Streamflow Response of an Agricultural Watershed to Seasonal Changes in Precipitation

Michael W. Van Liew, Jeanne M. Schneider, Jurgen D. Garbrecht

Abstract

Seasonal variations in precipitation on a watershed lead to variations in streamflow that in turn result in uncertainties that impede the efficient management of available water resources. This is especially true for management of reservoir storage and water releases during and at the end of the dry season when water demand is highest and streamflow supply is lowest. Anticipating streamflow amounts based on seasonal precipitation forecasts holds promise to estimate the probability of replenishment of depleted reservoir storage and helps identify best water supply management strategies related to anticipated streamflow and associated uncertainties. A study was conducted to evaluate the impact of hypothetical seasonal variations in precipitation on streamflow. The objective was to develop a prototype for streamflow response associated with a range of hypothetical precipitation forecasts. The prototype was developed for the 33 km^2 subwatershed 442 located in the USDA-ARS Little Washita River Experimental Watershed in Southwestern Oklahoma. The Soil and Water Assessment Tool was used to determine streamflow responses to hypothetical precipitation forecasts that represent changes of $\pm$ 20% and $\pm$ 40% for the fall quarter. Measured precipitation data for a period of record from 1971 to 2000 on the subwatershed was used to develop the hypothetical precipitation forecasts. Test results of this study indicate that hypothetical precipitation forecasts that are drier than normal lead to streamflow responses that approach baseflow conditions on the watershed, while forecasts that are wetter than normal lead to higher streamflow values characterized by considerable variability due to variations in storm size, duration, and intensity during the fall months. Results of this study suggest that utilization of precipitation forecasts coupled with the corresponding anticipated streamflow changes could provide sufficient risk-based information that enable water authorities to more effectively manage reservoir storage and water releases to meet water demands and downstream flow requirements.

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Introduction

Seasonal variations in precipitation have a major bearing on monthly or seasonal streamflow amounts in Southern Great Plains watersheds. Seasonal variations in streamflow, coupled with increased and competing demands for water by a growing population, place considerable pressure upon efficient management of available water resources. This is especially true for management of reservoir storage and water releases during and at the end of the dry season when water demand is highest and streamflow supply is lowest. Water resources managers and natural resources conservation agencies require better tools to more effectively assess and manage reservoir storage and water releases during and at the end of dry seasons.

Anticipating streamflow amounts based on seasonal precipitation forecasts holds promise to estimate the probability of replenishment of depleted reservoir storage. With such information, water authorities can make more informed decisions on releasing or withholding the reserve water storage at a time when water rationing is not uncommon in Oklahoma. For example, a forecast of wetter than average conditions coupled with the corresponding anticipated streamflow increases can provide sufficient risk-based information that may lead water authorities to delay imposing water restrictions or lift restrictions earlier in anticipation of likely increased streamflow.

The National Oceanic and Atmospheric Administration's Climate Prediction Center (NOAA/CPC) issues seasonal climate forecasts covering overlapping 3-month periods for the coming year (Schneider and Garbrecht 2003). These forecasts are issued monthly and can be viewed at the NOAA/CPC web site: www.cpc.ncep.noaa.gov. The predictive skill of these experimental forecasts has been improving as forecast techniques evolve and more data become available (Barnston et al. 1999, Mason et al. 1999, Barnston et al. 2000). The anticipated improvement in the reliability of these seasonal forecasts should produce valuable information that could be used to estimate reservoir inflow to more effectively manage reservoir storage and water releases for multiple competing demands. However, the cause and effect relationship between seasonal variations in precipitation and streamflow is not well known. A study was conducted to evaluate the impact of hypothetical seasonal variations in precipitation on streamflow. The objective of this study was to determine the streamflow response associated with a range of hypothetical precipitation forecasts for the fall quarter. This season of the year marks the beginning of the water year and corresponds to the onset of replenishment of reservoir storage. The prototype was developed for a sub-watershed located in the USDA-ARS Little Washita River Experimental Watershed in Southwestern Oklahoma.

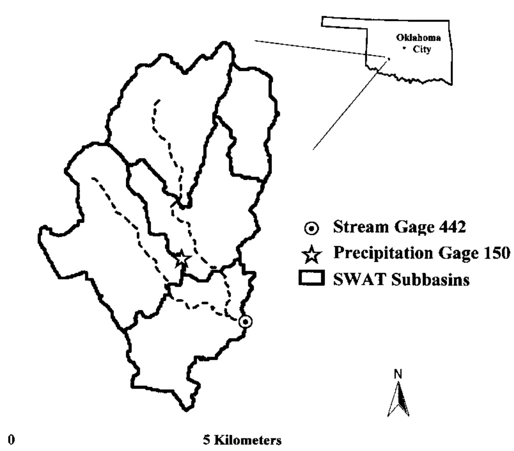

Figure 1. Location of Little Washita Experimental Watershed.

Methods

Test watershed

Subwatershed 442 of the Little Washita River Experimental Watershed (LWREW) is located about 100 km southwest of Oklahoma City and drains an area of 33 km^2 (Figure 1). The climate in the region is sub-humid to semi-arid, with an average annual precipitation during the past 40 years of about 800 mm. Average annual runoff from the watershed is 160 mm based on a period of record from 1992 to 2000. The topography of the watershed is characterized by gently to moderately rolling hills on predominantly silt loam soils. Conventional land use surveys from aerial photographs and point sampling show 54% of the watershed in rangeland, 41% in cultivation (primarily wheat and alfalfa), 1% in timber, and 4% in miscellaneous use (farmsteads, abandoned oil sites, and urban). Based on surveys (Allen and Naney 1991) and recently collected remotely sensed data, little change in land use has occurred on the watershed during the past 30 years, and for this study it was assumed that land use remained constant during the time period of study.

Model description and data input

One of the watershed loading and transport models included in the U.S EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) 3.0 is the Soil and Water Assessment Tool, referred to as SWAT (Arnold et al. 1998). This model was selected for simulating hydrologic response to precipitation on subwatershed 442. The model delineates a watershed as a number of sub-basins, which are simulated as homogeneous areas in terms of climatic forcing, but with additional subdivisions within each subbasin to represent different soils and land use types. Each of these individual land use areas is referred to as a hydrologic response unit (HRU). In this study the SCS runoff curve number option was used to estimate surface runoff from precipitation. Values of the curve number were adjusted during simulation to reflect changes in moisture conditions on the watershed (Arnold et al. 1998). Simulations conducted in this study by SWAT were performed within the ArcView Geographical Information System (GIS) of BASINS 3.0. This system includes a modular structure that contains a tool for optimizing the definition and segmentation of the watershed and network based on topography. It also consists of a tool for defining the HRUs over the watershed and an integrated user-friendly interface (Di Luzio et al. 2002).

Elevation, land use, and soil characteristics for the subwatershed were obtained from GIS data layers at a 30 by 30 m cell resolution. The elevation layer was developed from concatenated USGS DEM quads. The land use layer was obtained from a 1997 Landsat-5 thematic mapper image of the watershed, and the soils layer was obtained from STATSGO soils information (USDA-NRCS 1992) and from data reported by Allen and Naney (1991). A continuous precipitation recording gage within the subwatershed provided input for daily precipitation. Rainfall data were collected by the USDA ARS from 1971 to 2000, and streamflow data were collected by the U.S. Geological Survey at gage 442 between 1992 and 2000 (Figure 1).

Model calibration

SWAT was calibrated on subwatershed 442 by adjusting model parameters so that the measured and simulated streamflow from the 1992 to 2000 period of record agreed as closely as possible. Details of the procedure for model calibration are given by Van Liew and Garbrecht (2003) in a previous study on the LWREW. Results of the model calibration show that SWAT estimated annual runoff within $\pm$ 20% for 7 of the 9 years of record for subwatershed 442. A Nash Sutcliffe (Nash and Sutcliffe 1970) coefficient of efficiency was computed for measured and simulated monthly runoff for the period of record from 1992 to 2000, and indicates that simulation results were considered good.

Simulation methodology

Measured daily precipitation amounts for each of the 30 years of fall precipitation were input in SWAT to simulate hydrologic responses of the watershed. Since streamflow response depends on antecedent climatological and soil moisture conditions prior to fall months, the same antecedent conditions were simulated by the model for each fall quarter. Model simulations under dry and wet antecedent conditions must also be conducted, and are anticipated for future studies. Results of the model simulation were used to construct a flow exceedance curve and a precipitation streamflow response relationship for the fall quarter.

Results

Figure 2 displays the three-month total precipitation and flow exceedance curves for the fall quarter. The exceedance curves indicate the percent of time that a given amount of precipitation or streamflow, expressed in mm, is equaled or exceeded. Each curve is a statement of probability that a given amount of precipitation or streamflow will be equaled or exceeded. For example, there is an 80% probability that the amount of precipitation during the fall months will be equal to or greater than 93 mm, but only a 20% probability that it will be equal to or greater than 257 mm.

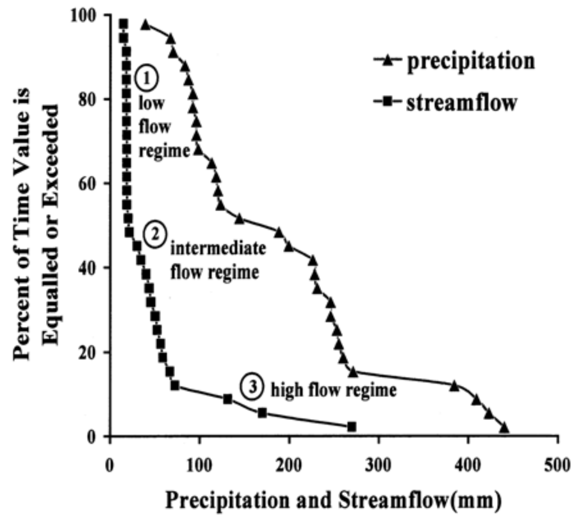

Figure 2. Precipitation and streamflow probability of exceedance curves for fall months on subwatershed 442.

Three general hydrologic responses are evident from the shape of the flow exceedance curve in Figure 2. These include 1) a low flow regime in the 55% to 100% flow exceedance range, 2) an intermediate flow regime in the 10% to 55% flow exceedance range, and 3) a high flow regime in the 0% to 10% flow exceedance range.

The three-month precipitation and corresponding streamflow data were also plotted in Figure 3 to develop a precipitation streamflow response curve. Simulation results suggest that for the 0 to 150 mm precipitation range, the precipitation streamflow relationship is very well defined, with baseflow as the dominant factor in governing streamflow. For the 150 to 300 mm range in precipitation, variation in the streamflow response reflects scatter in the data primarily associated with runoff due to varying storm sizes, intensities, and durations. Variability in streamflow response is even more pronounced in the 300 to 450 mm precipitation range, where values of streamflow range from 59 to 270 mm.

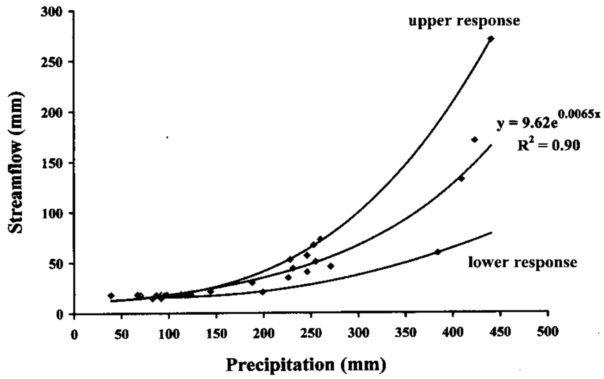

Figure 3. Precipitation streamflow relationship for fall months on subwatershed 442.

Streamflow data were fit to an exponential function:

$$y = 9.62e^{**}0.0065x \quad (1)$$

where y = streamflow in mm and x = precipitation in mm

Figure 3 also includes two additional curves that were constructed to designate the lower and upper streamflow responses that would be expected to occur for a given amount of precipitation. Equation (1) was used to estimate the streamflow response that would be expected to occur for a given precipitation amount corresponding to a particular probability of exceedance.

Table 1. Streamflow response for various precipitation forecasts for the fall months on subwatershed 442.

Precipitation Forecast	Probability of Exceedance (%)	Precipitation (mm)	Average Streamflow (mm)	Change in Avg Streamflow (%)	Lower Flow Limit (mm)	Upper Flow Limit (mm)
No Change	20	257	51	-	27	72
	40	228	42	-	26	53
	60	118	21	-	16	22
	80	93	18	-	15	17
+20%	20	308	71	+39	39	106
	40	274	57	+36	33	79
	60	142	24	+14	17	25
	80	112	20	+11	16	20
-20%	20	206	37	-27	23	44
	40	182	31	-26	20	35
	60	94	18	-14	17	18
	80	74	16	-11	16	16
+40%	20	360	100	+96	53	156
	40	319	77	+83	42	115
	60	165	28	+33	18	30
	80	130	22	+22	17	23
-40%	20	154	26	-49	17	26
	40	137	23	-45	16	24
	60	71	15	-29	15	15
	80	56	14	-22	14	14

For this study these streamflow responses were computed under normal climatic conditions at the 20%, 40%, 60%, and 80% precipitation exceedance levels (Table 1). Other levels could also be chosen to correspond to specific management decision points. The range in expected flows as estimated from the enveloping curves is also tabulated in Table 1 (last two columns). Under normal climatic conditions, the data show that precipitation equal to 228 mm (corresponding to a 40% probability of exceedance level) results in 42 mm of runoff during the fall quarter, with a possible range from 26 to 53 mm.

Figures 2 and 3 were utilized to determine the streamflow response to hypothetical precipitation forecasts. The forecasts were derived by shifting the precipitation exceedance curve in Figure 2 to the right or to the left to reflect a forecasted increase or decrease in the odds for precipitation. For this study the forecasts consisted of changes in fall precipitation equal to ± 20% and ± 40%. The curves presented in Figure 3 were then used to estimate the average and range in streamflow responses for precipitation at the 20%, 40% 60%, and 80% exceedance levels.

For fall precipitation forecasts that are drier than normal, the expected hydrologic response tends to approach baseflow conditions on the watershed. Forecasts in this direction therefore tend to reflect less scatter associated with storm variability. Test results show that a 40% less than normal precipitation forecast, for example, would on average lead to a 22% reduction in streamflow (14 mm, no range) at the 80% probability of exceedance level, and a 49% reduction in streamflow (26 mm, range 17 to 26 mm) at the 20% exceedance level (Table 1).

For fall precipitation forecasts that are wetter than normal, the hydrologic response of the watershed becomes increasingly more variable for respective increases in the departure from normal precipitation conditions. For example, a 20% greater than normal precipitation forecast results in a 39% increase in streamflow (71 mm, range of 39 to 106 mm) at the 20% probability of exceedance level, whereas a 40% greater than normal precipitation forecast leads to a 96% increase in streamflow (100 mm, range of 53 to 156 mm) at that exceedance level. Forecasts in this direction therefore tend to reflect increased variability in streamflow response due to wider variations in storm characteristics during the fall months.

Results of these hypothetical precipitation forecasts suggest that forecasts that are drier than normal lead to streamflow responses that approach baseflow conditions on the watershed, while forecasts that are wetter than normal lead to streamflow responses characterized by increased streamflow and considerable variability. These differences in hydrologic response are important factors that would need to be considered in developing risk-based information related to water resources management.

For application to water supply considerations, the analysis described herein for the fall season could also be extended to other antecedent conditions and other seasons of the year. Using the probabilities of streamflow response for each season over the course of a water year, a multiple stage water resources planning scheme could be implemented for a reservoir to meet various competing water needs during the year (Anderson et al. 2000). The first decision of how much water to store over the course of the coming wet season would be made at the beginning of the water year in the fall. The determination of how much water that would be needed for reservoir storage would be based on water supply and flood storage considerations. With potential changes in the probability of streamflow response for the winter and spring seasons, new decisions would be made as to what additional measures should be implemented for water supply considerations and flood protection. These decisions could be updated each month as new seasonal precipitation forecasts become available during the year. A set of lookup tables could be developed to evaluate various water availability classifications ranging from very wet to very dry conditions. These tables could be used to assess the impacts of storing, releasing, and conserving water for each water availability classification. In turn, a method that reflects risk and uncertainty associated with climatological forecasts would be available for water resources authorities to balance limited water supplies during the dry season with various competing demands.

Summary and Future Research

A study was conducted to evaluate the impact that seasonal variations in precipitation have on streamflow. A precipitation exceedance curve was constructed from 30 years of historical precipitation data for a 33 km^2 subwatershed of the Little Washita River Experimental Watershed. The Soil and Water Assessment Tool was then used to generate hydrologic responses to the historical record in order to develop prototype streamflow exceedance curve and precipitation streamflow response relationships. The precipitation exceedance curve and the precipitation streamflow response relationships were in turn used to determine streamflow responses to hypothetical precipitation forecasts that represent changes of ± 20% and ± 40% for the fall months. Results of this preliminary investigation reflect two types of uncertainty associated with the estimation of streamflow response from precipitation forecasts. One type of uncertainty is related to the nature of the forecast itself as defined by the precipitation probability of exceedance curve. The other type of uncertainty relates to the impact that storm characteristics such as size, duration, and intensity have on runoff. Both of these uncertainties must be considered in making risk based assessments of water resources as related to the replenishment of reservoir storage during a given season of the year.

This preliminary investigation was conducted only for the fall months of the year on subwatershed 442 under near average antecedent precipitation conditions. Model simulations also need to be completed for dry, average, and wet antecedent conditions for each of the seasons of the year. In this study the impact of hypothetical precipitation forecasts was based on computing relative changes in the 30 year historical precipitation record for the watershed. Studies anticipated for the future will utilize climate generation techniques to develop precipitation exceedance curves that represent NOAA/CPC precipitation forecasts. Results of these studies will also need to be extended to other watersheds in the Southern Great Plains to evaluate the effectiveness of this method as a tool to more effectively manage reservoir storage and water releases for competing demands.

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References

Allen, P.B., and J.W. Naney. 1991. Hydrology of the Little Washita River Watershed, Oklahoma. U.S. Department of Agriculture, Agricultural Research Service, Report ARS-90.

Arnold, J.G., R.Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment, Part I: Model development. Journal of the American Water Resources Association 34(1):73-89.

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.

Barnston, A.G., M.H. Glantz, and Y. He. 1999. Predictive skill of statistical and dynamical climate models in SST forecasts during the 1997-98 El Nino episode and the 1998 La Nina onset. Bulletin of the American Meteorological Society 80:217-243.

Barnston, A.G., Y. He, and D.A. Unger. 2000. A forecast product that maximizes utility for state-of-art seasonal climate prediction. Bulletin of the American Meteorological Society 81:1271-1279.

Di Luzio, M., R. Srinivasan, and J.G. Arnold. 2002. Integration of watershed tools and SWAT model into BASINS. Journal of the American Water Resources Association 38(4):1127-1141.

Mason, S.J., L. Goddard, N.E. Graham, E. Yulaeva, L. Sun, and P.A. Arkin. 1999. The IRI seasonal climate prediction system and the 1997/98 El Nino event. Bulletin of the American Meteorological Society 80:1853-1873.

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models, Part 1: A discussion of principles. Journal of Hydrology 10:238-250.

Schneider, J.M., and J.D. Garbrecht. 2003. A measure of the usefulness of seasonal precipitation forecasts for agricultural applications. Transactions of the American Society of Agricultural Engineers 46(2):257-267.

USDA-NRCS. 1992. State Soil Geographic Database (STATSGO) Data User's Guide. Publication 1492, U.S. Government Printing Office, Washington, DC.

Van Liew, M.W., and J. Garbrecht. 2003. Hydrologic simulation of the Little Washita River Experimental Watershed using SWAT. Journal of the American Water Resources Association 39(2):413-426.