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ANALYSIS OF WATER YIELDS OF THE SOLOMON RIVER BASIN, KANSAS

by

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CHAPTER 1

INTRODUCTION

Water is a valuable and sometimes scarce resource in western Kansas. A major source of water supply for northwest and northcentral Kansas is the Solomon River and its reservoirs. Located in an area that is primarily agricultural and dependent on irrigation, the Solomon River has become an increasingly important asset to Kansas. The water supply to this river is highly dependent upon precipitation that is often erratic and unreliable. The problems in the Solomon River Basin have ranged from flood to drought. The major dams on the Solomon River have provided a more consistent water supply to the area; however, even in the last three decades changes have taken place in the Solomon River Basin that have severely affected the flow in the river. Some the changes can be attributed to nature's sometimes erratic precipitation, and other changes are due to man's intervention. The objective of this report is to investigate the relationship between precipitation and basin yield, and to use this relationship to demonstrate how man's changing use of the land has affected the Solomon River Basin's water yield.

Study Area

The Solomon River Basin is an area of approximately 6,770 square miles located in northwestern and northcentral Kansas. The river originates west of the city of Colby where it consists of a north and south fork. The two forks wind their way eastward toward Cawker City where they join into the main stem of the Solomon River. In the western part of the basin, the river flows above the water table and is almost entirely dependent on precipitation. In the eastern part, particularly between Beloit and Niles, the river has cut below the water table and groundwater flow helps to sustain the flow (KWRB, 1981). The river becomes perennial in Sheridan County (USBR, 1978). The Solomon River continues to flow east and southeast where it flows into the Smoky Hill River which subsequently flows into the Kansas River. The Solomon River Basin is considered part of the Kansas River Basin, which is part of the larger Missouri River Basin. This study includes both the north and south forks of the river and the main stem of the river.

Settlement of this area began in the late 1850's with the reports of excellent crop yields and access to railroads. Dryland farming was somewhat successful, but insufficient rainfall, severe winds, and floods made farming difficult. Farmers often dug deep wells and built windmills to pump water for irrigation. In 1902, the Bureau of

Reclamation was created by Congress; however, it was not until 1944 that the Bureau began extensive planning for Kansas water resource development. The Flood Control Act of 1944 authorized the Missouri River Basin Project. This was a project throughout a ten state region designed to regulate the rivers of the Missouri River Basin for irrigation, flood control, electric power, navigation, and fish and wildlife conservation. In 1951, one of the most destructive floods in the history of Kansas occurred. The destruction caused by this flood helped to expedite construction of two dams on the Solomon River: Kirwin Dam on the North Fork and Webster Dam on the South Fork. Construction on these dams was started within the next two years. The flood of 1951 also caused planners to reevaluate the original design storage capacity of the dams and to double their flood storage capacities. Kirwin Dam was completed in 1958, and Webster Dam was completed in 1961. The last Missouri River Basin project to be completed in the Solomon River Basin was the Glen Elder Dam on the Solomon River near the city of Beloit. The Glen Elder Dam forms Waconda Lake which has a storage capacity of almost one million acre-feet, of which three-fourths is devoted to flood control (USBR, 1979). In addition to being a key element in the flood control plans of the basin, it serves as the municipal water supply for the city of Beloit.

Although flooding expedited the construction of these dams, their primary purpose is for water supply. In the past two decades, low flows in the river have caused water supply problems that threaten the effectiveness of the existing reservoirs. Both Webster and Kirwin Dams have experienced declining inflows, although Webster has had the most severe problem. In fact, in 1972 the Webster Irrigation District did not release any water from the reservoir for irrigation, and since then, less than full releases for irrigation have become the norm. The flows have generally been declining since the mid 1960's. Figure 3 shows that the entire basin had an average yield of 471,000 acre-feet prior to 1964 and an average yield of 278,000 acre-feet after 1964. This is a decline of approximately 40 percent.

Much previous work and research relating to the Solomon River has been completed. In 1976, the Bureau of Reclamation created the Solomon River Basin Management Study to investigate the reasons for the declining yield of the basin. Since 1978, the Solomon River Basin Management Study has published periodic public information bulletins on research progress (USBR, Bulletins 1-7, 1978-1982). Additionally, it has published major studies on runoff and ground analysis of the basin. Zovne et al. (1978) completed part II of the working paper "Soil and Water Conservation Practices Effects on the Water Budget of the

Solomon River, 1978". This study, with the best data available, estimated the effects of conservation practices on the basin. Another report by Koelliker et al. (1981) evaluated the effects of agricultural soil and water yield on the South Fork of the Solomon River. This study utilized a hydrologic computer simulation model with which the annual yield of the basin could be closely predicted. All of the previos studies concluded that conservation practices and irrigation pumping have caused extreme changes in the yield of Solomon River Basin. The difficult and underlying question is determine how much effect each of these factors has had upon the basin.

CHAPTER 2

METHOD OF ANALYSIS

Concept

The flow in the Solomon River is primarily dependent on direct runoff, which is a result of precipitation in the basin. Baseflow is of lesser importance, particularly in the far west where the river only flows during wet periods. The overall objective of this study was to use estimates of direct runoff and baseflow to predict the yield of the basin, and subsequently to use this prediction to show how conservation practices have changed the yield. This was done by predicting the yields for a set of land use conditions prior to the widespread use of conservation practices and then holding these conditions constant in the prediction method through the period of study. It was expected that this procedure would give a good prediction of yield prior to the widespread use of conservation practices and would give high predictions afterwards. The period of study used was 1920 to 1980.

Two methods of analysis were used. The first method was an adaptation of the method used in the Republican River Study (Koelliker et al., 1983) in which relative annual inflow to its reservoirs was predicted. The second method was a statistical correlation of two variables, annual runoff and annual precipitation, to the annual yield. Major assumptions used in the analysis were:

(1)Direct runoff is the major contributor to the Solomon River flow.

(2)Variations in annual evapotranspiration could be neglected and relative annual yield could still be predicted.

(3)The Soil Conservation Service (SCS) runoff equation would give good estimates of runoff on a long-term basis.

(4)Storm intensity could be neglected by using the SCS equation over an annual period

(5)Land use conditions were relatively constant prior to the widespread use of conservation practices.

Determination of Runoff

Surface runoff occurs when the rainfall rate is greater than the infiltration rate. The method used in this study to determine runoff from the basin was developed by the Soil Conservation Service (SCS). Factors which this method considers are: the amount of rainfall, soil type or infiltration capacity of the soil, land use, conservation practices, and the antecedent moisture condition of the soil (SCS, 1972).

The SCS method uses the equation:

$$Q = \frac{(P-.2S)^2}{P+.8S} \qquad (1)$$

where

Q = runoff in inches.

P = amount of rainfall in inches.

S = maximum potential abstraction (or the amount of rainfall that does not runoff).

The .2S term is the initial abstraction which consists mainly of interception, infiltration, and surface storage. It has been empirically determined by the SCS that .2 of the maximum potential abstraction occurs before any runoff occurs. Precipitation must exceed .2S before any runoff is expected. It has been found that the maximum potential abstraction can estimated by the equation:

$$\text{and} \quad S = \frac{1000}{CN} - 10 \qquad (2)$$

where

CN= curve number

The curve number represents the relative ability of a surface to produce runoff. It is a function of soil infiltration capacity, land use, conservation practices, and the antecedent moisture content of the soil.

From Equation 1 it can be seen that a threshold precipitation amount must be reached before a positive value for runoff is obtained. This mathematical equation is based on the assumption that runoff does not occur until a saturation limit of the soil has been reached and the infiltration rate no longer exceeds the precipitation rate (SCS, 1972).

Collection of Data

Precipitation data. Since the objective of this study was to analyze as large a time period as possible, representative stations had to be selected that would give long continuous records of rainfall data. All the stations selected had a continuous record for the period 1920-1980 (see Table 1). The eleven stations selected were: Colby, Hoxie, Norton, Hill City, Plainville, Phillipsburg, Alton, Smith Center, Beloit, Lincoln, and Minneapolis. The Thiessen polygon method (Linsley et al., 1981) was used to divide the basin into polygonal areas and then to weight the data for each station in proportion to its respective area. Figure 2 shows the Thiessen areas as they appear on a map of the basin. Table 2 shows the planimeter readings of areas and the determination of their weighting values.

Due to the hydrologic soil-cover complex of the basin, only rainfalls over one inch would produce appreciable runoff. For example, an area with a CN of 65 must have a rainfall of 1.08 inches before any runoff is predicted by the SCS runoff equation. For this reason, only daily rainfall events over 1.00 inch were collected for the eleven stations for the period 1920 - 1980. Daily rainfall records for the stations selected are maintained by National Oceanic and Atmospheric Administration (NOAA) and reported in *Climatalogical Data, Kansas*. These data were collected, and a micro-computer program was written which was able to file all the data and recall it for later calculations.

Basin yield. The gauging station that best represented the yield of the entire basin is at Niles, Kansas. The river flow data is measured by the U.S. Geological Survey and reported in *Water Supply Papers* (USGS, 1920-1980). The annual yield in acre-feet for the calendar year was recorded and filed on the micro-computer disk for later analysis.

Curve number data. The SCS curve number represents a surface's relative ability to produce runoff. With a curve number of 100 all rainfall would result in runoff. For a smaller curve number, the runoff would be less. The curve number is a function of the infiltration capacity of the soil or soil type, the use of the land (which includes conservation practices and land condition), and the antecedent moisture condition of the soil. All of these factors must be determined before the curve number can be estimated. The SCS has developed a table for determination of the curve number based on these factors (see Table 4). The methods used in this study to determine each factor of the curve number are described in the following paragraphs.

Soil types. Differences in the ability of soils to absorb rainfall or to produce runoff has led to the classification of soils into hydrologic groups. The classifications can be found in the National Engineering Handbook (SCS, 1972) and other hydrologic publications. The soil type throughout any of the Thiessen areas was not constant, nor did the Thiessen boundaries form good divisions for the different soil types. This presented the problem of determining the soil types that best represented the entire Thiessen area. This was done by estimating the percent of each soil type in the area and weighting each particular type of soil accordingly. The reference used for this determination was The Missouri River Basin Comprehensive Framework Study (1969). For example, in an area where the soil type was classified 50% group B and 50% group C, the runoff curve number was the mean of the the group B and group C curve number. The soil types for all the stations used are shown in Table 7.

Land use. Another factor that is considered in determination of the curve number for the SCS runoff equation is the land use. It is obvious that, for a given storm, runoff from a land surface used for pasture would be different from one used for row crops. The SCS method compensates for this by adjusting the SCS curve number for different types of land use. To determine the land use of each area, the U.S. Census of Agriculture was used as a reference (USDC, 1977). The land use in the basin is primarily pasture/range and croplands. The proportions are approximately equal and have not changed much with time. The percentages for each land use were calculated from the 1974 land use data. In determining the curve number, the non-terraced and non-contoured conditions were used to more closely approximate conditions prior to the advent of conservation practices. The county that dominated each Thiessen area was used to determine the predominant land uses. To simplify the immense task of determining specific land use, all of the land was considered to be one of four different uses. These uses were: fallow, row crops, grain crops, and pasture and others. Division of the land uses into these categories was modeled after the study of the Republican River Basin (Koelliker et al., 1983). All land that was not fallow, row crop, or grain crop was considered to have the same curve number as pasture. The land use data is shown on Table 5. The percentages of each type of land use were then used to weight and calculate the curve number.

Antecedent moisture condition. The final variable considered in determining the curve number was the antecedent moisture condition (AMC). AMC is the amount of water contained in the soil at the beginning of the rainfall. AMC I is dry, AMC II is moist, and AMC III is wet. Since determining the AMC before each rainfall event for the last 61 years would be an immense task, data was collected for the percentage of time in AMC I, II, and III for each Thiessen area. This data was obtained from the SCS in Salina, Kansas which had previously determined the percentages for the following stations: Colby, Hoxie, Hill City, Phillipsburg, Alton, Ellsworth, Belleville, Manhattan, Norton, and Hays. The variations in the percent of time in AMC I, II, and III were approximately linear with east-west distance; therefore, the values for the other stations that were needed were interpolated (see Table 4).

Determination of Curve Number

With the soil type, land use, and AMC determined, an average curve number for each station was determined. Table 4 is a reprint of the table of curve numbers for different hydrologic soil-complex covers as developed for the Republican River Study. These values were applied to the Solomon River and were used for determination of the curve number for each Thiessen area. Table 7 shows the the curve numbers determined by using a weighting technique. For example, the soil around Colby was determined to be primarily group B soil. The CN for AMC II in group B soil for the four different land uses was determined from Table 4. These values were then weighted by the appropriate percentages of land use (Columns c-f on Table 7). This resulted in an average AMC II curve number for the area. Finally, the percentage of overall time that an area was in AMC I, II, or III was used as a weighting factor to determine the final curve number. For example, Colby was in AMC I 95% of the time, AMC II 3.2%, and AMC III 1.8% of the time for a final weighted CN of 59.

Analysis of Data

The method of analysis that was first used on the data was a modification of the method used in the study of the Republican River Basin (Koelliker et al., 1983). In the Republican River Basin study, rainfall events were divided into daily rainfalls of 1.00 - 1.49 inches, 1.50 - 1.99 inches, and 2.00+ inches. The duration of each rainfall was collected so that each storm could then be classified according to its total rainfall and duration. Using historical data, each storm classification was assigned an average expected runoff. In the Republication River Basin, it was found that the relative amount of inflow could be approximated by the equation:

$$PINF = (1-A)P + A*IF^2 \qquad (3)$$

PINF is the predicted relative amount of average annual inflow. Relative amount is defined as the value for a particular period divided by the long-term average and expressed as a percentage. The P term is the relative annual rainfall and represents the effect that base flow had on the river yield. Specifically, it was determined by dividing the annual precipitation by the long-term average. The IF term in the PINF equation is the relative intensity factor and represents the effect of runoff on the basin yield. Specifically, it was determined by dividing the annual runoff by the average long-term average annual runoff. Annual runoff was determined by summing the runoff estimated for the daily storms as explained above. The A term is an estimate of the relative importance of the runoff factor in determining the relative yield of the basin. The IF term in the equation was squared to account for the wide variation in inflows that could not be accounted for by linear variations (Koelliker et al., 1983). Koelliker (1983) grouped the records into periods of five or more years which had either high or low flow amounts compared to the remainder of the record. A PINF equation was then derived to predict the relative inflow for these periods.

The method used in this study modified the previously described method by inputting each daily rainfall event over one inch into the SCS runoff equation to estimate the runoff produced. No storm duration time was used in the analysis of data for this method. Henceforth, in this report, the second term in the PINF equation will be referred to as the runoff factor (RO). The equation then becomes:

$$PINF = (1-A)P + A*RO^2 \qquad (4)$$

All other terms in the PINF equation were calculated the same as in the Republican River Study. Using this method, the PINF value represented a dimensionless relative value of basin yield. The reliability of the prediction was tested by dividing the actual basin yield by the PINF value and then plotting this value against time. A good PINF would show only small variations with time since the actual yield and PINF vary proportionally.

The second method of analysis used a regression analysis to relate the precipitation and runoff terms to the annual basin yield. In this approach, the yield of the basin would again be predicted by the baseflow and runoff. Annual precipitation was used to account for the base flow contribution. The runoff factor was, as in the previous method, determined by the amount of annual runoff calculated by the SCS equation. The annual runoff for each station was weighted according to its Thiessen percentage to determine the annual runoff for the entire basin.

With the determination of annual rainfall and annual runoff for the entire basin, these two factors were then used as independent variables in a regression analysis to determine their correlation to the annual yield. To determine the combined correlation of annual rainfall and annual runoff to basin yield, a multiple linear regression was conducted. Subsequently, to determine the separate correlations of annual runoff to basin yield and annual

precipitation to basin yield, bivariate linear regressions were conducted. The linear regressions were tested on both the variables themselves and on their logarithmic scales. The correlation coefficient was determined in all cases. The results of these analyses are discussed in the next chapter.

Use of the Micro-Computer

Analysis of such a large data base required the use of a computer. The micro-computer proved to be economical, efficient, and capable of the task. Specifically, a TRS-80 Model II with 64K memory was used. A program was written that was capable of filing all the precipitation records for the eleven stations and the annual yield data. This information could then be recalled to compute the runoff for each rainfall event in the period of record and to use this information in the analysis methods previously described. The micro-computer was also used to conduct the statistical analyses of the data. This program was capable of conducting a multiple linear regression with two independent variables for the entire 61 years of records. With modifications, the program was also able to file data points and then compute linear regression analyses on the common logarithms of the variables. Since there was no evidence that the relationship would be linear, the options of computing the data in logs made it possible to determine if the data were linear on log-log or semi-log scales. A flow chart of the computer program is shown in Figure 4 with a listing of the program in the Appendix.

CHAPTER 3

RESULTS

Results of Analysis Using PINF Equation

The PINF equation, developed for an analysis of the Republican River Basin (Koelliker et al., 1983), was applied in this study to the Solomon River Basin due to the similarities of the basins. The equation as applied to the Republican River was able to predict relative annual yields of the basin. The value of A that best fit the Republican River was found to be .7 (Koelliker et al., 1983). It was not assumed that the same value of A would fit the Solomon River; however, it was a good starting value for a trial and error approach. As explained in the previous chapter, the test of the validity of the PINF was the amount of variation of its plotting value (actual yield divided by PINF). A small deviation from the mean plotting value indicated that PINF was a good relative predictor. A good predictor, when converted to a plotting value, would plot as an approximate horizontal line, with time on the abscissa and plotting value on the ordinate. Some variation could be removed by using the moving average of the plotting value. It was expected that this horizontal plot would show a sharp decrease when extensive conservation practices began to be used.

The first analysis of the data using the PINF equation was conducted using a value of .7 for A. The PINF was calculated for each year of record, and the three-year moving average was taken of the plotting value (Table 8). Figure 5 shows a graph of these plotting values. The graph does show an average decrease in the plotting value after the mid 1960's; however, it was judged that the PINF plotting values were too variable to consider PINF a good predictor. These values had a mean of 5,286 (acre-feet/PINF) and a standard deviation of 2,349. Various other values of A were tried with no significant improvement in the variability of the plotting value.

Results of Statistical Analysis

Since the modified application of the PINF equation did not appear to be valid for the Solomon River Basin, an attempt was made to find the relationship between annual precipitation, annual runoff, and annual yield by means of regression analyses. Bivariate and trivariate linear regressions were conducted to determine the correlation of the variables. Yield was considered to be the dependent variable while annual precipitation and annual runoff were considered independent variables. There was no reason to expect that any of the regressions would be arithmetically linear; however, mathematical methods could be used to make exponential relations plot as linear. To establish the correlation, only the first 30 years of data were used, so that the effect of increased conservation practices on the curve number would not be a variable.

Initially, a trivariate linear regression was conducted to determine the correlation of both independent variables to the basin yield. Subsequently, bivariate linear regressions (using only one independent variables) were conducted to determine which variable had the strongest effect on the yield.

The results of the trivariate linear regression showed that on a arithmetic scale the best fit relationship had a coefficient of determination, R^2, of .67. This was the best correlation that was achieved. The logarithmic and semi-logarithmic plots had R^2 values of .63 and .60, respectively (see Table 9). The best trivariate linear regression relation was found to be:

$$Y = .1002 \times P + .2258 \times RO - 1.2765 \qquad (6)$$

where:

Y= annual yield in inches
P= annual precipitation in inches
RO= annual runoff in inches

The standard error of estimate was .4021 inches. This standard error was 35% of the average yield and was too large to consider the equation to be a good predictor of yield.

To determine which independent variable had the strongest correlation to yield, two bivariate linear regressions were conducted. The first regression correlated annual precipitation to annual yield. This analysis gave the best correlation on an arithmetic scale. The coefficient of determination, R^2, was .67 (see Figure 6 and Table 10). While the correlation was not particularly strong, it was considered to be significant. The regressions on semi-logarithmic and full logarithmic scales had R^2 values of .64 and .60, respectively. The second bivariate linear regression correlated annual runoff to annual yield. The best correlation was achieved on an arithmetic scale. This R^2 value was .35, which was considered too low to be significant (see Table 11).

Since neither of the two methods of analysis appeared to be a good predictor of yield, a comparison of similar years was conducted to better understand the results of the analyses. For example, years were selected that had similar annual precipitation and annual runoff data; their yields were then compared. Believing that the period 1920-1950 had stable land use conditions, all the comparisons were done within these years.

Example:

Year	Annual Precip(in.)	Estimated Annual Runoff x 100(in.)	Yield (ac-ft)
1927	25.90	45	794,000
1948	24.64	47	495,000

In this case, the yield of 1927 was almost twice that of 1948, although they had almost equal precipitation and runoff statistics.

A comparison of two years of equal precipitation but different runoffs shows again that the yield is not consistent with what would be expected.

Example:

Year	Annual Precip(in.)	Estimated Annual Runoff x100(in.)	Yield (ac-ft)
1923	22.17	19	458,000
1938	21.14	40	267,000

In this case, it was expected that the yield of 1938 would be higher than 1923; however, the opposite was true.

The above comparisons are not isolated cases. What they do seem to indicate is that there may be one or more other variables that are affecting the yield, or possibly that the predictions of runoff used in this study are not representative of the actual runoff.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

Using only the variables annual precipitation and annual runoff, with runoff calculated by the SCS equation, it is not possible to accurately predict the relative annual yield of the Solomon River. The test of the PINF equations showed that their predictions were innaccurate, while the best statistical correlation of the variables to the annual yield showed only a moderately strong correlation. The best fit relationship had a R^2 value of .67 with a coefficient of variation of 35%.

The bivariate regression analysis of the runoff and yield data showed that runoff has a very weak correlation with the annual yield, while annual precipitation showed a much stronger correlation to the annual yield. It was expected that runoff would have a stronger correlation with yield, since it was believed that runoff is the predominant source of inflow into the Solomon River. For this reason, it appears that the runoff predictions for the basin may be inaccurate. As stated in the previous chapter, the SCS equation for predicting runoff does not consider the intensity of the rainfall. In an area that typically has intense and violent storms, this may be a significant source of error in runoff prediction.