Hydrol. Earth Syst. Sci. Discuss., 8, 6227–6256, 2011
www.hydrol-earth-syst-sci-discuss.net/8/6227/2011/
doi:10.5194/hessd-8-6227-2011

Hydrology and
Earth System
Sciences
Discussions

Effects of antecedent soil moisture on runoff modeling in small semiarid watersheds of southeastern Arizona

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Received: 17 June 2011 – Accepted: 22 June 2011 – Published: 28 June 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Antecedent soil moisture prior to a rain event influences the rainfall-runoff relationship. Very few studies have looked at the effects of antecedent soil moisture on runoff modeling sensitivities in arid and semi-arid areas. This study examines the influence of initial soil moisture on model runoff prediction capability in small semiarid watersheds using model sensitivity and by comparing the use of antecedent vs. average long term soil water content for defining the model initial conditions for the modified Green-Ampt Mein-Larson model within the Rangeland Hydrology and Erosion Model (RHEM). Measured rainfall, runoff, and soil moisture data from four semiarid rangeland watersheds ranging in size from 0.34 to 4.53 ha on the Walnut Gulch Experimental Watershed in southeastern Arizona, USA, were used. Results showed that: (a) there were no significant correlations between measured runoff ratio and antecedent soil moisture in any of the four watersheds; (b) average sensitivities of simulated runoff amounts and peaks to antecedent soil moisture were 0.05 mm and 0.18 mm h^{-1}, respectively, with each 1 % change in antecedent soil moisture; (c) runoff amounts and peaks simulated with long term average soil moisture were statistically equivalent to those simulated with measured antecedent soil moisture. The relative lack of sensitivity of modeled runoff to antecedent soil moisture in this case is contrary to results reported in other studies, and is largely due to the fact that the surface soil is nearly always very dry in this environment.

1 Introduction

Soil water content in the upper soil layer prior to a rain event can be an important factor affecting the relationship between rainfall and runoff (Yair and Klein, 1973; Abrahams et al., 1988; Karnieli and Ben-Asher, 1993; Martinez-Mena et al., 1998; Castillo et al., 2003; Zehe et al., 2005; James and Roulet, 2009; Brocca et al., 2009a, b; Penna et al., 2010; Tramblay et al., 2010; Kampf, 2011). Runoff-controlling mechanisms in arid and semiarid watersheds can be somewhat different from those which regulate the hydrology of wetter environments. Runoff generation in semiarid and arid environments that are not dominated by snow is commonly attributed to an infiltration excess mechanism (Yair, 1996), while in humid regions runoff generation mechanisms of importance also include saturated-excess overland flow and lateral subsurface flow (Dunne and Black, 1970). Saturation excess overland flow, which occurs at relatively high levels of soil moisture, is completely dependent on antecedent moisture conditions (Castillo et al., 2003). In semiarid and arid environments saturated-excess overland flow is uncommon because initial soil moisture conditions are generally drier.

Several studies have examined the effect of antecedent soil moisture on runoff simulation in physically based models (Goodrich et al., 1994; Castillo et al., 2003; Zehe and Blöschl, 2004; Brocca et al., 2008; Sheikh et al., 2010), and shown that runoff simulation can be sensitive to antecedent soil moisture in semi-humid and humid areas. Brocca et al. (2008) also proposed a soil water balance model to accompany the Green–Ampt model as a component of rainfall–runoff modeling in a semi-humid catchment located in central Italy. Goodrich et al. (1994) found that runoff volumes and peak rates were not particularly different using antecedent soil moisture as calculated with spatially averaged remotely sensed data vs. a simple daily soil moisture model at the small (4.4 ha) and medium (631 ha) watershed scales in semiarid southeastern Arizona, USA. Using two storm events in two burnt watersheds (7.56 and 6.38 ha) and one un-burnt watershed (24.28 ha) in semiarid Spain, Castillo et al. (2003) found that the sensitivity of modeled runoff response to soil moisture depended on the rainfall amount. The modeled hydrological response after the high intensity, low frequency storm was independent of the initial soil water content; while the antecedent soil water content was an important factor controlling modeled runoff from the medium to low intensity storms.

Most rainfall-runoff models (e.g. Woolhiser et al., 1990; Nearing et al., 2011) use initial soil water content as one of the model initial conditions, where the soil water is either measured or estimated with a water balance model (Brocca et al., 2009a;

Tramblay et al., 2010). Results of some studies have suggested that for watersheds with overland flow occurring mainly as a result of infiltration excess, knowledge of the soil moisture prior to any rainfall event is fundamental to evaluating hydrological response due to its influence on soil matric suction (Wood, 1976; Karnieli and Ben-Asher, 1993; De Michele and Salvadori, 2002; Brocca et al., 2009b). Other studies have pointed to a secondary role for the antecedent soil water content in hydrological response compared with soil surface characteristics, especially due to soil crusting phenomena (Morin et al., 1989; Casenave and Valentin, 1992). Among the factors which govern infiltration, including rainfall, soil properties, and vegetation, antecedent soil moisture data prior to each rainfall event is often the most uncertain and least easily available (Karnieli and Ben-Asher, 1993). Soil water content monitoring at the watershed scale is difficult because of its space–time variability and because field measurements are costly and time consuming (Brocca et al., 2008). Soil moisture tracking models are often used, but uncertainty associated with any model parameter, including soil moisture, will generate uncertainty in model response (Nearing and Hairsine, 2011). Thus, the task of runoff modeling confronts the dilemma of determining how much emphasis should be placed on defining precise values of antecedent soil moisture as one of the model initial conditions due to both its effects on runoff response (model sensitivity) and its uncertainty and unavailability.

Because there are very few studies that have looked at the effects of antecedent soil moisture on runoff modeling sensitivities in arid/semi-arid areas, the objectives of this study were: (1) to examine the sensitivity of the measured runoff to rainfall ratio to measured antecedent soil water content, (2) to analyze the sensitivity of runoff depth and peak model output to soil moisture input, and (3) to test the prediction capability of runoff at a small watershed scale using measured storm-antecedent soil moisture vs. long-term average soil water content for model initial conditions using the Green-Ampt Mein-Larson model (Mein and Larson, 1973) for unsteady intermittent rainfall (Chu, 1978) within the Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al., 2011). A 9-yr record of measured rainfall, runoff, and soil moisture data from four small semiarid rangeland watersheds in southern Arizona, USA ranging in size from 0.34 to 4.53 ha were used.

2 Methods

2.1 Description of the Experimental Watersheds

This study was conducted using data from four small watersheds located on the Walnut Gulch Experimental Watershed near Tombstone in southeastern Arizona, USA, which is operated by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Southwest Watershed Research Center (Moran et al., 2008). The climate of the area is semiarid with annual precipitation of approximately 345 mm and highly spatially and temporally varying precipitation patterns dominated by the North American Monsoon. Monsoon storms are typically characterized as short-duration, high-intensity, localized rainfall events. Two thirds of the annual precipitation falls during the “monsoon” season from July through mid-September, and much of the remainder is concentrated in the winter months of December through February (Nichols et al., 2002). The channels in Walnut Gulch Experimental Watershed are dry most of the time (Nearing et al., 2007). Mean annual temperature in the Walnut Gulch Experimental Watershed measured is 17.7 °C, and the average monthly maximum temperature of 35 °C occurs in June, with average monthly minimum temperature of 2 °C in December (Nichols et al., 2002).

The four watersheds (i.e. Watershed 63.102, 63.103, 63.104 and 63.106) were located in what is referred to as “Lucky Hills” (Table 1 and Fig. 1) and ranged in size from 0.34 to 4.53 ha. Watersheds 63.102 and 63.106 are nested within 63.104. The vegetation in this area is dominated by desert shrub (mainly creosote and whitethorn) with canopy cover during the rainy season of approximately 25 % (Nearing et al., 2007). The elevation of the area is approximately 1360 m a.s.l.

The soil in the Lucky Hills shrub area is a gravelly sandy loam with approximately 52 % sand, 26 % silt, and 22 % clay. The organic carbon content of the soils is low (generally less than 1 %) (Nearing et al., 2007).

Watersheds 63.102, 63.103 and 63.104 are drained by well-developed, incised channel networks that efficiently deliver eroded particles to the watershed outlets (Nearing et al., 2005). Watershed 63.106 is smaller than the others and does not have a highly incised channel, but as with the other three also does not have a toe-slope area of noticeable deposition and sediment storage (Polyakov et al., 2009).

2.2 Instrumentation and data collection

All of the data for precipitation, rainfall, runoff, and soil moisture used in this study are available for public download through the Data Access Project at the USDA-ARS Southwest Watershed Research Center (Nichols and Anson, 2008).

Runoff was measured with calibrated, Santa Rita-supercritical flumes at the outlets of watersheds 63.102, 63.103, and 63.104, an H-flume at watershed 63.106 (Stone et al., 2008). Digital recorders consisting of potentiometers attached to the stilling well gear mechanisms and data loggers were used to record discharge depth (Stone et al., 2008).

88 rain gages are currently in operation within or adjacent to the 150 km^2 Walnut Gulch Experimental Watershed. Rainfall measured with digital gage 83 was used (Fig. 1). The precipitation record observed via the digital gages consists of rainfall depths at 1 min intervals during periods of rainfall (Goodrich et al., 2008).

Soil moisture was measured with a single sensor at a depth of 5 mm at 19 rain gages across the watershed since 2002. In 2002 soil moisture was sampled and reported every 30 min, but 20 min intervals were used since 2003 (Keefer et al., 2008). Soil moisture measured near rain gage 83 was used.

2.3 Data and analyses

Data were compiled for the four watersheds for the period of 2002–2010. The data sets collected included: (1) breakpoint rainfall; (2) runoff dates, times, durations, total storm-runoff volumes and peak runoff rates; and (3) volumetric soil water content of the upper 5 cm soil layer, including dates, times and soil moistures. Rainfall and runoff were matched with each other based on their start and end times. Antecedent soil moisture was matched to each rainfall event with the moisture recorded within 30 min before rainfall started. Daily rainfall depths and daily average moistures were computed using rainfall event data and averaged volumetric soil water content records with 20 min or 30 min intervals.

Other data gathered for running RHEM included soil and vegetation properties such as texture, bulk density, porosity, canopy cover, ground cover, and geomorphologic parameters such as average slope length and slope gradient. That information was obtained from previous studies (Nearing et al., 2007, 2011; Wei et al., 2007). Linear regression was used to compare simulated and measured runoff.

2.4 Analysis of measured runoff ratio as influenced by antecedent soil moisture

Runoff to rainfall ratios of events from the four small watersheds during 2002 to 2010 were calculated and matched to measured antecedent soil moisture. Linear correlation coefficients and scatter plots with the confidence ellipses of correlation were used to test the relationship between measured runoff ratio and antecedent soil moisture and to check if there is an observable threshold value of antecedent soil moisture that controlled the presence or absence of runoff.

2.5 RHEM Model parameterization and calibration

The Rangeland Hydrology and Erosion Model (RHEM) was used (Nearing et al., 2011), in which infiltration was computed using the Green-Ampt Mein-Larson model (Mein and

Larson, 1973) for unsteady intermittent rainfall as modified by Chu (1978). RHEM is an event-based derivation of the WEPP model, incorporating new soil erosion equations derived from rangeland data (Wei et al., 2009). RHEM represents hydrology and erosion processes under disturbed and undisturbed rangeland conditions, it adopts a new splash erosion and thin sheet-flow transport equation developed from rangeland data, and it links the model hydrologic and erosion parameters with rangeland plant communities (Nearing et al., 2011).

The model requires parameters for infiltration and runoff simulation, including the Green-Ampt effective hydraulic conductivity, K_e; effective matric potential, ψ; soil porosity, η; soil moisture saturation ratio; Darcy-Weisbach friction factor for runoff, fr; soil texture; slope lengths and gradients; and breakpoint rainfall data.

In this study, ψ,η, fr and soil texture were calculated using the methods available in the literature (Nearing et al., 2011); degree of saturation was calculated with volumetric soil moisture and soil porosity; slope lengths and gradients were calculated using DEMs with 1 m resolution based on LIDAR measurements; and effective hydraulic conductivity (K_e) values were calibrated using the nine year period of measured rainfall, runoff, and soil moisture data.

One hundred and eighty six rainfall-runoff events from watersheds 63.102, 63.103, 63.104 and 63.106 during the period of 2002–2010 were used to calibrate effective hydraulic conductivities, K_e (Table 2). During the calibration, runoff was simulated by RHEM with different K_e values ranging from 0.8 to 40 mm h^{-1} with increments of 0.1 mm h^{-1}. The calibrated K_e for each watershed was obtained by maximizing the Nash-Sutcliffe model efficiency, E (Nash and Sutcliffe, 1970). During the calibration, measured antecedent soil moisture for each event was used as the RHEM input.

2.6 Sensitivity analysis

Model sensitivity is the variation or change in a model response as a function of change in one or more model input parameters. Sensitivities of simulated storm-runoff volumes and peaks to antecedent soil moisture were analyzed by changing the input parameter of antecedent soil saturation ratio (volumetric soil water content divided by soil porosity) from 0 % to 48 % with increments of 3 %, corresponding to a range in volumetric soil moisture content from 0 % to 22.4 % with increments of 1.32 %, based on the statistical range of recorded soil moisture. Sixty rainfall-runoff events from each of watersheds during the period of 2002 through 2010 were simulated with the 18 antecedent soil moisture values.

The local Sensitivity Index (SI), also termed as the "one factor at a time", was used in this study. The local SI measures the partial derivative of Y with respect to x_i at point x^0 (Saltelli and Campolongo, 2000), and thus it quantifies the local model response (Y) to any given input parameter (x_i) at any point x^0 within the full input parameter space for the model. SI is defined by the equation:

$$\left\{\frac{\partial Y}{\partial x_i}\right\}_{x^0} = \frac{Y(x_1^0,\cdots,x_i^0+\partial x_i,\cdots,x_l^0)-Y(x^0)}{\partial x_i} \tag{1}$$

where l is the total number of input parameters. In this study, we were interested only in the sensitivity of model response to the parameter x_i that represented antecedent soil moisture, and SI was calculated based on incremental (step) changes in the value of volumetric soil moisture. Thus magnitude of SI in this study represents the change of runoff (mm) or peak rate (mm h^{-1}) caused by each 1 % change of volumetric soil moisture ($\Delta Y/\Delta x_i$).

2.7 Use of long-term average soil moisture as model input for each storm

As an alternative to using measured antecedent soil moisture for each storm, this study tested the predictability of runoff using the long term average soil water content as a substitute for measured soil moisture prior to each rainfall event. With calibrated K_e, runoff volumes and peak rates of 186 events in the four watersheds were simulated using long term average (2002–2010) soil moisture (indicated henceforth as AVSM) for each event as the model input. In order to further examine the effect of antecedent soil moisture on runoff, Nash-Sutcliffe model efficiency, E, and coefficient of determination r^2, between measured runoff volume and simulated runoff volume with AVSM were calculated and compared with the E and r^2 between measured runoff volume and simulated runoff volume with measured antecedent soil moisture (indicated henceforth as ANSM) as the model input. Linear regression was used to compare between runoff volumes and peaks simulated with AVSM and ANSM.

3 Results

3.1 Characteristics of precipitation, runoff and soil moisture

Annual measured precipitation at Lucky Hills during the period of study (2002–2010) ranged between 189 and 389 mm with a maximum recorded 24 h rainfall of 52 mm (Fig. 2). There were 60 rainfall-runoff events recorded in Lucky Hills that could be matched with antecedent soil moisture from 2002 to 2010 and a total of 186 runoff hydrographs were recorded from the four small watersheds, with the maximum runoff depth for each watershed ranging from 13.1 mm to 22.8 mm (Table 2). Average daily soil moisture measured on 3176 days during 2002 to 2010 was 3.6 %, with a maximum measured value of 21.3 % and median value of 2.4 %.

3.2 Relationships between measured runoff ratios and antecedent soil moisture

Among the 186 rainfall-runoff events, measured runoff to rainfall ratios ranged from 0 % to 60.6 % with a mean of 18.5 %, and antecedent soil moisture within 30 min before rainfall ranged from 1 % to 17 % with a mean of 8.2 %. There was no significant correlation ($\alpha = 0.05$) between runoff ratio and antecedent soil moisture in any of the four watersheds, with Pearson's correlation coefficients ranging from 0.10 to 0.15 (Fig. 3).

3.3 Simulation of runoff with measured antecedent soil moisture

Calibrated values of K_e for the four watersheds in Lucky Hills are given in Table 2. Figure 4 shows the relationships between the model input value of K_e as a function of model efficiency, E, from which the best estimation of K_e was determined. Calibrated K_e ranged from 2.7 to 7.5 mm h^{-1} for the four shrub land watersheds at Lucky Hills.

Linear regressions between measured and model predicted runoff volumes using the calibrated K_e values produced r^2 values ranging from 0.82 to 0.88 and E values ranging from 0.63 to 0.81 (Table 2 and Fig. 3). Most of the simulated runoff volumes of events fell within the 95 % confidence interval of the predicted values, the slopes of the linear regression equations were all nearly equal to 1 (1.06 to 1.08), and the intercepts were all small (−1.31 to −1.36 mm), indicating little systematic bias between simulated and measured runoff volumes (Fig. 5).

3.4 Sensitivity of simulated runoff to antecedent soil moisture

On average, the SI of simulated runoff volume to antecedent soil moisture (SI_Q) for all runoff events ranged from 0 to 0.28 mm with a mean of 0.05 mm, and the SI of runoff peak (SI_{Qp}) ranged from 0 to 0.85 mm h^{-1} with a mean of 0.18 mm h^{-1}. Figure 6 shows the average SI_Q and SI_{Qp} in each watershed. SI_Q from 66 % of events were less than 0.05 mm, showing that the for most events runoff volume increased less than 0.05 mm with each 1 % increase in antecedent soil moisture (Fig. 7). SI_{Qp} values from 59 % of events were below 0.2 mm h^{-1}.

3.5 Runoff simulation with average soil moisture as a substitute for measured daily antecedent soil moisture

The Nash-Sutcliffe model efficiencies and coefficients of determination between measured runoff volume and simulated runoff volume with record-averaged soil moisture (AVSM) (Table 3) were similar to those using the measured antecedent soil moisture for each event (ANSM) (Table 2). Runoff depths and peak rates simulated with AVSM were similar to those simulated with ANSM, with coefficients of determination, r^2, equal to 0.997 and 0.999, respectively (Fig. 8). The low sensitivity of runoff to soil moisture may be due to the very low variability of the values of the antecedent soil moisture condition. Antecedent soil moisture within 30 min before the measured 60 rainfall events ranged from 1 % to 17 % (Fig. 9) while recorded daily average soil moisture ranged from 0 to 21.3 % from 2002 to 2010. Differences were not as noticeable for peak runoff predictions (Fig. 8).

4 Discussion

The relative importance of the effect of antecedent soil moisture on runoff response is different in various environments (Brocca et al., 2009b; Penna et al., 2010). Western et al. (1998) analyzed relationships between watershed average soil moisture derived from point measurements and daily runoff coefficient for days with rainfall greater than 5 mm for the 10.5 ha semi-humid Tarrawarra watershed characterized by a silt loam soil type. Their results showed that the surface runoff was strongly controlled by soil moisture, with a threshold value of the volumetric water content varying from 41 to 46 %, below which no runoff occurred. Similarly, another study conducted by Brocca et al. (2004, 2005) on a semi-humid watershed (12.9 km^2) with sandy loam soils in central Italy indicated that only when antecedent volumetric soil moisture content was above approximately 36 % were the runoff coefficients generally greater than zero.

Runoff generation in hot semiarid and arid environments soils are often much drier in general, and the role of antecedent soil moisture can be less important. Castillo et al. (2003) attributed this to the controlling runoff mechanism of infiltration excess overland flow, as contrasted to saturation excess. By conducting a stochastic sensitivity analysis on the runoff response to different soil moisture scenarios using a physically based distributed model in semiarid Spain, Castillo et al. (2003) drew the following conclusion: “when infiltration excess overland flow is predominant, as a result of high rain intensities or less permeable soils, the runoff response does not depend on initial soil moisture. Runoff from less intense storms on soils of higher permeability is controlled by the soil water content of the surface soil layers and is more dependent on initial conditions." We know of no other studies that have looked at the effects of antecedent soil moisture on runoff modeling sensitivities in arid/semi-arid areas.

In the watersheds of this study the soils were almost always very dry; consequently, the variation in initial soil moisture was low and certainly saturation-excess overland flow did not occur. Furthermore, the storms that occur during the summer monsoon, and which cause the vast majority of the runoff, are characterized by relatively high rainfall intensity. Using our measured runoff and antecedent soil moisture data, we did not find a threshold value of antecedent soil moisture controlling the presence or absence of runoff, and there was no significant correlation ($\alpha = 0.05$) between runoff ratio and antecedent soil moisture in any of the four watersheds (Fig. 3).

Furthermore, sensitivity analyses showed that with each 1 % increase in antecedent soil moisture, the average simulated runoff volume and the peak runoff rates increased on average only 0.05 mm and 0.18 mm h^{-1}, respectively. Goodrich et al. (1994) used remotely sensed data to also show that runoff volumes and peak rates were not particularly sensitive to antecedent soil moisture at both the small (4.4 ha) and medium (631 ha) watershed scales in the Walnut Gulch Experimental Watershed.

5 Conclusions

Several rainfall-runoff models (e.g. Woolhiser et al., 1990; Nearing et al., 2011) use initial soil water deficit as one of the model initial conditions. However, soil water content monitoring at the watershed scale is difficult because of its space–time variability and because field measurements are costly and time consuming. Therefore, Brocca et al. (2008) investigated the reliability of a new and different structure for a soil water balance model (incorporating the Green–Ampt infiltration model) to be used as a component of an event-based rainfall–runoff model (Brocca et al., 2011a, b). For testing the reliability of the soil water balance model, Brocca et al. (2008) compared the "observed" and computed soil water content before several rainfall events (greater than 5 mm) of their test period (September 2003–May 2004). Their results showed that 90 % of the cases had an absolute error of computed soil water content less than 15 %. Moreover, the correlation ($r^2 = 0.80$, 0.88 for runoff depth and peak discharge, respectively) between runoff observed and estimated with a multiple linear regression incorporating modeled soil water was similar to that found ($r^2 = 0.79$, 0.91 for runoff depth and peak discharge, respectively) using observed soil water contents.

Castillo et al. (2003) suggested that the exclusion of the initial soil water content from the modeling approach may result in substantial errors in runoff predictions for most recurrent rainstorms (medium and low intensity storms) in semiarid environments. However, in the semiarid rangeland area of this study, runoff generation was driven by the portion of rainfall that occurred at a high intensity rather than its overall amount (Polyakov et al., 2010). In this study, runoff characteristics simulated with a nine year average of soil moisture (the coefficients of determination, r^2 ranging from 0.79 to 0.87 for runoff volume in four watersheds) were very similar to those simulated with measured antecedent soil moisture (r^2 ranging from 0.82 to 0.88 for runoff volume). This indicated that long term average soil moisture could be used as a substitute for measured antecedent soil moisture for runoff modeling of these watersheds. The explanation for this is that the soils are almost always very dry in this environment, and consequently, the variation in initial soil moisture is small. Results could be quite different in other semiarid rangeland environments in which soil moisture is more variable, and in particular in snow dominated regions.

Acknowledgements. USDA is an equal opportunity provider and employer. The authors thank the USDA-ARS Southwest Watershed Research Center staff for their efforts in collecting the data that made this research possible.

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Table 1. Characteristics of the watersheds in which rainfall, runoff and soil moisture were measured and used in this study.

Watershed	Area	Average slope steepness
	ha	%
63.102	1.46	10.5
63.103	3.68	7.8
63.104	4.53	10.5
63.106	0.34	8.9

Table 2. Calibrated Green-Ampt Effective Hydraulic Conductivities, K_e, for the four watersheds in Lucky Hills.

Watershed	Number of events	Measured runoff volume	Calibrated K_e	Nash-Sutcliff model efficiency, E	Coefficient of determination, r^2
		mm	mm h^{-1}		
63.102	45	0.1–17.1	5.7	0.737	0.855
63.103	46	0.0–20.7	4.6	0.752	0.855
63.104	39	0.0–13.1	7.5	0.627	0.817
63.106	56	0.1–22.8	2.7	0.810	0.882

Table 3. Nash-Sutcliff model efficiencies and coefficients of determination between measured runoff volumes and simulated runoff volumes using long term average soil moisture (2002–2010) for each event as the model input.

Watershed	Number of events	Measured range of runoff volumes	Average volumetric soil moisture	Nash-Sutcliff model efficiency, E	Coefficient of determination, r^2
		mm	%		
63.102	45	0.1–17.1	3.56	0.710	0.834
63.103	46	0.0–20.7	3.56	0.722	0.831
63.104	39	0.0–13.1	3.56	0.591	0.789
63.106	56	0.1–22.8	3.56	0.792	0.868

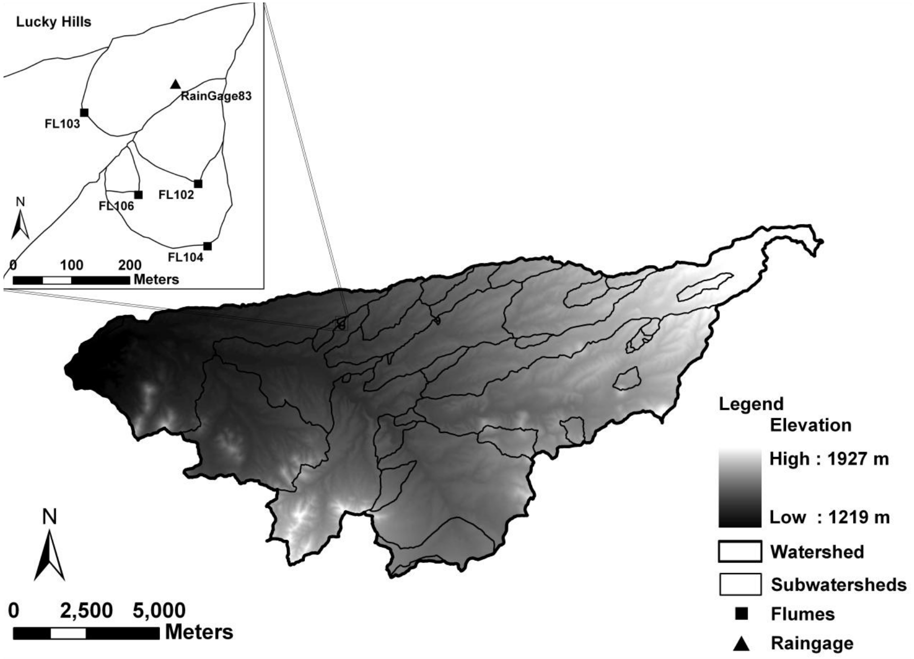

Fig. 1. Map of Walnut Gulch watershed with locations of watersheds and instrumentation used in this study. Soil moisture sensors were located near rain gages 82 and 83.

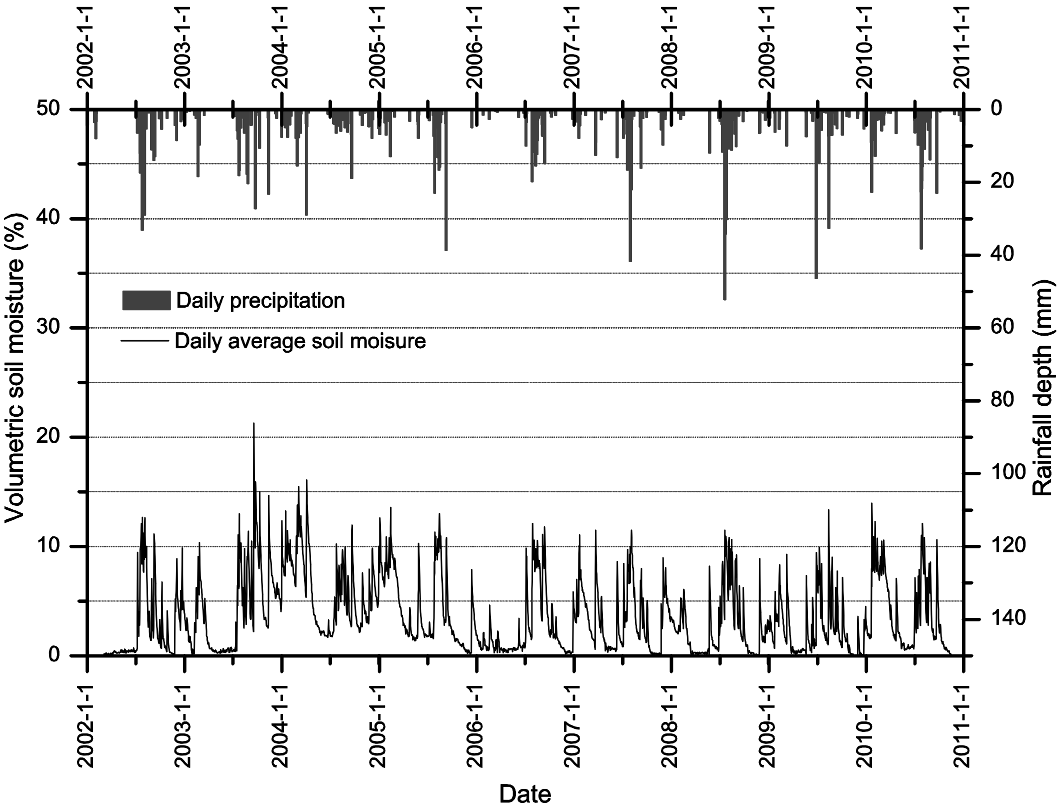

Fig. 2. Daily precipitation and daily average volumetric soil moisture in Lucky Hills from 2002 to 2010.

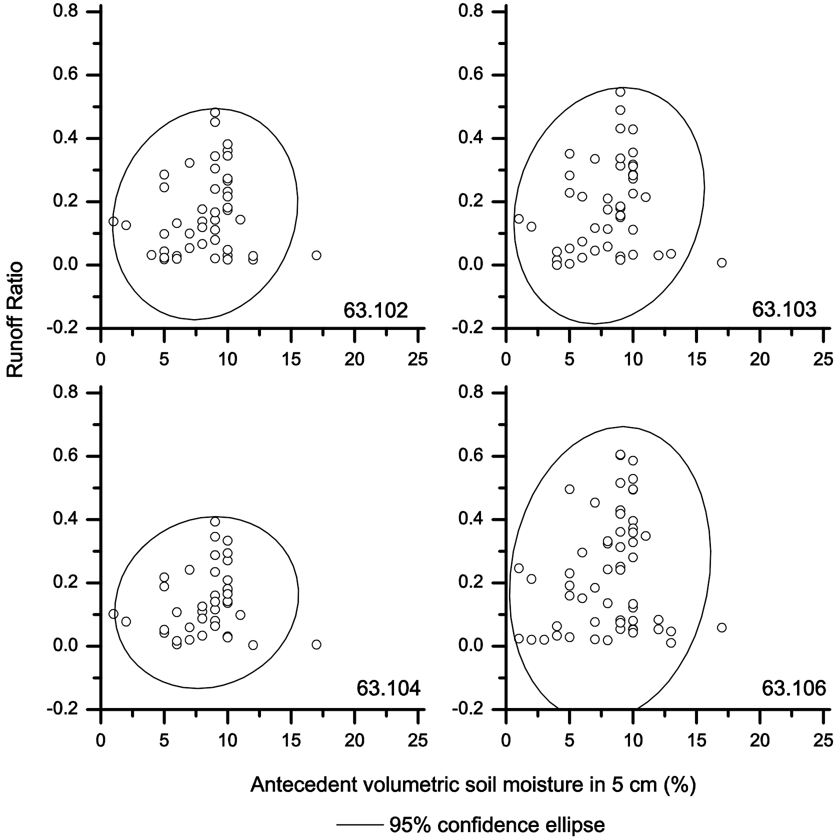

Fig. 3. Correlations between measured runoff ratio and measured antecedent soil moisture from the four watersheds (63.102, 63.102, 63.104 and 63.106) in Lucky Hills from 2002 to 2010. The confidence ellipse collapses diagonally as the correlation between two variables approaches 1 or −1. The confidence ellipse is more circular when two variables are uncorrelated.

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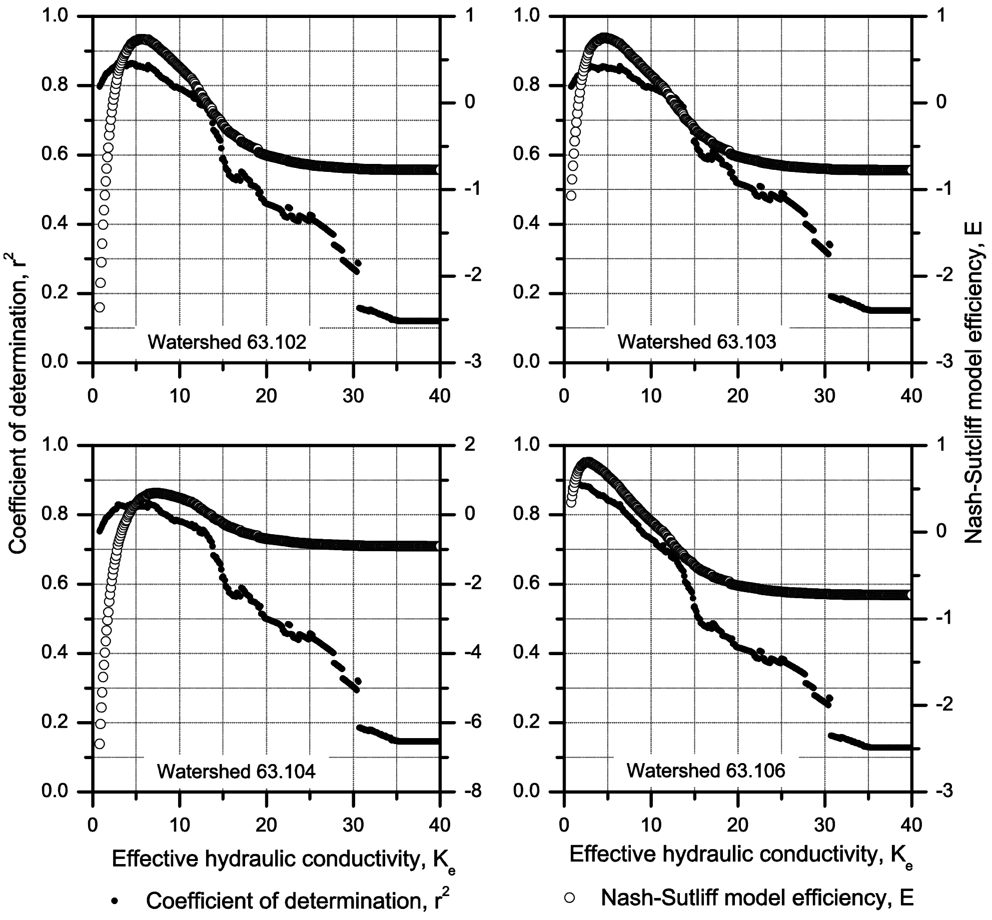

Fig. 4. Coefficients of determination and Nash-Sutcliff model efficiencies of the linear relationships between simulated and measured runoff volumes as a function of model input values of effective hydraulic conductivity K_e for calibration in Lucky Hills.

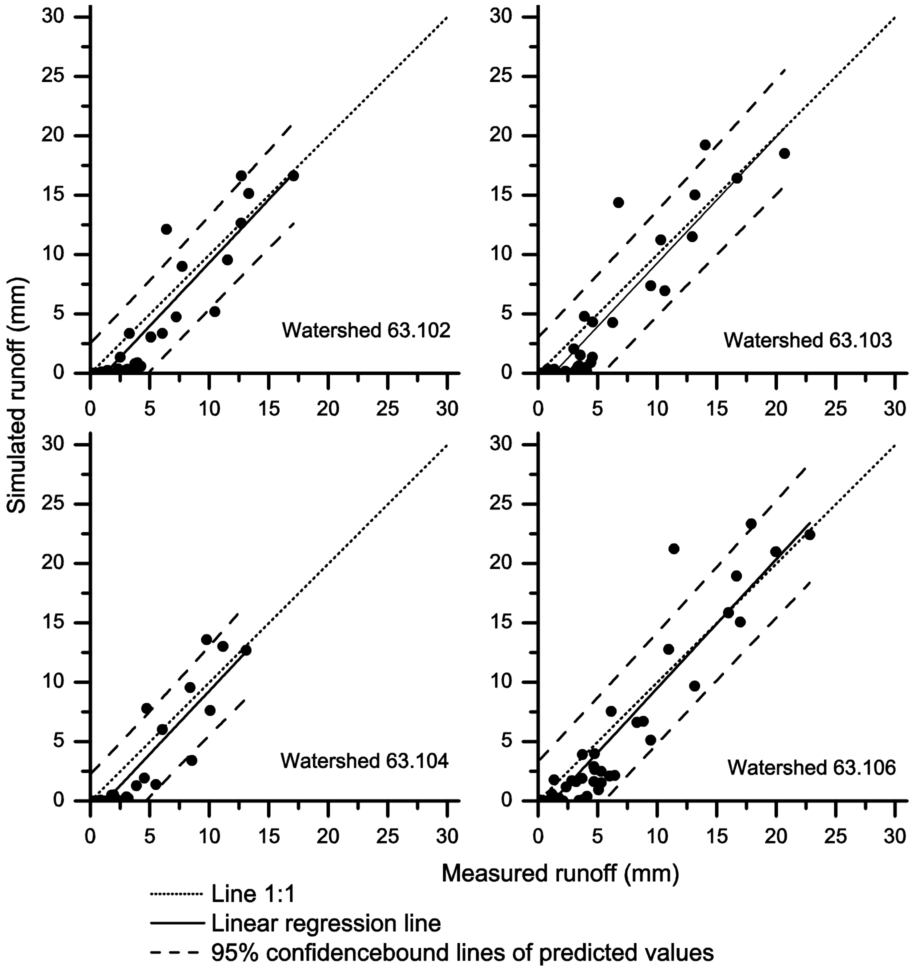

Fig. 5. Comparison of simulated runoff with measured runoff in the four watersheds in Lucky Hills.

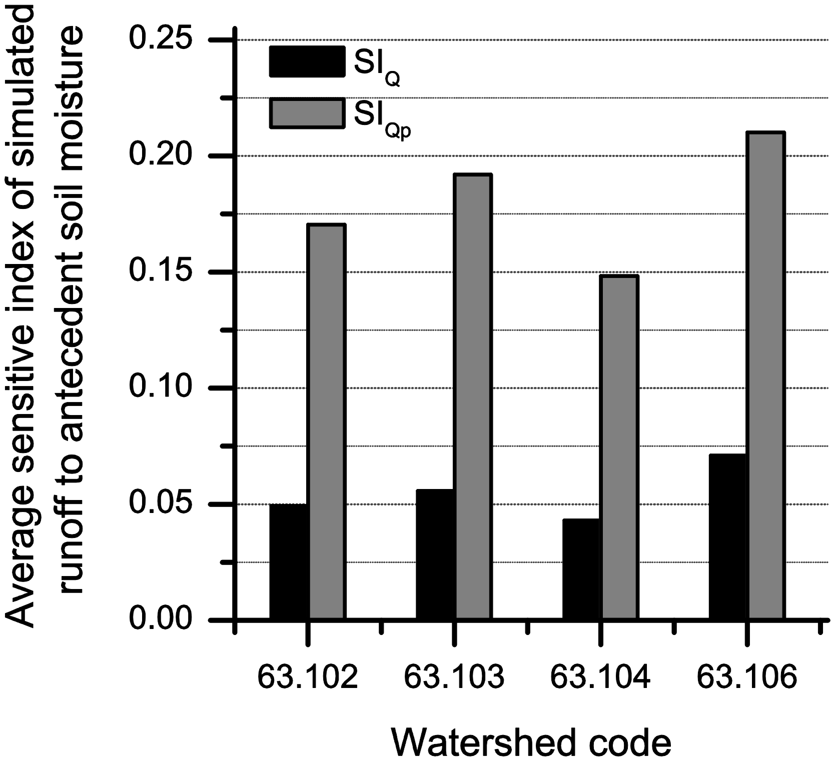

Fig. 6. Average sensitivity indices of simulated runoff volume (SI_Q) and peak (SI_{Qp}) to antecedent soil moisture in the Lucky Hills watersheds. SI_Q and SI_{Qp} represent the change in runoff volume (mm) and peak ($mm\,h^{-1}$) with each 1 % change in antecedent soil moisture.

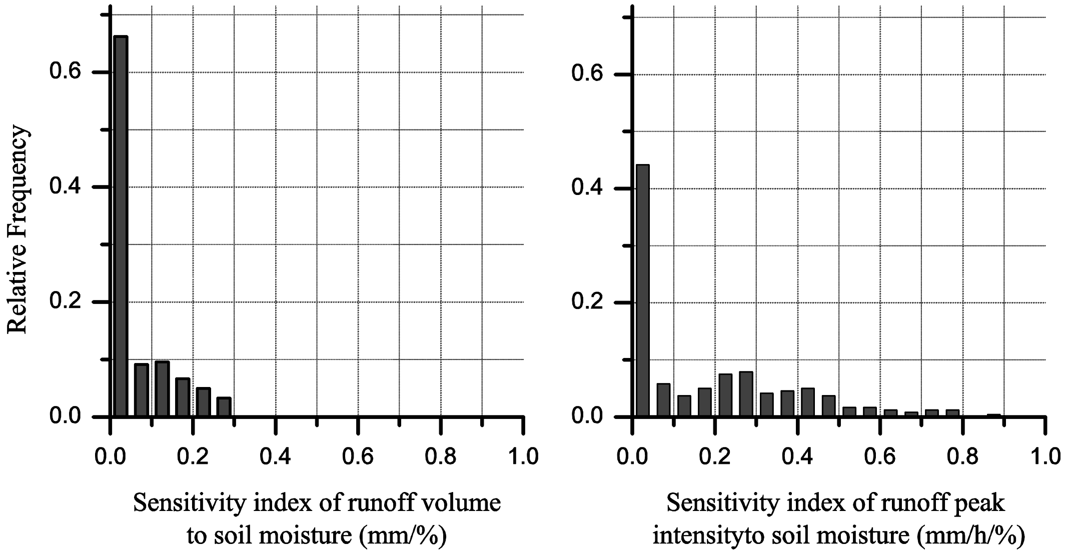

Fig. 7. Frequency distribution of the sensitivity index of simulated runoff volume (SI_Q, left) and peak (SI_{Qp}, right) to antecedent soil moisture. SI_Q and SI_{Qp} represent the change in runoff volume (mm) and peak ($\mathrm{mm\,h^{-1}}$) with each 1 % change in antecedent soil moisture.

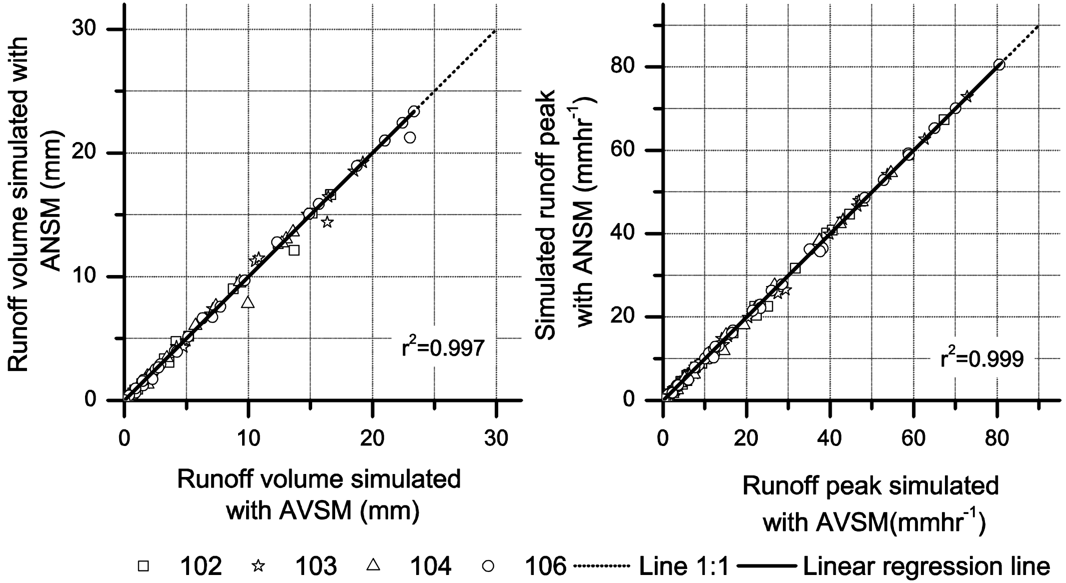

Fig. 8. Comparison of runoff volume simulated using antecedent soil moisture for each event (ANSM) and with the long-term average soil moisture (AVSM) as model input.

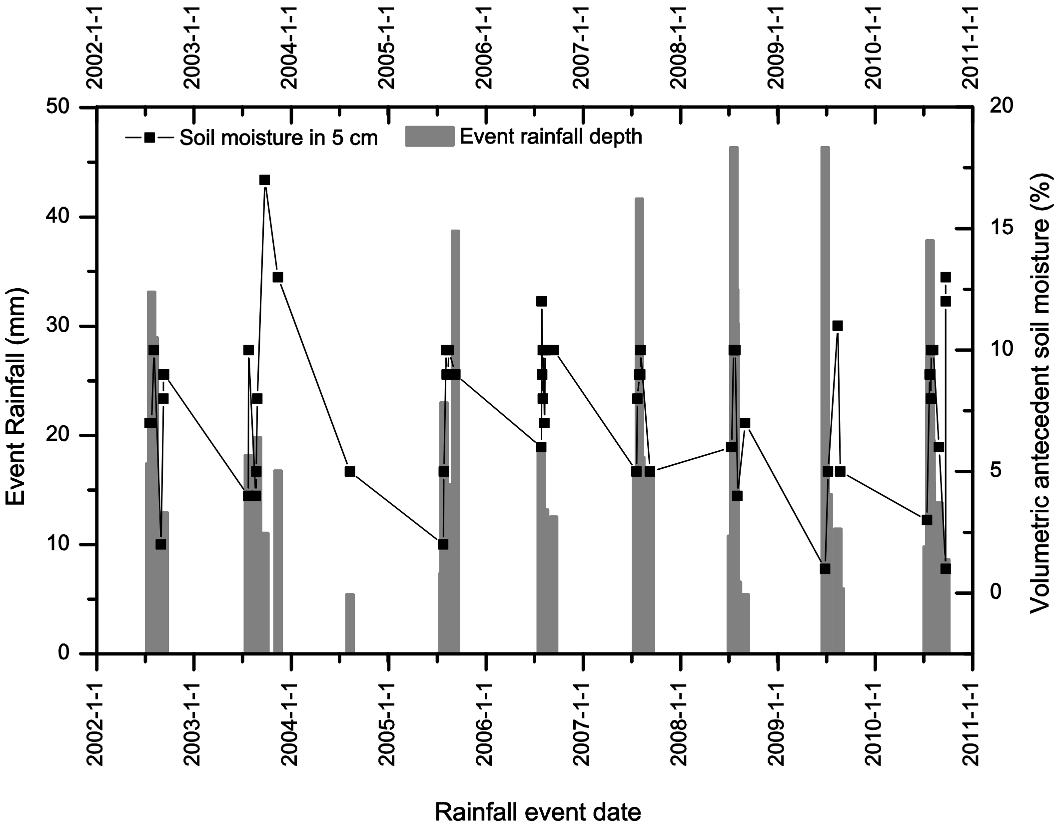

Fig. 9. Rainfall and volumetric antecedent soil moisture of all the 60 rainfall events recorded in Lucky Hills from 2002 to 2010.