A WATER BUDGET FOR A SEMIARID WATERSHED

by

Severo R. Saplaco, Peter F. Ffolliott, and William O. Rasmussen

INTRODUCTION

In the semiarid Southwest, water supplies are becoming scarce as water tables fall. Groundwater wells have been lowered about 20 meters to pump water in Tucson; while in Phoenix, wells must be drilled, on the average, 35 meters lower than they were originally to obtain water (Wright, 1966). Continuous use of the groundwater supply could lower water tables to a point that is uneconomical to pump for domestic uses. Once the groundwater supply is exhausted, alternative water sources must be tapped to minimize, if not prevent, productive lands from becoming unusable deserts.

To understand the development of water supplies, baseline hydrologic information is needed. In this study, the water budget on a small semiarid watershed was evaluated and models of surface runoff, soil moisture content, and suspended sediment were developed. In addition, a chemical analysis of runoff waters was performed and a water balance simulation model was evaluated.

DESCRIPTION OF STUDY

OBJECTIVES

The primary objective of this study was to evaluate the water budget of a small semiarid watershed. This objective was accomplished by identifying and quantifying the components of a water budget associated with a small instrumented watershed. The primary components considered were rainfall, surface runoff, soil moisture content, and (collectively) other water losses.

The water budget was conceptualized as:

$$P = SRO + SMC + L$$

where:

P = rainfall (cm);
SRO = surface runoff (cm);
SMC = soil moisture content (cm); and
L = other water losses (cm).

Secondary and tertiary objectives of the study were to develop regression models of surface runoff, soil moisture content, and suspended sediment, and to analyze the chemical quality of surface runoff, respectively.

THE STUDY AREA

The study site, a 6.5 hectare subwatershed which lies on the southeastern portion of the Atterbury Watershed, is located 16 km east of Tucson, Arizona. The watershed drains into the upper Santa Cruz River, in the geologic area of Arizona known as the basin and range province (Fogel, 1968).

The study site has an elevation of about 3200 feet (975 m). A relatively flat, single-slope terrain characterizes the entire watershed. Average slope is 3 percent, ranging from 1 to 6 percent. The aspect is northwest.

The authors are respectively, Assistant Professor, College of Forestry, University of the Philippines at Los Banos, College, Laguna, Professor and Assistant Research Professor, School of Renewable Natural Resources, University of Arizona, Tucson.

Youngs et al. (1931) identified the major soil series in the Atterbury basin as Tubac, Mohave, Laveen, Tucson, and Pinal. The soil textural classification ranges from sandy loam to clay loam. Gelderman (1964) reported sandy and gravelly soils on ridges of the western and central parts of the watershed. A cemented zone of lime accumulation occurs 15 to 60 cm below the surface. On the eastern side of the basin, soils are characterized by sandy loam and loam surfaces underlain by accumulation of clay. A zone of lime accumulation is found 50 to 75 cm below the soil surface. Soils along the virtually level drainage channels are characterized by loamy surfaces. These bottomlands are underlain by clay loams.

Soil infiltration characteristics vary. The sandy and gravelly sandy soils on the ridges of the eastern and central parts of the watershed have good infiltration rates. Good infiltration also occurs along the drainage channels; however, infiltration rates on the eastern side of the area are restricted by the clay subsoil (Gelderman, 1964).

The Atterbury Watershed has a semiarid climate. Mean annual precipitation is 28 cm, occurring during two distinct seasons: summer and winter. Approximately 55 percent of the mean annual precipitation falls during the summer months, primarily July and August (Fogel, 1968). Winter precipitation occurs mostly from December to February.

Summer precipitation is usually characterized by short duration, high intensity thunderstorms. These summer thunderstorms are the major source of surface runoff from small semiarid watersheds. Fogel (1968) reported that summer thunderstorms in southern Arizona are produced by the condensation of water vapor, slowly advected into the area by a light but steady flow from the Gulf of Mexico and the Atlantic Ocean.

Winter precipitation events are normally of low intensity and long duration. These winter events are the most important source of runoff and the resulting streamflow contributes largely to groundwater recharge. Winter precipitation results from the condensation of water vapor carried over the area by migratory cyclones as they move in a west to east direction (Fogel, 1968).

The watershed has sparse vegetation which offers little protection to the soil. The leaves of the dominant plant species are usually widely dispersed, thin, and small, which makes them ineffective in intercepting precipitation.

Major plant species are creosote bush, white thorn, jumping cholla, catclaw, mesquite, and a few palo verde. Few forbs, shrubs, and grasses, such as fluffgrass, gray thorn and zinnias are also present.

FIELD PROCEDURES

Rainfall data were collected in a Belfort weighing-type recording gauge from January 1972 to December 1976. In addition, rainfall was measured by three plastic Tru-check non-recording rain gauges from January through December 1976.

The recording rain gauge was installed by the Office of the Water Resources Research Center, University of Arizona, to obtain a long term record of rainfall. The three non-recording rain gauges were systematically installed to index variability of rainfall on the study site. Rainfall readings on the three non-recording gauges were made following a rainfall event.

Surface runoff was measured on an HL flume (Belfort Portable Liquid Level Recorder FW-I, which was installed by the Office of Water Resources Center, University of Arizona) from January 1972 through December 1976. Surface runoff was also measured on three 4 x 6 feet (1.22 x 1.83 m) runoff plots from January through December 1976. The runoff plots were installed adjacent to the non-recording rain gauges to obtain an index of on-site surface runoff. Runoff was collected after each storm in a 18.6 liter plastic bucket installed at the lower ends of the runoff plots. A sheet of plywood was used to prevent rainfall entry. The runoff plots were bounded by aluminum sheets buried 12 cm deep to prevent water inflow and outflow from the plots.

Soil moisture content was determined by the gravimetric method. Soil samples were collected at points along four transects established systematically on the study area. The interval between points was approximately 25 meters.

Three soil samples were gathered on each sampling point using a soil collector tube at depths of 0 - 5.1, 5.1 - 10.2, and 10.2 - 15.2 cm. The samples were placed in cans, weighed, oven dried at 110^{0}C for 24 hours, and reweighed. Soil samples were collected before and after each rainfall event from February through December 1976 to index the changes in soil moisture content. Rainfall was also measured at times of soil sampling.

Other water losses of the water budget were assumed to be a combination of evaporation, interception, and transpiration. Direct measurements of these losses were not made because of the lack of instrumentation. This component of the water budget was evaluated as a residual term in the total water budget.

Water samples used to analyze the water quality were collected from March through December 1976 in the 18.6 liter plastic bucket previously described. Before the samples were collected, water in the bucket was thoroughly stirred manually. Then, plastic bottles were submerged in the bucket until they were filled with water. The water samples were analyzed at the Soils, Water and Plant Tissue Testing Laboratory, Department of Soils, Water and Engineering, University of Arizona.

ANALYTIC PROCEDURES

Synthesis of the water budget; regression models of surface runoff, soil moisture content, and suspended sediment; and a water quality analysis were made. All the regression models were evaluated at the 0.05 alpha level.

The inventory method was used to evaluate the water budget for the entire watershed (Gray, 1973). Magnitude of the major components of the total water budget were evaluated. Rainfall and surface runoff were evaluated directly from field data; while, soil moisture content was determined using the soil moisture accounting procedure. In addition, the soil moisture content (in percent) was converted to cm of water (Blake, 1965). It was assumed that the difference in the soil moisture content before and after a rainfall event is the rainfall amount absorbed by the soil for that time interval.

Regression models of the HL flume and plot surface runoff were developed using stepwise regression analyses (Nie et al., 1975). In the stepwise procedure, one variable was entered into the regression at each stage, from best to poorest to explain the variance in the dependent variable. Regression models of soil moisture content and suspended sediment were also developed using a stepwise multiple linear regression analysis.

Water samples were analyzed for electrical conductivity, soluble salts, calcium, magnesium, sodium, chloride, sulfate, nitrate, fluoride, bicarbonate, and carbonate. The concentrations of all the chemical elements were expressed in mg/l.

RESULTS AND DISCUSSION

SYNTHESIS OF THE WATER BUDGET

A water budget for the 6.5-ha subwatershed during 1976, the year of detailed on-site measurement, was evaluated. The total annual rainfall for the study year was 20.2 cm, 6 cm lower than the 5-year (1972-1976) mean annual precipitation on the Atterbury Watershed. Approximately 55 percent of the total annual rainfall occurred during the summer months. A preponderance of summer rainfall on the Atterbury Watershed has been reported by Fogel (1968).

Out of 34 rainfall events, 10 events produced measurable runoff. The runoff-producing rainfall events occurred during the summer months (primarily July and August) and resulted in intense and localized rainfall.

Total surface runoff for the study year was 0.4 cm. The runoff-rainfall ratio was about 2 percent. Ratios for individual events ranged from 1 to 8 percent and closely resembled the runoff-precipitation ratio for the entire Tucson drainage (Sellers, 1965). However, the lower range of the runoff-rainfall ratio (1 percent) was smaller than the lower range (3 percent) for the entire Tucson drainage. This finding suggests that a lesser amount of rainfall was needed to initiate surface runoff from the smaller drainage of the study area (compared to a larger area of similar hydrologic characteristics).

The runoff-rainfall ratio for the study area was low in comparison with other vegetation zones in Arizona. The low ratio may be attributed to high evaporation potential and low precipitation input on the area. High evaporation potential and low precipitation in the desert shrub vegetation zone of Arizona has been reported by Ffolliott and Thorud (1975).

The total amount of rainfall absorbed by the soil (soil moisture content) within the 0 - 15.2 cm upper soil zone was 11.1 cm, or 55 percent of the total rainfall for the study year. The high amount of rainfall absorbed by the soil suggests good infiltration and percolation on the study site. A good infiltration characteristic of the soil up to a depth of about 0 - 20 cm at the eastern part of the Atterbury Watershed (where the study site is located) was observed by Gelderman (1964).

An evaluation of the amount of moisture absorbed by the soil at the three different soil depths (0 - 5.1, 5.1 - 10.2, 10.2 - 15.2 cm) indicated a decreased soil moisture content at the deeper soils immediately following rainfall. This may be due to a decreasing trend of moisture infiltration into the deeper soils caused by the increasing occurrence of lime accumulation and clay subsoils in addition to the lack of precipitation.

The other water losses component of the water budget was determined as a residual term. The total

amount of rainfall attributed to these losses was 8.7 cm, or about 43 percent of the total rainfall for the study year. The high amount of the other water losses component may be due to the high potential rate of evaporation on the study site. The high potential rate of evaporation on the area may be enhanced by the almost complete absence of grass cover during the study period. In addition to evaporation on the soil surface, intercepted rainfall contributes to the total water supply that would be available for evaporation.

Another potential factor for other water losses was moisture percolation below the 15.2 cm soil depth, the deepest soil depth considered in the study. However, it was assumed that rainfall percolation below the 15.2 cm soil depth was negligible. This assumption was based on field observations of impermeable lime accumulation on the study site at depths of about 10 - 15 cm.

SURFACE RUNOFF REGRESSION MODEL

Two regression models designed to predict surface runoff from the study area were developed. One model involves summer runoff-producing storms recorded at the HL flume gauging station from 1972 through 1976. This model may serve to evaluate surface runoff from the entire watershed. Another model consists of on-site surface runoff measured on the runoff plots. The plot runoff model may be used to evaluate the extent of on-site runoff contribution to the surface runoff from the entire watershed.

The surface runoff regression equation for the entire watershed is:

$$SRO = -0.24 + 0.26\ P + 0.19\ MXTR$$
$$r^2 = 0.76$$

where:

SRO = surface runoff (cm);
P = rainfall (cm); and
MXTR = maximum ten-minute rainfall (cm).

Schreiber and Kincaid (1967) reported a similar finding in on-site surface runoff from short-duration convective storms at the Walnut Gulch Experimental Watershed, Arizona; while, Osborn and Lane (1969) found comparable results in precipitation-runoff relations on small semiarid rangeland watersheds in Arizona.

The average value of the maximum ten-minute rainfall for the study year was used so that the equation may be solved to determine the minimum amount of rain needed to initiate runoff from the entire watershed. The equation was equated to zero and solved, with the solution indicating that at least 0.65 cm of rain was needed before surface runoff was generated at the HL flume gauging station. Initiation of surface runoff with the minimum rain of 0.65 cm may be true with the assumption that rain fell as suggested by the average ten-minute rainfall. This minimum rainfall is expected inasmuch as runoff occurs only with sufficient rainfall. The needed minimum rainfall to generate runoff from the watershed may help explain why only about 30 percent of the total rainfall events for the study year produced measurable runoff.

The regression equation of surface runoff from the runoff plot is:

$$SRO = -0.35 + 0.81\ P$$
$$r^2 = 0.87$$

where SRO and P were as defined previously.

To determine the minimum rainfall needed to generate runoff from the runoff plots, the equation was equated to zero and solved. The solution indicated that at least 0.43 cm of rain was needed before runoff was initiated from the runoff plots. This minimum rainfall was 30 percent smaller than what was needed to generate runoff from the entire watershed. It is generally assumed that the smaller the drainage area, the lesser amount of rainfall is needed to initiate surface runoff.

SOIL MOISTURE CONTENT REGRESSION MODEL

Regression equations to predict soil moisture content of soil samples gathered from the study sites after rainfall at three soil depths (0 - 5.1, 5.1 - 10.2 and 10.2 - 15.2 cm) were developed.

The equation of soil moisture content at a soil depth of 0 - 5.1 cm is:

$$SMC = 3.55 + 0.04\ RDUR$$
$$r^2 = 0.74$$

where:

SMC = soil moisture content (percent); and
RDUR = rainfall duration (minutes).

At the soil depth of 0 - 5.1 cm, minimum soil moisture content was 3.6 percent. This minimum soil moisture content approaches the wilting point level for sandy loam soils (Brady, 1974). A low soil moisture content was expected because of the high evaporation ratio and low precipitation input on the study area. The low minimum soil moisture content is perhaps one of the major factors that limits the occurrence and growth of grass species on the study site.

At a soil depth of 5.1 - 10.2 cm, the equation of soil moisture content is:

$$SMC = 2.75 + 0.02\ RDUR$$
$$r^2 = 0.75$$

The minimum soil moisture content at this soil depth (5.1 - 10.2 cm) was about 2.7 percent. This minimum soil moisture content was about 0.8 percent lower than the minimum soil moisture content at the 0 - 5.1 cm soil depth. This lower soil moisture content may be attributed to the delayed redistribution of moisture into the lower soil depth (Gelderman, 1964). In addition, soil moisture infiltration to recharge the soil moisture reservoir at the 5.1 - 10.2 cm soil depth may not take place when rainfall is limiting.

At the third soil depth (10.2 - 15.2 cm), the regression equation of soil moisture content is given as:

$$SMC = 2.5 + 3.13\ P$$
$$r^2 = 0.85$$

where:

SMC = soil moisture content (percent); and
P = rainfall (cm).

At this soil depth (10.2 - 15.2 cm), minimum soil moisture content was 1.05 and 0.24 percent lower than the minimum soil moisture content at the 0 - 5.1 and 5.1 - 10.2 cm soil depths, respectively. This result may be due to the combined effects of redistribution of moisture and limited amount of rainfall.

SUSPENDED SEDIMENT REGRESSION MODEL

A regression equation to predict suspended sediment of the runoff waters from the watershed was developed and is given as:

$$S = 1066.5 + 755.1\ P$$
$$r^2 = 0.77$$

where:

S = suspended sediment (mg/l); and
P = rainfall (cm).

The equation of suspended sediment indicated that surface runoff from the watershed carries over a thousand mg/l of suspended sediment. The suspended sediment from the study area was over 10 times greater than the acceptable level for aquatic life proposed by the Environmental Protection Agency (Campbell, 1976).

WATER QUALITY ANALYSIS

The mean electrical conductivity of the water samples was three times lower than the required amount in irrigation (Dutt and McCreary, 1970). Total soluble salts were 50 percent less than the total dissolved solids recommended by the Public Health Service in domestic water supplies; the recommended upper limit of total dissolved units is 500 mg/l.

The pH of the water samples was within the Environmental Protection Agency levels of acceptability for aquatic life, irrigation, and public water supply (Campbell, 1976). The water sampled had a low calcium content compared to the standard value set by the World Health Organization (Dutt and McCreary, 1970).

Cobleigh (1934) reported a limiting range for magnesium concentration of 100 to 200 mg/l for

domestic water supplies. Compared to this, magnesium concentration of the water samples was 50 and 100 times lower than the reported lower and upper limit, respectively. The sodium concentration of the water samples was also low, about 65 times lower than 200 mg/l, which is considered harmful to people with cardiac, renal, or circulatory diseases (Laubusch and McCammon, 1955).

The recommended Public Health Service limit for chloride concentration in drinking water is 250 mg/l (Dutt and McCreary, 1970), which is 55 times higher than the chloride concentration of the water samples collected in the study. The chloride concentration of the runoff waters was 50 times lower than the recommended Environmental Protection Agency limit in public water supply (Campbell, 1976). For sulfate concentration in drinking water, the recommended Environmental Protection Agency limit is 250 mg/l, which is 10 times higher than the sulfate concentration of the water samples.

The bicarbonate concentration of the water samples was over three times higher than the recommended maximum level of 50 to 60 mg/l (Dutt and McCreary, 1970). This maximum level applies in industrial water used for drinking, ice-making, and boiling. In terms of carbonate ion, the water samples had a zero concentration.

The fluoride concentration of the water samples was 10 to 15 times lower than the recommended Public Health Service level for domestic water supplies and for irrigation, as proposed by the Environmental Protection Agency (Campbell, 1976). Mean nitrate content of the water samples was 150 times lower than the concentration recommended by the Public Health Service in domestic waters (Dutt and McCreary, 1970).

Except for bicarbonate concentration, the concentration of all the other ions were within or lower than the limits set by the Public Health Service, the Environmental Protection Agency, or the World Health Organization for various water uses.

CONCLUSIONS

The results of the study lead to the following conclusions:

1. Over 30 percent of the total rainfall events produced measurable runoff. These runoff-producing rainfall events occurred during the summer months, primarily July and August.

2. The runoff-rainfall ratio was approximately 2 percent. The ratios ranged from 1 to 8 percent and were low in comparison with other vegetation zones in Arizona.

3. Soil moisture content accounted for about 55 percent of the total rainfall for the study year. Soil moisture content immediately following rainfall decreased with increasing soil depths.

4. About 43 percent of the total rainfall was attributed to other water losses. The high value of this component of the water budget may have been due to the high potential rate of evaporation on the study site.

5. Rainfall and maximum ten-minute rainfall were significant variables in a regression model of surface runoff from the entire watershed. Rainfall, alone, was the significant variable in the regression model of plot surface runoff. A greater amount of rainfall was needed to generate surface runoff from the entire watershed than from the runoff plots.

6. Rainfall amount and duration were significant variables in regression models of soil moisture content. The minimum soil moisture content decreased at lower soil depths.

7. Rainfall was the significant variable in a regression model of suspended sediment. The suspended yield from the study site was largely higher than those from other vegetation zones in Arizona.

8. Except for bicarbonate ion, concentration of the chemical constituents present in the runoff waters were within or largely lower than the limits set for various uses of water.

REFERENCES CITED

Blake, G. R. 1965. Bulk density. In Methods of soil analysis. Amer. Soc. of Agron., Inc., Madison, Wisconsin. No. 9, pp. 374-380.

Brady, N. C. 1974. The nature and properties of soils. McMillan Publishing Co., Inc., New York. pp. 175-179.

Campbell, R. E. 1976. Water quality as affected by forest management treatment in the Beaver Creek pine watersheds. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Study Plan FS-RM-1611, 27 p.

Cobleigh, W.M. 1934. Utilization of alkali water. Journal AWWA 26: 1063-1064.

Dutt, G. R., and T. W. McCreary. 1970. The quality of Arizona's domestic, agricultural, and industrial watersheds. Arizona Agricultural Experiment Station, Report 256, 83 p.

Ffolliott, P. F., and D. B. Thorud. 1975. Water yield improvement by vegetation management: Focus on Arizona. National Technical Information Service, PB-246 055, 1,094 p.

Fogel, M. M. 1968. The effect of spatial and temporal variations of rainfall and runoff from small watersheds. Ph.D. Dissertation, University of Arizona, 90 p.

Gelderman, F. W. 1964. A soil survey report of the Atterbury Watershed, Pima County, Arizona. USDA Soil Conservation Service, Special Report, pp. 1-4.

Gray, D. M. 1973. Handbook on the principles of hydrology: A general text with special emphasis on Canadian conditions. Water Information Center, Inc., 1,357 p.

Laubusch, E. J., and C. S. McCammon. 1955. Water as a sodium source and its relation to sodium restriction therapy patient response. Amer. Journal of Public Health and the Nation's Health 45:1337-1338.

Nie, N. H., C. H. Jenkins, S. G. Steinbrenner, and D. H. Bent. 1975. Statistical package for the social sciences. McGraw-Hill Book Co., New York. pp. 320-360.

Osborn, H. B., and L. Lane. 1969. Precipitation-runoff relations for very small semiarid rangeland watersheds. Water Resources Research 5:419-425.

Schreiber, H. A., and D. R. Kincaid. 1967. Regression models for predicting on-site runoff from short duration convective storms. Water Resources Research 3:389-393.

Sellers, W. D. 1965. Physical climatology. University of Chicago Press, Chicago. 272 p.

Wright, J. 1966. The coming water famine. Coward McCann, Inc., 247 p.

Youngs, F. O., A. T. Sweet, A. T. Strahorn, T. W. Glassey, and E. N. Poulson. 1931. Soil survey of the Tucson area, Arizona. USDA Bureau of Chemistry and Soil, Report 19, pp. 1-16.