7).

$$S_k^o = f(H_k, HSG) \qquad \forall k \tag{1}$$

$$CN_k^{'} = \frac{\alpha}{(S_k^o + \beta)} \qquad \forall k \tag{2}$$

$$\epsilon_k = \frac{CN_k^{'} - CN_{k=1}^{'}}{CN_{k=1}^{'}} \qquad k = 2....n \tag{3}$$

$$CN_1^m = CN^{II} \tag{4}$$

$$CN_k^m = CN^{II}(1 + \epsilon_k) \qquad k = 2....n \tag{5}$$

$$S_k^m = \frac{\alpha}{CN_k^m} - \beta \qquad k = 2...n \tag{6}$$

$$R_k^m = \frac{(P - 0.2(S_k^m))^2}{P + 0.8(S_k^m)} \qquad \forall k \tag{7}$$

The adjusted and normal curve numbers CN_k^m, and CN^{II} respectively can be linked using Eq. (8). The values of CN_k^m, H_k and CN^{II} can be linked in a useful parametric relationship of the form defined by Eq. (8) similar to the one that links CN^{II} and CN^{III} (Mishra and Singh 2003). For the Eq. (8) to be valid, optimal parameter values (θ, δ) need to be estimated from available data.

$$CN_k^m = \frac{CN^{II}}{(\theta H_k + \delta)} \qquad \forall k \tag{8}$$

A conceptually simple optimization formulation can be developed to obtain the parameters (θ, δ) of the relationship given by Eq. (9). The objective function is given by Eqs. (9) and (8) can be used as an equality constraint in this formulation.

Minimize

$$\sum_{k=1}^{n} \left| CN_k^m - \left\{ \frac{CN^{II}}{\left(\theta H_k + \delta \right)} \right\} \right| \qquad (9)$$

The variable k refers to an index for a discrete value of HWT and n is the number of such discrete HWT values (i.e., H_k). Since the decrease in the HWT may result in reduced soil storage capacity and can lead to the higher value of CN, then an equivalency between adjusted curve number CN_k^m and wet antecedent moisture condition-based CN (CN^{III}) can be established. Based on the soils information and High-Water Table (HWT) conditions, a functional relationship between soil storage capacity and HWT can be established. The relationship can then be used to calculate soil moisture capacity at different water table depths. A power relationship established by Gregory et al. (1999) is given by Eq. (10).

$$S_k^o = a H_k^b \qquad \forall k \qquad (10)$$

The constants a, b, are derived based on region-specific information about soil moisture capacities and HWT conditions. The relationship can be used to calculate soil moisture capacities at different water table depths to obtain adjusted curve numbers. These curve numbers are then used for obtaining runoff values and peak discharges in the event-based hydrologic simulation model that uses an SCS curve number approach. Continuous simulation using the Soil Moisture Accounting (SMA) approach can also be used to assess the variations of peak discharges in relation to changing groundwater depths.

3 Case Study Region and Application of Methodology

Single and continuous event models incorporating the methodology proposed are applied to a case study area, a watershed (referred to as Bowlegs Creek watershed) selected in Polk County, Florida. The spatial and hydrologic data for this study are obtained from several sources. The following description of the hydrology and hydrogeology of the region was adopted from Spechler and Kroening (2007). The County, located in the central part of the Florida peninsula, and is approximately 64 km wide and 80 km long and has an area of about 4722 km^2, of which 484 km^2 is water. The climate of this region is classified as humid subtropical and is characterized by hot, wet summers and mild, relatively dry winters. Rainfall is unevenly distributed throughout the year. About 55% of the annual rainfall total is due to convective thunderstorms that frequently occur between June and September. Application of the proposed methodology in this study is carried out using single and continuous event modeling approaches. Data (i.e., streamflow, evapotranspiration, rainfall and others) required for latter modeling approach are also collected.

3.1 Spatial and Hydrologic Data Sets

The Bowlegs Creek watershed is adopted for simulation of peak discharges and evaluation of runoff depths with proposed methodology using an Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model. The study area and stream network, the location of the outlet and rain gauges are shown in Fig. 2. The study area has 24 different types
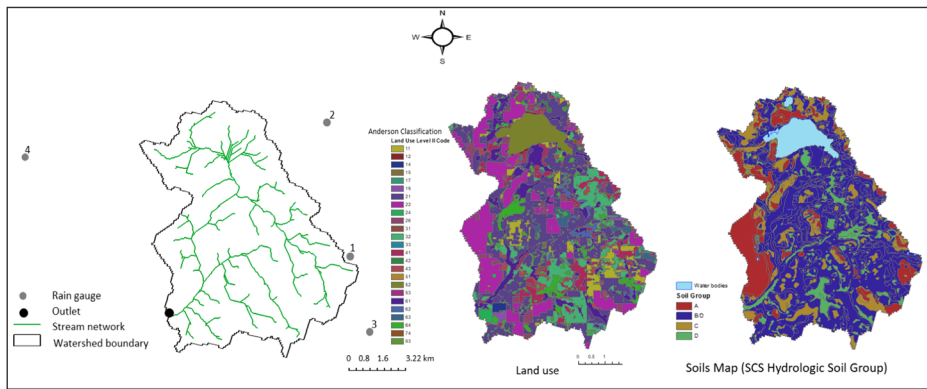
Fig. 2 Details of watershed (boundary, land use and soils) and location of rain gauges in the case study region

of land use and land cover classifications. The dominant land cover types are crop land, pasture land, tree crops, shrub lands and brush lands. These land cover types occupy almost 65% of the watershed area. The percentages of each land cover presented in the watershed are shown in Table 1. Figure 2 shows different land uses and soil groups in the study area. Soil groups of types B/D and A are dominant in the study area. The soil group characterization of the study watershed is also shown in Fig. 2. Anderson level II classification (Anderson et al. 1976) for Land Use and Land Cover (LULC) is used in the current study. For the single event model, SCS curve number and SCS unit hydrograph approaches were used as loss and transform methods respectively. A 24-h precipitation depth of 280 mm based on 100-year return period,

Table 1 Land use description and details of classification

Land use level II code	Land use description	Percentage area (%)
21	Cropland and pastureland	30.80
22	Tree crops	20.15
32	Shrub and brush land	13.90
41	Upland coniferous forests	7.25
61	Wetland hardwood forests	6.75
11	Residential, low density	4.38
52	Lakes	3.36
64	Vegetated non-forested wetlands	3.33
26	Other open lands (rural)	2.51
43	Upland hardwood forests	1.71
64	Vegetation	1.69
62	Wetland coniferous forests	1.09
63	Wetland forested mixed	0.92
12	Residential, medium density	0.58
19	Open land	0.55
53	Reservoirs	0.27
14	Commercial and services	0.26
31	Herbaceous (dry prairie)	0.14
17	Institutional	0.14
33	Mixed rangeland	0.11
15	Industrial	0.06
74	Disturbed land	0.03
51	Streams and waterways	0.01
83	Utilities	0.01

with SCS type III distribution that is appropriate for the region and a lag-time of 9.94 h are used. For continuous simulation model, SMA and Clark's unit hydrograph approach were used as loss and transform methods respectively.

The Watershed Modeling System (WMS), a comprehensive graphical modeling environ-ment, is used for watershed delineation, geometric parameter calculations, spatialy analysis for overlay computations (CN, rainfall depth, roughness coefficients and others), cross-section extraction from terrain data. The composite curve number is calculated by integrating Land use and soil type maps. Based on the type of land use and hydrologic soil group (Table 1). The composite curve number calculations are reported in Table 2. Water bodies are considered as impervious areas in the study area. CNs are assigned to each type of land use based on the hydrological soil group (Table 2). Details of the study area along with hydrologic process parameters are provided in Table 3. The study area has no rain gauge inside the watershed. However, four rain gauges are located outside the watershed. Each rain gauge has a minimum of twenty years of rain fall data with several days of missing values. Among the four rain gauges, rain gauge number 1 (West Frost rain gauge station) is the closest rain gauge to the watershed. Missing values in this rain gauge were filled using inverse-distance-based interpo-lation using data from three remaining rain gauges. The hydrologic model simulated the

Table 2 Composite curve number calculation

HSG	Land use description	CN	Area (km2)	Product (CN × Area)
B	Herbaceous Tundra	79	11.02	870.47
B	Shrub and Brush Tundra	67	52.8	3537.86
C	Herbaceous Tundra	86	11.37	977.63
C	Shrub and Brush Tundra	77	9.7	746.86
B	Cropland and Pasture	69	8.96	618.40
B	Dry Salt Flats	84	2.48	208.58
A	Herbaceous Tundra	68	20.21	1374.53
A	Shrub and Brush Tundra	48	4.19	201.13
C	Cropland and Pasture	79	2.48	196.16
D	Herbaceous Tundra	89	0.58	51.80
A	Dry Salt Flats	74	0.58	43.07
A	Cropland and Pasture	49	3.34	163.49
D	Shrub and Brush Tundra	83	2.06	170.67
C	Dry Salt Flats	90	1.32	118.72
B	Evergreen Forest Land	60	5.82	349.18
C	Evergreen Forest Land	73	0.35	25.49
D	Residential	86	10.98	944.26
A	Evergreen Forest Land	36	0.47	16.76
D	Cropland and Pasture	84	0.58	48.89
B	Orchards, Groves, Vineyards, Nurseries, and Or	66	0.23	15.36
C	Orchards, Groves, Vineyards, Nurseries, and Or	77	0.19	14.94
A	Residential	57	0.08	4.42
A	Orchards, Groves, Vineyards, Nurseries, and Or	45	0.35	15.71
A	Herbaceous Rangeland	49	0.04	1.90
D	Evergreen Forest Land	79	0.62	49.04
B	Lakes	0	1.24	0.00
B	Herbaceous Rangeland	69	0.19	13.39
D	Lakes	0	0.62	0.00
D	Dry Salt Flats	92	0.04	3.57
C	Herbaceous Rangeland	79	0.04	3.07
B	Confined Feeding Operations	79	0.04	3.07

CN (Weighted) = 71

Table 3 Basin and meteorological parameters

Parameter	Description or Value
Basin	
Basin area	153 km^2
Loss method	SCS curve number
Transform method	SCS unit hydrograph
Graph type	Standard
Lag time	9.9 h
Meteorological	
Precipitation type	SCS storm
Storm type	SCS Type III
Precipitation depth	279.4 mm
Design storm	100 Year

response of Bowlegs Creek watershed in Polk County, Florida, for two continuous data sets that span more than a year. The source of the rainfall data is rain-gauge precipitation at a daily time step, which was obtained from the Southwest Florida Water Management District (SWFWMD) database.

4 Results and Analysis

Results from application of single and continuous event models to evaluate the influence of high groundwater table conditions on peak discharge are discussed in this section. Based on the soil type and ground water conditions in the case study, a functional relationship between soil storage capacity and HWT (high water table) or groundwater table established in a previous study by Gregory et al. (1999) is used in this study. This relationship with a function form given by Eq. (10) is then used to calculate soil moisture capacity at different water table depths, and the adjusted curve numbers based on Eq. (5) are calculated. These curve numbers are used in a hydrologic simulation model (e.g., HEC-HMS model) for estimation of peak discharges using a SCS curve number approach. The peak discharges are estimated using HEC-HMS using the basin and meteorological parameters provided in Table 3. The SCS curve number derived based on land cover and land use and soil group information is equal to 71. A coefficient (*a*) value equal to 2.67 and an exponent value equal to 0.97 are used in the relationship $S = a H^b$ and the curve numbers are calculated based on different HWT conditions. The coefficient and exponent values are based on field observations of soil moisture capacity and depth of the water table (Gregory et al. 1999) from the basin of interest in this study. The HWT condition refers to water table height below the soil surface.

Several experiments are conducted to assess the influences of variants of functional relationship that link S and HWT values on peak discharges. Different functional relationships are obtained by varying the values of the coefficient (a) and exponent (b). Initially, the values of 2.67 and 0.97 for coefficient and exponent appropriate for the region from previous study are used in the power relationship respectively. The peak discharge values based on HWT conditions derived from the functional relationship and adjusted curve numbers are shown in Fig. 3. It is evident from the figure as the HWT (water table depth from the soil surface) decreases the peak discharge and adjusted value of CN increases. The increases in CN values directly link to decreases in soil moisture retention capacity and increases runoff. The
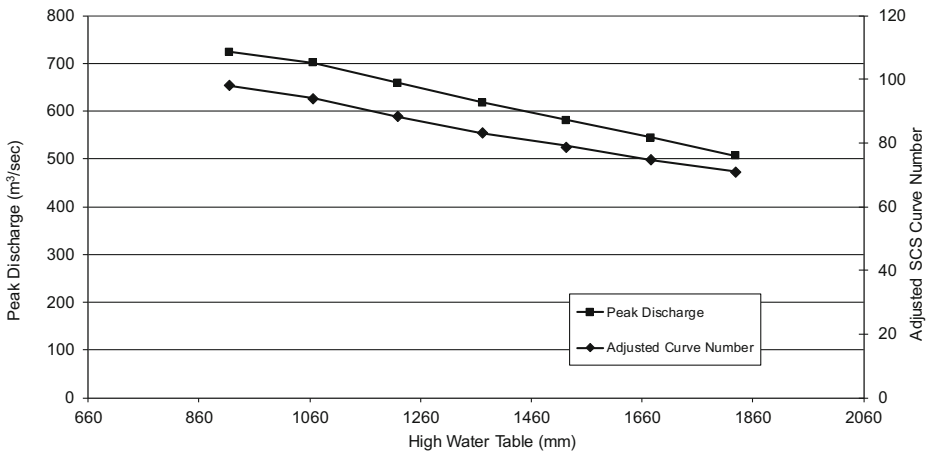
Fig. 3 Variation of peak discharge and curve number based on high water table (HWT) conditions (parameters: a = 2.67, b = 0.97)

percentage increases in the peak discharges based on HWT conditions are shown in Fig. 4. A maximum increase of 43% is noted when the HWT reaches a value 914 mm. Three other cases with different values for coefficient and exponent (a = 1, b = 0.97; a = 3, b = 0.97; a = 2.67, b = 1) are evaluated. The changes in percentage increases in peak discharge values with decreasing values HWT are shown in Fig. 5 for different functional relationships derived based on different values of a and b. Variation of adjusted curve numbers with respect to HWT are shown in Fig. 6 for different relationships. It is clear from the variations of adjusted curve numbers and peak discharges that the functional form selected for linking S and HWT influences the rate at which peak discharge increases. The coefficient and exponent values of 2.67 and 0.97 respectively for functional relationship (Eq. (10)) are region-specific values obtained from a previous study (Gregory et al. 1999) and are not applicable to any other region.
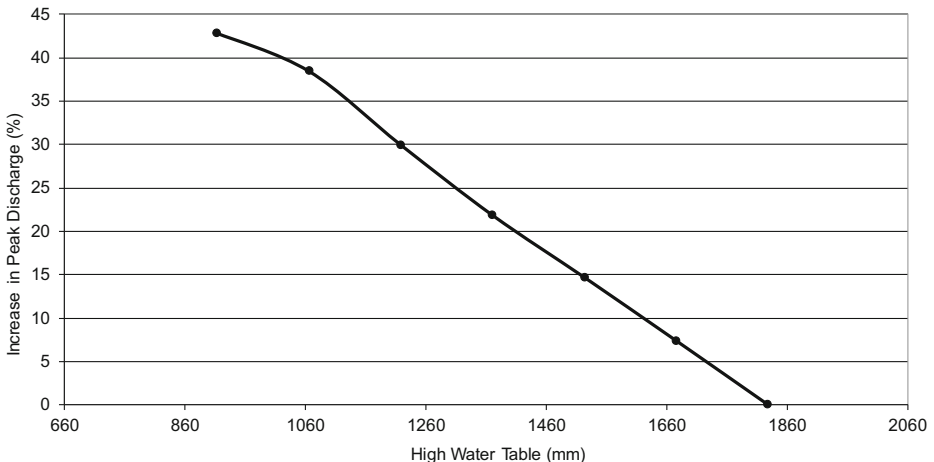

Fig. 4 Increase in peak discharge based on high water table conditions (parameters: a = 2.67, b = 0.97)
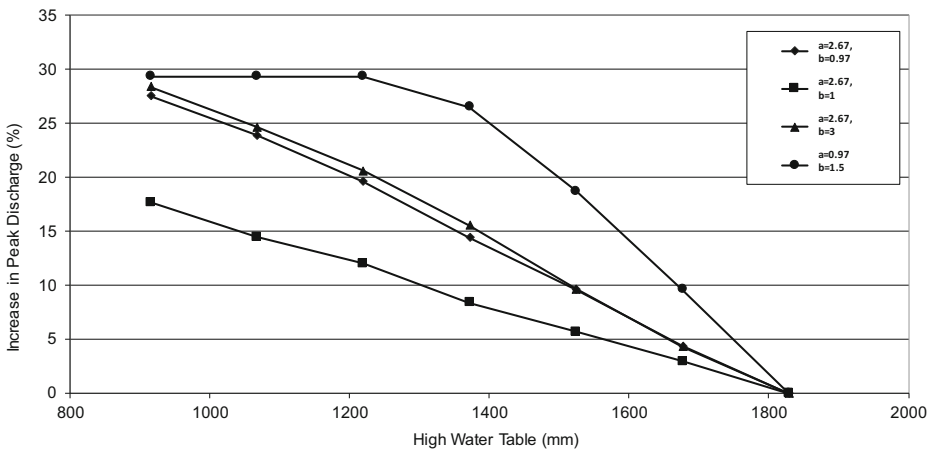
Fig. 5 Increase in peak discharge based on high water table conditions for different parameter values

Variations in runoff depths based on different HWT values are also evaluated using SCS CN method. Results related to changes in the runoff depth with the decrease in HWT (refer Fig. 1) are documented in Table 4. A largest increase of 48% in runoff depth compared to that obtained when HWT is at 1829 mm from the surface is noted for this case study region when the HWT reaches a value of 914 mm. Once the value of HWT is lower than this value, the CN value exceeds the maximum possible value of 98 for any type of land cover and soil type. The adjusted curve numbers based on the high-water table conditions can be compared with the standard curve numbers published by SCS (1972) for different Antecedent Moisture Conditions (AMCs). SCS categorizes AMCs based on dry, normal (or average) and wet conditions. These AMCs are referred to as AMC I, AMC II and AMC III for dry, normal and wet conditions respectively.

A comparison of adjusted curve numbers and AMC-based curve numbers is provided in Table 5. It is evident from the results shown in Table 5, that at 1067 mm depth of HWT the value of adjusted curve number is equal to curve number for AMC III (wet condition) based on an initial curve number of 71 based on AMC II (normal or average condition). This
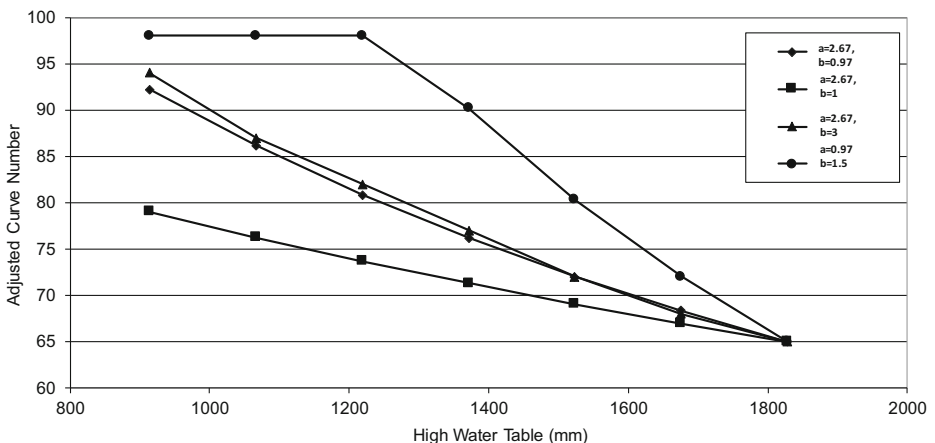

Fig. 6 Variations in adjusted curve number based on high water table conditions for all parameter values

Table 4 Variations in adjusted curve numbers and runoff depths based on different values of HWT

HWT (mm)	Adjusted CN	Soil storage capacity (mm)	Initial abstraction (mm)	Runoff (mm)	Increase in runoff (%)
914	98	5.2	1.0	273.3	48.0
1067	94	15.9	3.2	261.2	41.5
1219	88	33.6	6.7	242.8	31.5
1371	83	51.2	10.2	226.1	22.5
1524	79	68.8	13.8	211.0	14.3
1676	75	86.3	17.3	197.2	6.8
1829	71	103.7	20.7	184.6	–

equivalency between AMC III and adjusted curve number is used as a motivation to develop a relationship (given by Eq. (8)) between the adjusted curve number, CN based on AMC II and HWT. The two parameters, θ, δ, are obtained using a nonlinear generalized reduced gradient (GRG)-based optimization solver and their values are 0.00032 and 0.413 respectively. A Mean Relative Error (MRE) (derived based on observed and estimated values of adjusted curve number) of 0.4% was obtained suggesting the validity of the proposed parametric relationship. A recent study by Gregory et al. (1999) found that the soil storage capacity under AMC I, AMC II and AMC III conditions compared well with those of the typical regional values for both natural (native soils) and developed (disturbed soils) conditions in the case study region. Also, at shallow HWT depths, the AMC III values calculated from the detailed survey data in their study matched with the typical values in the region. These observations from the study by Gregory et al. (1999) confirm the utility of the relationship in Eq. (8) with estimated parameters (θ, δ) proposed in this study.

A continuous event simulation feature within HEC-HMS model that uses Soil Moisture Accounting (SMA) approach is also used for evaluation of proposed methodology in this study. SMA as a loss rate method and Clark unit hydrograph were implemented as a rainfall-runoff transform method in the simulation model. Historical streamflow data available at the outlet of the watershed and precipitation data, monthly evapotranspiration data from the case study watershed were used for calibration of the hydrologic simulation model. The automated calibration procedure available in HEC-HMS is used for calibration of SMA parameters. Reasonable calibration and validation results were noted with a correlation coefficient close to 0.77 derived based on observed and predicted streamflow values for a period June 1997 to November 1998. Lack of any rain gauge station in the watershed can be attributed to lower than expected correlation value based on observed and predicted flows. The relationship

Table 5 Equivalency of adjusted curve numbers and curve numbers based on AMC III (wet conditions)

HWT (mm)	Adjusted CN	CN AMC II	AMC III
762	98	94	98
914	92	82	92
1067	86	72	86
1219	81	64	81
1371	76	60	78
1524	72	54	71

AMC Antecedent Moisture Condition

linking S and H based on Eq. (10) used earlier for single event model was again adopted for this continuous model. Based on the decrease in the HWT value from 1829 mm to 152 mm, adjusted CNs are calculated by using a value of 71 as a CN II when HWT is at 1829 mm. Information about the percentage decrease in the soil storage capacity with decreasing values of HWT was used to modify the soil storage capacities appropriately. Soil storage and tension storage values at a depth of 1829 mm were used as initial values and are modified in model simulations for different values of HWT. A 30% percent increase in the peak discharge was noted using the continuous event modeling approach based on simulation runs at different values of HWT for 1 year. While the modifications of soil and tension storage values in SMA approach based on HWT are possible, these values cannot be held constant as these values are updated in every single time step of the model simulation. The single and continuous simulation models provided different results in terms of increases in peak discharges. The percentage increase was higher for single event model compared to that from the continuous simulation model. Further research is needed to incorporate changing soil moisture conditions due to HWT in SMA approaches.

5 General Remarks

The patterns and mechanisms of flooding in areas dominated by surface and groundwater interactions due to shallow groundwater table are different from those related to traditional over-bank flooding. While it is essential to assess those interactions or influences, the impact of high water tables on floods needs to be evaluated. Also, the peak flood discharges are a function of several factors that include: flat terrain, highly permeable soils, and high-water tables. Models capable of considering the interactions in hyporheic zone and relevant processes should be adopted for modeling the groundwater-surface water interactions. The variation of soil moisture due to changes in high groundwater table conditions can be addressed by explicitly characterizing and modeling soil moisture zones and the groundwater table conditions. The complexity of the soil moisture variations linked to groundwater table conditions warrants changes to soil infiltration equations. Single event models may not be fully capable of characterizing the groundwater-surface water interactions and soil moisture exchanges. However, valuable insights can be gained into the influences of groundwater table conditions on peak discharges when these models are used. Extensive spatial and temporal hydrologic data are required for characterizing the relationship between soil moisture capacities and groundwater table conditions. Relationships linking the soil moisture capacity and groundwater table heights need to be developed. Single and continuous simulation models may provide different results with respect to increases in peak discharges. Peak discharge values are extremely sensitive to soil moisture conditions. Variability of these conditions and corresponding peak discharges can be evaluated using sensitivity and uncertainty analysis approaches.

In many hydroclimatic settings, saturated and shallow groundwater table conditions play a critical role in causing and exacerbating floods. Models capable of characterizing the saturation overland flow explicitly are needed to fully understand the influence of shallow groundwater tables on soil moisture conditions. Continuous simulation models for extended periods are recommended for characterizing the sub-surface soil moisture capacities related to changing groundwater levels. Different AMCs linked to the varying groundwater table conditions can be modeled using single event and continuous simulation models. However, the results from such simulations for design rainfall events should serve only as preliminary assessments of expected

changes in peak discharges. A hydrological model used for simulating infiltration and percolation losses should account for all the flows entering, moving within, and leave the system, as well as storages changes within the system. SMA is a viable approach in a hydrologic simulation model that is capable of accounting for the surface and sub-surface processes that affect the peak flooding rates. Data relevant to hydrogeology of the region becomes crucial for accurate soil characterization.

6 Conclusions

A conceptual modification of SCS curve-number method to incorporate effects of the high-water table (HWT) in reference to groundwater table conditions is presented and investigated in this work. The HWT conditions are incorporated in the CN method through a region-specific realistic nonlinear relationship that links water table depth and soil storage capacity. An adjusted CN number as a replacement of base CN based on land use and land cover is obtained for use in SCS runoff estimation method. A single event model that uses CN and continuous event model that uses soil moisture accounting approaches are developed to evaluate the influences of HWT on peak discharges that are critical for management of floods. Results from this study show that an equivalency between CN based on HWT conditions and traditional antecedent moisture condition-based CN can be established. Also, a parametric functional relationship with two variables (base CN, depth of HWT) linking the adjusted curve number is developed. The parametric constants of this functional relationship conditioned on a pre-specified relationship linking HWT and soil storage capacity are obtained using an optimization formulation. Results from a single event and continuous event simulation models suggest that peak discharges increase as the water table approaches closer to the land surface. Adjusted CNs or CNs obtained through parametric relationship can be used in single event hydrologic simulation models used for runoff estimation.

Compliance with Ethical Standards

Conflict of Interest None.

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