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Potential implications of pre-storm soil moisture on hydrological prediction

Muhammad Ajmal [a,b], Muhammad Waseem [a], Hung Soo Kim [c], Tae-woong Kim [d,*]

[a] Department of Civil and Environmental Engineering, Hanyang University, Seoul 04763, Republic of Korea
[b] Department of Agricultural Engineering, University of Engineering and Technology, Peshawar 25120, Pakistan
[c] Department of Civil Engineering, Inha University, Incheon 22212, Republic of Korea
[d] Department of Civil and Environmental Engineering, Hanyang University, Ansan 15588, Republic of Korea

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Abstract

Numerous hydrological models with various complexities, strengths, and weaknesses are available. Despite technological development, the association of runoff accuracy with the underlying model's parameters in watersheds with limited data remains elusive. Evaluating the soil moisture impacts at the watershed scale is often a difficult task, but it can be vital to optimally managing water resources. Incorporating pre-storm soil moisture accounting (PSMA) procedures into hydrologic models affects the watershed response to generate runoff from storm rainfall. This study demonstrated the impact of pre-storm and post-storm soil moisture in order to circumvent major obstacles in accurate runoff estimation from watersheds employing the conventional curve number (CN) model. The proposed hydrological lumped model was tested on a data set (1,804 rainfall-runoff events) from 39 watersheds in South Korea. Its superior performance indicates that the reconciliation of pre- and post-storm conceptualization has the potential to be a solution for efficient hydrological predictions and to demonstrate the complex and dynamic nature of tractable hydrological processes. The statistically significant results reveal that the proposed model can more effectively predict runoff from watersheds in the study area than the conventional CN model and its previously proposed modifications.

Keywords: Pre-storm soil moisture; Runoff prediction; Storm rainfall; Watershed abstraction

1. Introduction

Modeling to quantify and assess watershed excess storm water resulting from rainfall and its interaction with land cover is a complex, dynamic and nonlinear process (Borah, 2011; Durbude et al., 2011). The key elements in selecting a feasible and systematic simple rainfall-runoff model include the identification of candidate models, a suitable performance evaluation criteria in replicating observed data to produce reasonable estimations, and the quantification of uncertainty. The first step which comprehends the development of conceptual models is based on the available knowledge of subject matter, theory and belief (Gupta et al., 2012). The identification of feasible simple candidate hydrological models is vexed by the range of models available to suit different hydro-climatic conditions and watersheds and divergent degrees of belief in the significance of different processes they represent.

The Natural Resources Conservation Service (NRCS) Curve Number (CN) model developed by the United States Department of Agriculture (USDA) uses soil types, land cover information, and antecedent moisture conditions (AMCs) to estimate runoff based on the water balance concept (NRCS, 2004). This model is hereafter referred to as the conventional CN model. Runoff occurs after rainfall (P) exceeds the initial abstraction (I_a) that takes into account the infiltration, interception, and surface storage in small depressions. The maximum possible runoff from a watershed is $P - S$ (Cao et al., 2011), where S is the maximum potential retention or watershed storage index. The advantages of the conventional CN model are based on vast field experience, the fact that it is widely applicable across the globe, and that it has been integrated into various hydrological models (Wang et al., 2012). In the literature, there is a vast history of the conventional CN model due to its simplicity, flexibility, convenience, and dependence on a single parameter (Ponce and Hawkins, 1996). However, the standard assumption of initial abstraction (I_a) as 20% of the maximum potential retention (S),

* Corresponding author. Department of Civil and Environmental Engineering, Hanyang University, Ansan 15588, Republic of Korea. Tel.: +82 31 400 5184; fax: +82 31 436 8170.
E-mail address: twkim72@hanyang.ac.kr (T.-W. Kim).

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its corresponding three classes of antecedent moisture conditions, and the absence of a reliable pre-storm soil moisture accounting (PSMA) procedure cause some discrepancies in runoff estimation (Michel et al., 2005; Sahu et al., 2007). In order to achieve satisfactory results, the model parameters should be calibrated using measured rainfall-runoff data from various climatic settings (Ajmal and Kim, 2015). In addition, accounting for a proper PSMA procedure might increase the model prediction capability (Michel et al., 2005).

Soil moisture plays crucial role in the partitioning of storm rainfall into runoff and infiltration within a watershed. Therefore, the adjustment of soil moisture in rainfall-runoff models can enhance both the prediction and the forecasting of runoff (Brocca et al., 2010). Williams and LaSeur (1976) examined the impacts of a PSMA procedure and its promising results using the conventional CN model. However, less attention was given to the identification of the impact of soil initial water content on storm runoff characteristics (Brocca et al., 2008). Recently, Michel et al. (2005) investigated the concept of PSMA procedure and found that its incorrect interpretation caused several structural inconsistencies in the conventional CN model. They suggested an improved PSMA procedure for reliable runoff prediction. Nonetheless, the model has the demerits of sudden jumps in runoff estimation. Afterward, Sahu et al. (2007) criticized the model introduced by Michel et al. (2005) for not having any expression for pre-storm soil moisture store level (V_o). To circumvent this constraint, they proposed a consistent PSMA procedure by incorporating an expression for V_o. The value of V_o was adjusted as a parameter dependent on watershed AMCs in their simplified version. Likewise, Sahu et al. (2007) assumed that the S and S_a (an intrinsic parameter) in Michel et al. (2005) were invariable throughout the previous five days of rainfall (P_5) and caused ambiguity in deriving the expression for V_o. More recently, Sahu et al. (2010) reformulated the Mishra and Singh (2003) modification by incorporating a new parameter for antecedent moisture dependent on P_5 and assuming that the watershed is always dry five days before the onset of rainfall. This assumption is rarely valid for many watersheds (Wang et al., 2012). Furthermore, Durbude et al. (2011) made amendments to the Michel et al. (2005) formulation by introducing the PSMA procedure adopted from Geetha et al. (2008) at the cost of the new optimized parameters and claimed improved runoff prediction.

Despite the evident scientific development, runoff prediction from ungauged watersheds is still a serious challenge (Skaugen et al., 2015). It has been acknowledged by Yadav et al. (2007) that structural error and non-identifiability of conceptual rainfall-runoff models parameters pose a serious constraint for efficient runoff prediction from ungauged watersheds. In this regard, the hydrological model should be parametrically efficient and identifiable from watersheds characteristics (Skaugen et al., 2015). Various contributors (e.g., Michel et al., 2005; Sahu et al., 2007, 2010; Geetha et al., 2008; Durbude et al., 2011) have reformulated the conventional CN model with the intention of increasing its suitability for continuous hydrologic applications at the cost of introducing new parameters. Incorporating new parameters in these models made them less appealing for use in ungauged watershed analysis, and the simplicity and convenience were reduced (Grimaldi et al., 2013), because model parameters were mostly estimated from watershed characteristics and/or other hydrological and climatic setting (Skaugen et al., 2015). To avoid these limitations, Perrin et al. (2003) argued that lumped rainfall-runoff models based on PSMA procedure are efficient tools for use with water resources applications. They further demonstrated that the difficulty in assigning a definite structure to a model is primarily due to the unavailability of any widely accepted general hydrological theory to simulate watershed characteristics. To maintain the simplicity rule of lumped models, the current study structured an ensemble rainfall-runoff model by merging the conventional CN model and the GR4J (Génie Rural á 4 paramètres Journalier, in French) model with consideration of the PSMA procedure by Michel et al. (2005). The GR4J is a conceptual rainfall-runoff model based on four free parameters. It was developed after gradual improvements of the work carried out within the National Research Institute of Science and Technology for Environment and Agriculture (NRISTEA), France (Perrin et al., 2003).

2. Methodology

2.1. Description of study area and hydrometeorological data

The South Korean climate is characterized by extreme seasonal variation. Summer is hot and humid due to the heavy rainfall associated with the East-Asian Monsoon, whereas winter is cold and dry under the influence of the dominant Siberian air mass. Approximately 60 percent of the annual rainfall occurs from July to September. The extreme precipitation in the wet season causes flood damage, whereas water shortage might arise during the dry season (October to March) (Jung et al., 2013). For the current study, 39 watersheds with an extension ranging from 42.32 to 888.01 km^2 were selected based on the availability of the parameters essential for model assessment and evaluation. The locations of these watersheds are shown in Fig. 1.

The watershed characteristics (topography, hydrologic soil groups, soil types, land cover/use, etc.) and 30 min time step measured rainfall data were provided by the Korea Meteorological Administration (KMA) and Ministry of Land, Infrastructure, and Transport (MOLIT), whereas the Hydrological Survey Center (HSC) of Korea provided the discharge measurements recorded at the same time step. The data of 1,804 rainfall-runoff events during the 2005–2012 period were used in this study. Table 1 shows a summary of the fundamental hydrological and morphometric parameters used in this study. All of those storm events were scrutinized and differentiated for AMCs (AMC-I, AMC-II, and AMC-III) based on P_5 (Durbude et al., 2011). Only the large storm events were selected for the analysis of the models, because the conventional CN model shows a bias toward small storm events ($P \leq 25.4$ mm) (Ajmal and Kim, 2015; Hawkins et al., 2009).

The ArcCN-Runoff (an Arc GIS 10.1 tool for generating watershed CN and runoff maps) was employed to derive the composite normal conditions of the watershed CNs from the digital elevation models (DEM) of the soil types and land