Published in: Garbrecht, J. D., J. M. Schneider, and M. W. Van Liew. Monthly Runoff Predictions Based on Rainfall Forecasts in a Small Oklahoma Watershed. Journal of the American Water Resources Association, 42(5):1285-1295.

Monthly Runoff Predictions Based on Rainfall Forecasts in a Small Oklahoma Watershed

Jurgen D. Garbrecht, Jeanne M. Schneider, and Michael W. Van Liew
USDA-ARS, Grazinglands Research Laboratory, 7207 West Cheyenne St.
El Reno, Oklahoma 73036

Key Words:
Runoff; stream flow; surface water; forecast; rainfall-runoff; rainfall.

Abstract

Conditions under which monthly rainfall forecasts translate into monthly runoff predictions that could support water resources planning and management activities were investigated on a small watershed in central Oklahoma. Runoff response to rainfall forecasts was simulated using the hydrologic model SWAT. Eighteen scenarios were examined, representing combinations of wet, average, and dry antecedent rainfall conditions, with wet, normal, and dry forecasted rainfall. Results suggest that for the climatic and physiographic conditions under consideration, rainfall forecasts could offer potential application opportunities in surface-water resources, but only under certain conditions. Pronounced wet and dry antecedent rainfall conditions were shown to have greater impact on runoff than forecasts, particularly in the first month of a forecast period. Large forecast impacts on runoff occurred under wet antecedent conditions, when the fraction of forecasted rainfall contributing to runoff was greatest. Under dry antecedent conditions, the majority of forecasted rainfall was absorbed in the soil profile, with little immediate runoff response. Persistent three-month forecasts produced stronger impacts on runoff than one-month forecasts due to cumulative effects in the hydrologic system. Runoff response to antecedent conditions and forecasts suggest a highly asymmetric utility function for rainfall forecasts, with greatest decision-support potential for persistent wet forecasts under wet antecedent conditions when the forecast signal is least dampened by soil-storage effects. Under average and dry antecedent conditions, rainfall forecasts showed little potential value for practical applications in surface-water resources assessments.

Introduction

Water resources planning and management seeks to balance seasonal and interannual variations in water availability and demand. Three-month overlapping seasonal rainfall forecasts are issued monthly by NOAA's Climate Prediction Center (CPC; Barnston et al., 2000) and may offer application opportunities in support of water resources planning and management. Pagano et al. (2001) recognized the potential of seasonal climate forecasts to anticipate variations in water availability (also, Changnon and Vonnhame, 1986). However, these forecasts played only a marginal role in the decision-making process to date (Pulwarty and Redmond, 1997; Sonka et al., 1992). Nonetheless, increasing skill in climate forecasts is expected to lead to improved surface-water predictions and risk-based management of water supply (De Souza and Lall, 2003; Poveda et al., 2003; Piechota et al., 2001; Anderson et al., 2000). Incorporation of seasonal forecasts into real-world applications is not a straightforward or well-established process. Waage et al. (2001) conducted decision experiments based on past reservoir operations with and without forecast consideration, and illustrated the value of reservoir management decisions based on forecast information. However, methodologies that utilize climate forecasts to predict stream flows or manage reservoir operations are an area of active research (Franz et al., 2003; Shaman et al., 2003), and forecast-driven water resources predictions, consideration of climate uncertainty, and practical formulation of risk-based decision support remain a challenge (Mishra, 2001).

In this study, monthly runoff response to hypothetical rainfall forecasts was examined by means of hydrologic model simulations on a small Oklahoma watershed. Monthly rainfall forecasts were given as a distribution of possible rainfall outcomes, called probabilistic forecasts, which in turn led to a distribution of simulated runoff responses. Objectives of this study were to: (1) analyze changes in predicted runoff distributions as a result of wet, average and dry rainfall forecasts; (2) identify conditions under which rainfall forecasts were likely to translate into runoff responses that could be suited for water resources decision making; and, (3) illustrate the probabilistic nature of predicted runoff information derived from probabilistic rainfall forecasts and how this information could be used. Even though forecasts were hypothetical, this study exemplified the potential forecasts may hold for water resources applications, and was intended to promote a better understanding of capabilities and limitations of probabilistic forecasts for water resources applications. In the remainder of this paper, monthly probabilistic rainfall forecasts are simply referred to as forecasts.

Experimental design

Hydrologic simulation was used to quantify stream flow response to hypothetical wet, average, and dry forecasts following wet, average, or dry antecedent rainfall conditions. The hydrologic model SWAT (Small Watershed Assessment Tool; Arnold et al., 1993) was selected to simulate runoff response of a 32.9 km^2 watershed within the Little Washita River Research Watershed in central Oklahoma. SWAT is a model that enjoys a wide application in the agricultural and environmental science community, and has been thoroughly tested and validated over many years of diverse applications (Jayakrishman et al., 2005; Bosch et al., 2004; Tripathi et al., 2004; Harmel et al., 2000; Spruill et al., 2000). Physiographic, weather and runoff data for the selected watershed were readily available, and stream flow was found to be sensitive to rainfall variations (Garbrecht et al., 2004a; Van Liew et al., 2003). Rainfall and stream flow had a bimodal regime with high flows in spring, moderate flows in fall, and low flows in summer and winter. Climate drivers for SWAT consisted of daily rainfall, average air temperature, and solar radiation, which were assumed to be uniform over the watershed. Snow rarely occurs in central Oklahoma and usually melts within a day or two, and therefore snow was not a factor affecting runoff regime and rainfall-runoff simulation. SWAT was calibrated with nine years of historical weather and runoff data (Oct. 1992 through Sep. 2000). Simulated and observed monthly runoff values produced a coefficient of determination (R^2) of 0.8 and a Nash-Sutcliffe Efficiency (NSE) coefficient of 0.8 (Nash and Sutcliff, 1970). According to Motovilow et al. (1999) a NSE coefficient above 0.75 represents a good simulation of observed data. For this forecast impact study, the physiographic input parameters that described the watershed (topography, soil properties, vegetation characteristics, etc.) were optimized by model calibration and kept constant for the forecast impact simulations.

For this study, a hypothetical 1-month and a 3-month forecast were considered for October and October through December (Oct-Dec), respectively. Forecasts are traditionally expressed as Probability of Exceedance (PoE) curves, as illustrated in Figure 1 for a wet forecast. In this figure, the heavy line represents the "normal" rainfall distribution derived from the 1961-1990 period of data, while the thin line represents the forecast distribution. For a wet forecast, the distribution is shifted upward and to the right. An upward shift indicates an increase in probability of reaching or exceeding a given rainfall value, while a rightward shift is the increase in rainfall amount for a given exceedance probability. A horizontal shift near the center of the distribution is herein referred to as the "size" of the forecast. Forecast quality and skill are important forecast characteristics and objects of intense studies in atmospheric simulations and development of forecasting methodologies (e.g. Barnston et al., 2005; Barnston et al., 2003; Hartmann et al., 2002). For this study, forecast impact was the central issue, and hypothetical forecasts were assumed to be of good quality and high skill. A review of forecasts since 1995 showed forecasts in the cool-season to be stronger and more frequent than in the warm season, mainly due to the effects of an El Nino Southern Oscillation teleconnection in fall and winter. Within this favorable forecast period, an October forecast was selected because water resources decisions at the end of a dry summer season may benefit from runoff predictions in early fall, and an Oct-Dec forecast was selected to capture cumulative impacts of persistent weather patterns on runoff which may also lead to better opportunities for water resources applications.

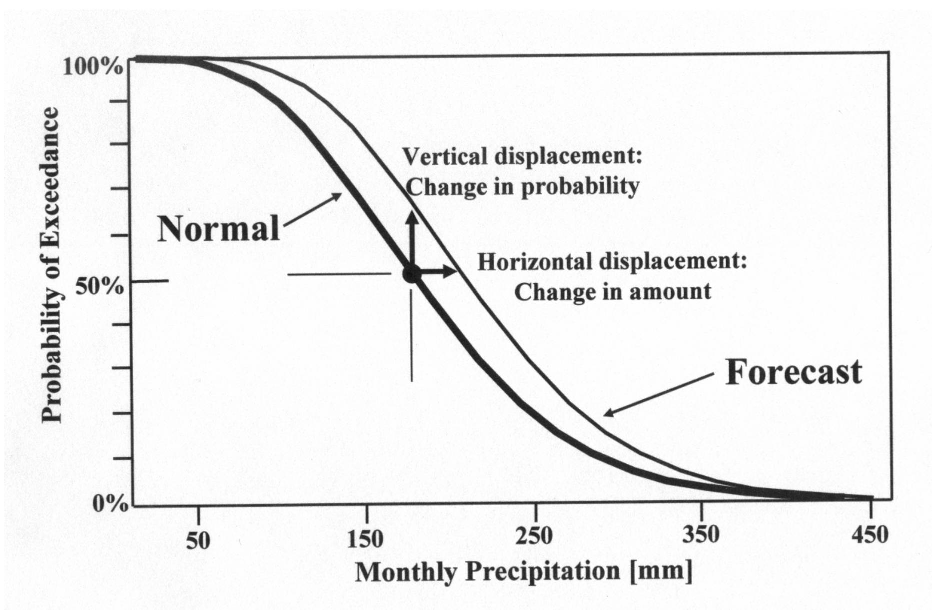

Figure 1. Schematic of a probabilistic wet rainfall forecast given as an upward shift in probabilities from normal conditions.

Wet or dry forecasts were defined as a ±15% shift at the mean of the rainfall distribution to either the wet or dry side, respectively (horizontal shift of the distribution in Fig. 1). Forecast size of ±15% was selected arbitrarily, but was comparable to strong wet forecasts issued by CPC since 1995 for central Oklahoma. Sequences of daily rainfall corresponding to the hypothetical forecasts were generated using the experimental stochastic weather generator SYNTOR, a variant of the WGEN weather generator (Richardson and Wright, 1984; Richardson, 1982a, 1982b and 1981). WGEN was modified to accept monthly forecast departures from normal conditions, and to generate corresponding daily rainfall outcomes (Garbrecht et al., 2004b; Garbrecht and Zhang, 2003). Daily air temperature and solar radiation were stochastically generated, assuming normal conditions. Seasonal temperature forecasts were not considered in this study because a review of past forecasts showed them to be small in size and lacking correlation with rainfall forecasts in central Oklahoma. Using the weather generator SYNTOR, ensembles of 200 sequences of daily weather were generated for each wet, average and dry rainfall forecast for October, and October through December. Each ensemble outcome was an internally consistent sequence of possible daily weather that reflected the forecast statistics.

For this study, September 30th was assumed to mark the present; prior to September 30th the weather was known, and after September 30th forecasted weather applied (Fig. 2). Actual historical weather data were used for runoff simulations for the nine months leading up to September 30th. Using known past weather data mimics real-time simulation where the past is represented by observed weather and the future by a number of possible weather outcomes.

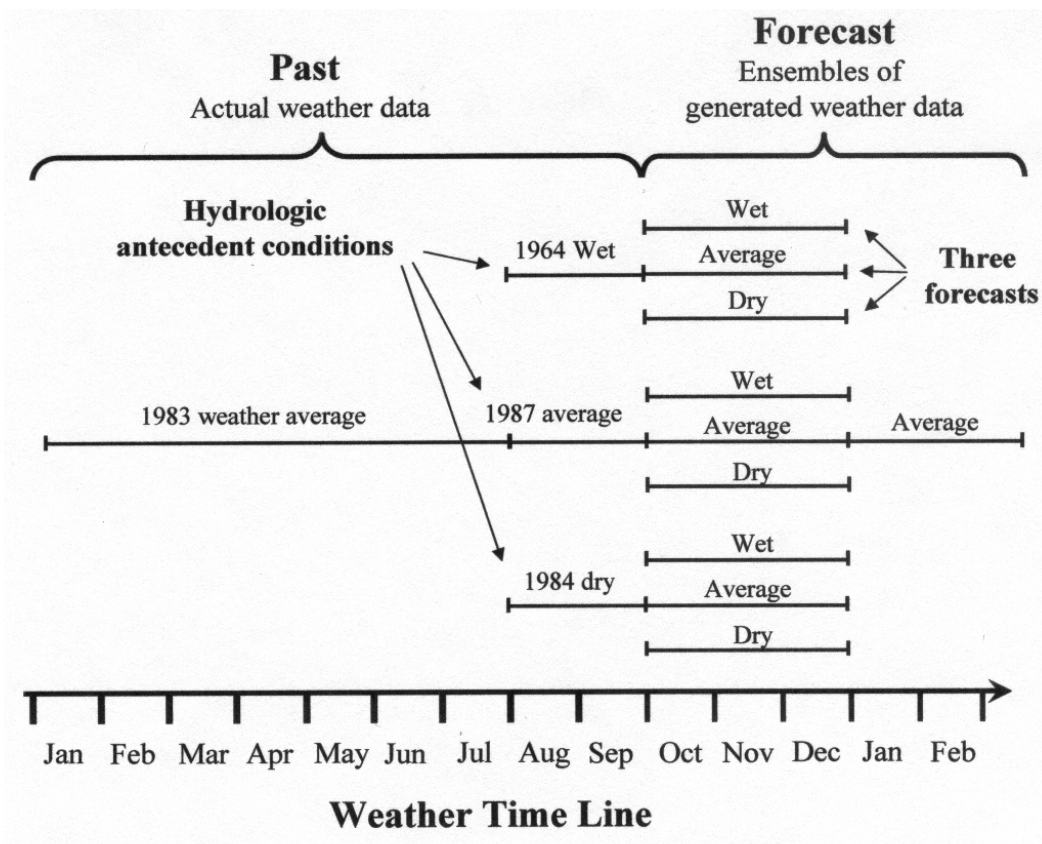

Figure 2. Time line for the weather data used to drive SWAT simulations.

Weather data for January through July 1983 were selected for past weather because that year reflected long-term average climatic conditions. Weather data for August and September were for 1964, 1987 and 1984 and represented wet, average, and dry antecedent rainfall conditions, respectively. Rainfall values were 92, 58 and 17 mm, respectively, and the upper and lower values represent the 90th and 10th percentile of the 1961-1990 August-September rainfall record. In the remainder of this paper antecedent rainfall conditions are simply referred to as antecedent conditions. These wet, average and dry antecedent weather scenarios were followed by ensembles of stochastically generated rainfall representing the wet, average and dry forecasts for October. Weather past the October forecast was stochastically generated to represent the 1961-1990 average weather conditions. Generated weather data past the forecast period were necessary because runoff continued to respond to forecasts for several months afterwards due to runoff lag and hydrologic system memory. The same approach was applied to develop the weather scenarios for the Oct-Dec forecasts.

Three antecedent August-September conditions, combined with each of three forecast conditions, produced a total of nine scenarios for the October forecasts, and a parallel set of nine scenarios for the October through December forecasts. For each scenario, SWAT simulations were started in January with identical initial hydrologic watershed conditions (soil moisture, groundwater level, plant parameters, etc.), and driven by identical January through September weather. This lead-up simulation ensured that all internal SWAT simulation variables had settled to a weather-driven state at the beginning of the October forecast period. Each of the nine scenarios involved an ensemble of 200 simulations, with a full Jan-Dec simulation for each of the 200 weather outcomes. An example of 200 monthly rainfall outcomes for the wet antecedent condition and dry October through December forecast is shown in Figure 3. The "known" rainfall for January through September is identified by a single line, followed by 200 distinct lines representing the ensemble of stochastic rainfall outcomes for the dry Oct-Dec forecast and average conditions for January through March.

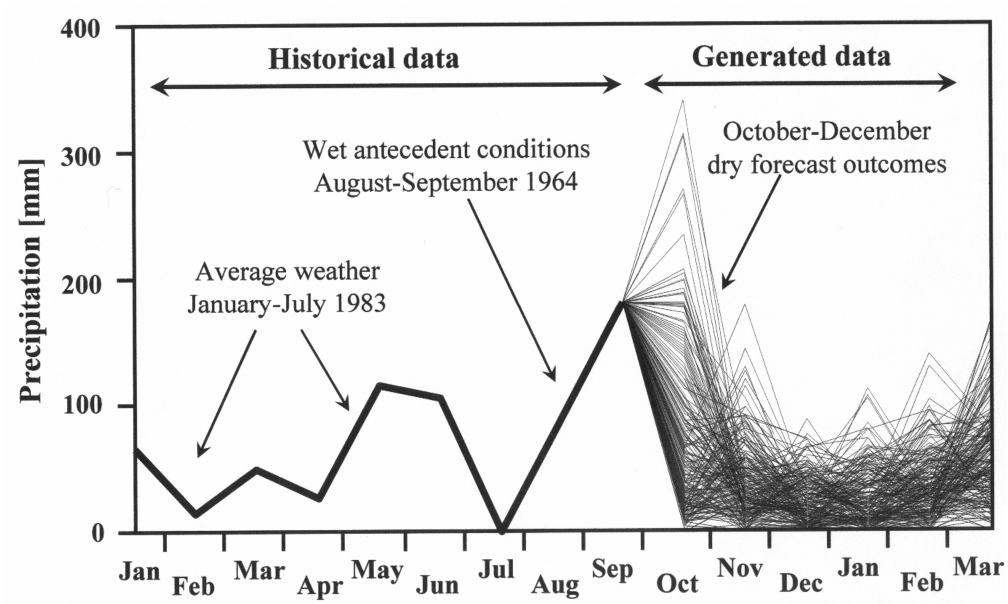

Figure 3. Example sequence of monthly rainfall for wet antecedent conditions and a dry Oct-Dec forecast.

SWAT simulations were conducted on a daily time step and daily simulated runoff was aggregated into monthly runoff values. Thus, each weather scenario produced an ensemble of 200 monthly runoff responses which in turn were displayed as probability of exceedance (PoE) curves. Stream flow values have been normalized over watershed area and are expressed in units of runoff depth (millimeters) to facilitate numerical comparison with rainfall depth. Thus, stream flow values in all tables and figures are given as runoff depth. Runoff depth was evaluated for the periods of October, and October through December to capture runoff lag and hydrologic system memory effects. Potential utility of a stream flow prediction was then interpreted in terms of changes in runoff depth across scenarios (larger changes implied greater potential for decision making). Differences between scenarios were best visualized by PoE curves, and change in risk of exceeding a flow threshold can easily be read from the PoE curves.

Results

October forecasts

Two hundred generated daily rainfall outcomes for October reproduced a range of wet-dry day sequences, number of rainy days and amounts of rainfall. Average rainfall characteristics were calculated from this generated daily rainfall for wet, average and dry forecast conditions. Statistics of October rainfall are shown in Table 1. Departure in mean rainfall of wet and dry forecasts from average was about 12 [mm], and was statistically significant at the 0.05 level (two-sample Wilcoxon-Mann-Whitney rank sum test). Also, standard deviation of rainfall, minimum and maximum rainfall, and number of rainy days were all larger for the wet forecast than for the dry forecast. The opposite was true for the coefficient of variation.

Table 1. Rainfall statistics of the October forecast.

Forecast (monthly rainfall)	Dry (-15%)	Normal	Wet (+15%)
Mean P [mm]	71.4	84.0	95.9
St. Dev. P [mm] (Coeff. of variation)	65.5 (0.92)	70.4 (0.84)	76.2 (0.79)
Max. P [mm]	339	454	495
Min. P [mm]	0	0	2.8
Average number of rainy days	5.3	5.6	5.9

Runoff depth was simulated for the nine scenarios, and resulting monthly runoff-depth statistics are displayed in Table 2 for three flow periods: October, October through December, and October through March. The following inferences were drawn from these statistics: first, the forecast related directly to runoff depth, a reflection of the cause-effect relationship between rainfall and runoff. Second, impacts of antecedent conditions on flow were larger than those due to forecasts. This was in part attributed to the strong wet/dry antecedent conditions selected from the historical record, compared to the modest forecast for October of only a ±15% shift at the mean. Third, antecedent conditions were a strong indicator of flow variability as measured by the coefficient of variation. However, for given antecedent condition, flow variability changed little with forecast. Fourth, runoff depth response is most sensitive to forecasts under wet antecedent conditions. Under dry antecedent conditions a larger portion of the rainfall was retained within the watershed than under wet conditions, thereby not contributing to runoff depth. And, fifth, about half or less of the runoff depth impact due to October forecasts occurs during the month of October itself. The other half or more of the impact occurs during months following the October forecast, which reflects runoff lag and hydrologic system memory.

Table 2. Statistics of simulated October runoff depth for wet, average, and dry antecedent conditions, and ensembles of wet, normal and dry October forecasts. First value is mean runoff depth in mm; second value is coeff. of variation (round brackets); third value is difference in runoff depth between normal and wet/dry forecasts [square brackets].

Runoff depth for the month of October in [mm]			
Antecedent conditions	Wet	Neutral	Dry
Forecast: Wet (+15%)	**23.0** (1.36) [+2.7]	8.5 (2.67) [+1.8]	**2.4** (5.57) [+1.0]
Forecast: Normal	20.3 (1.37)	6.7 (2.77)	1.4 (5.92)
Forecast: Dry (-15%)	**16.1** (1.09) [-4.2]	**4.2** (2.32) [-2.5]	0.7 (4.78) [-0.7]
Runoff depth for months October through December in [mm]			
Forecast: Wet (+15%)	**52.7** (0.83) [+5.1]	22.1 (1.53) [+3.6]	6.4 (3.37) [+2.2]
Forecast: Normal	47.6 (0.80)	18.5 (1.53)	4.2 (3.41)
Forecast: Dry (-15%)	**42.1** (0.76) [-5.5]	**14.8** (1.53) [-3.7]	**3.0** (3.48) [-1.2]
Runoff depth for months October through March in [mm]			
Forecast: Wet (+15%)	**83.3** (0.64) [+6.6]	**41.8** (1.04) [+5.7]	**13.6** (2.15) [+3.0]
Forecast: Normal	76.7 (0.62)	36.1 (1.05)	10.6 (2.26)
Forecast: Dry (-15%)	**70.0** (0.59) [-6.7]	**31.5** (1.04) [-4.6]	8.5 (2.15) [-2.1]

Forecasted mean runoff depths that are statistically different from normal at the 0.1 significance level are identified in bold (two-sample Wilcoxon-Mann-Whitney rank sum test).

While flow is an important consideration for water resources planning and management, the probability of exceeding a particular decision threshold is equally important. Runoff exceedance curves for the month of October and the nine scenarios are shown in Fig. 4. Three important patterns were recognized. First, large separations between exceedance curves for different antecedent conditions clearly demonstrate the dominant influence of antecedent conditions over forecasts. Thus, knowing antecedent conditions is more relevant for flow prediction than having a forecast for the upcoming month. Second, under wet antecedent conditions, runoff depth always exceeded 7.5 mm. This reflected the existence of simulated base flow conditions for low October rainfall. Under average and dry antecedent conditions, there was very little if any base flow. A review of observed stream flow conditions under similar rainfall conditions confirmed this interpretation. Third, under dry and average antecedent conditions, changes in runoff exceedance probability due to October forecasts were small, predominantly under 5%. This reflected the retention of rainfall in the soil. On the other hand, under wet antecedent conditions, more of the forecasted rainfall signal reached runoff and changes in exceedance probability due to forecasts were about twice as large as those for dry and average antecedent conditions. Thus, the highest decision-making potential of these single-month forecasts is for wet antecedent conditions. Similar runoff depth responses were found when considering runoff depth for October through December.

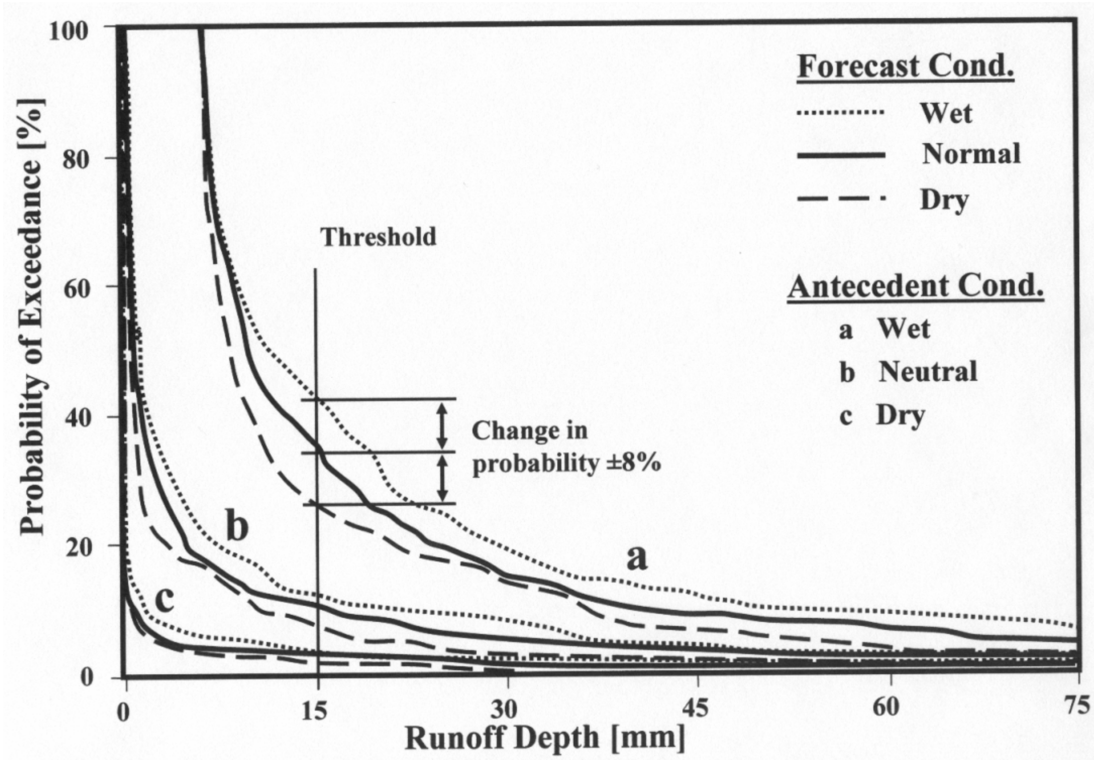

Figure 4. Exceedance frequency of October runoff depth for wet, average and dry October forecasts.

Use of exceedance curves to determine the decision potential of a forecast is illustrated for a threshold runoff depth of 15 mm (Fig. 4). This threshold value was intentionally chosen to highlight the most favorable decision potential for given watershed and forecast conditions. For dry antecedent conditions, there was about a 3% chance of exceeding the runoff-depth threshold value, with little change due to forecasts. For average antecedent conditions, the exceedance probability increases to 10%, with an additional ± 3% difference in exceedance probability due to wet/dry forecasts. For wet antecedent conditions, the exceedance probability is 35%, with a ± 8% difference in exceedance probability due to wet/dry forecasts. If one were confronted at the beginning of October with a decision situation that involved the probability of exceeding the 15 mm runoff-depth threshold, then pronounced wet/dry antecedent conditions would be the primary driver for determining the exceedance probability. Forecasts contributed to a lesser degree, and primarily under wet antecedent conditions. Thus, for the watershed considered in this study, an October rainfall forecast departure of 15% or less provided limited decision-making opportunities under average and dry antecedent conditions, with the best opportunities under wet antecedent conditions.

October through December forecasts

While single-month forecasts may support short-term water management decisions, seasonal forecasts are more relevant for decisions that are sensitive to persistent dry or wet periods. Impacts of three-month Oct-Dec wet/dry forecasts on flow are considered in this section. Monthly rainfall statistics for wet, normal, and dry forecasts were calculated from generated daily weather (Table 3). Departures in mean monthly rainfall from normal for wet or dry forecasts were 12, 7, and 5 [mm] for October, November and December, respectively, or about 24 [mm] for the entire period. The departures of each of the three months from normal are statistically significant at the 0.1 level (two-sample Wilcoxon-Mann-Whitney rank sum test), and the total departure of the three months together is significant at the 0.01 level. Trends in these rainfall statistics due to forecasts were similar to those discussed in conjunction with the October forecast.

Table 3. Statistical characteristics of Oct-Dec forecasts; values are for October, November and December, respectively.

Forecast (monthly rainfall)	Dry (-15%)	Normal	Wet (+15%)
Mean P [mm]	71.4; 38.6; 24.2	84.0; 46.0; 30.1	95.9; 53.4; 33.7
St. Dev. P [mm]	65.5; 31.1; 19.3	70.4; 39.9; 26.3	76.2; 40.6; 28.3
Max. P [mm]	339; 178; 88	454; 200; 150	495; 212; 142
Min. P [mm]	0; 0; 0	0; 0; 0	2.8; 0; 0
Average number of rainy days	5.3; 4.7; 4.9	5.6; 4.8; 4.8	5.9; 4.7; 5.0

Statistics of simulated runoff depth for Oct-Dec forecasts are shown in Table 4. The difference in runoff between wet/dry forecasted and normal conditions are statistically significant at the 0.05 level (two-sample Wilcoxon-Mann-Whitney rank sum test) for all antecedent conditions. Inferences drawn from the runoff depth in Table 4 were similar to those for the October-only forecast in Table 2, with the following two major distinctions. First, shifts in runoff exceedance curves due to Oct-Dec forecasts were larger than for the October-only forecast, but differences due to wet/dry antecedent conditions remained dominant. The stronger impact of forecasts on flow was the result of cumulative effects. Rainfall early in the forecast period preconditioned soil saturation levels, which in turn affected runoff and stream flow potential in the latter part of the forecast period. And second, lag in runoff response to forecast departures was strongest for dry antecedent conditions, with about 50% of runoff changes occurring in the three months following the Oct-Dec forecast period. Under average and wet antecedent conditions, higher soil saturation leads to more immediate runoff response during the forecast period, with about 60% and 65% of runoff changes occurring during the forecast period.

Table 4. Statistics of simulated runoff depth flow for wet, average, and dry antecedent conditions, and ensembles of wet, normal, and dry forecasts. First value is mean runoff depth in mm; second value is coeff. of variation (round brackets); third value is difference in runoff depth between normal and wet/dry forecasts [square brackets].

Runoff depth for months October through December in [mm]			
Antecedent conditions	Wet	Neutral	Dry
Forecast: Wet (+15%)	**55.4** (0.82) [+7.8]	**24.2** (1.47) [+5.7]	**7.3** (3.15) [+3.1]
Forecast: Normal	47.6 (0.80)	18.5 (1.53)	4.2 (3.41)
Forecast: Dry (-15%)	**39.4** (0.76) [-8.2]	**12.7** (1.63) [-5.8]	**2.4** (3.85) [-1.8]
Runoff depth for months October through March in [mm]			
Forecast: Wet (+15%)	**88.5** (0.65) [+11.8]	**46.4** (1.04) [+10.3]	**17.0** (2.00) [+6.4]
Forecast: Normal	76.7 (0.62)	36.1 (1.05)	10.6 (2.26)
Forecast: Dry (-15%)	**64.5** (0.59) [-12.2]	**27.0** (1.08) [-9.1]	**6.4** (2.34) [-4.2]

Forecasted mean runoff depths that are statistically different from normal at the 0.05 significance level are identified in bold (two-sample Wilcoxon-Mann-Whitney rank sum test).

Runoff exceedance curves for the nine scenarios associated with Oct-Dec forecasts are shown in Fig. 5. Dominance of antecedent conditions over forecasts remained the most recognizable feature. The striking difference between this Oct-Dec forecast situation and the previous October-only forecast was the larger change in exceedance probability due to forecasts. For dry and average antecedent conditions the change in exceedance probability was between 5% and 10%, and for wet antecedent conditions the change was mostly in the 10% range. Thus, forecasts that persist over several months have more impact on stream flow than one-month forecasts and offer higher decision making potential. These findings changed little when stream flow for October through March was considered.

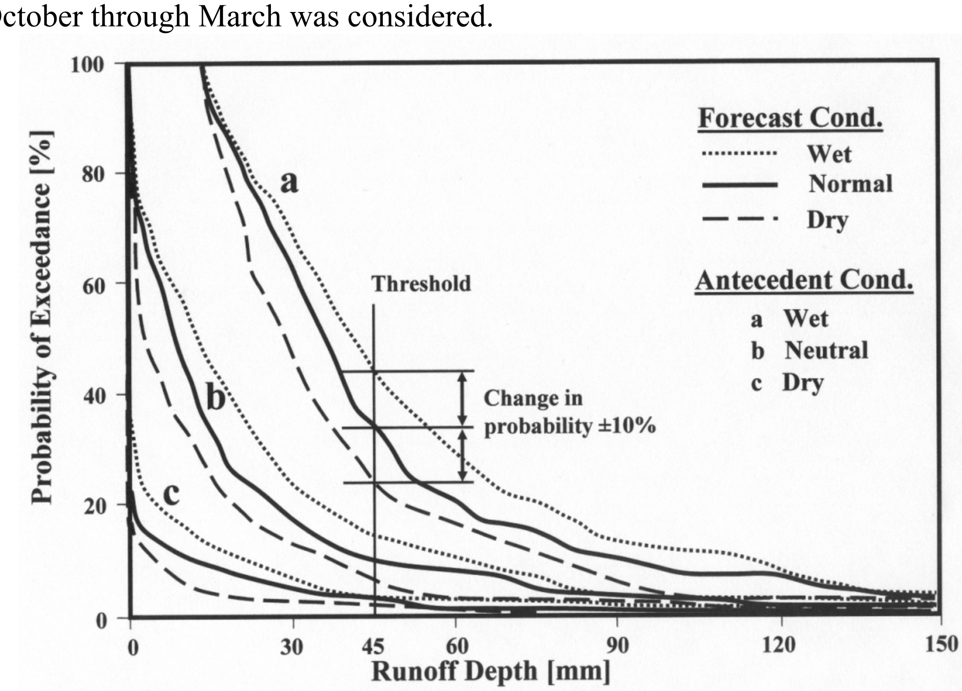

Figure 5. Exceedance frequency of Oct-Dec runoff depth for wet, average and dry Oct-Dec forecasts.

Change in Oct-Dec runoff exceedance probability as a function of forecast and antecedent conditions is illustrated for a runoff-depth threshold value of 45 mm (Fig. 5). For dry antecedent conditions, the probability of exceeding the threshold value was 5%, with minimal contribution due to the forecasts. For average antecedent conditions, the exceedance probability increases to 10%, with a ± 5% change due to forecasts, and, for wet antecedent conditions, the exceedance probability jumped to about 35%, with a ±10% variation due to forecasts. Pronounced wet/dry antecedent conditions were still the primary variable defining the runoff exceedance probability, but forecasts introduced a sizable contribution under average and wet antecedent conditions. Thus, for the watershed under consideration, a forecasted 15% increase in Oct-Dec following average to wet antecedent conditions provided the best decision opportunity among the various scenarios of this study.

Conclusions

Monthly runoff for a small watershed in central Oklahoma was simulated for wet, average and dry forecasted rainfall, each under wet, average and dry antecedent rainfall conditions. Objectives were to quantify changes in simulated runoff distribution with and without forecasts; to determine conditions under which probabilistic rainfall forecasts likely translate into runoff predictions that could support water resources applications; and, to illustrate the probabilistic nature and use of forecast-derived runoff information. The Soil Water Assessment Tool (SWAT) was used to simulate runoff response. Hypothetical wet and dry forecasts for October and Oct-Dec consisted of a ±15% shift at the mean of the observed monthly rainfall distribution. Such forecasts were representative of seasonal rainfall forecasts issued by NOAA's Climate Prediction Center. Daily weather corresponding to these monthly forecasts was generated by means of a stochastic weather generator. Wet, average and dry antecedent conditions for August and September were selected directly from the historical weather record. Runoff for eighteen scenarios of forecasts and antecedent conditions was simulated, sensitivity of runoff response to forecasts and antecedent conditions was determined, and conditions that produced runoff predictions with highest application potential were identified.

The following four conclusions can be drawn from this study: first, antecedent hydrologic conditions and rainfall forecasts produced a broad range of runoff responses that present good potential for water resources applications. Effects of pronounced wet and dry antecedent conditions on runoff in the first months of a forecast period were larger than corresponding impacts of forecasts. Thus, pronounced wet or dry antecedent conditions can be better indicators of expected runoff than forecasts themselves. Second, one-month forecasts, under average and dry antecedent conditions, had little impact on runoff due to watershed storage effects and offered limited potential for water resources applications. Third, forecasts that persisted several months had larger impact on runoff due to cumulative effects and represented a greater application potential than single-month forecasts. Forecast impact on runoff was lagged in time and applications involving cumulative runoff considerations could potentially derive a greater benefit than applications based on immediate, short-term runoff response. And, fourth, runoff responses to forecasts and antecedent conditions suggested a highly asymmetric utility function for forecast derived applications. Greatest forecast-based application potential was for persistent forecasts under wet antecedent conditions when forecast signals were least dampened by watershed storage effects. Under average and dry antecedent conditions, forecasts showed little potential for surface-water resources applications.

The findings of this study are specific to the climatic and physiographic conditions of the watershed under consideration. However, the trends in runoff response to forecasts are believed to be representative for similar watersheds in the region. It is also recognized that the actual application potential of forecasts ultimately depends on the specifics of the application itself.

Literature Cited.

Anderson, M.L., M.D. Mierzwa, and M.L. Kavvas, 2000. Probabilistic Seasonal Forecasts of Drought with a Simplified Coupled Hydrologic-Atmospheric Model for Water Resources Planning. *Stochastic Environmental Research and Risk Assessment,* 14:263-274.

Arnold, J. G., P. M. Allen, and G. Bernhardt, 1993. A Comprehensive Surface-Groundwater Flow Model. *Journal of Hydrology*, 142:47-69.

Barnston, A. G., A. Kumar, L. Goddard, and M. P. Hoerling, 2005. Improving Seasonal Prediction Practices Through Attribution of Climate Variability. *Bulletin of the American Meteorological Society*, 86:59-72.

Barnston, A. G., S. J. Mason, L. Goddard, DeWitt, D. G., and S. E. Zebiak. 2003. Multimodel Ensembling in Seasonal Climate Forecasting at IRI. *Bulletin of the American Meteorological Society*, 84:1783-1796.

Barnston, A. G., Y. He, and D. A. Unger, 2000. A Forecast Product that Maximizes Utility for State-of-the-Art Seasonal Climate Prediction. *Bulletin of the American Meteorological Society*, 81:1271-1279.

Bosch, D. D., H. M. Sheridan, H. L. Batten, and J. G. Arnold, 2004. Evaluation of SWAT Model on a Coastal Plain Agricultural Watershed. *Transactions, American Society of Agricultural Engineers,* 47(5):1493-1506.

Changnon, S.A. and D.R. Vonnhame, 1986. Use of Climate Predictions to Decide a Water Management Problem. *Water Resources Bulletin,* 22:649-652.

De Souza, F. A. and U. Lall, 2003. Seasonal to Interannual Ensemble Stream Flow Forecasts for Ceara, Brazil: Applications of a Multivariate, Semiparametric Algorithm. *Water Resources Research,* 39:1307-1307.

Franz, K. J., H. C. Hartmann, S. Sorooshian, and R. Bales, 2003. Verification of National Weather Service Ensemble Stream Flow Predictions for Water Supply Forecasting in the Colorado River basin. *Journal of Hydrometeorology,* 4:1105-1118.

Garbrecht, J. D., M. W. Van Liew, and J. O. Brown, 2004a. Trends in Rainfall, Stream flow and ET in the Great Plains. *Journal of Hydrologic Engineering*, 9(5):360-367.

Garbrecht, J. D., J. M. Schneider, and X. J. Zhang, 2004b. Downscaling NOAA's Seasonal Rainfall Forecasts to Predict Hydrologic Response. *In Combined Preprints CD-ROM of the 84th American Meteorological Society Annual Meeting, 10th Conference on Hydrology*, Session 6, Paper 6.8, January 11-15, 2004, Seattle, WA, published by AMS, 45 Beacon Street, Boston, MA 02108-3693.

Garbrecht, J. D., and X. J. Zhang, 2003. Generating Representative Sequences of Daily Rainfall for Agricultural Simulations. *Journal of Applied Engineering in Agriculture,* 19(4):423-429.

Harmel, R. D., C. W. Richardson, and K. W. King, 2000. Hydrologic response of a Small Watershed Model to Generated Precipitation. *Transactions, American Society of Agricultural Engineers,* 43(6):1483-1488.

Hartman, H. C., Pagano, T. C., Shorooshian, S., and Bales, R., 2002. Confidence Builders: Evaluating Seasonal Climate Forecasts from User Perspectives. *Bulletin of the American Meteorological Society*, 83:683-698.

Jayakrishnanm R., R. Srinivasan, C. Santhi, and J. G. Arnold, 2005. Advances in the Application of the SWAT Model for Water Resources Management. *Hydrological Processes*, 19(3):749-762.

Mishra, S., 2001. Dealing with Uncertainty in Environmental Model Prediction. *Earth Observation System, Transactions, American Geophysical Union,* 82:47.

Motovilov, Y. G., L. Gottschalk, K. England, and A. Rodhe, 1999. Validation of a Distributed Hydrologic Model Against Spatial Observations. *Journal of Agricultural and Forestry Meteorology*, 98-99:257-277.

Nash, J. E. and J. V. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models, Part 1 - A Discussion of Principles, *Journal of Hydrology,* 10(3):282-290.

Pagano, T. C., H. C. Hartmann, and S. Sorooshian, 2001. Using Climate Forecasts for Water Management: Arizona and the 1997-1998 El Nino. *Journal of the American Water Resources Association,* 37:1139-1153.

Piechota, T. C., F. H. S. Chiew, J. A. Dracup, and T. A. McMahon, 2001. Development of Exceedance Probability Stream Flow Forecast. *Journal of Hydrologic Engineering,* 6:20-28.

Poveda, G., O. J. Mesa, and P. R. Waylen, 2003. Nonlinear Forecasting of River Flows in Columbia Based on ENSO and its Associated Economic Value for Hydropower Generation. *Climate and Water,* 16:351-371.

Pulwarty, R. S. and K. T. Redmond, 1997. Climate and Salmon Restoration in the Columbia River Basin: the Role and Usability of Seasonal Forecasts. *Bulletin of the American Meteorological Society,* 78:381-397.

Richardson, C. W., 1981. Stochastic Simulation of Daily Rainfall, Temperature, and Solar Radiation. *Water Resources Research,* 17(1):182-190.

Richardson, C. W., 1982a. A Comparison of Three Distributions for the Generation of Daily Rainfall Amounts. In Singh, V. P. (Ed.), *Statistical Analysis of Rainfall and Runoff*, pp. 67-78, Proc. Int. Symp. On Rainfall-Runoff Modeling, Water Resources Publications, 700 pp.

Richardson, C. W., 1982b. Dependence Structure of Daily Temperature and Solar Radiation. *Transaction of the American Society of Agricultural Engineers,* 25(3):735-739.

Richardson, C. W. and D. A. Wright, 1984. WGEN: A Model for Generating Daily Weather Variables. U. S. Department of Agriculture, Agricultural Research Service, ARS-8, 83 p.

Shaman, J., M. Stieglitz, S. Zebiak, and M. Cane, 2003. A Local Forecast of Land Surface Wetness Conditions Derived from Seasonal Climate Predictions. *Journal of Hydrometeorology,* 4:611-626.

Sonka, S. T., S. A. Changnon, and S. L. Hofing, 1992. How Agribusiness Uses Climate Predictions: Implications for Climate Research and Provision of Predictions. *Bulletin of the American Meteorological Society,* 73:1999-2008.

Spruill, C. A., S. R. Workman, and J. L. Taraba, 2000. Simulation of Daily and Monthly Stream Discharge from Small Watersheds Using the SWAT Model. *Transactions, American Society of Agricultural Engineers,43(6):1431-1439.*

Tripathi, M. P., R. K. Panda, N. S. Raghuwanshi, and R. Singh. 2004. Hydrological Modelling of a Small Watershed using Generaqted rainfall in the Soil and Water Assessment Tool Model. Hydrological Processes, 18(10):1811-1821.

Van Liew, M. W., J. M. Schneider, and J. D. Garbrecht, 2003. Stream Flow Response of an Agricultural Watershed to Seasonal Changes in Rainfall. K. G. Renard, S. A. McElroy, W. J. Gburek, H. E. Canfield, and R. L. Scott (Eds.), U. S. Department of Agriculture, Agricultural Research Service, The 1st Interagency Conference on Research in the Watershed, Benson, AZ.

Waage, M. D., C. K. Baldwin, R. G. Steger, and T. J. Bray, 2001. Incorporating Seasonal Stream Flow Forecasts into Operational Decision Making. Proceedings of the 16th Annual Western Snow Conference, Sun Valley, Idaho.