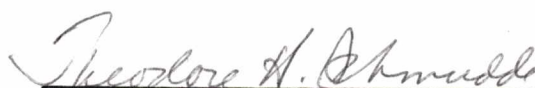


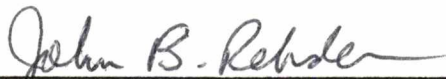
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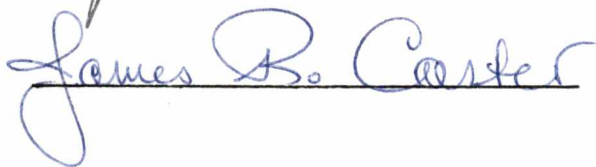
I am submitting herewith a thesis written by Volker Jaeger entitled "The Influence of Groundwater Storage on Floodflow." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.



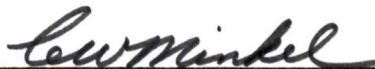
Theodore H. Schmudde, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:



The Graduate School

4

THE INFLUENCE OF GROUNDWATER STORAGE
ON FLOODFLOW

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Volker Jaeger
March 1984

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ABSTRACT

The purpose of this thesis is to determine the relationship between groundwater storage and floodflow through case studies of two drainage basin with contrasting size and geo-hydrological qualities. It is assumed that empty groundwater storage space is capable of reducing the magnitude of a flood. Water balance analysis is used to evaluate the degree of flood reduction due to groundwater recharge by computing the amount of storm water that went into storage. The availability of empty groundwater storage is assessed through an evaluation of the moisture conditions that preceded each flood, the antecedent moisture conditions. Simple correlation and multiple regression analysis were employed to evaluate the relationship between floodflows, volume of storm precipitation, Fanteecedent moisture conditions, and the calculated storage. or one basin, that of the Grand River in Missouri and southern Iowa, the anticipated relationships showed up clearly and proved statistically valid. For the other basin, that of the Powell River in northeastern Tennessee and southern Virginia, the flood reducing effect was not evident from the data used. However, it is believed that for this basin also, a similar effect would become apparent if better data were available. It is concluded, that under some circumstances, groundwater storage can reduce the magnitude

of floods, and that this effect should be taken into consideration by flood prediction models.

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CHAPTER 1

INTRODUCTION

The Problem

Flooding is determined by such drainage basin factors as size, shape, slope, vegetative cover, soils, and bedrock. Storms of comparable magnitude will show varying flood impacts, depending on the characteristics of the basin over which they occur. The runoff response of a basin can be crucial in determining its erosional activity and potential for agriculture and other landuses. A high proportion of runoff, caused by steep slopes, lack of vegetation, or shallow soils might lead to water deficiency during major parts of the year, in spite of what normally would be sufficient rainfall. Similar conditions may also lead to frequent flooding which imposes limitations for landuse.

The opposite is the case when the proportion of immediate runoff is relatively low. This may be due to deep soils with a high waterholding capacity, dense vegetation, and / or a moderately sloped landscape. Here, periods of drought can be overcome more easily, since a significant proportion of the previous rainfall may have gone into soil storage. The flood response to heavy storms is likely to be delayed, thus reducing the crest while extending the time of the floodflows.

Scopes of the Study and Hypotheses

This study investigates the influence of the soil and groundwater storage capacity on floodflow. Two basins with dissimilar physiographic characteristics and located in different climatic zones are investigated. To a degree the pair roughly approximates the two situations discussed above. The objectives of this study are as follows:

1. To develop a methodology that produces quantitative measures for the interaction between groundwater and soil storage and floodflow. This method is to be based on readily available data.
2. To apply this methodology to two watersheds representing contrasting geologic, geomorphic, and climatic parameters, and to explain the interaction.
3. To compare the results for both basins and to account for the differences.

To achieve goal 2 and 3, the following basic hypotheses will be tested.

1. The storage potential in soils and aquifers leads to a reduction of the floodflow. In other words, if the amount of rainfall is controlled, the floodflow will be inversely correlated to the available storage space.
2. The amount and kind of storage space depends on the geo-hydrological configuration of the watershed. From this it follows, that if two basins are distinctly different in their soil and groundwater storage capacities, such storages

will result in flood reductions of different magnitudes and of a different time scale.

Literature Review

There are numerous studies concerned with the prediction and the explanation of the flood behavior of, usually small, watersheds. A widely used approach is to explain the mean annual flood or comparable statistical measures for a sample of basins. Taylor and Schwarz (1952) related size and slope characteristics of basins to the peak flow and time lag in unit hydrographs. Potter (1953) investigated the peak flows of 51 watersheds in the Allegheny-Cumberland Plateau. The main determining factor was, not surprisingly, the watershed area. However, the explanatory power of the correlation could be improved significantly when variables accounting for the vegetative cover, rainfall intensity, and channel characteristics were introduced. Wong (1963), through multivariate factor analysis, concluded that length of the main stream and average channel slope are important factors in determining the mean annual flood. White and Reich (1970) first drew attention to the role of limestone bedrock in modifying the floodflow. They propose that well developed karst features should have a dampening effect on the flood hydrograph. Excess storm water is taken into temporary storage and is released shortly after, thus stretching the time base of a

flood and reducing its peak flow. In a later study (1976), White could not prove this effect, but gained evidence that carboniferous bedrock, along with other basin parameters, influences the flood behaviour of a basin.

A different approach is presented by Muller (1976). While all the above mentioned authors try to explain the variation of floods within a sample of watersheds, Muller concentrated on a single large basin, that of the Mississippi River above Vicksburg. He calculated the water budgets for three of the rivers major floods, those of 1927, 1973, and 1975. He then compared his estimates of surplus with the measured river stages for each flood. The calculated surplus was the greatest for the 1973 flood, but the stage and the duration were not as great as for the 1927 flood. Muller assumes that this discrepancy is caused by huge amounts of empty storage space in soils and aquifers which absorbed a part of the surplus during the 1973 flood season. He supports this idea with the fact that this flood was preceded by more than a decade of sub-normal precipitation. This might very well have led to a severe depletion of groundwater resources, thus providing large volumes of unoccupied storage space. The 1927 flood, in contrast, was preceded by comparatively wet years. He concludes, that climatic variables and their effect on groundwater levels should be taken into consideration for land management and flood protection models.

In a more recent paper (1980), Muller analyzes what influence the change in various basin parameters has on water yield. One of those changes, the process of suburbanisation, goes along with an increase of impervious surfaces. The runoff from those developed areas becomes prominent especially during dry periods, when the unoccupied storage space of the undeveloped lands with high infiltration rates absorbs the surplus. This again underlines the important role of storage in runoff estimates.

Kapotova (1972) determined the reduction of springtime snowmelt floods due to groundwater recharge as the difference between the storage volumes at the end and at the beginning of the flood season. Since the groundwater storage varies little at the end of the flood season, the amount of the floodflow reduction depends mainly on the groundwater level at the beginning of the flood. In other words, the reduction of a flood is a direct function of the volume of unoccupied storage potential. Kapotova's findings support Muller's hypothesis, although they were derived by an entirely different method, and were generated in a quite different environment.

Methodology

The methodology proposed here is based on the following assumptions:

1. Both watersheds have a limited storage potential in soils and aquifers which is a function of the basin characteristics. It is assumed constant through time.
2. This storage volume is capable of absorbing significant amounts of water during a flood generating storm.
3. The volume of empty storage space at the beginning of a flood is a function of the moisture conditions that preceded the flood, or the antecedent moisture conditions.

The two study areas are the Powell River watershed above Norris Lake, a medium sized basin in Tennessee and Virginia, and the Grand River basin, located in north-central Missouri and adjacent parts of southern Iowa.

The computation of water budgets is part of the procedure. The portion of the precipitation that remains when discharge and evapotranspiration have been subtracted is assumed to have gone into temporary storage. As indicators for the antecedent moisture conditions, the areal precipitation volumes for time periods ranging from three to sixty days before the beginning of the major storm were calculated. A precise discussion of the procedures is subject of the second chapter.

The data used were: Discharge records from the U.S. Geological Survey gage no. 6-9020, Grand River near Sumner, Mo. and U.S.G.S. gage no. 3-5320, Powell River near Arthur, Tn. For the water years 1960/61 through 1969/70 they are published in the U.S.G.S. Water Supply Papers no. 1910

and 2110 for the Powell and no. 1919 and 2119 for the Grand River. The more recent data are published in "Water Resources for Tennessee" and "Water Resources for Missouri" respectively, also by the U.S. Geological Survey.

The precipitation data for the Grand River and the temperature data for both basins were obtained from "Climatological Data" published by the U.S. Environmental Data Service, formerly the U.S. Weather Bureau. The rainfall data for the Powell River basin are published by the Tennessee Valley Authority as "Precipitation in the Tennessee River Basin".

The second part of the procedure consists of simple correlation and multiple regression analysis. The indicators for the antecedent moisture conditions were taken as predictors (independent variables) for the dependent variables discharge, storage and derivations of those. The analysis was conducted with the University of Tennessee DEC-10 digital computer and the REGRESSION and NEW REGRESSION routines of the "Statistical Package for the Social Sciences" (SPSS) software package. The NEW REGRESSION procedure proved to be powerful and well suited for this problem.

The analysis employed here is directed toward a null hypothesis (H_0). H_0 represents the opposite of what the reasearcher expects to be the case, which is the actual hypothesis (H_1). Instead of a direct proof of H_1 , it is the

goal of the analysis to reject the null hypothesis at a significance level as high as possible. In this case the set is:

H0: There is no relationship between antecedent moisture conditions and the storage / discharge.

H1: There is a relationship between the antecedent moisture conditions and the storage / discharge.

This is the basic structure of the analysis. It will be shown in detail in the third and fourth chapters.

CHAPTER 2

PROCEDURE

This chapter consists of a detailed discussion of the methods and procedures that were employed to quantify the components for the water balance computations.

The Watershed Areas

In order to estimate the volume of rainfall over a watershed, its exact area has to be known. This was done by outlining the basin boundaries on mosaics of U.S.G.S. topographical maps at a scale of 1:250,000 and plotting the locations of the rainfall stations on those maps. There were eight for the Powell River and twenty-five for the Grand River basin.

There are several ways to calculate the average rainfall depth over an area. The simple mean of the data would be justified if the stations were evenly distributed over the two basins. Since this is not the case, a method has to be found that takes their distribution into consideration. There are basically two methods that make this possible, the isoline and the proximal approaches. The first one requires the drawing of isohyetal maps for each storm event. The volume of rainfall can then be determined by measuring the area for each isoline interval and multiplying this with the corresponding rainfall depth. The

application of this approach would require the drawing of forty maps to estimate the storm precipitation and an additional hundred-sixty to get the measures for the antecedent rainfall volumes. These numbers illustrate quite clearly why this method was not pursued.

The proximal approach was chosen instead. The most widely used and accepted procedure is the establishment of Thiessen polygons. The watershed is subdivided into sections of varying size and shape depending on the density and location of the data points - the rain gage stations. For a discussion of this technique, see Thiessen, 1911, Linsley, 1949, or Mead, 1950. Advantages of this method are that it is objective, and that it facilitates repeated calculations. Once the polygons have been established and their area has been determined, the measured rainfall depth simply has to be multiplied by the area of the corresponding polygon, and the sum of these area-rainfall products is the precipitation volume for the entire watershed. Figures 1 and 2 show both watersheds with the rain gage locations and the Thiessen polygons.

Precipitation

The precipitation data are published as daily sums in inches. The volumes for the storm precipitation as well as the indicators for the antecedent moisture conditions were

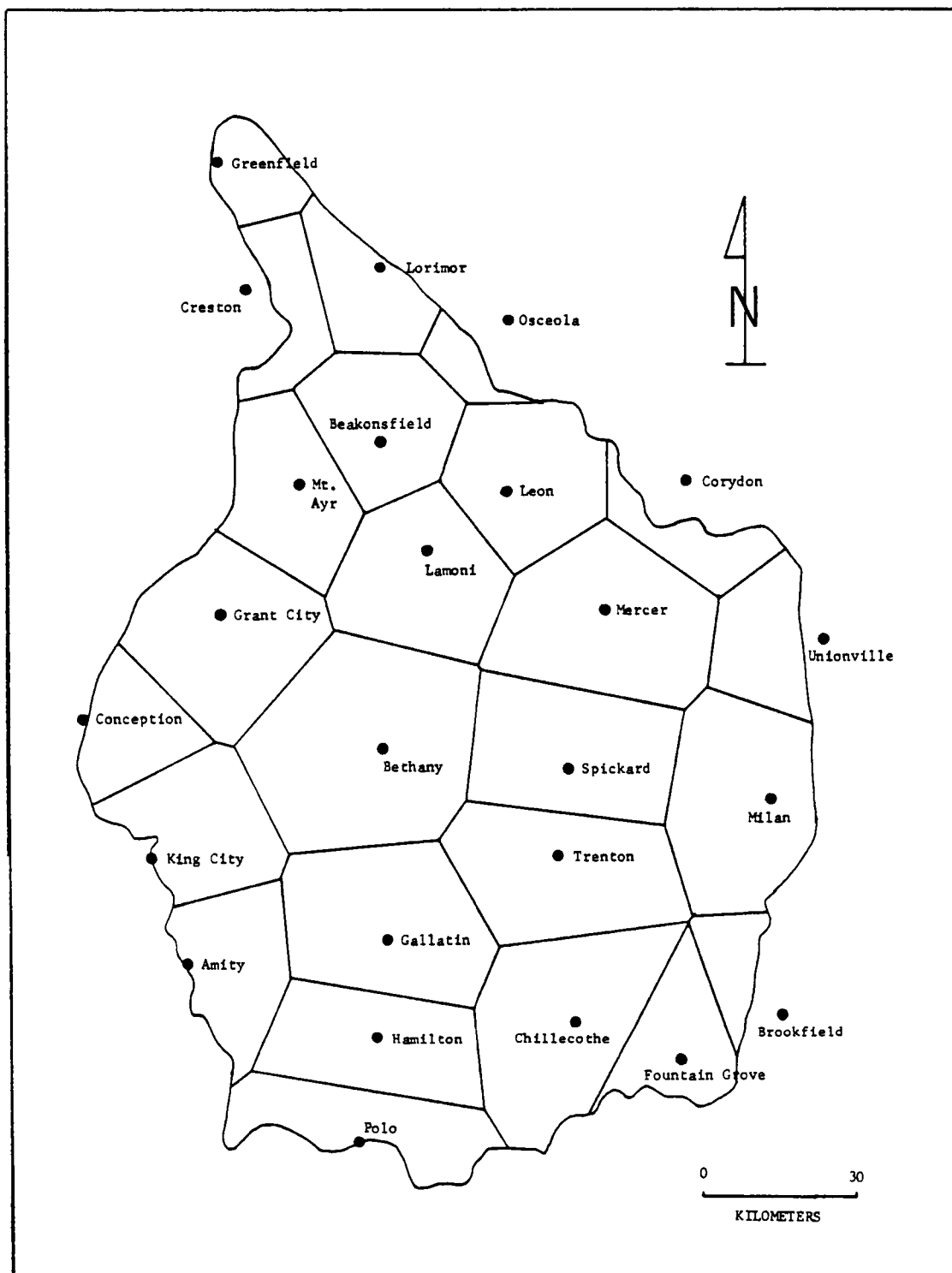


Figure 1. The Grand River Watershed with Raingage Stations and Thiessen Polygons.

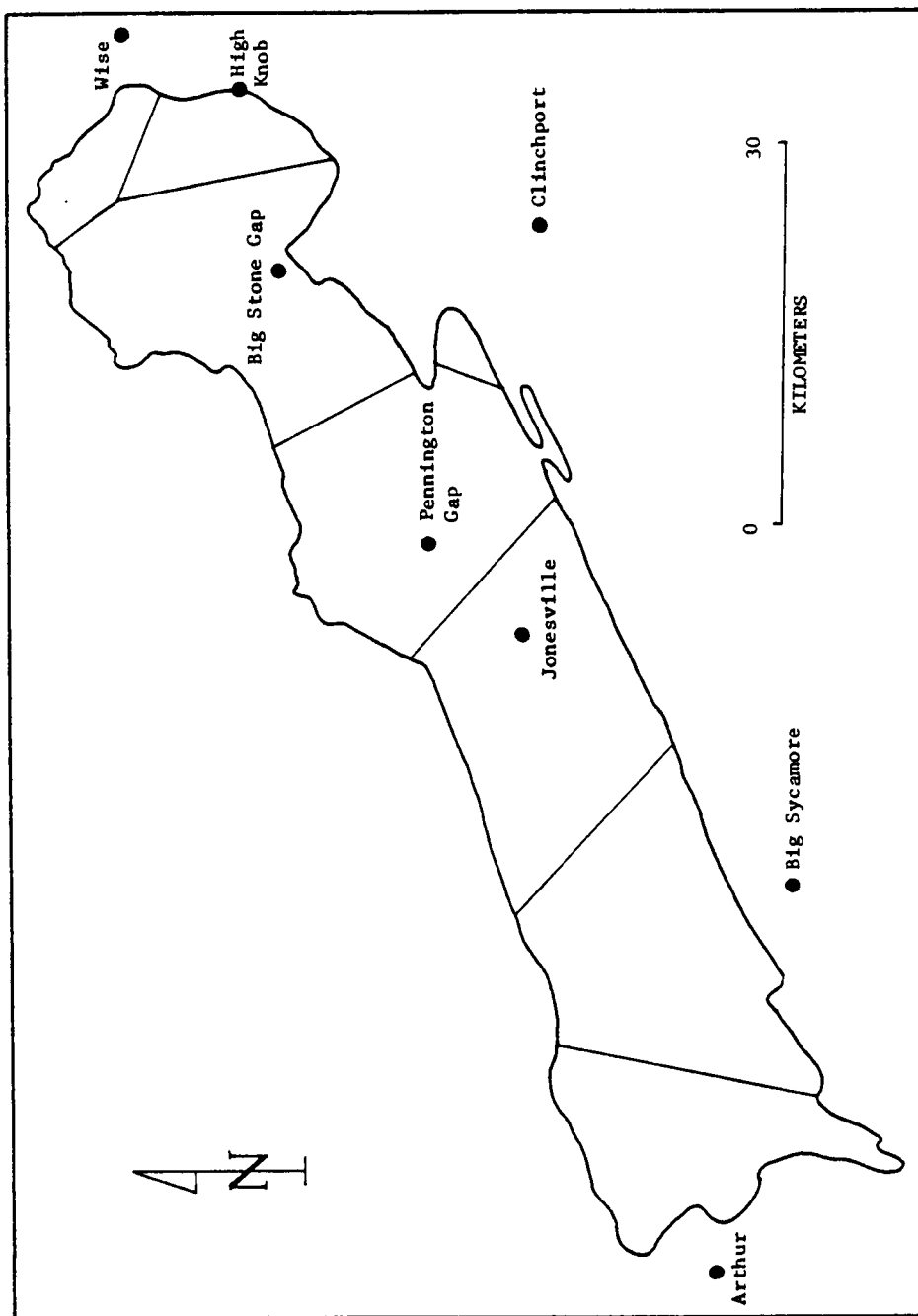


Figure 2. The Powell River Watershed with Rainage Stations and Thiessen Polygons.

computed according to the Thiessen polygon procedure discussed above.¹

For the Powell River basin the rainfall volumes for the three (P3), seven (P7), fourteen (P14), and thirty days (P60) preceding each flood generating storm were computed. For the Grand River basin, P3 was not determined because the larger area and other basin characteristics made a slower flood response likely. To account for this fact, P60, the rainfall volume for the sixty preceding days, was calculated instead.

Most rain gages have incomplete records. The data are missing for days, months, or even several years. In order to avoid the redrawing of the Thiessen Polygons for the reduced number of stations, the missing data were substituted by the mean of the readings of the neighboring stations.

Runoff

The runoff data are published as average daily discharges in cubic feet per second. Initially, the twenty flood events for each basin that showed the highest daily averages were chosen to be analysed in this study. This method worked well for the Powell River basin, but had to be modified for the Grand River. Here, some of the major

¹The areas for the whole watersheds and the individual polygons were computed with help of the program "AREA.FOR", and the areal rainfall volumes through "RAINFA.FOR". Both programs are listed in Appendix B.

floods were generated partly by snowmelt. This was detected when the runoff volumes were compared to the rainfall depths of the corresponding storms. Some of the most severe floods were preceded by only minor storms of a short duration. A possible interpretation is that rainfalls generated under warm front passing over the area cause the melting of temporarily accumulated snow, and generate large amounts of surplus in a short period of time.

A short period water budget cannot be calculated under these circumstances and the antecedent moisture conditions are difficult to account for. To ensure that the results of this study are not falsified by the melting or the accumulation of snow, all floods occurring November through March were excluded from the analysis for the Grand River basin.

To calculate the volume of the floodflow, it is necessary to know the exact time duration of a flood. On discharge hydrographs, which were drawn for each case, the points of strongest positive, Pt1, and negative change of slope, Pt2, were determined. The corresponding points of time, t1 and t2, were regarded as the beginning and the end of the flood period respectively. This is shown on Figure 3. The volume of the floodflow then is the sum of the average discharges between t1 and t2 multiplied with the duration of the flood, t, in seconds, when $t = t_2 - t_1$.

The floodflow so determined represents the amount of

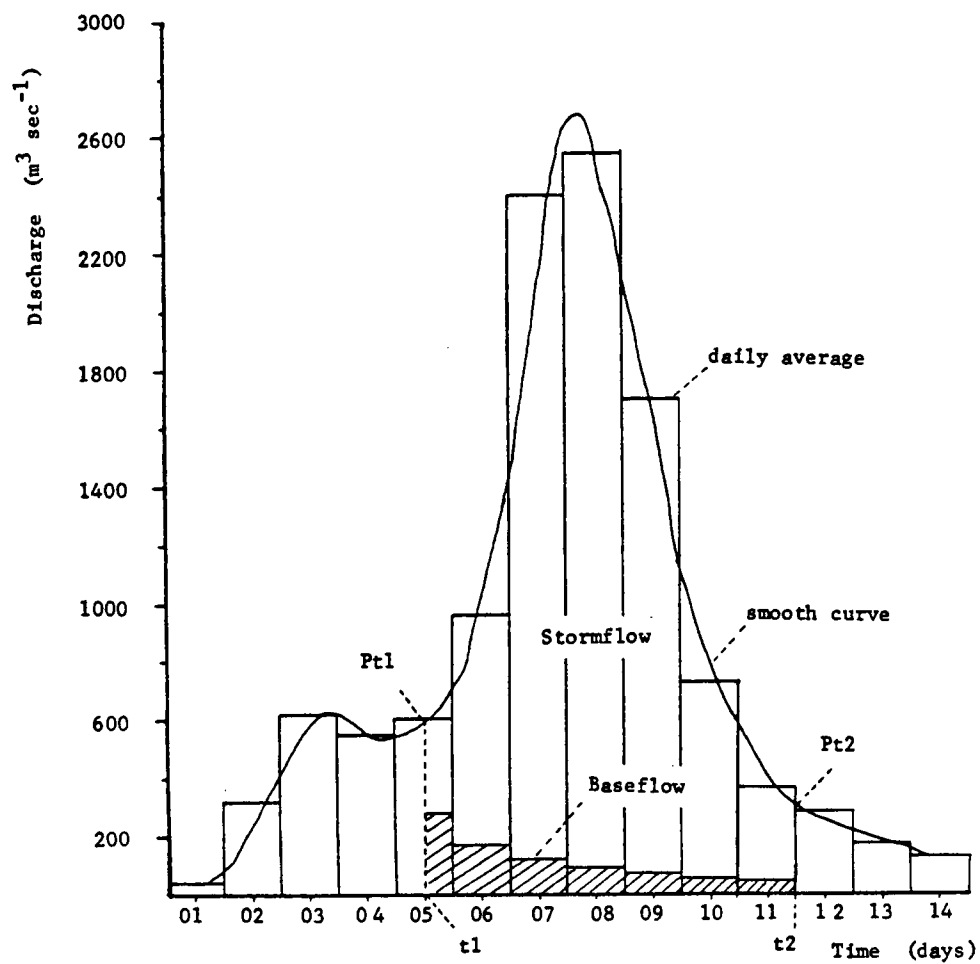


Figure 3. Sample Flood Hydrograph of the Grand River.

discharge during a flood. This, however, does not mean that the entire discharge has been caused by the storm that preceded the flood. A part of this discharge would have occurred even if this storm had not taken place at all, because it is due to antecedent rainfall. This quantity is referred to as baseflow.

In order to calculate the baseflow, the rate of discharge recession for periods without precipitation has to be known. For a number of dry periods the daily recession, Q , was calculated and then plotted on log-paper against the value of the initial discharge, Q . The lines were visually fit to the data. The resulting discharge recession graphs, one for each basin, are shown as Figures 4 and 5. From these graphs, the daily rate of recession can be determined for any Q . An estimate for the discharge of the following day can be obtained by subtracting this value from the initial Q .

To calculate the volume of the baseflow, the discharge value of the day preceding the flood is taken as the initial Q . Then ΔQ is read from Figure 4 or 5 and subtracted from Q . $Q - \Delta Q$ then represents the average baseflow for the first day of the flood. This is repeated until the end of the flood is reached. The steplike pattern at the bottom of the hydrograph on Figure 3 illustrates the result. The volume of the baseflow then is calculated in the same manner as it is described above for the floodflow.

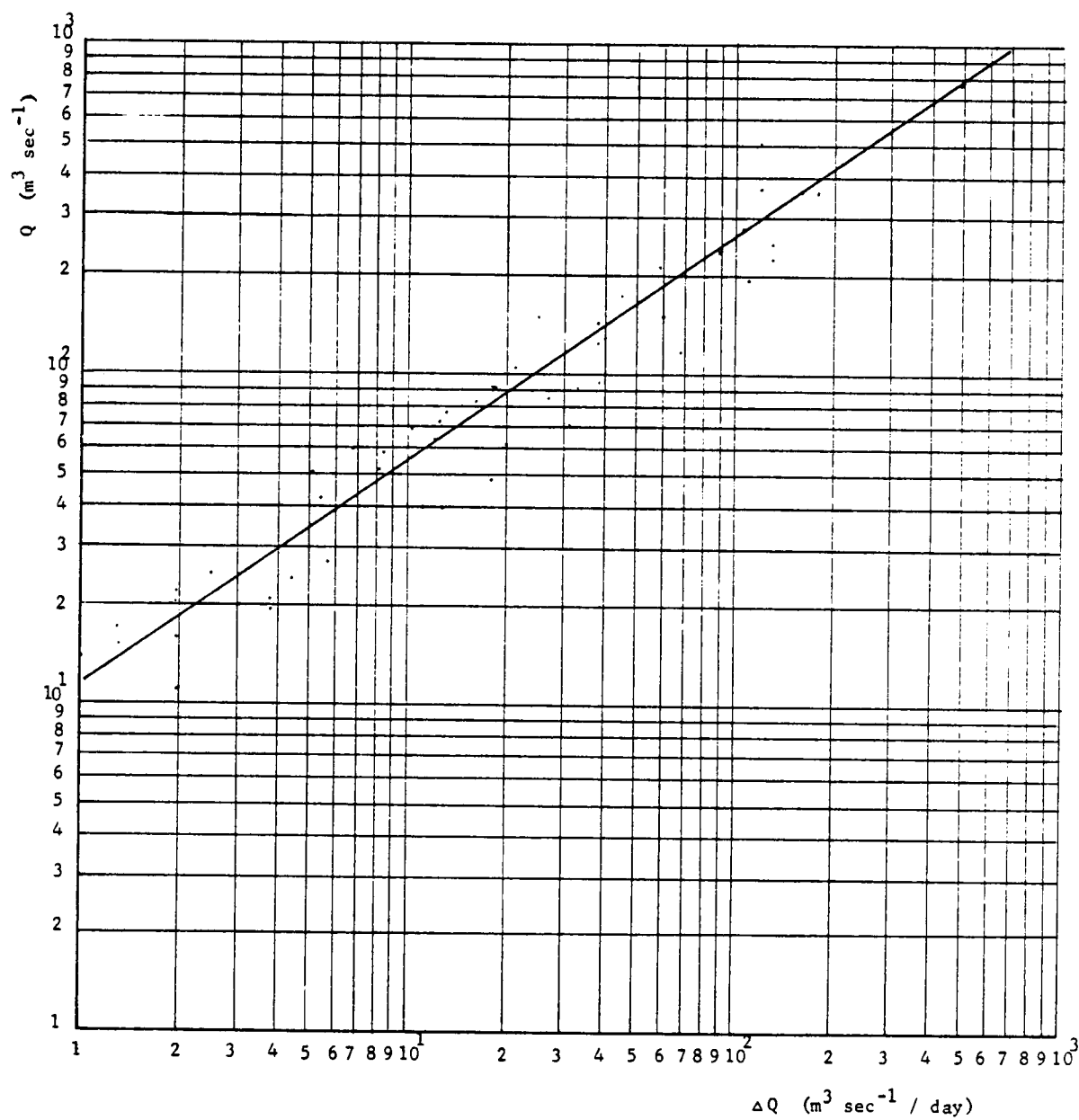


Figure 4. Baseflow Recession Graph - Grand River.

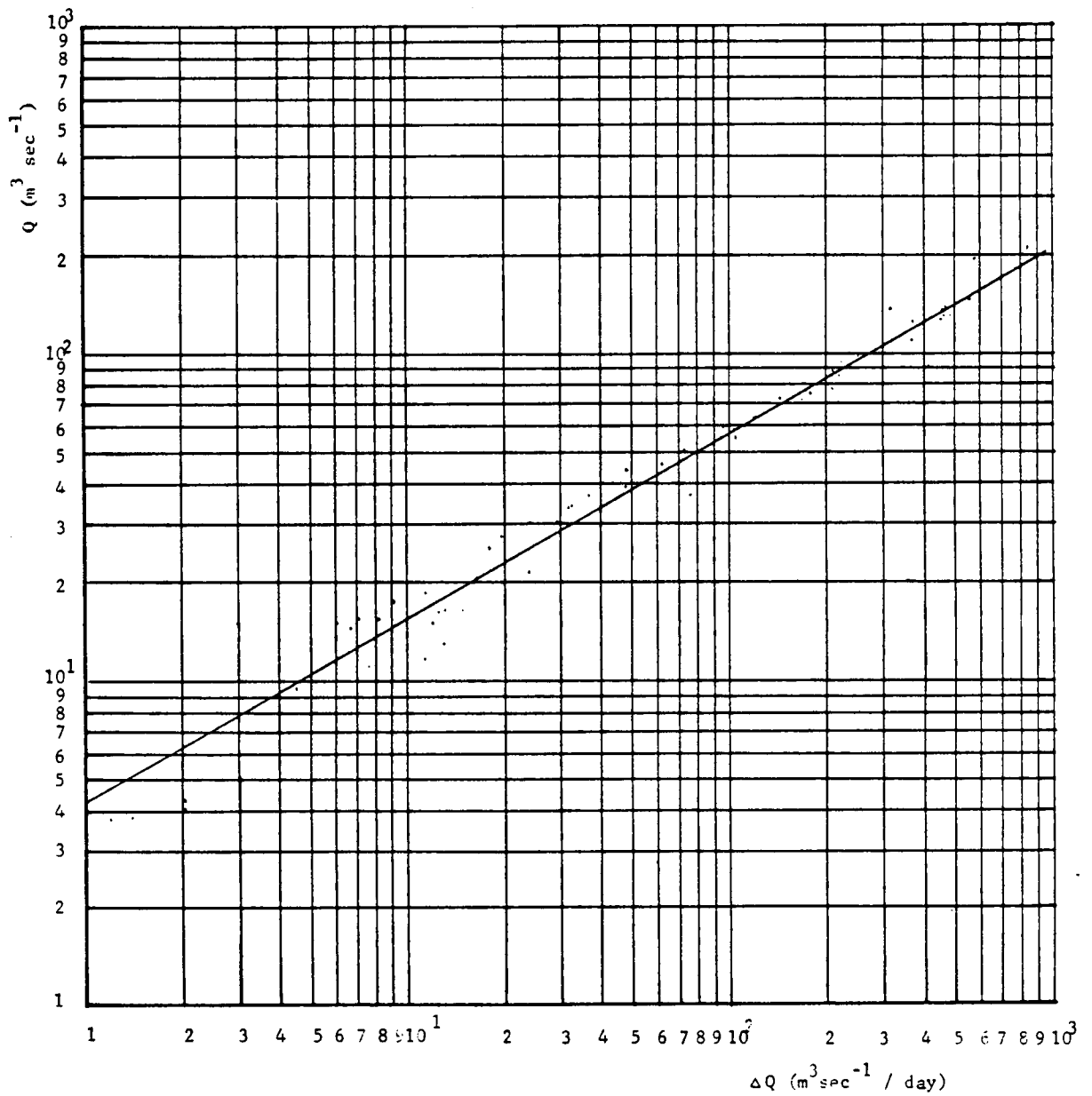


Figure 5. Baseflow Recession Graph - Powell River.

The difference, floodflow minus baseflow is computed for use in the water balance equation. It represents the part of the total discharge that was generated by any storm, or the stormflow.

Evapotranspiration

Among the numerous assessments for evapotranspiration, the method according to Thornthwaite was chosen (Thornthwaite, 1957). For a discussion, I refer to the literature. This choice was made because the data requirements are easily met. Those are daily and monthly temperature averages. The daily means of temperature had to be computed since the raw data consists of maximum and minimum readings.

Compared to precipitation, temperature is a rather unproblematic dimension since its spacial variation is rather low. Considering this, it appeared justified to regard the data of only one station as representative for the watershed as a whole. To make the best possible choice, first the areal mean of all stations was computed for several flood and storm events, and then compared with the measurements of each single station. The station, the readings of which approximated the mean temperatures the best, was chosen to represent the whole basin. This is Corydon, Missouri for the Grand River basin and Pennington Gap, Virginia for the Powell basin. Through this

simplification, considerable amounts of time could be saved.

The potential evapotranspiration (PE) was calculated for the periods of time starting with the beginning of the flood generating storm and ending with the termination of the floodflow. It is assumed to be constant over each basin. The potential evapotranspiration represents the amount of water that will evaporate and transpire under a set of standard conditions, assuming unlimited supply. This condition was always the case for the Powell River basin. The rainfall depth always exceeded the depth of the potential evapotranspiration, so that it is justified to regard PE as an close estimate of the actual evapotranspiration, AE.

For the Grand River basin, such a generalisation could not always be made. Some storms affected only parts of the basin, leaving the rest with little or no precipitation. In these regions, the actual evapotranspiration is limited by the water supply, thus AE is less than PE. To appreciate this fact, the estimated depth of the potential evapotranspiration was compared to the measured rainfall depth at each station. When PE exceeded the precipitation, the latter value (P) was assumed to represent the depth of the actual evapotranspiration, AE. With these values, the volume of AE then was computed through the Thiessen method.

Sources of Error

The accuracy of this method is mainly limited by the

quality of the available rainfall and discharge data. The collection of rainfall data, a sampling procedure, is pursued with a small sample, 25 gages for the Grand and 8 for the Powell River watershed. It is obvious that such a network cannot register but the basic pattern of the areal rainfall variation. It is very well possible that localized storms remain unnoticed by any station.

The discharge data published by the U.S.G.S. is generally considered to be ninety percent accurate. This figure, however, is lower for periods of high discharges, as they are used in this study (Muller, 1976).

The temporal resolution for both precipitation and discharge data does not allow as precise a definition of the storm- and floodflow periods, as it is desirable. Finally, additional error components are contributed by the methods here employed, especially by the estimates of the actual evapotranspiration and the storm precipitation.

In spite of these inadequacies, it is believed that the general trends and relationships that were anticipated can be shown clearly, and that the validity of this study is not seriously affected.

CHAPTER 3

ANALYSIS OF THE GRAND RIVER BASIN

Physiography

The Grand River is a tributary of the Missouri River. The watershed above the gage site Sumner, Missouri has an area of approximately 17,800 sq km (6,880 sq miles), which makes it larger than the state of Connecticut. The main water courses draining the area besides the Grand River are the Thompson River, which originates in south-central Iowa, and its tributary the Weldon River. The southwestern part of the basin is drained by Shoal Creek. The basic drainage pattern is shown on Figure 6.

Terrain varies from smooth plains in the southeast and irregular plains in the west, to open low hills in the northeastern portion of the basin (Hammond, 1964). This means between fifty and eighty percent of the area are in gentle slopes in the southern and western sections of the watershed. For the portion characterized as open low hills, the percentage of land in gentle slopes is reduced to an average between twenty and fifty percent. For the whole area the local relief ranges between 30 and 100 meters (100 - 300 feet). The lowest elevation is the datum of the gage near Sumner, at 192 meters (631 feet). To the northwest, elevations rise gently, and exceed 400 meters (1312 feet) in the northwestern most corner of the watershed near the springs of the Thompson River.

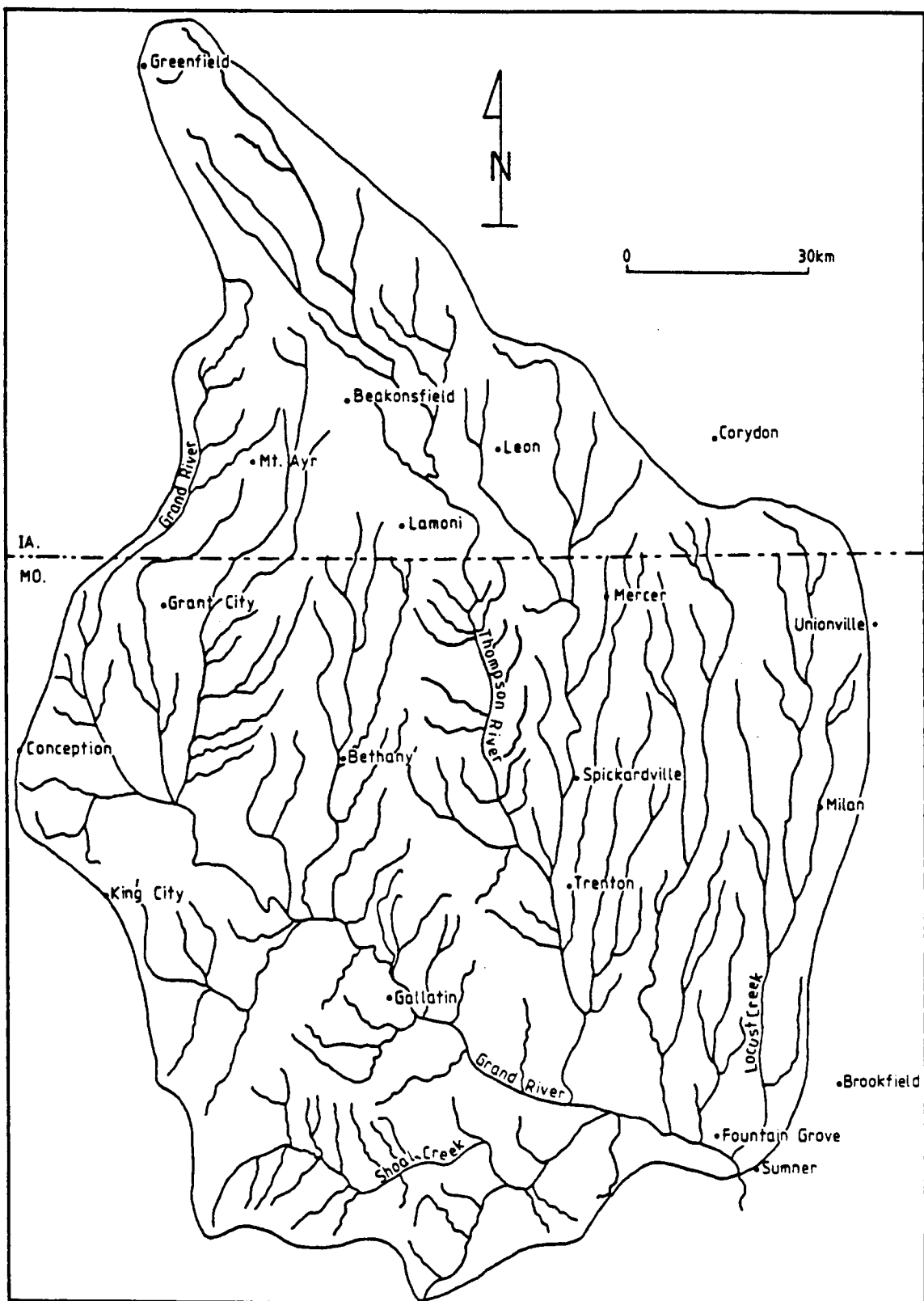


Figure 6. Drainage Pattern of the Grand River Basin.

The geologic structure of northern Missouri and southern Iowa for hydrologic concerns is dominated by Pleistocene deposits from the Illinoian and Kansan glaciations. The series consists of unconsolidated till covering nearly the entire basin, layers of loess on river terraces and parts of the uplands, and terrace material. The thickness of these materials varies greatly between less than 1 meter to more than 120 meters (3 to 400 feet). The evaluation of borehole records for eight Missouri counties that are part of the study area revealed the distribution shown on Figure 7. Exposures of Pennsylvanian bedrock consisting of shales, sandstones, and limestones occur where major rivers have cut through the Pleistocene deposits. Figure 8 shows an example for the pattern of parent materials and soils in a part of Harrison Co., Missouri, which is in the center of the Grand River basin.

The role of the Quaternary deposits in the hydrologic cycle is twofold. The glacial till consists of silty clay interstratified with layers of sand, gravel and boulders, thus providing an aquifer with large groundwater storage potential. This potential, however, is quite variable. In absence of coarse material the downward percolation of water is restricted, while the layers of sand and gravel provide an excellent aquifer.

While the till deposits are largely associated with the

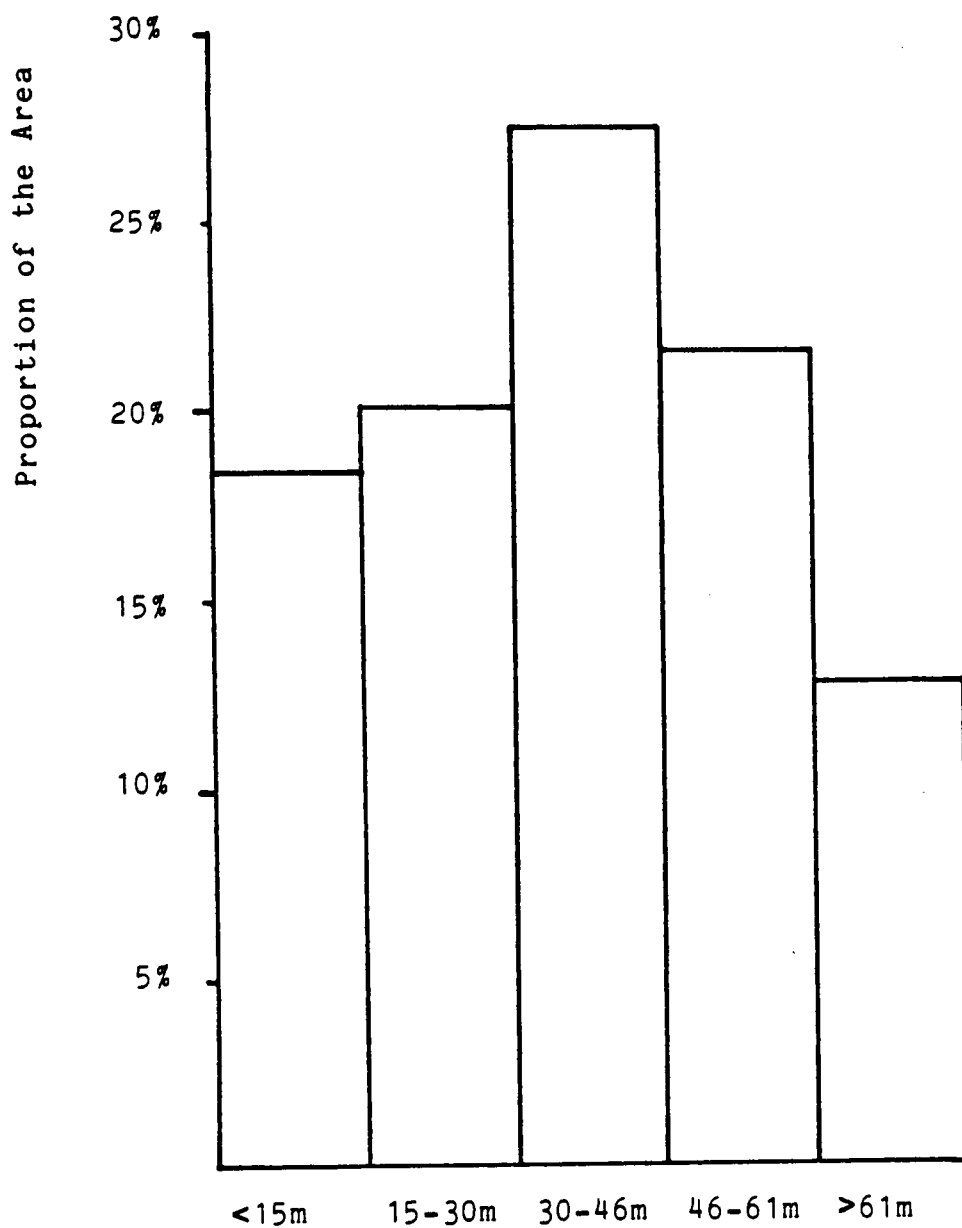


Figure 7. Depth of the Glacial Drift in North-Central Missouri, Based on Borehole Records.

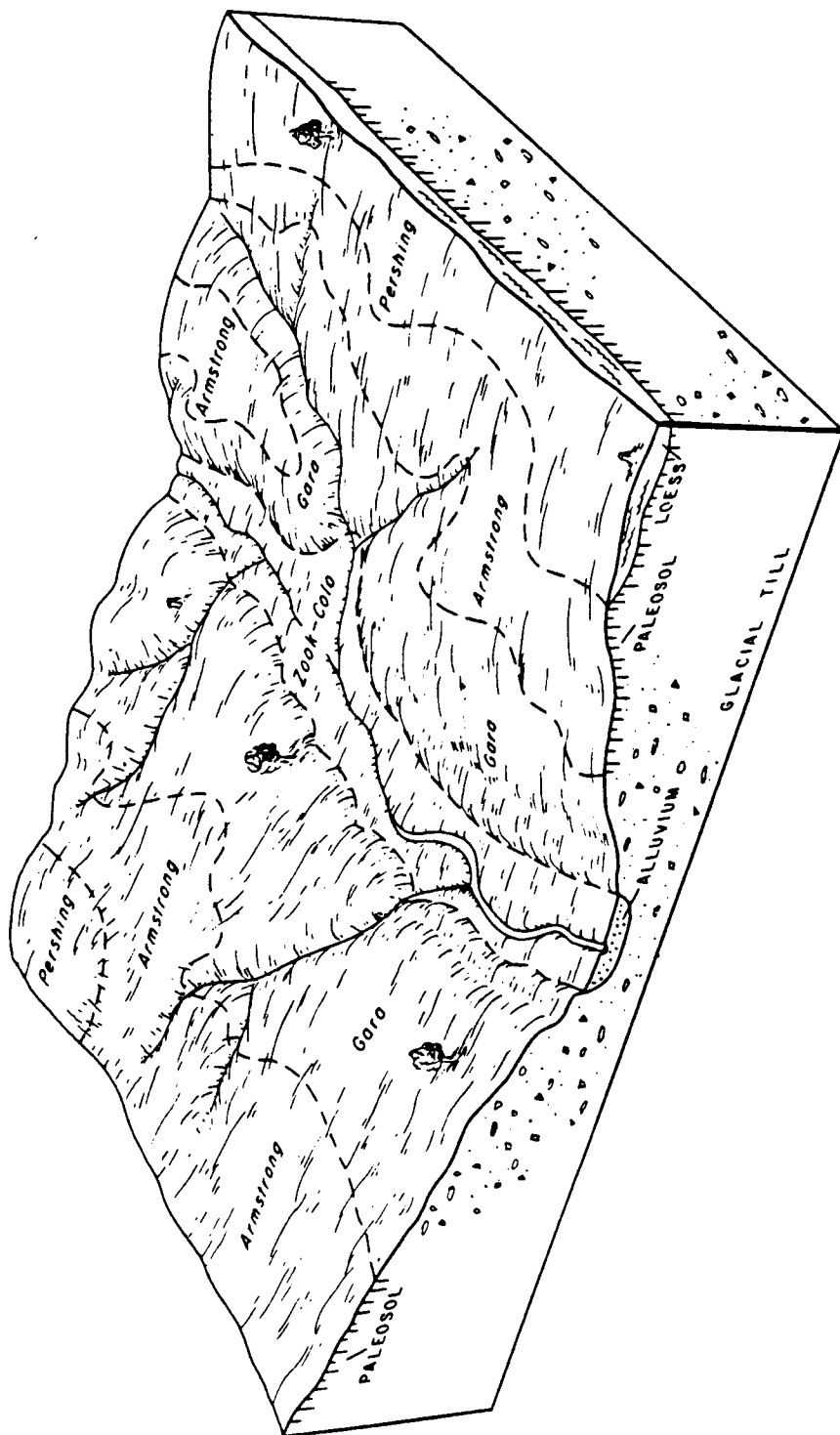


Figure 8. Typical Pattern of Soils and Parent Material in Harrison Co., Mo.
 Source: United States Department of Agriculture, Soil Conservation Service. Soil Service of Harrison County, Missouri.
 Washinton: U.S. Government Printing Office, 1979.

Kansan stage, the loess material is younger and was deposited during the Illinoian and Wisconsin glaciations. Its role as an aquifer is minor because of the very fine, silty texture. The second role of the Quaternary deposits is that of a factor in determining the soil type. Soils that have developed on loess or till lacking coarse material usually have poor permeability and high rates of runoff. Soils are generally well developed over the whole basin with depths of 200 cm (80 inches) and more. The average available water holding capacity of 200 mm per meter of depth is also quite high (Soil Survey, Harrison County). Nevertheless, a complete recharge during high intensity rainfalls is unlikely due to low infiltration rates.

Climate

The climate of the Grand River basin is continental, dominated by cold winters and long, hot summers. Table 1 presents some data on temperature and precipitation as recorded in Bethany, Missouri, for the period of 1951 - 1974. Chief characteristics are the high daily and annual temperature range as opposed to the small areal temperature variation that was mentioned in the previous chapter.

Most of the precipitation occurs during the summer. There are two maxima, one in June and one in September separated by a slight drop during July and August, the two hottest months. The two columns to the right of the average

TABLE 1. Temperature and Precipitation Recorded at Bethany, Mo. 1951 - 1974.

Month	Temperature				Precipitation			
	Average daily maximum	Average daily minimum	Average daily	2 years in 10 will have max. min.	Average	2 years in 10 will have < >	Average # of days snowfall with <2.5mm	
	°C	°C	°C	°C	mm	mm	mm	
January	1.4	-10.1	-4.3	17.2 -27.8	25	7 40	3 180	
February	5.0	-6.9	-0.9	20.0 -24.4	27	10 40	3 114	
March	10.6	-2.3	4.2	26.7 -17.8	58	23 86	5 142	
April	18.8	4.7	11.8	31.1 -7.2	85	44 118	7 25	
May	24.4	10.6	17.6	32.8 -1.1	109	78 138	8 0	
June	29.2	15.8	22.5	36.1 5.6	120	74 160	8 0	
July	31.8	18.1	24.9	39.4 7.8	101	51 141	6 0	
August	30.8	16.7	23.8	37.8 7.2	106	55 147	6 0	
September	26.4	11.8	19.2	35.0 -0.6	120	41 184	7 0	
October	20.8	6.2	13.5	32.2 -6.7	88	27 137	5 3	
November	11.5	-0.8	5.4	24.4 -15.0	41	9 67	3 36	
December	4.0	-6.4	-1.2	18.9 -23.3	30	13 44	3 178	
Year	17.9	4.8	11.4	39.4 -28.9	909	734 1076	64 678	

Source: Adapted from Soil Survey, Harrison Co.

precipitation show the great variance of the actual rainfall depth. Years of drought are as likely as years of excessive moisture. On the average, there is little snow accumulation, partly because the precipitation is low during the cold season. Nevertheless, snowmelt can become a factor in the generation of floods in late winter.

High intensity rainfalls associated with thunderstorms are common in the basin. An average of 56 thunderstorms occur each year, half of them during the summer. The heaviest daily rainfall recorded at Bethany was 155 mm (6.09 inches) on October 11, 1973. It was part of the storm that generated flood no. 16 of this study.

Water Balance

The components and the results of the water balance computations are shown on Table 2. The unit for all measures is millions of cubic meters, with the exception of those that are percentages. P represents the storm precipitation, the amount of water that enters the basin during a storm. AE stands for actual evapotranspiration. The floodflow (FF) is the amount of water discharged during a flood, and the baseflow (BF) is the proportion of the floodflow that is assigned to antecedent rainfall. Thus the stormflow (SF) is derived by subtracting the baseflow from the floodflow, and it represents the portion of the discharge that was generated by the storm precipitation, P .

TABLE 2. Components of the Water Balance for the Grand River.

Flood #	P*	AE*	FF*	BF*	SF*	SFPC**	ST*	STPC**
1	2341.7	387.5	740.2	17.4	722.8	30.9	1231.4	52.6
2	988.2	91.2	778.5	55.8	722.7	73.1	174.3	17.6
3	815.9	0.0	766.4	72.3	694.1	85.1	121.8	14.9
4	838.8	322.8	298.2	35.1	263.1	31.4	252.9	30.2
5	1671.9	950.0	886.5	50.5	836.0	50.0	-114.1	-6.8
6	595.4	415.0	492.8	47.3	445.5	74.8	-265.1	-44.5
7	713.0	123.6	396.6	58.1	338.5	47.5	250.9	35.2
8	923.8	264.4	317.9	17.1	300.8	32.6	358.6	38.8
9	841.4	523.3	364.3	53.2	311.2	37.0	7.0	0.8
10	1550.0	991.1	881.7	50.3	831.4	53.6	-272.5	-17.6
11	1314.3	560.4	339.9	13.0	326.9	24.9	427.0	32.5
12	1234.5	346.2	639.8	46.7	647.1	52.4	241.2	19.5
13	974.7	282.7	534.5	30.1	504.4	51.7	187.6	19.2
14	919.3	282.7	596.6	82.1	514.5	56.0	122.9	13.3
15	1922.3	565.3	836.2	50.4	785.8	40.9	571.2	29.7
16	1559.4	517.5	912.4	34.5	877.9	56.3	164.0	10.5
17	971.8	601.8	406.7	34.8	371.9	38.3	-1.9	-0.2
18	1631.9	583.5	561.0	21.9	539.1	33.0	509.3	31.2
19	982.8	200.6	518.4	76.5	441.9	45.0	340.3	34.6
20	2200.0	756.9	804.8	49.7	755.1	34.3	688.0	31.4

* in 10^6 m^3 .

** in percent.

The storage then is the residual of the water balance equation, i.e., the amount of water that went into storage. This is correct under the assumption that P is a precise estimate for all the water that entered, and EE for all the liquid water that left the watershed during a defined period of time. The estimation of the evapotranspiration is also assumed to be correct. The equation then is:

$$P - AE - (FF - BF) = ST \quad (1)$$

or

$$P - AE - SF = ST \quad (2)$$

In addition to the absolute values, the storm flow and the storage are expressed as percent of the storm precipitation, SFPC and STPC respectively.

Some of the values in Table 2 require explanation, especially the negative values of the storage for floods no. 5, 6, 10, and 17. Negative values mean that for the period of a storm and the flood that results, more water leaves the basin than enters it, which appears contradictory to the above made assumptions. Errors during the data collection and processing are probably responsible for this. During thunderstorms or generally stormy weather, turbulence is created around rain gages that may lead to a significant underestimation of the rainfall depth. On the other hand, the evapotranspiration can easily be overestimated. High intensity rainfalls over soils with poor infiltration rates will result in runoff even if the precipitation is less than

the moisture demand, as expressed by the potential evapotranspiration. Finally, the accuracy of discharge data is rather low during periods of flood stage, which might have caused an overestimation of the floodflow.

For those reasons, the figures of the water balance components should not be regarded as accurate values, but rather as indicators of a general trend. The negative values for the storage can be interpreted to mean that very little or virtually no water went into storage. The same should be done for the percentage measures of the storage, STPC. In a strict sense, negative percentages are meaningless here. Nevertheless, as indicators of a trend and in the statistical analysis below, they are quite useful.

Table 3 shows the volumes of the antecedent rainfall as they are applied in the correlation and regression analysis below.

Simple Correlation Analysis

To detect and to evaluate the strength of the relationships between the components of the water budget and the amounts of antecedent rainfall, simple correlation coefficients were calculated. Table 4 shows some of the results. Simple correlation does not necessarily assume a causal relationship between pairs of variables, but simply determines the strength of their association. Here,

TABLE 3. Volumes of Antecedent Rainfall for the Grand River Basin.

Flood #	P7*	P14*	P30*	P60*
1	49.3	1018.5	1359.8	4682.2
2	546.0	582.6	1374.8	6270.4
3	295.0	1249.4	1846.9	5329.7
4	453.9	1442.9	2285.0	2377.6
5	726.4	2469.0	2529.3	4345.0
6	646.0	1568.0	4894.2	5507.0
7	766.5	1215.0	1714.0	2012.9
8	47.4	914.9	1541.7	2149.5
9	1299.4	1610.2	1728.9	2482.4
10	912.0	2169.7	2942.9	4867.8
11	38.2	481.6	1524.0	2216.1
12	1544.2	2144.9	3028.8	6140.3
13	157.0	1132.2	2413.8	5058.4
14	974.7	1194.6	2649.2	9003.3
15	781.4	1278.0	2350.8	3779.2
16	688.7	2176.4	5684.4	7369.2
17	609.4	769.1	1802.0	2197.9
18	571.9	820.3	2567.5	3853.6
19	1622.6	1629.7	2003.9	3208.1
20	1176.1	1254.4	3096.2	4872.5

* in 10^6 m^3 .

TABLE 4. Correlation Coefficients for the Grand River Basin.

	FF	BF	SF	SFPC	ST	STPC
P	.618*	-.319	.661*	-.404	.630*	.331
P7	.181	.633*	.125	.081	-.232	-.198
P14	.468*	.316	.447*	.240	-.429	-.454*
P30	.338	.063	.339	.312	-.371	-.569*
P60	.636*	.373	.613*	.559*	-.106	-.246

*Significant at the .05 level.

however, it makes sense to regard the storm precipitation P, and the antecedent rainfall volumes P7 through P60, as predictors for the various discharge components and the storage. The coefficients marked with an asterix are significant at a level of 95% (0.05) or better, which is considered satisfactory for this study.

Not surprisingly, the storm precipitation shows a quite strong positive correlation with floodflow, stormflow, and the presumed storage. However, coefficients of roughly 0.6 indicate that other factors than P might also be important in determining these measures. The correlation with the stormflow is somewhat stronger than the one with the floodflow. This is so, because the baseflow, which is due to antecedent moisture, has been excluded. For the same reason, the correlation between P and BF is essentially meaningless. Also, the correlation between the storm precipitation and STPC and SFPC makes no sense, since P is a part of the equations determining those measures.

Turning to the antecedent rainfall volumes, P7 shows a strong positive correlation with the baseflow. This means that the baseflow is predominantly generated by rainfall that preceded the major storm only by a short period of time. For all other components, P7 is insignificant.

The storage, in absolute and in relative numbers, is negatively correlated to P14 and P30. The moisture conditions of the fourteen and thirty days prior to the

flood appear to have a strong influence on the availability of empty groundwater storage space. Through this, they influence the proportion of the storm precipitation that is retained and not discharged. Thus the greater the precipitation during the antecedent P14 to P30 period, the less storage is available for any given floodflow. The coefficient of -0.429 for the correlation between storage and P14 is just beyond the 95% confidence interval, so that a formal proof of the initial hypothesis through this value is not possible. When, however, the storage is expressed as percentage of P , then the correlation coefficient with P14 is significant at the 95% and the one with P30 at the 99% level. Through this, the null hypothesis that denied a relationship between antecedent rainfall and groundwater storage potential has been rejected with 99% confidence.

Floodflow and stormflow are positively correlated with the antecedent rainfall, with P60 having the highest level of significance. Also here the null hypothesis can be rejected at a confidence level of 99% or better. This means that there is a relationship between the magnitude of a flood and the antecedent moisture conditions.

Multiple Regression Analysis

The above discussion of a simple correlation analysis shows the strength of the association for several pairs of variables. It does not strictly differentiate between

dependent and independent variables. The following multiple regression analysis has the goal to explain the variance of a dependent variable through combinations of independent variables. This may result in estimates on how well certain water balance components can be explained by other variables and in equations that could predict those components for future floods. Since flood prediction is beyond the scope of this study, the latter possibility will be ignored.

The variables to be explained are storage, floodflow, stormflow, and baseflow. The predictors are the storm precipitation, antecedent rainfall volumes, and the actual evapotranspiration.

The variables for the antecedent rainfall are of a cumulative nature, which means that any higher order variable includes the values of all variables of lower order. For example, P60 includes the values of P30, P14, and P7, while P30 includes only those of P14 and P7. Since this causes these variables to be autocorrelated, only one can be entered in any regression equation. In order to avoid this problem and to get a better temporal resolution of the antecedent rainfall, the differences between those values have been computed. The variable P60-30 now stands for the rainfall that occurred between the thirtieth and sixtieth day, P30-14 for the rainfall between fourteenth and thirtieth day, and P14-7 for the rainfall between the seventh and fourteenth day prior to the flood generating

storm. These variables now are statistically independent and may be entered as sequences into the regression equations.

The results of the multiple regressions are summarized in Table 5. R and R-Squared are coefficients of determination. They express the explanatory power of the regression equation. R-Squared may be interpreted as the portion of the variance of the dependent variable that is explained by the regression. For example, 64.6% of the variance in the variable storage can be explained by a regression with P and P14 as independent variables.

The last two columns serve to test the statistical significance of the regressions. This was achieved through the F-test procedure. A significance level of 95% (0.05) as it was considered sufficient for the correlation analysis, is greatly exceeded in all instances.

The presumed storage is best explained by a rather complex equation containing P, P7, P14-7, P30-14, and AE. The latter variable increases the explained variance by more than twenty percent, from a R-Square of 0.665 to one of 0.868. This means that the temperature conditions during the flood and storm periods, which are mainly responsible for the magnitude of AE, play a major role in determining the amount of water that can go into storage.

Stormflow and floodflow are explained by identical sets of variables. While the storage is best explained by

TABLE 5. Results of the Multiple Regression Analysis for the Grand River Basin.

Dep. Variable	Indep. Variables	R	R ²	F	Sig. F
STORAGE	P, P14	0.804	0.646	15.49	0.0001
	P, P30	0.746	0.556	10.65	0.0010
	P, P7, P14-7, P30-14	0.816	0.665	7.46	0.0016
	P, P7, P14-7, P30-14, AE	0.931	0.868	18.35	0.0000
STORMFLOW	P, P60	0.846	0.716	21.46	0.0000
	P, P14, P30-14, P60-30	0.888	0.789	14.01	0.0001
	P, P14, P30-14, P60-30, AE	0.888	0.789	10.46	0.0002
	P, P60	0.832	0.692	19.12	0.0000
FLOODFLOW	P, P14, P30-14, P60-30	0.884	0.781	13.38	0.0001
	P, P14, P30-14, P60-30, AE	0.884	0.781	9.99	0.0003
	P7, P60-30	0.746	0.557	10.68	0.0010
	P7, P14-7, P30-14, P60-30	0.754	0.569	4.95	0.0096

rainfall that preceded the flood by less than a month, FF and SF depend more on precipitation that occurred earlier than that. Here the evapotranspiration does not contribute to the explained variance.

So far, the analysis has focussed on the flood reducing effect of groundwater storage which is determined by the antecedent moisture conditions. In the case of ample antecedent rainfall, however, not only this flood reducing effect is nullified, but the discharge of groundwater may even cause the oppsite, an increase of floodflow. This groundwater component of the total discharge was formerly defined as baseflow. It is expected to correlate directly to the antecedent rainfall, as it can be seen on Table 4.

In the multiple regression analysis the baseflow is the component with the weakest explanation. Since it is, by definition, a product of the antecedent rainfall, the storm precipitation cannot be included in the equation. Of the four remaining variables, P7 and P60-30 have the strongest impact. This is evidence for a dual nature of the baseflow. One part of the baseflow is generated by rainfall shortly before the storm, and retained by the soil for no more than a few days. This part is represented through P7. The second component is discharge from layers of sand and gravel imbedded in the glacial drift. It originates from rain that fell more than a month before the major storm, and slowly percolated through the glacial deposits. This part is represented by P60-30.

Summarizing, it can be said that both correlation and regression procedures portrayed the interrelationships between the variables as they were expected, and supported the anticipated hypotheses. The generally rather high coefficients of determination (R-Squared) show that the applied methodology is appropriate.

CHAPTER 4

THE POWELL RIVER BASIN

Physiography

The Powell River is a tributary of the Clinch River. Norris Lake lies at the confluence of the two rivers. The area of the Powell River watershed above Arthur, Tennessee, which is upstream of the impounded waters of Norris Lake, is 1,774 sqkm (685 sqmiles). Compared to the Grand River basin, the Powell River basin covers only one tenth as much area (1,774 vs. 17,800 sqkm). It is located in the "Valley and Ridge" portion of northeastern Tennessee and the southwestern tip of Virginia. The stateline between Kentucky and Virginia partially coincides with the boundaries of the watershed. Figure 9 shows the basic drainage pattern.

The basin has a long and narrow shape and stretches northeast-southwest along the strike of the ridges. Major ridges are Wallen Ridge and Powell Mountain on the south side of the basin and Cumberland and Little Black Mountains on the north side . At Big Stone Gap, Virginia the Powell River cuts through Stone Mountain, a ridge within the watershed.

The Powell River and its tributaries have only narrow floodplains, and a large portion of the drainage basin is in

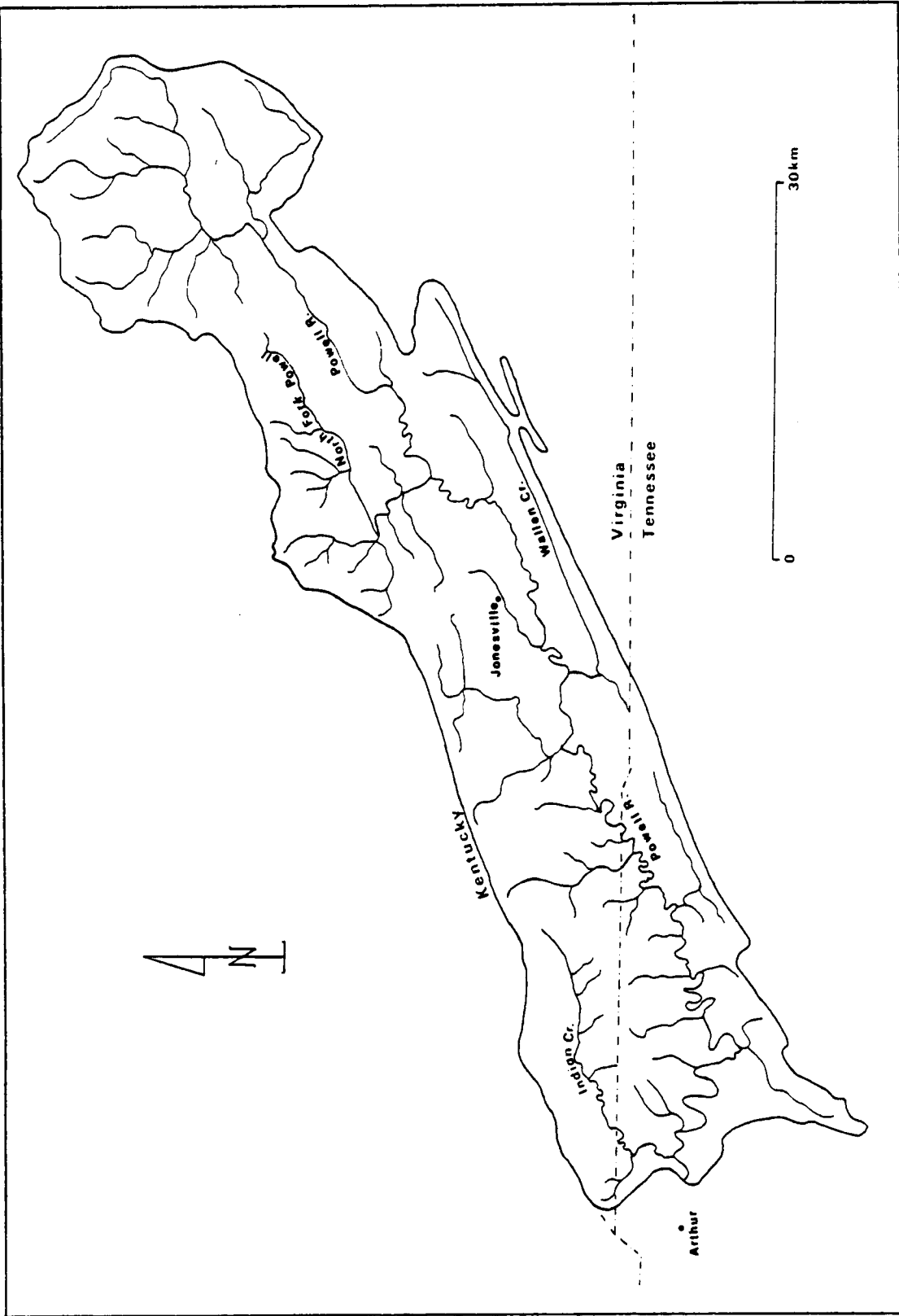


Figure 9. Drainage Pattern of the Powell River Basin.

steep slopes, with gentle slopes limited to the valley bottoms. Elevation ranges from 318 m (1044 feet) at the gaging station near Arthur, Tennessee to over 1100 m (3608 feet) in the northern portion of the basin.

The geologic structure of the area is dominated by strongly folded sedimentary rocks. Ordovician limestones and dolomites belonging to the Chickamauqua and Knox groups are the bedrock under large parts of the basin. This has important implications for the drainage behavior. Dolomite and limestone are carbonate rocks, which means they are subject to solution by acids contained in the rainfall, especially carbonic acid. Numerous sinkholes throughout the area are a visible proof for this process. Other phenomena of such a karst topography are cave systems that link those sinkholes together, which are often impossible to detect from the surface. Figure 10 gives an impression of the structure.

The karst features in conjunction with the prevailing steep slopes are responsible for the quite rapid and flashy response of the basin to heavy rainfalls. Sinkholes provide easy access to underground drainage routes and facilitate fast transport of the water. At the same time, the caves serve as temporary storage space that may absorb a portion of the runoff after a storm, and it is not likely that this water is retained for a long time in the groundwater. Despite the potential to store water in caverns and cracks,

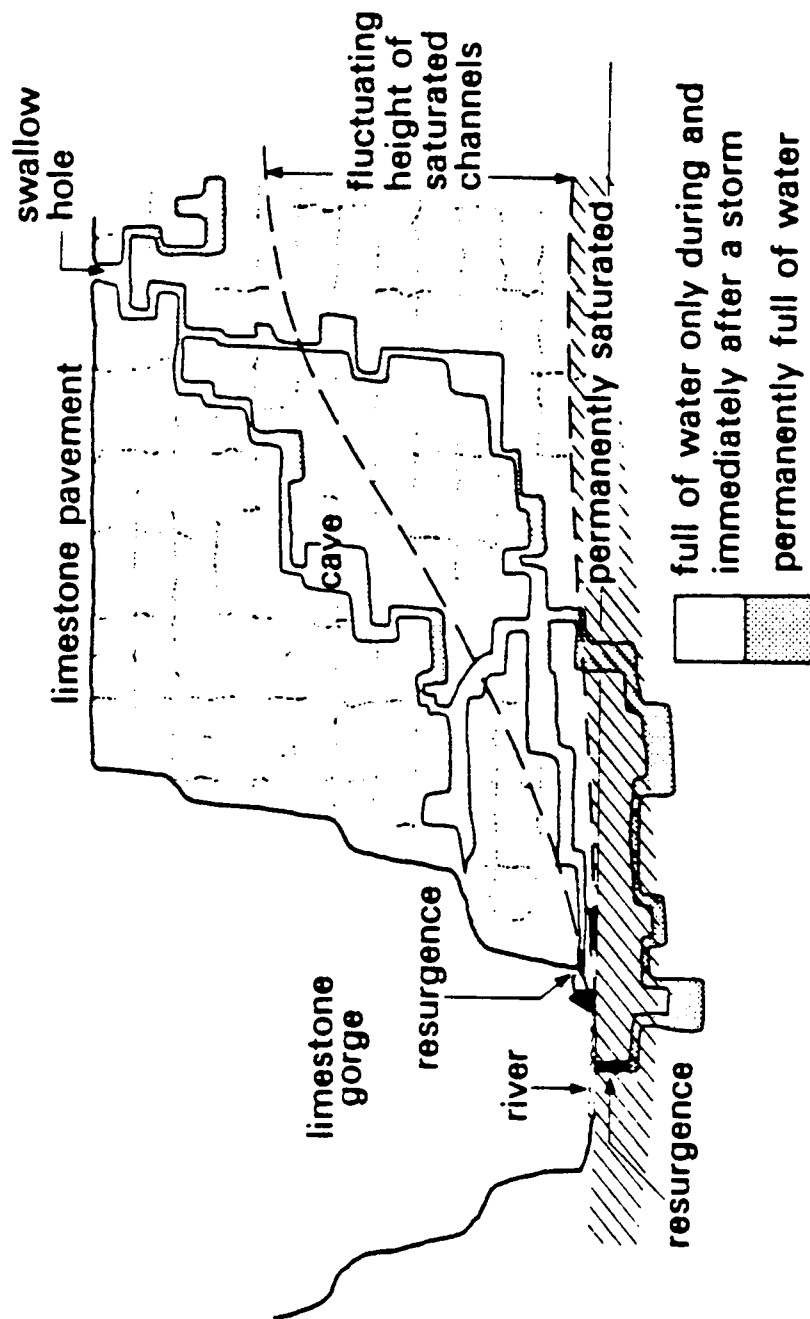


Figure 10. Principal of Drainage in Karst Environments.
 Source: Knapp, Brian. Elements of Geographical Hydrology.
 London: George Allen & Unwin, 1979.

dolomites and limestones can be quite impervious rocks and poor aquifers.

Those soluble rocks are underlain by other sediments, especially shales, which seal the Powell basin against leakage into neighboring watersheds. This effect is enhanced by the synclinal structure of the valleys in this physiographic region.

The soils in the area vary from shallow to deep, depending on parent material and terrain. While they are generally shallow along steep slopes and on shales, they might be well developed on the valley bottoms, especially if they are based on alluvium or on clayey or cherty, dolomitic limestones (Springer and Elder, 1980).

Climate

The climate of the Powell River basin is warm and humid, with the temperature varying with the altitude. Table 6 shows some data for Pennington Gap, Virginia at an altitude of roughly 420 m (1380 feet).

The annual variation of the mean temperatures is not very high. No month of the year has an average temperature below the freezing point. During spring and summer, the temperature rises moderately to the maximum in August and then to the minimum in January. Unfortunately, information on temperature extremes and daily variations were not available.

TABLE 6. Temperature and Precipitation at Pennington Gap, Virginia 1941 - 1970.

Month	Temperature		Precipitation			
	Daily Average	Monthly Average	1 year in 20 will have <	1 year in 20 will have >	Average # of days with > 25.4 mm	Average snowfall
	°C	mm	mm	mm		mm
January	1.3	124	47	220	0.95	185
February	2.5	121	36	240	0.95	145
March	6.6	139	63	235	1.40	125
April	12.5	100	42	240	0.80	10
May	17.2	94	35	165	0.70	0
June	21.1	104	50	170	1.00	0
July	22.8	139	62	230	1.60	0
August	22.3	104	43	180	1.05	0
September	19.1	81	22	145	0.75	0
October	13.3	62	12	145	0.50	0
November	6.8	94	42	155	0.75	45
December	2.3	116	42	190	1.15	110
Year	12.3	1278			12.00	620

Source: Compiled from Atlas of Virginia Precipitation (Hayden, 1979) and Climatological Data (U.S. Environmental Data Service).

The average annual precipitation of 1278 mm (50.3 inches) is typical for the humid southeastern United States. It varies little throughout the year, with slight maxima in March and July and a minimum in October. In spite of the small average annual variation, months of very little precipitation are as likely as periods of excessive moisture. High intensity rainfalls most frequently occur in July, caused by convective thunderstorms, and in early spring. The impact of the spring storms can be expected to be stronger due to the dormant stage of the vegetation, the lower evaporation rate, and the greater probability of antecedent moisture.

Snow may fall December through April. Accumulation is generally reduced to the higher altitudes because the average temperatures are too high in the lowlands.

Water Balance

The components of the water balance for the Powell River basin are shown on Table 7. For the definition of the components, see the corresponding section of the previous chapter. Even though the problem with the negative values for the storage does not occur here, all figures should be regarded with some caution. The sources of error that were discussed for the Grand River basin should not be ignored for this basin either.

The smaller size of the basin together with

TABLE 7. Components of the Water Balance for the Powell River.

Flood #	P*	AE*	FF*	BF*	SF*	SFPC**	ST*	STPC**
1	264.2	5.7	202.4	30.2	172.2	65.2	86.3	32.6
2	140.5	1.8	125.7	27.0	98.7	70.7	40.0	28.6
3	210.4	8.9	163.6	16.6	147.0	70.0	54.5	25.7
4	139.3	9.3	89.4	15.9	73.5	53.2	56.5	40.0
5	151.0	11.6	94.6	8.0	86.6	57.6	52.8	35.3
6	172.5	10.7	144.4	11.8	132.6	76.9	29.2	17.1
7	261.4	1.8	183.7	3.4	180.3	69.0	79.3	30.4
8	190.5	35.1	100.7	8.9	91.8	48.4	63.6	33.7
9	151.7	26.8	85.6	7.4	78.2	51.7	46.7	31.3
10	204.7	6.7	199.2	15.8	183.4	89.3	14.6	7.3
11	228.5	5.4	168.1	10.8	157.3	68.6	65.8	28.7
12	275.6	9.6	188.7	14.1	174.6	63.4	91.4	32.5
13	117.9	4.0	77.4	7.2	70.2	59.3	43.7	37.3
14	199.4	5.4	209.5	21.0	188.5	95.0	5.5	2.5
15	133.8	20.2	92.5	10.1	82.4	61.7	31.2	23.1
16	204.7	1.8	179.7	21.0	158.7	77.6	44.2	21.5
17	154.6	15.7	79.8	9.4	70.4	45.2	68.5	44.5
18	357.1	15.5	293.3	16.8	276.5	77.6	65.1	18.2
19	139.5	0.9	83.4	6.9	76.5	55.2	62.1	44.3
20	84.0	6.4	77.2	22.4	54.8	65.5	22.8	27.4

* in 10^6 m^3 .

** in percent.

physiographic factors points toward a faster response to precipitation than was the case for the Grand River basin. With this in mind, the indicators for the antecedent moisture conditions were chosen for somewhat shorter periods of time, ranging from three to thirty days prior to the begin of the major storm. The values are listed on Table 8.

Simple Correlation Analysis

For this basin, as it was discussed for the other basin in the previous chapter, simple correlation coefficients were calculated to evaluate the strength of the association between the antecedent moisture conditions and the components of the water balance. Table 9 shows those correlation coefficients. Again, P , and P_3 through P_{30} may be regarded as predictors (independent variables) for the water balance components, even though in simple correlation there is no strict distinction between dependent and independent variables.

Looking at Table 9, it becomes apparent that only the storm precipitation, P is highly correlated to some of the discharge components and the storage. Only the coefficients with floodflow, stormflow, and the storage are significant at the 0.05 level, which means a confidence of 95%. Those with FF and SE are so strong, that it appears unlikely that other factors than the storm precipitation are important in determining those variables. The correlation with storage

TABLE 8. Volumes of Antecedent Rainfall for the Powell River Basin.

Flood #	P3*	P7*	P14*	P30*
1	14.6	27.8	77.8	267.0
2	19.0	37.2	74.6	140.0
3	0.5	141.1	173.3	256.9
4	5.7	219.2	379.0	441.9
5	2.7	60.2	63.5	178.9
6	0.1	36.1	79.8	150.6
7	43.3	72.1	78.3	143.9
8	18.7	58.9	65.1	201.1
9	5.5	7.9	84.5	154.4
10	28.0	59.4	105.2	170.2
11	18.2	38.5	73.2	110.9
12	2.3	40.9	80.7	218.1
13	0.0	30.3	73.4	388.4
14	7.7	72.9	260.6	335.2
15	34.8	59.8	101.0	174.6
16	47.8	68.4	79.9	186.2
17	5.4	31.3	64.1	137.1
18	12.7	48.0	91.6	186.2
19	4.0	8.8	105.1	247.5
20	73.1	81.2	109.4	186.7

* in 10^6 m^3 .

TABLE 9. Correlation Coefficients for the Powell River Basin Using the Complete Data Set.

	FF	BF	SF	SFPC	ST	STPC
P	.902*	.132	.992*	.378	.503*	-.287
P3	.013	.244	-.017	.201	-.242	-.224
P7	-.027	.147	-.046	-.016	-.093	-.016
P14	.005	.206	-.030	.135	-.256	-.119
P30	-.110	.140	-.132	-.045	-.070	.131

* Significant at the .05 level.

is significant, but not as strong as it was in the case of the Grand River basin. Here again, the coefficients with the baseflow and the percent measures of stormflow and storage should be ignored.

Since the correlation coefficients of all antecedent rainfall measures with the water balance components are beyond the 95% confidence interval, the initial null hypothesis could not be rejected. This means that there is no statistical proof for a relationship between the antecedent rainfall and the amount and the proportion of the storm precipitation that goes into storage. The same is true for the amount and the proportion of the stormflow. Coefficients of -0.242 and -0.256 for the storage with P3 and P14 respectively are slight evidence for a relationship between storage and antecedent rainfall as anticipated.

An analysis of residuals suggests excluding flood no.14 from the analysis because it represents an abnormality. The coefficients for the analysis, when flood no.14 is excluded, are shown on Table 10. Some general differences are apparent. The correlation coefficients for the storm precipitation and P3 with the water balance components are stronger here than the ones for the complete data set. Nevertheless, most of them are still beyond the 0.05 significance interval. Even though a proof of a hypothesis is not possible, those coefficients support the notion of a rapidly responding drainage basin, as expected. The

TABLE 10. Correlation Coefficients for the Powell River
Basin Under Exclusion of Flood # 14.

	FF	BF	SF	SFPC	ST	STPC
P	.926*	.127	.943*	.420	.589*	-.319
P3	.045	.278	.012	.308	-.337	-.345
P7	-.046	.137	-.064	-.010	-.070	.024
P14	-.144	.121	-.164	-.132	-.056	.170
P30	-.215	.074	-.232	-.266	.100	.391

* Significant at the .05 level.

coefficients for P7 through P30 are weaker than the ones for the complete data set. Some of them point in the opposite of the expected direction, but they are statistically insignificant.

Multiple Regression Analysis

As for the Grand River basin, multiple regression analysis was applied to the Powell River basin to explain the variance of a dependent variable through combinations of independent variables. This also serves the purpose to sort the independent variables into important and unimportant ones.

Tables 11 and 12 respectively summarize the results of the regressions for the complete data set and for the set under exclusion of flood no. 14. As is known from the simple correlation, all water balance components, with the exception of the baseflow, are dominated by the storm precipitation as a predictor. In the case of the storage, the explanatory power of a regression can be improved by roughly ten percent when P3 and P30-14 are included. The evapotranspiration is here insignificant, which means that the temperature conditions during a storm and a flood do not affect the amount of water that presumably goes into storage. The statistical significance for all those equations is rather low, and only the first one with P as the sole predictor meets the criterium of being significant at the 0.05 level.

TABLE 11. Results of the Multiple Regression Analysis for the Powell River Basin Using the Complete Data Set.

Dep. Variable	Indep. Variables	R	R ²	F	Sig. F
STORAGE	P	0.503	0.253	6.08	.0239
	P, P3	0.534	0.286	3.40	.0573
	P, P3, P30-14	0.576	0.332	2.65	.0840
	P, P3, P30-14, AE	0.582	0.338	1.92	.1600
FLOODFLOW	P	0.902	0.814	78.90	.0000
	P, AE	0.927	0.860	52.22	.0000
	P, P30, AE	0.927	0.860	37.76	.0000
STORMFLOW	P	0.922	0.851	102.43	.0000
	P, AE	0.940	0.884	64.52	.0000
	P, P30, AE	0.940	0.884	40.53	.0000
BASEFLOW	P3	0.244	0.060	1.41	.2998
	P3, AE	0.383	0.147	1.46	.2588
	P3, P14-7, AE	0.446	0.199	1.32	.3011

TABLE 12. Results of the Multiple Regression Analysis for the Powell River Basin Under Exclusion of Flood # 14.

Dep. Variable	Indep. Variables	R	R ²	F	Sig. F
STORAGE	P	0.589	0.347	9.03	.0080
	P, P3	0.647	0.419	5.78	.0129
	P, P3, P30-14	0.668	0.446	4.03	.0276
	P, P3, P30-14, AE	0.668	0.446	2.82	.0660
FLOODFLOW	P	0.926	0.857	102.02	.0000
	P, AE	0.946	0.895	67.85	.0000
	P, P30, AE	0.948	0.900	44.75	.0000
STORMFLOW	P	0.943	0.889	135.93	.0000
	P, AE	0.956	0.915	85.94	.0000
	P, P30, AE	0.960	0.921	58.43	.0000
BASEFLOW	P3	0.278	0.077	1.43	.2488
	P3, AE	0.386	0.149	1.40	.2743
	P3, P14-7, AE	0.405	0.164	0.98	.4281

The evidence is somewhat different for the dependent variables floodflow and stormflow. They are very well explained by P alone, and only with the addition of AE was it possible to improve the explanations. The antecedent rainfall, here represented by P30, does not appear to play any role in determining those measures. The significance of the regressions for both, FF and SF with P and AE as independent variables, is extremely high.

The baseflow is again the variable that is the hardest to explain. At the best, some twenty percent of its variance ($R\text{-square}=0.199$) can be accounted for through P3, P14-7, and AE. a slight indication for the complex nature of the baseflow as it was detected in the analysis of the Grand River basin, is also present, through the variables P3 and P14-7. The first one represents the part that has been retained for a short time by the soil, and in this case possibly by cave and sinkhole systems. The second represents water that has been withheld between one and two weeks, and was then discharged. This effect is probably due to small storage spaces such as cracks and pores in the bedrock, or in the alluvium.

The importance of AE in determining the baseflow can be explained by the quicker rainfall response of the Powell basin. BF is mainly generated a few days prior to the beginning of the major storm. The temperatures during this

time are likely to be comparable to those of the storm and flood periods, thus resulting in similar volumes for the evapotranspiration which reduces the available water for the baseflow. Since the significance of all equations explaining the baseflow is very low, the above discussed relationships between antecedent rainfall and baseflow are not proved, but their validity is indicated.

For this watershed, the anticipated hypothesis that assumed a causal relationship between antecedent moisture conditions and the amounts of storage and discharge during a flood period, could not be proved. The antecedent rainfall appears to have hardly any influence on most of the components of the water balance.

CHAPTER 5

FINDINGS AND CONCLUSION

The influence of groundwater storage capacity on floodflow and flood reduction has been investigated for two basins with contrasting physiographic character.

Results

For the Grand River basin the anticipated hypothesis, which assumed a flood reducing effect of groundwater storage space, was statistically proved by the correlation and multivariate analyses. The correlation coefficients show a rather strong positive association of the flood parameters, floodflow and stormflow, with the antecedent rainfall. This means that storms that were preceded by a period of high precipitation produced comparatively larger volumes of runoff than storms that followed after a dry period. During periods of drought, groundwater is depleted, resulting in empty storage space that is capable of absorbing a portion of the storm water. This storage space is not available if a storm occurs after a period of sufficient moisture supply, and a higher proportion of the storm water goes to runoff.

Not only moisture conditions that existed immediately prior to the storms, but also those of several weeks or months prior to the flood showed an influence on the availability of empty storage space. This means that

rainfall, once it becomes part of the groundwater, is retained there for a rather long time, and is only slowly released.

The amount of the computed storage was not quite as clearly associated with the antecedent rainfall as was expected. The magnitude of the storm, expressed by P , influences the amount of the stored water substantially. Only when this influence was controlled, by expressing the storage as a proportion of the storm precipitation (STPC), did the anticipated relationship show up clearly and the hypothesis appears to be verified.

The multiple regression analysis generally supported those findings. Through an equation containing the variables for the antecedent moisture conditions, the storm precipitation and the evapotranspiration, roughly 87% of the variance in the storage could be accounted for. The rainfall occurring between seven and thirty days prior to the storm (P_{30-14} , P_{14-7}), proved to be the most important part of the antecedent rainfall in determining the degree of the flood reduction.

Stormflow and floodflow are not quite as well explained as the storage. Nevertheless, some 80% of their variance can be accounted for through models containing the antecedent rainfall in combination with storm precipitation and evapotranspiration. Here, the moisture conditions that existed more than one month prior to the flood (P_{60-30}) appear to be the crucial variable.

The delayed response of the Grand basin to precipitation can be explained by its moderate relief and immense volumes of glacial drift, which serves as the main aquifer. Water storage is located in the layers of coarse material within the drift. Release from this storage may be hindered by strata containing clayey materials of poor permeability.

For the Powell River basin, these same relationships could not be demonstrated. This may be largely due to the different geo-hydrological character of the basin and was not totally unexpected. Groundwater storage space consists largely of cracks and caves in the soluble bedrock which should offer easy access for storm water and thus reduce the floodflow. The same characteristics, however, reduce its capability to retain water for a long time, and discharge of groundwater into stream flow should be more rapid than in the Grand basin. For this reason, the moisture conditions for periods of several days to several weeks prior to the flood generating storm do not strongly influence the availability of empty groundwater storage space. It is also possible that stormwater, which has gone in groundwater storage, is released back to surface drainage routes so quickly that it is included in volumes of storm- and floodflow. Such difficulties with groundwater storage for basins with soluble bedrock were encountered by White (1976).

Nevertheless, the evidence gained through correlation and regression procedures suggests that for some basins the available groundwater storage space can reduce floodflow. To prove this effect also for fast responding basins and those with soluble bedrock, better data, recorded possibly on an hourly base, would be needed.

The analysis of the relationship between baseflow and antecedent moisture represents a side track from the main line of the research. Here, no attempt was made to prove any of the anticipated hypotheses. Nevertheless, it appears to be a relationship worth investigating.

Since the antecedent rainfall is responsible for the amount of the stored groundwater, it can also be expected to influence the discharge of groundwater, i.e., the baseflow. The expected relationship is a direct one; a high antecedent rainfall will create large volumes of baseflow and vice versa.

In the case of the Grand River basin, this relationship could clearly be demonstrated. Baseflow is strongly correlated with P7, the antecedent rainfall of the week previous to the major storm. This indicates that the baseflow consists mainly of water that has been retained only shortly in the subsurface before it was discharged. A second component of the baseflow, however, is caused by precipitation that occurred up to several months before the flood generating storm. This water has percolated deeply

through the layers of glacial deposits and remained there for a long time before it became part of the baseflow. This time lag offers some insight into the geo-hydrology of a basin. In the case of the Grand basin, it indicates a slow response to precipitation.

For the Powell River basin the baseflow is rather poorly explained, but some indication of its complexity is present. The time lag, however, is much shorter, only some ten days. This demonstrates that the Powell basin can not retain rainwater over a long period of time, and responds quickly to precipitation.

Critique and Outlook

This study clearly showed the flood reducing effect of groundwater recharge in the case of a large, slow responding basin. For a watershed of smaller size and physiographic qualities that cause a quick and flashy response to rainfall, the hypothesized relationship could not be verified using the data available to the author.

Since the raw data were available only in printed form, data processing would be much more efficient if computerized data could be accessed. Then an analysis could be conducted for a larger sample of basins using data collected on a smaller time scale. This would also facilitate the introduction of additional variables such as rainfall intensity and peak floodflow, which could greatly enhance

the significance of a study such as this one for flood prediction purposes.

The influence of antecedent rainfall on flooding has been shown in this study. It is therefore recommended that the relationship between climate and groundwater storage should be further investigated and taken into consideration by flood prediction models. Under certain conditions the potential of groundwater storage might even serve as an alternative or addition to the construction of surface reservoirs. This could be achieved by increasing the available storage space through artificial withdrawal or by easing the access to existing, but confined aquifers. However, until these options can seriously be considered, better data and a more accurate calibration of the groundwater storage potential for basins are required.

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LITERATURE

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APPENDICES

APPENDIX
A

DEFINITIONS

Antecedent Moisture Conditions: Moisture conditions that existed preceding to a flood generating storm.

Antecedent Rainfall: The volume of precipitation which occurred during specified periods prior to the beginning of the flood generating storm. P3, P7, P14, P30, and P60 represent the precipitation volumes of the three, seven, fourteen, thirty, and sixty days preceding any flood generating storm.

Baseflow (BF): Portion of the floodflow that is due to antecedent rainfall. It represents discharge of groundwater.

Floodflow (FF): Volume of discharge during a defined flood period. It is composed of stormflow and floodflow.

Stormflow (SF): Portion of the floodflow which is due to the storm precipitation.

Storm Precipitation (P): Volume of rainfall that occurred during a defined storm period over a drainage basin. It creates the floodflow.

Storage (ST): Portion of the storm precipitation that is retained from being discharged and is assumed to have gone into groundwater storage. It represents the residual of the water balance equation.

APPENDIX
B

PROGRAMS

```

C      /*****
C      /*
C      /*          AREA.FOR
C      /*
C      /***PURPOSE: THIS PROGRAM COMPUTES THE AREAS OF THE
C      /*          INDIVIDUAL POLYGONS AND OF THE WATERSHED AS
C      /*          A WHOLE FOR A GIVEN THIESSEN POLYGON MAP.
C      /*
C      /***USAGE: THE USER HAS TO PROVIDE A READILY DRAWN
C      /*          POLYGON MAP OF THE STUDY AREA. THE PROGRAM
C      /*          IS STARTED BY TYPING 'DO TCS E, AREA.FOR'.
C      /*          THE USER IS THEN ASKED TO SPECIFY THE NUMBER
C      /*          OF POLYGONS OF THE STUDY AREA, TO ENTER A
C      /*          SCALE AND A STOP AREA, AND TO INPUT THE
C      /*          OUTLINES OF THE POLYGONS THROUGH A DIGITIZ-
C      /*          ING TABLET. THE PROGRAM STORES THE COORDINA-
C      /*          TES OF THE POINTS THAT WERE ENTERED IN A
C      /*          FILE NAMED "AREA.DAT" AND THE COMPUTED
C      /*          VALUES FOR THE SIZE OF THE INDIVIDUAL POLY-
C      /*          GONS AND THE WHOLE AREA IN THE FILE "AREA.
C      /*          OUT". THE PROGRAM ENDS WHEN THE FORMERLY
C      /*          ASSIGNED NUMBER OF POLYGONS HAS BEEN DIGI-
C      /*          TIZED.
C      /*
C      /***PROGRAMMER:  CHENG LUI
C      /***APPLICATIONS AND USAGE RESTRICTIONS: NONE
C      /***DATE:   FEBRUARY 27, 1984
C      /***OTHER:  COMMENTARY BY VOLKER JAEGER
C      /*
C      /*******
C
C
C      DIMENSION NX(100),NY(100)
C      /* OPEN OUTPUT FILES */
C      OPEN (UNIT =21,FILE='AREA.DAT')
C      OPEN (UNIT =22,FILE='AREA.OUT')
C      /* INITIALIZE TCS */
C      CALL INITT(30)
C      CALL TSEND
C      CALL ANMODE
C      CALL SETBUF(3)
C      /* ASK FOR NUMBER OF POLYGONS */
C      WRITE (5,10)
10    FORMAT (2X,'HOW MANY REGIONS DO YOU HAVE ?')
C      ACCEPT *,J
C      WRITE (21,30) J
C      /* INITIALIZE TABLET */
C      CALL TSEND
C      CALL TABINT(0,0,0)
C      /* INITIALIZE TCS */
C      CALL INITT(30)
C      CALL BELL
C      /* CALCULATE THE SCALING FACTOR */

```

```

WRITE (5,17)
17  FORMAT (' INPUT SCALE- TWO POINTS')
    CALL TSEND
    CALL ONEPNT(IX1,IY1)
    CALL BELL
    CALL ONEPNT(IX2,IY2)
    CALL BELL
    CALL TSEND
    WRITE (5,20)
20  FORMAT(' WHAT IS THE DISTANCE ?')
    ACCEPT *,SCALE
    SCALE = SCALE / ((IX1-IX2) ** 2. + (IY1-IY2) ** 2.) ** .5
    CALL INITT(30)
    CALL TSEND
    CALL BELL

C
C      /* STOP AREA; END THE INPUT FOR ONE POLYGON */
C      /* AND THE NEXT POLYGON MAY BE DIGITIZED */
WRITE (5,18)
18  FORMAT(' INPUT STOP AREA')
    CALL ONEPNT (ISX1,ISY1)
    CALL BELL
        CALL ONEPNT (ISX2,ISY2)
    CALL BELL

C
    DO 100 I = 1 , J
        CALL INITT
        CALL TSEND
        WRITE (5,32) I
32  FORMAT (' AREA ',I2)
C
        AREA = 0

C
        CALL BELL
C      /* DIGITIZE THE BOUNDARY OF A POLYGON */
        DO 200 II = 1 , 100
            CALL ONEPNT (IX,IY)
            CALL BELL
            IF ((IX .GE. ISX1 .AND. IX .LE. ISX2) .AND.
                (IY .GE. ISY1 & .AND. IY .LE. ISY2)) GO TO 1000
            NX(II) = IX
            NY(II) = IY
200        CONTINUE
C
1000       CONTINUE
        II = II - 1
        IF (II .LE. 1) GO TO 100
C      /* STORE THE COORDINATES IN FILE 'AREA.DAT' */
        WRITE (21,30) II
        DO 250 K = 1 , II
            WRITE (21,30) NX(K),NY(K)
30        FORMAT (2(2X,I3))
250       CONTINUE

```

```

C      /* CLOSE THE BOUNDARY OF THE POLYGON */
      K = II +1
      NX(K) = NX(1)
      NY(K) = NY(1)
C      /* COMPUTE THE AREA OF THE POLYGON */
      DO 300 N = 1 , II
      AREA = AREA + .5 * (NY(N+1) + NY(N)) * (NX(N+1)
- NX(N)
300    CONTINUE
C
      AREA = ABS(AREA * SCALE **2.)
      SUM = SUM + AREA
C      /* STORE THE SIZE OF THE POLYGON AREAS */
      WRITE (22,40) I, AREA
40     FORMAT (2X,'AREA ',I2,' IS=',F20.3,' SQUARE KM.')
C
      AREA = 0
100    CONTINUE
C
      WRITE (22,41) SUM
41     FORMAT (2X,' TOTAL AREA IS',F20.3, ' SQUARE KM.')
C
      CALL FINITT(0,0)
      CLOSE (UNIT = 21, FILE = 'AREA.DAT')
      CLOSE (UNIT = 22, FILE = 'AREA.OUT')
      STOP
      END

```

```

C  /*****
C  /*
C  /*          RAINFA.FOR
C  /*
C  /***PURPOSE:  THIS PROGRAM COMPUTES THE AVERAGE
C  /*          RAINFALL DEPTH AND THE TOTAL VOLUME OF
C  /*          THE PRECIPITATION OVER A DRAINAGE BASIN.
C  /*
C  /***USAGE:  IN ORDER TO RUN THIS PROGRAM, A DATA
C  /*          FILE CONTAINING INFORMATION ON THE SIZE
C  /*          OF THE INDIVIDUAL POLYGONS OF A THIESSSEN
C  /*          POLYGON MAP, HAS TO BE PRESENT. SUCH A
C  /*          FILE, NAMED "AREA.OUT", CAN BE CREATED
C  /*          THROUGH THE PROGRAM "AREA.FOR". IF FILES
C  /*          WITH DIFFERENT NAMES WILL BE USED, THE
C  /*          PROGRAM HAS TO BE ADJUSTED. TO START, ONE
C  /*          TYPE 'RUN RAINFA.FOR'. THE PROGRAM THEN
C  /*          ASKS FOR THE NUMBER OF POLYGONS (AREAS)
C  /*          AND THEN FOR THE DATA. IT ENDS BY ITSELF
C  /*          WHEN THE DATA FOR ALL AREAS HAVE BEEN
C  /*          ENTERED. THE RESULTS ARE STORED IN A FILE
C  /*          CALLED "RAIN.DAT".
C  /*
C  /***PROGRAMMER:  CHENG LUI
C  /***APPLICATION AND USAGE RESTRICTIONS:  THIS
C  /*          PROGRAM IS DESIGNED TO RUN WITH THE DATA
C  /*          FILE "AREA.OUT". THE UNIT OF ENTERED
C  /*          DATA PRECIPITATION DATA SHOULD BE INCHES
C  /*          AND THE OUTPUT OF THE PRECIPITATION
C  /*          VOLUME WILL BE IN CUBIC METERS.
C  /*DATE:          FEBRUARY 27, 1984
C  /*OTHER:  COMMENTARY BY VOLKER JAEGER
C  /*
C  /*****
C
C          /* OPEN INPUT AND OUTPUT FILES */
C          OPEN (UNIT = 21, FILE = 'AREA.OUT')
C          OPEN (UNIT = 22, FILE = 'RAIN.DAT')
C
C          WRITE (22,5)
5          FORMAT(' STATION',5X,'AREA(SQUARE KM)',8X,'RAINFALL',
C          &          8X,'RAINFALL*AREA')
C          TYPE 10
10         FORMAT (' INPUT THE NUMBER OF AREAS')
C          ACCEPT 15, N
15         FORMAT (I4)
C
C          DO 100 I = 1, N
C          TYPE 20 ,I
20         FORMAT(' INPUT THE RAINFALL OF AREA #',I4)

```

```

C      /* INPUT RAINFALL */
      ACCEPT 25,RAIN
25     FORMAT(F12.3)
C
C      /* INPUT AREA */
      READ (21,30) AREA
30     FORMAT(13X,F20.3)
      ARRA = AREA * RAIN
      TARRA = TARRA + ARRA
      TRAIN = ARRA + TRAIN
      TAREA = TAREA + AREA
      WRITE(22,28) I,AREA,RAIN,ARRA
28     FORMAT(1X,I2,F20.3,F20.2,F20.3)
100    CONTINUE
C
C      /* OUTPUT RESULTS */
      WRITE(22,32) TAREA
32     FORMAT(' TOTAL AREA IS  = ',F10.3 , ' SQ KM')
      WRITE (22,33) TRAIN
33     FORMAT(' TOTAL RAINFALL = ',F10.3, ' INCH')
      AVG = TRAIN / TAREA
      WRITE (22,35) AVG
35     FORMAT(' THE AVERAGE IS = ',F10.3,' INCH')
      TARRA = TARRA * 0.0254 * 1.0E4
      WRITE (22,40) TARRA
40     FORMAT(' RAINFALL VOLUME = ',E20.13,' CUBIC MTR')
      CLOSE (UNIT = 21, FILE = 'AREA.OUT')
      CLOSE (UNIT = 22, FILE = 'RAIN.DAT')
      STOP
      END

```

VITA

Volker Jaeger was born in Linz, West Germany on July 18, 1959. He attended elementary and secondary schools in Linz and graduated from "Staatliches Martinus Gymnasium, Linz" in June, 1978. After his military service, he entered the "Friedrich Wilhelms Universitaet, Bonn" in October, 1979 with a major in Geography. He received his "Vor-Diplom" in June, 1981. With the help of an exchange student grant and a Fulbright travel grant, he entered the University of Tennessee in September, 1981. He accepted a graduate assistantship in September, 1982, and received a Master of Science degree in Geography in March, 1984.