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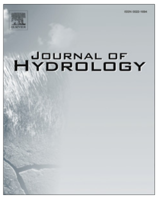

Evolution of a parsimonious rainfall–runoff model using soil moisture proxies

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SUMMARY

Pre-storm soil moisture conditions play a crucial role in the analysis of the physical processes involved in conceptual rainfall–runoff modeling and for demonstration of the soil–water–atmosphere interaction. Runoff quantification is of common interest to most hydrologists who study rainfall–runoff modeling. The scientific community prefers hydrological models with a smaller number of parameter requirements and superior performance, because of the increased water resource applications. In order to circumvent the impacts of sudden undesirable jumps (e.g., in the conventional CN model) in runoff estimation, we investigated the integral effects of soil moisture proxies before and after rainfall occurrence so as to reduce the structural inconsistencies of the previous models. Accordingly, these sudden jumps were avoided by incorporating a new expression that varied from storm to storm and with prior rainfall. Similarly, the utilization of additional information to calibrate new parameters reduced the applicability to ungauged watersheds. By persisting with the principle of simplicity and avoiding over-parameterization, a new model was developed and validated using measured data of 1804 storm rainfall–runoff events from 39 South Korean watersheds. The significant results exhibited by the suggested one-parameter model in comparison to those of the other contenders were hydrologically justified using three statistical metrics and scatter plots.

1. Introduction

Hydrologists across the globe have been struggling over the past several decades to improve rainfall–runoff models (Perrin et al., 2003). In order to manage some of the fundamental hydrological problems and their applications, such as forecasting, exploitation, and control of river flows, the development and improvement of mathematical rainfall–runoff models has involved a recurring theme to increase the understanding of hydrological processes (Senbeta et al., 1999). An understanding of the rainfall–runoff process is essential in order to make realistic predictions in ungauged watersheds. In this regard, hydrological models should be parametrically efficient (i.e., parsimonious) and identifiable from the available watershed data (Skaugen et al., 2015). The development of these types of models is indispensable for the quantification of excess water from rainfall (Michel et al., 2005). In the modern era, more emphasis has been placed on development of physically rainfall–runoff models; however, conceptual and empirical models have their own advantages (Senbeta et al., 1999). Overparameterization in hydrological modeling increases the complexity of parameter identification and is obviously problematic for prediction of hydrological processes in ungauged watersheds (Skaugen et al., 2015). Researchers have demonstrated that overparameterization prevents the possibility of locating a better-calibrated value for unidentifiable parameters (Jakeman and Hornberger, 1993; Wagener, 2003; Wagener and Wheater, 2006; Van Werkhoven et al., 2008; Grimaldi et al., 2013).

The most simple, easy to use, and flexible model supported by ample documentation is the Natural Resources Conservation Service (NRCS) Curve Number (CN) model, which has been widely used across the globe (Michel et al., 2005). This model is easily applicable for estimation of runoff from ungauged watersheds, because of the smaller number of parameters required. The runoff-producing capability essentially depends on a single parameter, i.e., CN, which reflects the watershed characteristics including

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soil type, land use/treatment, surface conditions, and antecedent moisture conditions (AMCs) (Sahu et al., 2007). Nonetheless, hydrologists have debated the empirical framework and the physical bases of the model for decades in order to verify their mathematical consistency and application significance (Michel et al., 2005). The conventional CN model (hereafter, simply the CN model) has some limitations and misinterpretations due to the basic empirical assumptions (Garen and Moore, 2005; Grimaldi et al., 2013; Ajmal and Kim, 2015). Among others, Eli and Lamont (2010) have recently reported that the CN model is not appropriate for incremental runoff estimation from rainfall.

In rainfall–runoff modeling, characterization of soil moisture variability is vital for the determination of the association between the hydrologic response of a watershed and the land–atmosphere interaction (Brocca et al., 2008; Tramblay et al., 2010). Incorporating the physical soil moisture accounting (SMA) procedure can increase the model's runoff prediction capabilities (Michel et al., 2005). Williams and LaSeur (1976) were the first to incorporate the SMA procedure into the CN methodology. However, only a few attempts have been made to identify the impacts of soil initial water content on storm runoff characteristics. Western et al. (1998) demonstrated that surface runoff is controlled by soil moisture, with some of the threshold depending on the depth over which the soil moisture is averaged. Similarly, Brocca et al. (2008) advocated for incorporation of the SMA procedure in order to better interpret the runoff generation dynamics from a watershed.

Owing to the complications in soil moisture content monitoring, the antecedent precipitation index (API) that accounts for initial soil moisture has been addressed and practiced in hydrologic modeling (Brocca et al., 2008). The CN model uses the previous five-day rainfall (P_5) depth to differentiate the watershed initial losses (Sahu et al., 2007). Due to the fewer parameter requirements and simplicity, this model has enjoyed a long history of applications. However, based on the model's empirical basis, its application to catchments with different characteristics could be inappropriate (Ponce and Hawkins, 1996). In addition, there is no proper SMA parameterization except for the one used for CN variation (Michel et al., 2005). Although the CN model is more attractive and widely applied due to the simplicity of calculation, it must be improved by avoiding the sudden jumps in runoff estimation. In order to overcome the structural inconsistencies of the CN model, Michel et al. (2005) proposed an SMA procedure for improved runoff prediction. Sahu et al. (2007) criticized the SMA procedure proposed by Michel et al. (2005) for not circumventing "the quantum jumps" in runoff estimation and extended their work by suggesting a new SMA procedure based on P_5. However, the interpretation of the value of V_o (soil moisture before the rainfall occurrence) by Sahu et al. (2007) has some structural inconsistencies depicting inefficient runoff estimations, especially from mountainous watersheds. In their study, Sahu et al. (2010b) evaluated and compared different models including the CN model and the modifications by Michel et al. (2005) and Sahu et al. (2007), respectively. They reported that the modification by Sahu et al. (2007) which is an amendment of Michel et al. (2005) by introducing a new relationship for V_o resulted in an overall improvement for runoff prediction from a diverse rainfall–runoff data set obtained from 76 small agricultural watersheds in the United Sates. Similarly, other researchers (e.g., Chung et al., 2010; Sahu et al., 2010a; Babu and Mishra, 2012) claimed improved modified CN models. However, prior to simplification, all these modifications were suggested based on optimizing different parameters which might cause these models less appealing for runoff prediction from ungauged watersheds of other climatic setting.

In order to evaluate the runoff prediction consistency, this study initially investigated the CN model and its modifications suggested by Michel et al. (2005) and Sahu et al. (2007). Next, we assembled the concepts of the CN model's standard initial abstraction and the SMA procedure suggested by Michel et al. (2005) in order to improve the runoff predictability from ungauged watersheds. To avoid sudden jumps in runoff estimation, a new expression was conceptualized based not only on the watershed storage index (S), but also on the individual storm magnitude and prior rainfall in order to accentuate the variation from storm to storm. This new expression can provide continuous variation in the S value for dry, normal, and wet conditions, unlike the fixed S. In addition, to validate the superiority of the new one parameter model, it was tested for agreement between the measured and predicted data for 1804 storm events from 39 watersheds. Likewise, the performance of the suggested model and its competitors was evaluated using different statistical techniques.

2. Study area and hydro-meteorological data

2.1. Study area

The study area consisted of 39 forest-dominated steep slope watersheds in South Korea. The locations of the individual watersheds are shown in Fig. 1. The selected watersheds were characterized by low to high elevations that varied from 26 to 911 m with an average slope in the range of 7.50–53.53%. Forest and agricultural land occupied the largest portion of the watersheds, followed by urbanized and grass land, respectively, as mentioned in Table 1. Other land covers made up a smaller proportion of the individual watershed area. Two major and common soil textures were loam and sandy loam with some fractions of silt loam. The overall climatological variation in the Korean territory was demonstrated by Ajmal and Kim (2015).

2.2. Hydro-meteorological data

The Korea Meteorological Administration (KMA) and the Ministry of Land, Infrastructure, and Transport (MOLIT) provided rainfall measurements continuously recorded with 30-min time step, whereas the discharge measurements recorded at the same time step were collected from the Hydrological Survey Center (HSC) of Korea. Similarly, the MOLIT also provided the land cover information. The collected measurements included 1804 rainfall–runoff events from 39 watersheds occurring between 2005 and 2012. The numbers of individual watershed storm events ranged from 19 (Heukcheon) to 89 (Cheoncheon and Kyeongan). Based on the runoff coefficient ($C = Q/P$), the numbers of watersheds with dry ($C \leqslant 0.35$), normal ($0.36 < C \leqslant 0.65$), and wet conditions ($C > 0.66$) were 28, 11, and none, respectively, where P and Q were the measured rainfall and runoff values, respectively (Durbude et al., 2011). Using the P_5 criterion (Ajmal and Kim, 2015), the number of events from all of the watersheds with dry ($P_5 < 35.56$), normal ($35.56 \leqslant P_5 \leqslant 53.34$), and wet ($P_5 > 53.34$) conditions were 916, 236, and 652, respectively.

3. Methodology

The base flows for all of the events were separated using the straight-line hydrograph method (Deshmukh et al., 2013). In order to avoid bias in estimating runoff using the CN model, the measurements were first screened in order to exclude small rainfall events ($P < 25.4$ mm) (Hawkins et al., 2009). The P_5 criterion was applied to demonstrate the differentiation in watershed antecedent conditions for adjusting CN and its corresponding S values from normal to dry and wet conditions (Sahu et al., 2007). The composite CNs obtained from the land cover characteristics were