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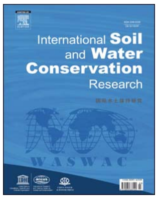

Original Research Article

Effect of spatial scale on runoff coefficient: Evidence from the Ethiopian highlands

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ABSTRACT

The runoff coefficient (RC) is the ratio between the runoff and rainfall amounts and is scale dependent, which is due in part to the heterogeneity of watershed characteristics. This study quantified the spatial scale effects on runoff using long-term rainfall-runoff data on runoff plots and small watersheds. Effect of spatial scale on RC was studied for 12 runoff plots (2 m by 15 m) and three small watersheds (113–477 ha) in the highlands of Ethiopia using a total of 4397 and 13,925 15-day cumulative pairs of rainfall and runoff data at watershed and runoff plot scales, respectively. The observed average RC of runoff plots was extrapolated based on the extent of representation of a particular watershed in terms of slope, land use, cover and soil type. The weighted RC of plots was then compared with the observed RC of the watershed to determine a scale factor for extrapolation. A decrease in RC from plot to the watershed was observed in Anjeni and Andit Tid watersheds, while an increase in RC in Maybar watershed illustrates the role of specific watershed conditions in determining the scale effect. This, in turn, suggests that the variation in scale factor is not well explained by the difference in the area alone. The scale effect of runoff generation was better explained by extrapolating the RC based on the representation of different watershed characteristics. Thus, extrapolation exercises in runoff modeling and scaling efforts of soil and water conservation practices should consider the scale effect cautiously.

1. Introduction

Sustainable watershed management is a guarantee for reducing watershed degradation (Temesgen, 2015). Thorough understanding of the hydrological processes, amongst which surface runoff generation is a fundamental process of interest (Stewart, Liu, Rupp, Higgins, & Selker, 2015), is crucial in watershed management. It has greater importance for prioritizing watersheds and selection of hot spot areas (Ramana, 2014). Runoff coefficient is the ratio of runoff to rainfall, and it is the basic input parameter in the hydrologic designs (Merz, Blöschl, & Parajka, 2006). Detailed understanding runoff coefficient of an area helps to facilitate up-scaling of best soil and water conservation practices (BSWCP) that generate low runoff. In the process of up-scaling, extrapolating results from smaller to larger scales requires a due consideration of the scale effect (Gebirrye, 2004). However, extrapolation is possible only when scale factors are well understood in specific conditions. Due to lack of measured reliable data across different scales, many studies emphasize on model-based extrapolations. So far, many studies give less focus to scale problems and its determinant factors using long-term measured data (Yair & Raz-Yassif, 2004).

Several studies indicated that smaller areas have generated more runoff due to greater runoff coefficient than larger areas (Feng & Li, 2008; Penna, Mantese, Gobbi, & Borga, 2011). The result from a study on scale effect using 0.05 ha, 90 ha, and 1100 ha stated that the runoff coefficient was observed to decrease as area increases (Cerdan et al., 2004). In their study, the soil type and slope were kept similar while the percentage of arable land was

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heterogeneous and found to be the major factor for the difference in runoff coefficient. On the contrary, a direct relationship between runoff coefficient and the watershed area was also reported (Prats, Wagenbrenner, Martins, Malvar, & Keizer, 2015). According to Feng and Li (2008), a study undertaken using six sub-basins having different drainage area shows that a smaller basin is found to have smaller runoff coefficient. Moreover, a runoff between 1 m^2 and 10 m^2 plots showed the non-significant difference (Asadzadeh, Gorji, Vaezi, & Shorafa, 2012). Stone, Nichols, Goodrich, and Buono (2008) generalize that humid area show an inverse relationship between runoff coefficient and drainage area while semi-arid areas exhibit the direct relationship. This implies that scale effect is not only explained by area but also other important watershed characteristics. Thus, quantifying the magnitude of scaling factor (SF) and recognizing the controlling factors is found critical to the rainfall-runoff relations (Leys, Govers, Gillijns, BeRCkmoes, & Takken, 2010; Wu, Jones, Li, & Loucks, 2006).

Inference about larger watersheds using results from smaller watersheds is often misleading. Simple linear up-scaling or extrapolation would not be valid since a watershed could not be considered as the sum of individual plots (Cerdan et al., 2004). Penna et al. (2011) underline that a rainfall-runoff process examined at small experimental plots can offer insights about the same process occurring at larger scales. On the contrary, Sadeghi, Gholami, Sharifi, Khaledi, and Homaee (2015) reported that plots could not give accurate data for larger scale outcomes. The low accuracy of extrapolation is often associated with the subjective interpretation of data and inconsistencies in parameter estimation at larger watersheds (Hughes, Kapangaziwiri, & Tanner, 2013).

Spatial scale effects in hydrological processes are usually described by watershed heterogeneity in terms of slope, soil, and land uses (Wu et al., 2006). Separate and combined effect of heterogeneous characteristics can cause different runoff generation conditions in an area (Gomi, Sidle, Miyata, Kosugi, & Onda, 2008; Lin & Wang, 2010; Mounirou, Hamma, Harouna, Jean-Emmanuel, & Gil, 2012). Yildiz and Barros (2009) state the importance of incorporation of detailed information that has consequences at the spatial scales of interest will help to effectively forecast spatial variability of hydrologic responses. This situation, thus, demands further investigation of the spatial scale effect with respect to the extent of representation of plot characteristics on heterogeneous watersheds. One can use the runoff coefficient corresponding to the different plots with various characteristics to explain the spatial scale effect on a heterogeneous watershed. Therefore, quantifying the magnitude of scale effects using runoff plot and watersheds are found to be critical undertakings in a situation where measured data is not available.

Addressing spatial scale effect with reference to the representation of characteristics of small plots to the particular watersheds help to guide land and water management implementation efforts. In due course, effective watershed management under up-scaling approach could be promoted. The present study was conducted in humid and sub-humid watersheds in the Ethiopian highlands. Therefore, the objective of the study was to analyze and model effects of spatial scale on the runoff coefficient. The scale effect was analyzed at watershed (113–477 ha) and runoff plot (30 m^2) scales. Long-term rainfall and runoff data both at plot and watershed level were aggregated into fifteen-day interval and ordered separately based on ranking. To quantify the runoff coefficient at the watershed level, the relative magnitude runoff coefficient of runoff plots were weighted by the areal extent of combined plot characteristics including slope, land use, and soil. Eventually, the scale effect was analyzed by comparing the weighted runoff coefficient of runoff plots with the measured runoff coefficient at the watershed level.

2. Materials and methods

2.1. Description of the study areas

The study was conducted in three experimental watersheds located in the Ethiopian highland, namely Anjeni, Andit Tid, and Maybar watersheds. The watersheds were established in the early 1980s by the Soil Conservation Research Project (SCRP). The watersheds are located in humid and sub-humid agro-ecological zones of the country with an altitude range between 2407 and 3548 m a.s.l. (Fig. 1). Cereal-based cropping system mixed with livestock is the dominant farming system. The major biophysical features of the watersheds are presented in Table 1. The main reason to focus on these watersheds is that the watersheds are equipped with the hydro-meteorological monitoring system at watershed and runoff plot level and availability of long-term rainfall-runoff data since the 1980s. Daily rainfall and runoff data from runoff plot and daily discharge data from watershed level were recorded for the last three and half decades.

Each watershed has four 2 m by 15 m runoff plots. The different runoff plot setup represents different classes of the slope, soil type, and crop cover types by considering the heterogeneity of the watersheds. As depicted in Table 2, the slope, soil, and land use characteristics of the plots and their area proportion from the total watershed are described by different research works (Abebe, Hurni, & Gete, 2013; Abrham, Tilashwork, Tesfaye, & Abdlesemed, 2016; Binyam, 2009; Elias, 2009; Tegenu, 2009; Woubet et al., 2013; Yakob, 2009).

2.2. Rainfall and runoff data

A long-term data on rainfall, runoff at the plot level, and streamflow at the outlet of the watersheds have been collected since the early 1990s and used for the analysis. A cleaned dataset was collected from Water and Land Resource Center (WLRC). Out of the total dataset, Thirteen years (i.e., in the period of 1987–1993, 1996–1998, 2000 and 2008), six years (1987–1992) and twenty years (i.e., in the period of 1988–1989, 1991–1993, 1995, and 2000–2013) rainfall and runoff data were used respectively for Anjeni, Andit Tid, and Maybar watersheds. Missing data for any single month was excluded from analysis.

Since the study watersheds are small, rainfall was considered to be similar throughout each watershed area. Daily rainfall depths were computed from successive rainfall events. In the runoff test plots, runoff collection tanks were emptied every morning at 8:00 a. m. Therefore, daily rainfall and runoff amount were considered to be of the total duration between two consecutive tank emptying periods. Even among plots, emptying a tank and taking a soil sample and water depth measurements were time-consuming task compelling to reach the next test plot lately (Bayabil, Tebebu, Stoof, & Steenhuis, 2015; Junker, 2012). Total daily runoff from the test plot was computed using procedures proposed by SCRP (1982, 1984). The river stage-discharge relationships for each watershed is developed and calibrated by Bosshart (1996) and was adopted to generate discharge data of each watershed. Thus, total runoff in each study watershed for any rainfall event was computed using the adopted rating curve equations relating streamflow (Q) and streamflow stage (H). Base flow was determined using constant-discharge method (Raghunath, 2006). Thereafter, surface runoff was computed by deducting base flow from the total runoff. Daily rainfall-runoff data was then obtained by adding all events on a specific day. In order to consider watershed sizes, the runoff volumes computed were divided by the plot as well as the watershed area and resulted in runoff depth.

The rainfall and runoff data were subject to screening to exclude the outliers and avoid unnecessary errors. Because of low rainfall resulting in unrealistic high runoff flow, it is customary to use large storm events the lowest limit being 25.4 mm (Ajmal,

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