809

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Hydrologic Effects of Brush to Grass Conversion

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Abstract

A physically based rainfall-runoff model is used to detect hydrologic response to artificially induced vegetation changes on a semiarid watershed. Model parameters are optimized using a subset of rainfall-runoff events from the period prior to the induced changes. Simulated results are produced by both the mathematical model and a paired watershed regression relationship. Anomalous model results are explained making use of the regression results. Model error is partially attributed to small changes in hydrologic response and the selection of the optimization set.

Introduction

Two approaches have been used to evaluate the effects of land use change on the hydrologic regime of a watershed. The most common has been to instrument paired watersheds and to establish regression relationships between hydrologic variables during a calibration period. After treatment, the observed variables on the treated watershed are compared with those predicted by regression from the control watershed to determine the effects. Mathematical models provide an alternative method. The model parameters are estimated by optimization techniques using data obtained during the pretreatment period. After treatment, the observed variables are compared with those predicted by the model to determine the effects of the change. The mathematical modeling approach requires less data but will have limited success in detecting small changes because the

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coefficient of determination between observed and model predicted hydrologic variables is usually smaller than for paired watersheds.

The rainfall-runoff model KINEROS [Woolhiser et al. (in press)] has achieved considerable success in estimating surface runoff from small semiarid watersheds as indicated by the Nash-Sutcliffe efficiency statistic (Nash and Sutcliffe 1970). The purpose of this study is to determine if the KINEROS model can detect changes in runoff volumes due to conversion of a small watershed from brush to grass.

Description of Watersheds and Treatments

Data from two watersheds located within the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Walnut Gulch Experimental Watershed in southeastern Arizona (Renard 1970) were used in this study. Lucky Hills Watershed 106 (LH-106) has an area of 0.89 acres (0.36 ha). Runoff is measured with a 3 ft. (0.91 m) H-flume and records are available since 1965. Lucky Hills Watershed 102 (LH-102) has an area of 3.61 acres (1.46 ha) and is adjacent to LH-106. Runoff has been measured with a Santa Rita type flume (Smith et al. 1982) since 1973. Rainfall is measured with weighing-type recording rain gages. Average annual rainfall for the period of record is 11.03 in. (280 mm). Soils on both watersheds are texturally classified as sandy loams. Surface runoff generally occurs during the months of July, August, and September and is caused by intense, short duration thunderstorms.

LH-106 was treated with the herbicide tebuthiuron (*N*-[5-(1,1-dimethylethyl)-1,3,4-triadiazol-2-yl]-*N*,*N'*-dimethylurea) in Feb. 1981 at a rate of 0.75 lb/acre (0.84 kg/ha) active ingredient to kill the woody plants. The dominant woody species were creosotebush (*Larrea divaricata* cav.), whitethorn (*Acacia constricta* Benth.) and tarbush (*Flourensia cernua* DC.). A 1984 evaluation of transects on LH-106 and LH-102 showed that virtually all of the woody plants had been killed on LH-106 and that the canopy cover was 12% compared with 46% for LH-102. Although no pretreatment canopy measurements were made on LH-106, the canopy cover should have been very close to the 46% measured on LH-102 in 1984.

In June 1984 both watersheds were seeded to a mixture of grasses and forbs. Seeding was accomplished with a land imprinter (Dixon and Simanton 1980) which created small runoff areas and adjacent depressions. These imprints were obliterated by erosion and deposition after about 2 years. An evaluation of the transects in 1986 showed total canopy cover to be 30 and 36% for LH-106 and LH-102, respectively. Of this total 19 and 2% were grasses established by reseeding. The most abundant species were Lehmann lovegrass (*Eragrostis lehmanniana* Nees) and Cochise lovegrass (*Eragrostis lehmanniana* Nees x *E. trichophora*). The highest density of grass was in the small first order channels. A much earlier and better stand of grass was achieved on LH-106 and it has persisted longer than on LH-102. Neither watershed has been grazed by domestic livestock since 1965 but rabbits have grazed both watersheds heavily since seeding and have contributed significantly to the near depletion of the grass on LH-102.

Analysis of Data

Rainfall and runoff data for watersheds LH-106 and LH-102 are shown in Table 1. These data demonstrate the low mean and the large year to year variability of annual runoff from these semiarid rangelands. In the modeling analysis and the paired watershed analysis described in the subsequent text, only storms with runoff greater than 0.01 inch (0.254 mm) were used. These storms accounted for 92 and 89% of the total runoff for watersheds LH-106 and LH-102, respectively.

The event-oriented, physically-based, distributed rainfall runoff model, KINEROS, was used to model runoff from both LH-106 and LH-102. A detailed description of this model is provided elsewhere [Woolhiser et al. (in press)]. Watershed geometry is represented as a cascade of planes and channels and the Smith-Parlange infiltration model (Smith and Parlange 1978) is used in an interactive manner at each computational node to determine surface runoff rates. Parameters required include: interception depth, saturated hydraulic conductivity, K_s, a parameter related to the sorptivity (G), soil porosity, rock content, Manning's n, and geometry of the planes and channels. The daily water balance component of the chemical transport model, CREAMS (Knisel 1980) was run for the period of record to provide an estimate of the initial soil water content at the beginning of each runoff producing rainfall event.

A topographic map with a one ft. (0.3048 m) contour interval was used to determine the geometry of the 23 planes and seven channels used to describe the surficial characteristics of the watershed. Soil texture and rock content were determined at six locations and initial estimates of G and K_s were obtained from regression relationships and from values in tables presented by Rawls et al. (1982). Manning's n values were estimated from tables in Woolhiser et al. (in press). Channel cross section geometry was obtained by field measurement. Optimization techniques were used to provide the best fit to pretreatment events. Ten pretreatment events with runoff volumes greater than 0.01 in. (0.254 mm.) were selected as an optimization set. They were chosen to cover the range from

TABLE 1. Annual Precipitation and Runoff for LH-106 and LH-102.

	Annual Rainfall		Runoff			
			LH-106		LH-102	
Year	in.	(mm)	in.	(mm)	in.	(mm)
1973	10.33	262.4	0.75	19.1	0.72	18.3
1974	14.19	360.4	1.17	29.7	1.16	29.5
1975	11.84	300.7	2.69	68.3	2.48	63.0
1976	10.21	259.3	0.34	8.6	0.38	9.7
1977	15.91	404.1	1.78	45.2	2.02	51.3
1978	17.21	437.1	0.24	6.1	0.35	8.9
1979	9.82	249.4	0.06	1.5	0.08	2.0
1980	4.86	123.4	0.16	4.1	0.15	3.8
1981	10.80	274.3	1.17	29.7	0.92	23.4
1982	8.90	226.1	1.25	31.8	0.79	20.1
1983	17.08	433.8	1.12	28.5	0.83	21.1
1984	15.43	391.9	2.21	56.1	2.36	59.9
1985	11.52	292.6	0.88	22.4	1.19	30.2
1986	10.86	275.8	0.72	18.3	0.98	24.9
1987	7.54	191.5	0.07	1.8	0.26	6.6
mean	11.77	299.0	0.97	24.6	0.98	24.9
std. dev.	3.57	90.7	0.79	20.1	0.77	19.6
Pretreatment period (1973-80)						
mean	11.80	299.7	0.90	22.9	0.92	23.4
std. dev.	3.94	100.1	0.93	23.6	0.90	22.9
Tebuthiuron treatment (1981-83)						
mean	12.26	311.4	1.18	30.0	0.84	21.3
std. dev.	4.28	108.7	0.07	1.8	0.06	1.5
Grass/imprint (1984-87)						
mean	11.34	288.0	0.97	24.6	1.20	30.5
std. dev.	3.24	82.3	0.90	22.9	0.87	22.1

small to large storms, from dry to wet initial conditions and from simple to complex storm rainfall intensity patterns. The number of events chosen was a compromise; a larger number of events would lead to a better calibration but computational time for multivariate optimization quickly becomes a limiting factor. It was assumed that the relative values of K_s and n were correct so the parameters to be optimized were multipliers of K_s and n. The Nash-Sutcliffe (Nash and Sutcliffe 1970) efficiency criterion, E, was used as the objective function:

$$E = 1 - \sum_{i=1}^{N} \left(Q_{oi} - Q_{si}\right)^2 / \sum_{i=1}^{N} \left(Q_{oi} - Q_o\right)^2 \qquad (1)$$

where Q_{oi} is the observed runoff volume for the *ith* event, Q_{si} is the simulated value and Q_o is the mean of the observed values for the set of N events. An efficiency value of 0.92 for runoff volume was achieved for the optimization set. For a set of 30 verification events during the pretreatment period, a statistic of 0.93 for volume was obtained. Scatter plots of simulated runoff volumes versus observed values for the optimization set and the verification runoff events at LH-106 are shown in Figures 1a and 1b. The computed versus observed points cluster very close to the 1:1 line for the optimization set but the model has a tendency to overpredict the volume for the verification set. The fact that the two largest events are in the verification set may account for some of this bias.

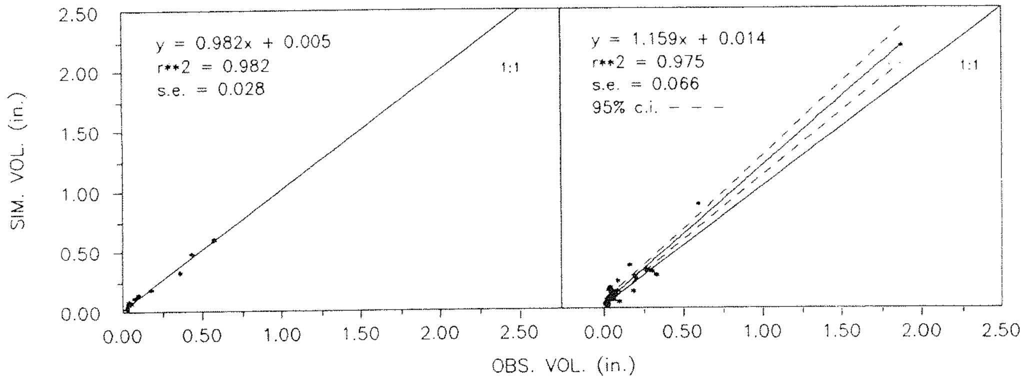

Figure 1a. Simulated versus observed runoff volumes for pretreatment period (1973–80) optimization events for LH106.

Figure 1b. Simulated versus observed runoff volumes for pretreatment period (1973–80) verification events for LH106.

The KINEROS model was used to estimate runoff hydrographs for the period 1981-83 when LH-106 was nearly devoid of living vegetation and for the period 1984-87 when grass had become established. The same parameters and watershed geometry used during the pretreatment period were used in both KINEROS and CREAMS so the model results could be interpreted as estimates of runoff that would have occurred without treatment. There is some evidence that vegetation changes in this rainfall zone will result in very small (Simanton et al. 1977) or undetectable changes in runoff (Bosch and Hewlett 1982). From physical reasoning we might expect an increase in runoff during the 1981-83 period due to higher initial soil water content, reduced interception by the brush canopy, and possible deterioration of surface soil structure followed by a decrease in runoff during the 1984-87 period due to increased interception, increased depression storage and higher infiltration rates as a result of land imprinting effects and better cover. It is recognized that these changes are transient but in our analysis we will assume that the changes occur in a stepwise manner.

Plots of simulated versus observed runoff volumes for the period 1981-83 at LH-106 are shown in Figure 2 and in Figure 3 the same variables are plotted for the period 1984-87. We note that the range of runoff volumes for the period 1981-83 is rather restricted, with all events being smaller than 0.5 in. (12.7 mm). More simulated events are above the line of equality than below so we might conclude from a quick inspection of Figure 2 that runoff *decreased* during this period. For the period 1984-87 (Figure 3) we would conclude that there was a substantial decrease in the runoff volumes. If we examine the relationships between measured runoff at LH-106 and LH-102 we have a different interpretation. A double mass plot of annual runoff from LH-106 and LH-102 is shown in Figure 4. An examination of this figure suggests that runoff increased on LH-106 relative to LH-102 during 1981-83 followed by a relative decrease for the period 1984-87. We calculated the regression relationship between the runoff volumes for all events greater than 0.01 in. (0.254 mm) from LH-106 during the pretreatment period and concurrent runoff volumes for LH-102 and calculated the 95% confidence region for the true regression line. The same procedure was followed for the samples from the 1981-83 period and the 1984-87 periods. The hypothesis of equality of runoff for LH-106 and LH-102 could not be rejected for the pretreatment period and for the 1984-87 period. The changes indicated by the regression analyses were consistent with the double mass plot. The question thus arises "Why do the model results apparently differ from the results we infer from an analysis of paired watershed data?"

To answer this question we first examine Figure 1b and note that for the verification set the model *overestimates* runoff. This overestimation is especially pronounced if we consider the runoff events with volume less than 0.5 in. (12.7 mm) where many more points are above the 1:1 line than are below it. Thus we would expect the model estimates to be biased high even if the watershed had not been treated. If there had been an increase in the runoff from LH-106 during the 1981-83 period the model might still show an overprediction, provided the increase was small. To examine this factor more closely we used KINEROS to estimate runoff from LH-102. The watershed geometry was modeled with 51 planes and 17 channels and optimization

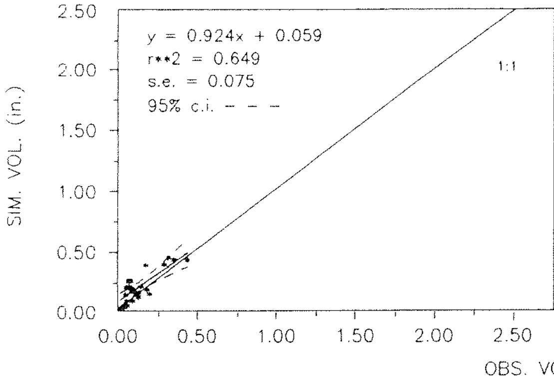

Figure 2. Simulated versus observed runoff volumes for Tebuthiuron treatment period (1981–83) for LH106.

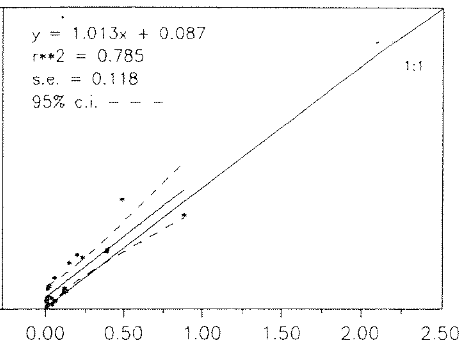

Figure 3. Simulated versus observed runoff volumes for imprint/grass establishment period (1984–87) for LH106.

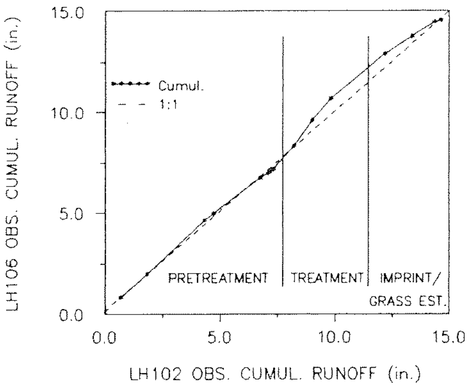

Figure 4. Double Mass curve of accumulated annual volume of runoff at LH106 versus LH102.

procedures were identical to those used for LH-106. The errors of estimation $Q_{si} - Q_{oi}$ for LH-106 versus the errors for LH-102 for the 1973-80 pretreatment period as well as the 1981-83 and 1984-87 periods are shown in Figures 5a-5c. These errors are highly correlated. Points appear to shift downward during the 1981-83 tebuthiuron period and upward during 1984-87 grass establishment period. These shifts indicate an increase in runoff for LH-106 relative to LH-102 for the 1981-83 period and a decrease in the following period.

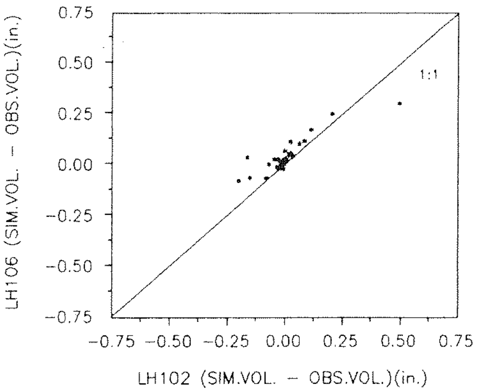

Figure 5a. Simulation errors for LH106 versus simulation errors for LH102, pretreatment period (1973-80).

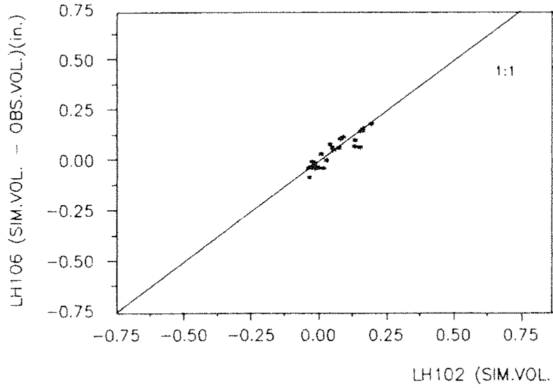

Figure 5b. Simulation errors for LH106 versus simulation errors for LH102, Tebuthiuron treatment period (1981-83).

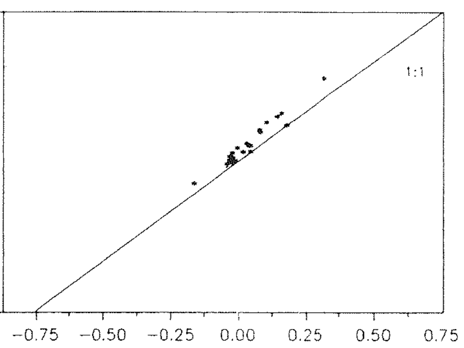

Figure 5c. Simulation errors for LH106 versus simulation errors for LH102, imprint/grass establishment period (1984-87).

Discussion and Conclusions

The objective of this study was to determine if a physically based rainfall runoff model could be used to detect changes in the runoff regime due to vegetation changes in a small semiarid watershed. Analysis showed that model predictions can be misleading if the model parameters are estimated from a small subset of the pretreatment runoff data and the changes in runoff volumes are small. When model errors for the treated watershed were compared with those for an adjacent watershed we found that the apparent inconsistency between model results and data disappears. However, this insight could only be gained because paired watershed data were available.

Part of the modeling error is due to the fact that the two largest events were not in the optimization set. We have also found that model results can be improved by using two raingages instead of one gage to provide rainfall input and by accounting for the small scale spatial variability of the saturated hydraulic conductivity within a plane element.

The results of this study support those of Langford and McGuinness (1976) who found that the standard error of estimate for a model is greater than that for paired basins. Our results are also consistent with the conclusions of Simanton et al. (1977) whose analysis suggested runoff decreases due to brush to grass conversion and the conclusions of Ffolliott and Thorud (1977) and Hibbert (1983) that brush to grass conversion should result in no significant increases in water yield from semidesert shrublands.

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