IDENTIFYING CAUSE OF DECLINING FLOWS IN THE REPUBLICAN RIVER

By Jozsef Szilagyi[1]

ABSTRACT: The Republican River, shared by three states, Colorado, Nebraska, and Kansas, has yielded depleted streamflow at the Nebraska-Kansas border for about 20 years when compared to values preceding 1970. Based on model results estimating the average annual water balance of the basin, it is concluded that the observed decline in runoff cannot be explained by changes in climatic variables over the area; rather, it is the result of the combined effects of the following human activities: crop irrigation, change in vegetative cover, water conservation practices, and construction of reservoirs and artificial ponds in the basin. These human-induced changes have one property in common: they all increase the amount of water being evaporated over the basin, thereby reducing the amount of water available to runoff.

INTRODUCTION

The Republican River basin's 57,599-km^2 drainage area is shared by three states: Colorado, Nebraska, and Kansas (Fig. 1). Nebraska has the largest single share of the drainage area, 22,464 km^2 (39% of total); Colorado can claim about 17,855 km^2 (31%), and the rest, about 17,280 km^2 (30%), belongs to Kansas [U.S. Department of Agriculture (USDA) 1978], from which about 11,520 km^2 (20%) lies upstream of Hardy, Neb., near the Nebraska-Kansas border.

In the past decades, significantly reduced flows have been recorded in practically all tributaries of the basin, including the main-stem Republican River itself (Szilagyi 1999). Fig. 2 shows the observed decline in runoff at the Nebraska-Kansas border near Hardy. It combines annual discharges in the Republican River with discharges measured in the Courtland Canal, which diverts irrigation water from the river in Nebraska across the border to Kansas.

Dwindling surface water in the basin has alarmed farmers in all three states sharing the Republican River's water for crop irrigation. A question arises about whether the observed decline in the river flow is a consequence of human activity, most prominently irrigation practices, or a naturally occurring phenomenon attributable to decadal cycles in climatic variables. To pinpoint the cause of the decline in surface water resources is of some significance, because it paves the way to attempts at alleviating the problem. For example, if the reduction in streamflows is of a natural cause, then it may be futile to expect to return to flow levels observed in the past, even if steps are taken to curb consumptive water use in the basin. On the other hand, if the decline in runoff is clearly attributable to an increase in human-triggered consumptive water use, then historical flow values may serve as a guide in evaluating the effect of new water conservation measures.

This study aims to investigate the cause of the observed decline in surface runoff in the Republican River basin. More specifically, it attempts to verify whether the observed reduction in runoff between two 20-year periods (i.e., 1949–1968 and 1977–1996) is explainable solely by changes in climatic variables or not. An answer to this dilemma is especially important before the states sharing the Republican River basin lay claims accusing each other of overexploitation of the basin's surface water. Note, however, that this study considers the Republican River basin as the unit of water balance investigations. The conclusions put forward in this study are strictly valid for the entire basin as a whole; therefore, no state- or any subregion-specific subconclusions can be drawn from this study alone.

DATA ANALYSIS

The decline in runoff values at the Nebraska-Kansas border (Fig. 2) over two 20-year periods (i.e., 1949–1968 and 1977–1996) is accompanied by a similar reduction in the runoff ratio values (Fig. 3). Runoff ratio is the percent of precipitation that emerges as runoff. This ratio for the Republican River is very small; only 1–2% of the annual precipitation contributes to annual runoff. This means that a slight change in the hydroclimatic variables may cause a significant change in runoff according to (Wigley and Jones 1985)

$$ro = \frac{p - (1 - rr)et}{rr} \tag{1}$$

where ro = relative change (i.e., the ratio between the disturbed and undisturbed values) in runoff as a function of relative changes in precipitation p and evapotranspiration et; and rr = runoff ratio. For example, if rr is 0.02, then a 1% decrease in precipitation results in a 50% decrease in runoff, assuming evapotranspiration did not change. Unfortunately, (1) cannot be used for diagnostic purposes (e.g., to predict changes in evapotranspiration between the two periods investigated) because the runoff ratio clearly changed significantly between the two 20-year periods (Fig. 3) in the Republican River basin. Still, (1) demonstrates that any slight change in precipitation

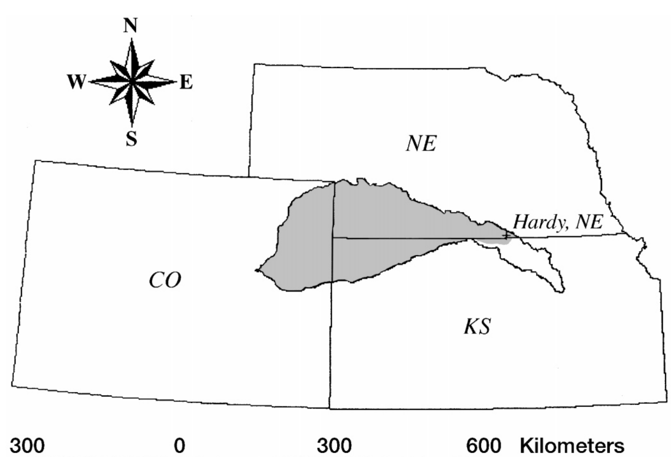

FIG. 1. Republican River Basin; Shaded Part Designates Contributing Drainage Area above Hardy at Nebraska-Kansas Border

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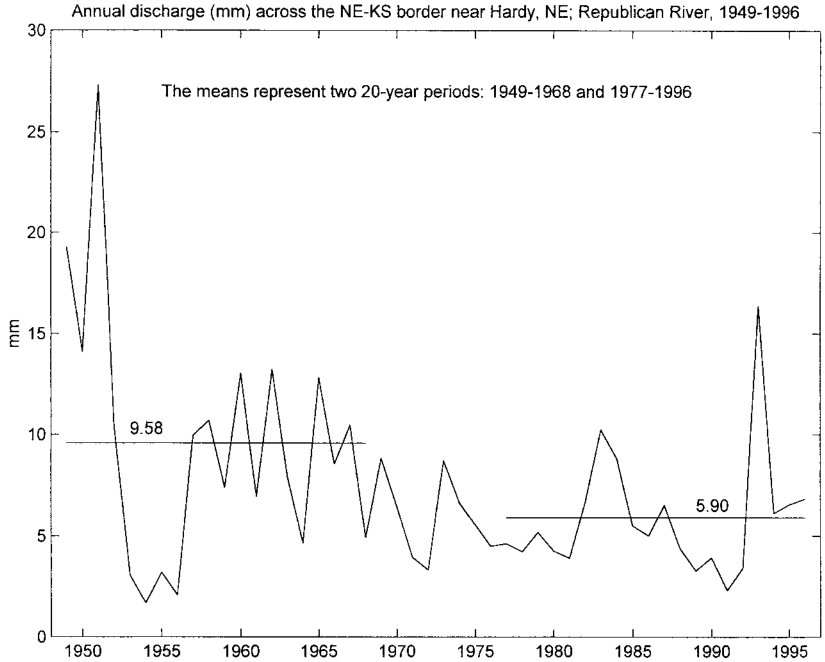

FIG. 2. Annual Discharge (mm) across Nebraska-Kansas Border, near Hardy (Numerical Values in Graph Are Mean Annual Runoff in Two Distinct 20-Year Periods: 1949–1968 and 1977–1996, Respectively)

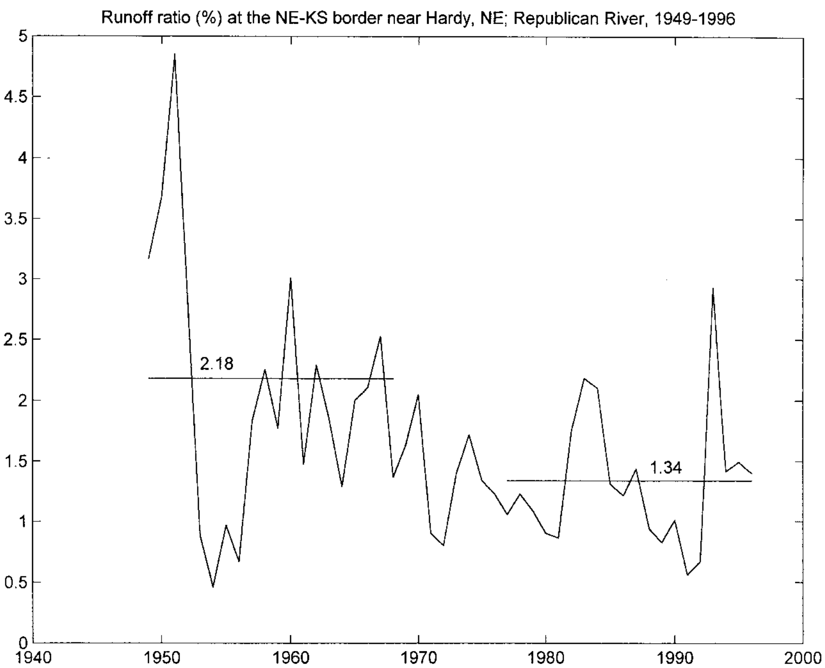

FIG. 3. Annual Runoff Ratios (%) at Nebraska-Kansas Border near Hardy

or evapotranspiration or both must have an amplified effect on runoff in a small runoff ratio case, such as the Republican River basin.

To detect changes in precipitation over the basin, seven stations have been selected from the National Climatic Data Center cooperative station network. The criterion for the station selection were to have the maximum length of continuous data with the minimum number of days with missing data. The longest continuous records of daily precipitation measurements in the basin started in the fall of 1948. The search resulted in seven stations where the average number of days with missing data is <5% of the total record. Fig. 4 displays the names and locations of the precipitation stations within the Republican River basin. In addition to the precipitation stations, three stations with long-term, reliable temperature measurements were also selected from the same source and displayed in Fig. 4.

The results of the data analysis are summarized in Figs. 5–8. Annual precipitation remained virtually unchanged at 440 and 441 mm, respectively, for the two 20-year periods (Fig. 5). This is in accordance with Lettenmaier et al. (1994). Note that, for the calculation of the basin-representative annual precipitation values, the Thiessen-polygon [e.g., Maidment (1993)] technique was applied. Although the mean annual pre-

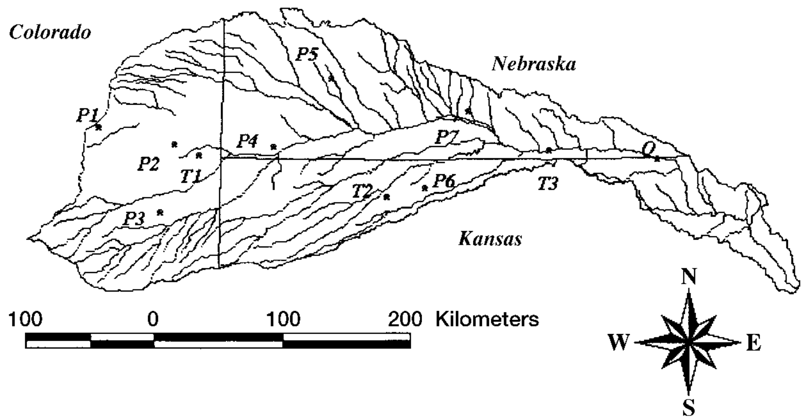

FIG. 4. Locations of Precipitation P, Temperature T, and Discharge Q Measurements: P1 = Akron, Colo.; P2 = Eckley, Colo., P3 = Joes, Colo.; P4 = Benkelman, Neb.; P5 = Hayes Center, Neb.; P6 = Norcatur, Kans.; P7 = Edison, Neb.; T1 = Wray, Colo.; T2 = Oberlin, Kans.; T3 = Franklin, Neb.; and Q = Hardy

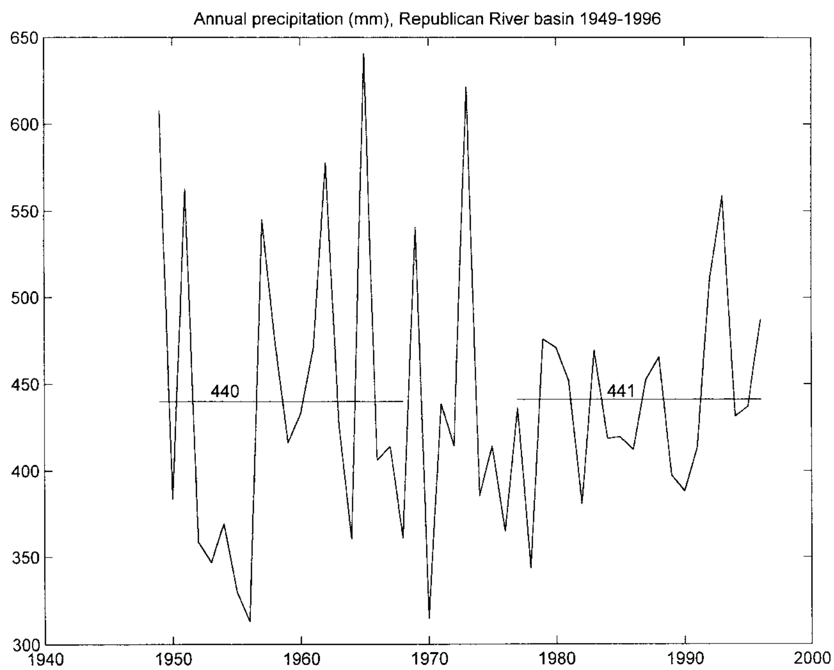

FIG. 5. Annual Precipitation (mm), Republican River Basin above Hardy

cipitation did not change in the past 50 years or so, its distribution within a year clearly did. In the first 20-year period, there were on average 115 precipitation events in the basin. A precipitation event or storm is defined as the period of rainy days in straight succession, and as such, the minimum length of a precipitation event/storm is 1 day. Although in the first period a mean storm frequency of 115 can be observed, in the second period this increases to 126 year^{-1} (Fig. 6). This means that lately the same amount of annual precipitation has been caused by a larger number of storm events per year, which means less precipitation per storm, which in itself can have an effect, although not trivial, on runoff. Although less precipitation per storm may reduce runoff, a shortened mean period between storms results in higher levels of soil moisture which would, on the other hand, enhance runoff. To help resolve this ambiguity, a Monte Carlo-simulation based daily water-balance model (Milly 1994) is applied for the Republican River basin. The application of some kind of a model to explain watershed response to climatic changes is further justified because of changes in other climatological variables within the basin.

The mean annual temperature of the watershed rose from 10.5° to 10.8°C between the two periods (Fig. 7). An increasing trend in annual mean temperature in the study area is corroborated by Lettenmaier et al. (1994). This translates into an increase in the potential evapotranspiration (PET) values, which, applying the Jensen and Haise (1964) equation, can be estimated

$$\mathrm{PET} = (1.6742 \cdot 10^{-2})R(0.014(1.8T + 32) - 0.37) \quad (2)$$

where R = incident solar radiation (calorie cm^{-2} day^{-1}); T = mean monthly air temperature (°C); and PET is in millimeters per day. In lieu of measured radiation data, an estimate of R can be obtained the following way (Prescott 1940):

$$R = R_e\left(a + b\left(\frac{BS}{DL}\right)\right) \quad (3)$$

where R_e = extraterrestrial radiation in the same units as R; a and b = dimensionless empirical constants; BS = number of hours with bright sunshine; and DL = number of daylight hours. In general, a and b depend on location, season, and the

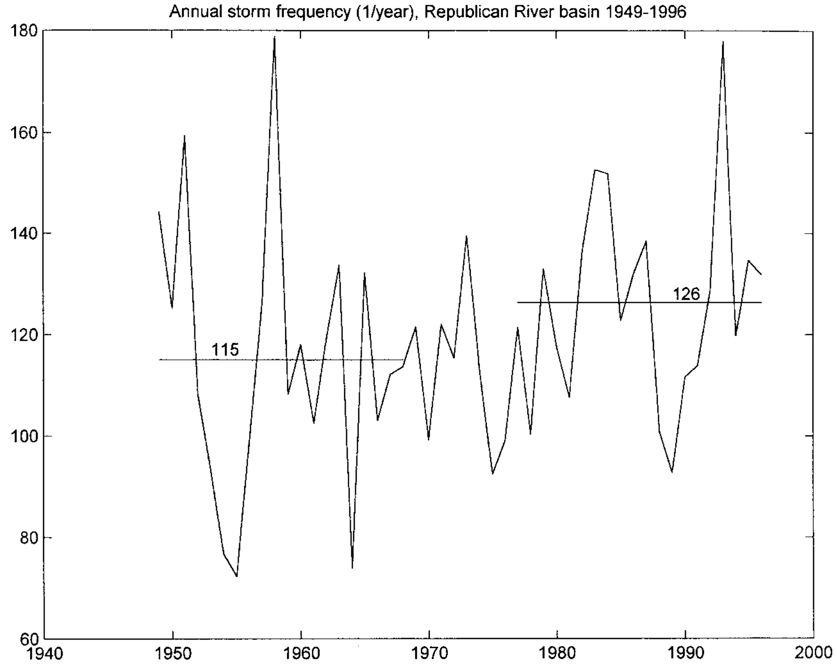

FIG. 6. Annual Storm Frequency (1/year), Republican River Basin above Hardy

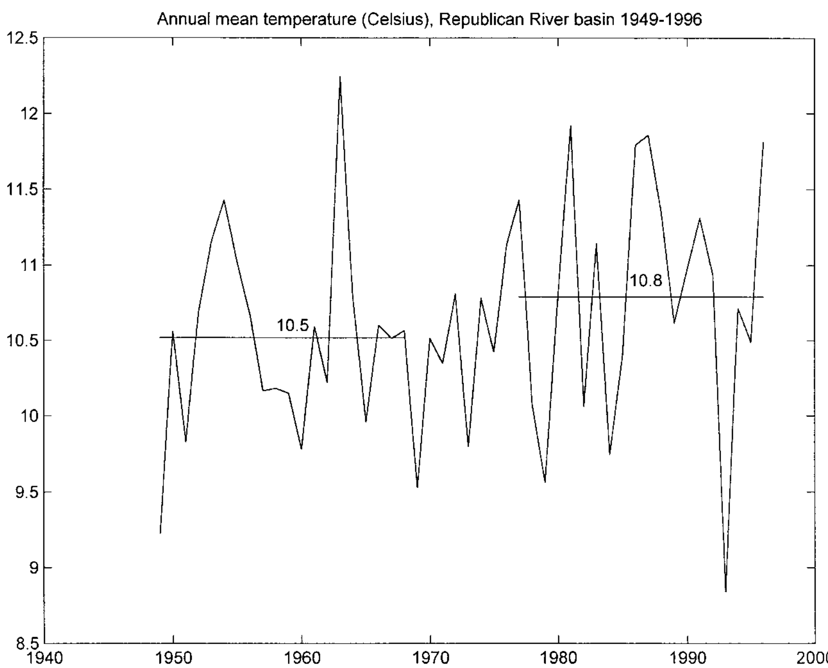

FIG. 7. Annual Mean Temperature (°C), Republican River Basin above Hardy

state of the atmosphere (Brutsaert 1982), and R_e and DL depend on latitude and time of the year. Estimated average values of a and b for selected locations as well as R_e values as a function of latitude and time of year can be found in Brutsaert (1982). Fig. 8 demonstrates the increase in mean annual PET between the two periods. An increase in PET values entails an increase in the atmosphere's ability to absorb more of the water in it, which, under unchanged mean soil moisture and land-cover conditions, would result in enhanced evapotranspiration from the basin.

The above changes in hydrometeorological variables necessitate the application of a water-balance model to quantify watershed response in terms of mean annual runoff and the runoff ratio. More specifically, the main objective of this study is to check if the above-mentioned changes in precipitation, temperature, and PET alone can explain the observed significant decline (about 40%) in mean annual runoff (Fig. 2) between two 20-year periods in the past half century.

MODEL APPLICATION

Milly (1994) presented an approach to estimating relationships between climate, soil-water storage, and average annual water balance. In this study, his model is applied to the Republican River basin above Hardy, using hydro-climatic data from the two distinct 20-year periods (i.e., 1949–1968 and

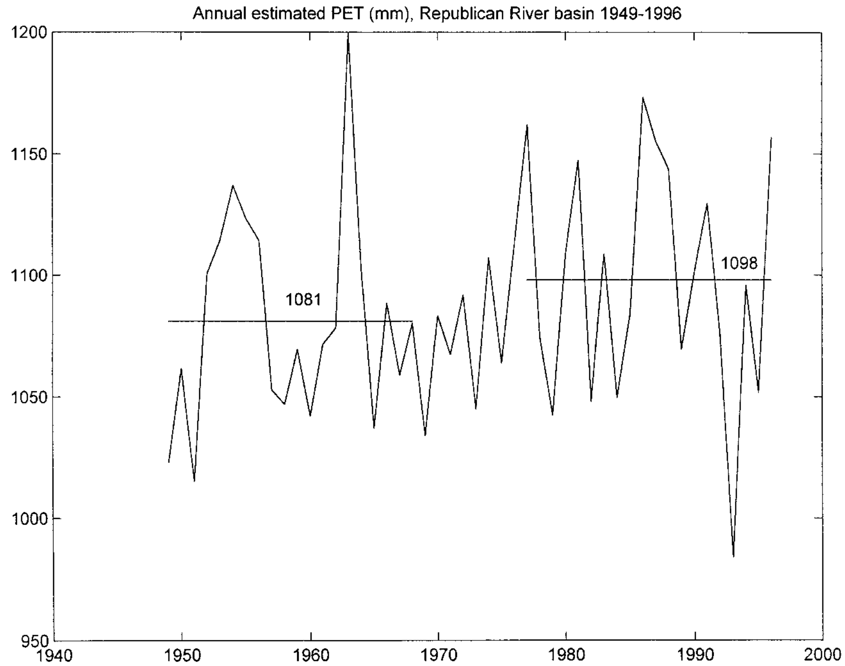

FIG. 8. Annual Estimated PET (mm), Republican River Basin above Hardy

1977–1996). A detailed description of the model can be found in Milly's paper (1994); the basic assumptions and building blocks of the model are summarized below with a detailed explanation of how it was applied to the study area.

The model assumes that (1) the soil is permeable enough to exclude ''saturation from above'' of the soil during storm events; (2) evapotranspiration occurs at its potential level while soil moisture is above the permanent wilting point of the vegetation; (3) any soil moisture in excess of the field capacity of the soil will contribute to runoff; and (4) there is no water contribution to runoff from the soil when its moisture content is below its field capacity value. With regard to these assumptions, the water balance of the soil is formulated as follows:

$$\frac{dw}{dt} = 0, \quad \text{if } P > \text{PET and } w = w_0 \tag{4a}$$

$$\frac{dw}{dt} = 0, \quad \text{if } P < \text{PET and } w = 0 \tag{4b}$$

$$\frac{dw}{dt} = P - ET, \quad \text{otherwise} \tag{4c}$$

where w = water content of the soil in excess of the permanent wilting point (L); w_0 = plant available water (L), defined as the difference between the water contents at field capacity and at the permanent wilting point; P = precipitation depth (L); and dt is 1 day. From Assumption (1), (4a), and (4b), it follows that the daily evapotranspiration ET in the model is estimated as

$$ET = \min(\text{PET}, P + w) \tag{5}$$

where min stands for the minimum of the two values. Daily runoff in the model is estimated by means of closing (4) and (5) with the help of the lumped mass conservation equation of the soil

$$\frac{dw}{dt} = P - ET - RO \tag{6}$$

where RO is runoff (L).

The plant available water w_0 can be calculated (Milly 1994)

$$w_0 = \int_0^{\infty} [SM_{FC}(z) - SM_{WP}(z)]\alpha(z)\, dz \tag{7a}$$

where SM_{FC} and SM_{WP} = soil moisture content values at field capacity and at the permanent wilting point of the vegetation, respectively; and α = fraction of area at depth z that is affected by the root system of the vegetation. Often $\alpha(z)$ is approximated as having a value of unity from the surface to a depth (i.e., the rooting depth RD of the vegetation) below which $\alpha(z)$ is thought to vanish (Milly 1994). In this case (7a) transforms into

$$w_0 = \int_0^{RD} [SM_{FC}(z) - SM_{WP}(z)]\, dz \tag{7b}$$

which, after finding a representative mean value for the two soil moisture contents, can be written

$$w_0 = RD(\downarrow SM_{FC} - \downarrow SM_{WP}) \tag{7c}$$

where the arrow designates averaging along the vertical direction. Although $\downarrow SM_{FC}$ is generally taken to be a function of physical soil texture only, RD (L) is a function of both physical soil type and vegetation cover. Combining geographic information system layers of vegetation type and physical soil texture, a mean rooting depth of 1.15 m and a $\langle \downarrow SM_{FC} \rangle$ value of 0.28 were obtained (Thornthwaite and Mather 1957; Rawls et al. 1983). The angle bracket designates a spatial averaging over the basin. Using these values, plus assuming that $\downarrow SM_{WP}$ can be estimated as one-half of $\downarrow SM_{FC}$ (Linsley et al. 1992), a mean plant available water $\langle w_0 \rangle$ of 161 mm was derived for the Republican River basin.

Spatial variability over the basin in the model is taken into account by means of the probability distribution function of w_0. In case of a strong spatial variability, the probability distribution function of w_0 can be considered of an exponential type (Milly 1994)

$$f(w_0) = \lambda \exp(-\lambda w_0) \tag{8}$$

where $\lambda = \langle w_0 \rangle^{-1}$. The cumulative distribution of the n = 20 distinct w_{0i} values applied for the Republican River basin is displayed in Fig. 9. The mean runoff of the basin can be obtained (Milly 1994)

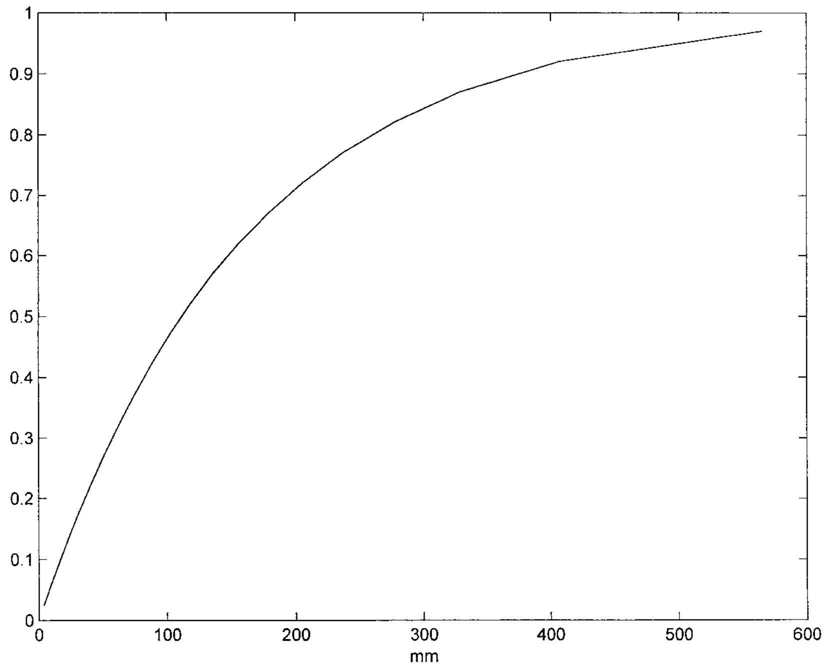

FIG. 9. Cumulative Distribution of 20 Distinct Plant-Available Water-Holding Capacity Values Applied in Model; Mean = 161 mm

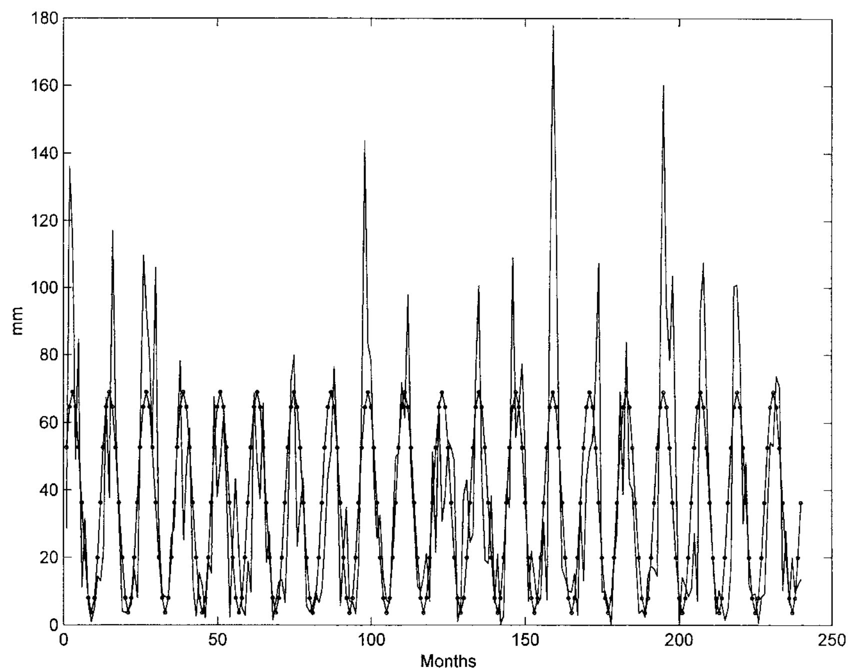

FIG. 10. Time Series of Monthly Areal Precipitation (mm), Republican River Basin, 1949–1968 (Line with Circles Illustrates How Seasonality in Variable Is Incorporated in Model)

$$\langle RO \rangle = n^{-1} \sum_{i=1}^{n} RO(w_{0i}) \tag{9}$$

provided that the w_{0i} values are located at the centers of n equal-probability sections of $f(w_0)$. The w_{0i} values can be obtained by integrating (8) to equal

$$\int_0^{w_{0i}} f(w_0)\, dw = \frac{i - 0.5}{n} \tag{10}$$

where $i = 1, \ldots, n$. The water-balance model was run repeatedly with each of the so-derived 20 distinct w_{0i} values; the resulting mean daily runoff was obtained by means of (9).

Temporal variability of precipitation P and PET is also accounted for in the model. The mean monthly values of precipitation P_m and PET_m are expressed

$$P_m(t) = \bar{P}[1 + \delta_P \sin(\omega t)] \tag{11a}$$

$$\mathrm{PET}_m(t) = \overline{\mathrm{PET}}[1 + \delta_{\mathrm{PET}} \sin(\omega t)] \tag{11b}$$

where the overbar denotes an annual average; $t = 1, \ldots, 12$; and δ_P and δ_{PET} = ratios of the amplitudes of the annual harmonics to the annual averages of P and PET and can be obtained by Fourier analysis of the monthly values with the time origin set to the end of April and $2\pi\omega^{-1}$ equal to 1 year, where

ω (T^{-1}) = circular frequency. Similarly, the mean monthly storm-arrival rate SF_m can be expressed

$$SF_m(t) = \overline{SF}[1 + \delta_{SF} \sin(\omega t)] \tag{11c}$$

where the SF_m values for each month are estimated from the daily precipitation values P_{md} (Rodriguez-Iturbe et al. 1984; Milly 1994)

$$SF_m = \frac{2(\overline{P_{md}})^2}{T[\mathrm{var}(P_{md})]} \tag{12}$$

where T = 1 day.

Figs. 10–12 illustrate how accounting for seasonal variability through (11) in the model compares with time series of monthly values of the same variables for the first 20-year period modeled. Note that negative values in Fig. 11 are the result of retaining only the annual harmonic value in the Fourier analysis. These values, however, cause no difficulties in the modeling effort and are permitted (Milly 1994) to ensure that the seasonal integrals of PET are consistent with the Jensen-Haise estimates. No day-to-day variability is allowed in the model for PET, unlike the case of precipitation, which is

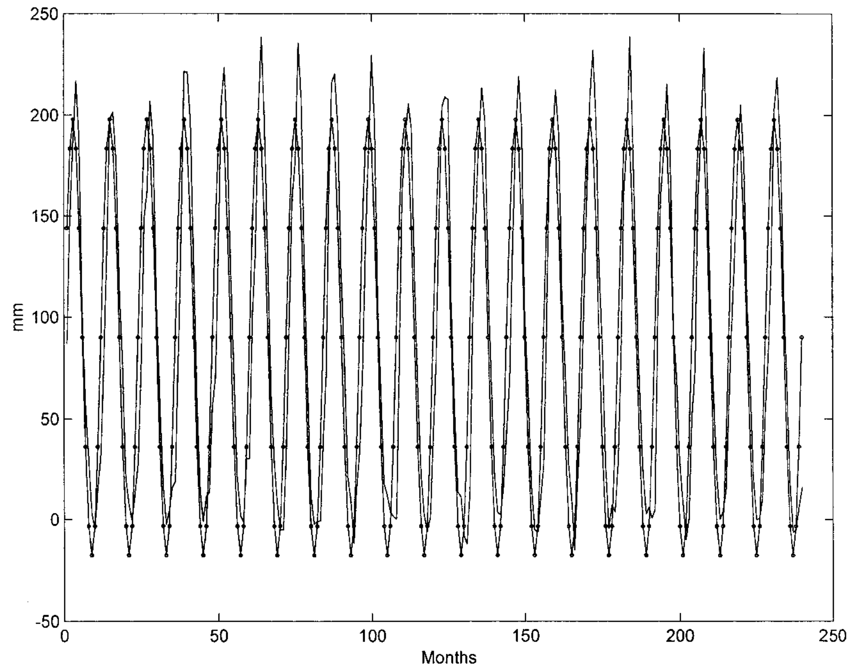

FIG. 11. Time Series of Monthly Estimated PET (mm), Republican River Basin, 1949–1968 (Line with Circles Illustrates How Seasonality in Variable Is Incorporated in Model)

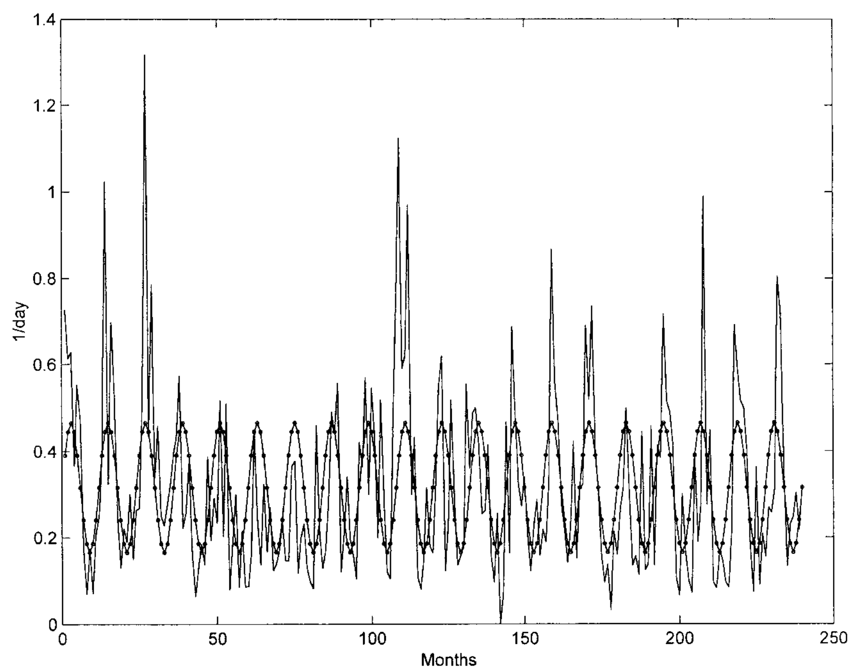

FIG. 12. Time Series of Monthly Storm Frequencies (day^{-1}), Republican River Basin, 1949–1968 (Line with Circles Illustrates How Seasonality in Variable Is Incorporated in Model)

TABLE 1. List of Model Parameters

a = 0.23; b = 0.542; BS/DL = 0.7; <RD> = 1.15 m; <$\downarrow SM_{FC}$> = 0.28; <$\downarrow SM_{WP}$> = 0.14; n = 20; <w_0> = 161 mm			
1949-1968	(1977-1996)		
$\overline{SF}$ = 0.32	(0.34) [day^{-1}];	δ_{SF} = 0.47	(0.43) [-]
$\overline{P}$ = 36.29	(36.13) [mm/month];	δ_P = 0.90	(0.79) [-]
$\overline{PET}$ = 90.06	(91.19) [mm/month];	δ_{PET} = 1.19	(1.17) [-]

TABLE 2. Measured *M* and Modeled *S* Long-Term Mean Values of Hydro-Climatological Variables for Periods 1949–1968 and 1977–1996 [Relative Error Δ (%) Is Defined as $\Delta = 100 \cdot |M - S|/M$]

1949-1968		Δ [%]	1977-1996		Δ [%]
$\overline{T}_{yr}$ = **10.5** [°C]			**10.8**		
$\overline{P}$ = **440** [mm/yr]	432*	1	**441**	434*	2
$\overline{RO}$ = **9.58** [mm/yr]	10.54*	10	**5.90**	10.55*	78
$\overline{RO/P}$ = **2.18 [%]**	2.44*	12	**1.34**	2.43*	81
$\overline{PET}$ = 1081 [mm/yr]	1085*	0.4	1098	1098*	0
$\overline{ET} = \overline{P - RO}$ = **430** [mm/yr]	421*	2	**435**	423*	3
mean storm arrival rate = **115** [1/yr]	107*	7	**126**	115*	9

Bold = measured value; * = Monte Carlo/hydrologic model-generated mean of 50-year daily values. The Jensen-Haise technique (2) was used to estimate PET.

allowed to vary on a daily basis. The amount of precipitation on rainy days is assumed to follow an exponential distribution (8), with its parameter changing according to the month of the year; i.e., $\lambda_m = P_m/SF_m$. The interstorm periods are generated by means of a Poisson process, where the probability that the number of days is k ($k = 0, \ldots, \infty$) between storm events is given by

$$P(t = k) = \frac{\beta_m^k}{k!} \exp(-\beta) \tag{13}$$

where $\beta_m = SF_m^{-1}$ (day).

The water-balance model was run repeatedly with each of the 20 different w_0 values with parameters taken first from the period 1949–1968 and then from 1977–1996. With each parameter set, the model was run for 100 years and the last 50 years were retained for further analysis. Discarding the first 50 years in both cases was necessary because of missing information on the initial soil-moisture conditions (Milly 1994) of the basin. Note that the lack of basinwide information on soil moisture prohibits the application of the model directly with the observed data and instead necessitates a Monte Carlo-type simulation, which ensures that the water-balance analysis would not be influenced by uncertainties in the initial conditions when numerically integrating (6). See Table 1 for a list of the model parameters.

MODEL RESULTS AND DISCUSSION

Table 2 summarizes the results of model simulations. For the first 20-year interval, the model-simulated long-term means of the hydro-climatic variables are practically within 10% of the means taken directly from the observed data. The observed and model-simulated long-term means of annual runoff are 9.58 and 10.54 mm, respectively, a 10% error in model accuracy for mean annual runoff. Note that both long-term mean annual precipitation (440 mm) and long-term evapotranspiration (430 mm) are recaptured by the model with a 1–2% accuracy. However, these small inaccuracies in simulating those two variables are amplified in the accuracy of the mean annual runoff (i.e., 10%) because of the small runoff ratio of about 2% in (1). In fact, the application of (1) with the observed and model-generated long-term mean annual precipitation and evapotranspiration plus observed runoff ratio values can predict the expected error in runoff due to the use of slightly inaccurate precipitation and evapotranspiration values in the model. Indeed, (1) confirms the observed 10% increase in modeled long-term mean annual runoff in comparison with the observed value.

The picture changes dramatically for the second 20-year interval. Although long-term mean annual precipitation (441 mm) and evapotranspiration (435 mm) were modeled again with rather high accuracy (i.e., 2–3%), long-term mean annual runoff and the runoff ratio were very poorly reconstructed by the model, with a corresponding error of about 80%. Note that the model predicts no changes in long-term mean annual runoff although annual mean temperature, estimated mean annual PET, model-generated mean annual precipitation, and observed and model-generated mean storm arrival rates all increased slightly in comparison with the previous model period. The explanation is that, with the slight increase of Monte Carlo-generated precipitation, the water-balance model predicted a similar slight increase in evapotranspiration. Note that, in this case, (1) predicts only a very small error (about 2%) in runoff because of inaccuracy in the modeled precipitation and evapotranspiration values. Even the direction of this predicted error by (1) in long-term mean annual runoff is the opposite of what is observed; i.e., the model overshoots runoff significantly, whereas (1) predicts a slight undershoot. A logical explanation for this contradiction is that observed runoff in the Republican River should be much larger (about what the model predicts) as a response to the hydro-climatological variables in the period 1977–1996 than what is actually observed.

As a preliminary conclusion, it can be stated here that the observed decline in runoff within the Republican River basin in the period 1977–1996 cannot be explained by the observed changes in the hydro-climatological variables within the same period. Let us now turn our attention to other possible contributing factors not yet included in the model.

Certainly many things changed in the watershed over the past 50 years. Many reservoirs and artificial ponds have been constructed in the basin. Vegetation cover has been transformed drastically from a predominantly rangeland-type landscape (i.e., prairie grass) into dry and irrigated croplands, which entailed the application of different water conservation practices that, in turn, would lead to a decrease in surface runoff. But perhaps the most important factor changing the water balance of the watershed has been the adoption of center-pivot irrigation in the basin.

In 1990 the U.S. Geological Survey (USGS) estimated the annual irrigated water depth in the basin as 26 mm. Irrigated land covers about 7% of the drainage area. From these two values it follows that irrigated crops receive an extra 370 mm a year on top of an annual precipitation of about 440 mm. Assuming 3 months of irrigation annually, this translates into 4 mm of extra water daily over the summer season for the irrigated crops. Rerunning the water-balance model with this additional source of ''precipitation,'' an extra 164 mm results in mean annual evapotranspiration over irrigated cropland on top of the basin's modeled mean annual *ET* of 423 mm. Note that irrigation itself cannot increase long-term runoff in the basin, because water is simply moved within the basin from either the channels or the ground water to the surface, where it becomes a net loss of the basin's water balance through evapotranspiration. Spreading this additional *ET* over the entire drainage area, one obtains an 11.5-mm increase in mean annual evapotranspiration for the basin, almost exactly what has been observed in the second period studied (i.e., 435-mm observed versus 434.5-mm modeled) (Table 2). This model result therefore suggests that irrigation practices (mostly center pivot) in the Republican River watershed may have caused a small increase in the percentage of the basin's evapotranspiration in addition to the naturally occurring *ET* for 1977–1996. Unfortunately, there is no data available on estimated irrigation water volumes for the entire basin before 1968; therefore, one cannot estimate what percentage of the basin's *ET* came from irrigation for 1949–1968. Most probably, the role of irrigation in the water balance was negligible during that period. This assertion is supported by the fact that in 1973 there were only about 600 center-pivot systems in Nebraska's part of the basin (Nebraska Natural Resource Commission Web site). By 1985, it had grown to 2,700, almost a fivefold increase. Note that, because of typically lacking irrigation data, the USGS estimated value (i.e., 26 mm/year) for 1977–1996 may contain a significant error. Because of this and because of the simplifying assumptions about irrigation practices herein, the model estimate of extra *ET* coming from irrigation should be regarded with caution. The only relevance of such calculations is that they demonstrate that, in principle, the difference between model-simulated and observed *ET* rates for 1977–1996 may, in fact, be explained by factors not included in the original model setup.

SUMMARY AND CONCLUSIONS

The present study investigated whether declining runoff in the Republican River basin can be explained solely by changes in the hydro-climatological variables. A simple daily water-balance model was applied in combination with a Monte Carlo-type simulation of daily precipitation. This allowed one to model the mean water balance of the basin with hydro-climatological data representative of two distinct 20-year periods: 1949–1968 and 1977–1996. The model had previously been applied by Milly (1994) to model the mean water balance of the United States east of the Rocky Mountains, and it explained 88% of the geographical variance of observed runoff within that area. Although the hydrological processes included in the model are clearly oversimplified (e.g., no infiltration-excess overland flow), this kind of modeling approach is especially attractive because (1) the model results do not depend on the generally unknown initial soil-moisture conditions; and (2) the model does not have any parameters to be optimized.

Based on the model results, it can be stated that the observed significant decline in runoff (a change from 9.58 to 5.9 mm/year between the two periods) cannot be explained by corresponding changes in the hydro-climatological variables between the two periods. The decline may be caused by a combination of other factors such as the construction of reservoirs and ponds in the basin, change in vegetation cover, introduction of water conservation practices, and widespread application of irrigation techniques (mostly the use of center-pivot systems).

The main finding of the modeling effort (i.e., hydro-climatic variables alone cannot explain the observed runoff decline in the Republican River above Hardy) is thought to be important in helping decision makers involved in resolving conflicting water resources interests among stakeholders, farmers, conservationists, or even states sharing the watershed.

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NOTATION

The following symbols are used in this paper:

a, b = dimensionless empirical constants;
BS = hours of bright sunshine on average day (T);
DL = daylight hours on average day (T);
ET = evapotranspiration (LT^{-1});
et = ratio of long-term disturbed evapotranspiration to its long-term undisturbed value;
k = number of days between storm events;
n = number of distinct plant-available water values considered in model;
P = precipitation (LT^{-1});
p = ratio of long-term disturbed precipitation to its long-term undisturbed value;
R = incident solar radiation ($EL^{-2}T^{-1}$);
R_e = extraterrestrial radiation at outer boundary of earth's atmosphere ($EL^{-2}T^{-1}$);
RD = rooting depth of vegetation (L);
RO = runoff (LT^{-1});
ro = ratio of long-term disturbed runoff to its long-term undisturbed value;
rr = ratio of long-term disturbed runoff ratio to its long-term undisturbed value;
SF = storm frequency (T^{-1});
SM_{FC} = soil water content at field capacity;
SM_{WP} = soil water content at permanent wilting point of vegetation;
t, T = time (T);
w = water content of soil in excess of SM_{WP};
w_0 = plant available water;
z = distance in vertical direction (L);
α = fraction of area at depth z that is affected by root system of vegetation;
β = parameter of Poisson process;
δ = ratio of amplitude of annual harmonics to annual average of variable;
λ = parameter of exponential distribution;
$\underline{\omega}$ = circular frequency (T^{-1});
$\bar{\ }$ = temporal average;
$\langle\ \rangle$ = spatial average; and
$\downarrow$ = average taken along vertical direction.