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COMPLETION REPORT

GROUNDWATER HYDROLOGY OF AN AGRICULTURAL WATERSHED

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SUMMARY

Wisconsin is fortunate to have outstanding groundwater resources. But increasingly these resources are being stressed. The most obvious stresses involve contamination from a variety of sources, including septic systems, landfills, underground tanks, and agricultural chemicals. In addition, the amount of available groundwater is gradually being reduced. The greatest threat to groundwater quantity is urban expansion, which typically results in increased pumping and decreased recharge.

Our ability to effectively manage each of the various stresses to groundwater quality and quantity depends to a large extent on our ability to understand and quantify groundwater flow systems, particularly with respect to the spatial distribution of groundwater recharge. The goal of the research reported here was to improve our understanding of the spatial distribution of groundwater recharge in the Driftless Area of southwestern Wisconsin. In particular, we focused on the Black Earth Creek and Garfoot Creek watersheds and the Sugar River watershed, adjacent watersheds in western Dane County. In addressing the issue of groundwater recharge, we considered two problems. The first was to determine the relative contribution of various landscape elements to groundwater recharge. The second was to explore the extent to which there were differences between the groundwater and surface-water divides.

We addressed the first problem by means of flow measurements on a 3.4 hectare hillslope watershed in the Garfoot Creek watershed, a sub-watershed of Black Earth Creek. Based on water-budget calculations we were able to estimate groundwater recharge during snowmelt periods over three successive years. (Snowmelt events are the most important events for recharge in the region.) These measurements provide information about the amount of recharge which occurs in farmed uplands and wooded hillslopes. Using U.S. Geological Survey (USGS) stream gage data on Garfoot Creek, we were able to show that our results could be generalized for the larger watershed.

The problem of determining groundwater divides was addressed through a number of measurements of baseflow at several locations in the region. Flow-monitoring stations were established on a major spring feeding into Garfoot Creek and at a location on the Sugar River. We also used USGS streamflow data collected on Garfoot Creek and Black Earth Creek, as well as current-meter surveys made at a number of locations in the region. Finally, we consulted water-table maps recently compiled by the Wisconsin

Geological and Natural History Survey.

As result of these investigations, we made several findings which are of fundamental significance to understanding and quantifying the regional hydrological cycle and hence to managing the critical water resources of the region. These findings are:

- The wooded hillslopes and the farmed uplands are the primary groundwater recharge areas in the region. Recharge rates are highest on the wooded hillslopes, because they have the highest infiltration rates and receive runoff from adjacent farmed areas. Valley bottoms are not important sites for recharge.

- Significant amounts of runoff infiltrate the hillslope gullies, which are ubiquitous in the Driftless Area as a result of many years of abusive agricultural practices.

- Black Earth Creek receives groundwater discharge which emanates in the Sugar River watershed. Much of this water recharges well outside of the Black Earth Creek watershed.

Each of these findings has important management implications:

- Any loss of wooded hillslopes and uplands will decrease groundwater recharge. The cumulative effect of many such losses will be dessication of spring-fed wetlands, reduced baseflows, and decreased groundwater supply. Programs for protecting groundwater recharge must focus on wooded hillslopes and uplands.

- Gullies in the Driftless Area may partially explain the widespread contamination of wells in the region by nitrates and pesticides. The common use of grade stabilization structures to control gully erosion may worsen groundwater contamination by increasing the duration of runoff. (On the other hand, grade stabilization structures may increase groundwater recharge.)

- Efforts to protect baseflow-fed trout streams has focused largely on the stream corridor. Clearly attention also needs to be directed to recharge areas, particularly those which lie outside of the surface-water divide. Recharge areas which are most removed from the watershed may be the most critical.

1. INTRODUCTION

Wisconsin is fortunate to have outstanding groundwater resources. Groundwater provides about half of the public water supply and virtually all of the water for irrigation and rural domestic. In addition, groundwater discharge into streams, lakes and wetlands is essential to the integrity of these surface-water resources.

But increasingly Wisconsin's groundwater resources are being stressed. The most obvious stresses involve contamination from a variety of sources, including septic systems, landfills, underground tanks, and agricultural chemicals. In addition, the amount of available groundwater is gradually being reduced. The greatest threat to groundwater quantity is urban expansion, which typically results in increased pumping and decreased recharge

In theory, it is possible to manage each of the various stresses to groundwater quality and quantity. Federal, state, and local laws enable a variety of programs which deal with issues such as pesticide regulation, stormwater management, wellhead protection, and landfill siting and management. However, the effectiveness of such programs depends to a large extent on our ability to understand and quantify groundwater flow systems, particularly with respect to the spatial distribution of groundwater recharge.

Groundwater recharge is the source of all groundwater. Effective management of groundwater quality and quantity requires the identification and quantification of critical recharge areas. Because most management strategies involve the regulation of certain activities, the success of these strategies is strongly dependent on the precision with which recharge areas are identified. The failure to include a critical recharge area in a management program limits the effectiveness of that program. Conversely, management restrictions on noncritical areas cause unnecessary economic losses, and undermine the credibility and political viability of management programs.

This report describes research conducted during the last two years of a four year project undertaken to improve our understanding of the spatial distribution of groundwater recharge in the Driftless Area of Wisconsin, which occupies the southwestern portion of the state. Results from the first two years of the project are reported in Amann (1993) and Potter *et al.* (1995). The Driftless Area was chosen for study because:

- It has significant water resources, which critically depend on groundwater recharge; these include productive deep aquifers, abundant springs, and baseflow-dominated streams which support prized trout fisheries.

- The region is predominantly agricultural, but is gradually changing to urban/suburban uses. The groundwater has been and continues to be degraded by agricultural activities, and is facing new threats from urban/suburban development.

- Over a sufficiently large spatial scale (of about 10 square miles) the region is reasonably homogeneous with respect to the factors affecting groundwater recharge.

2. DESCRIPTION OF STUDY AREA

The primary locus of this study was the Garfoot Creek watershed, a 5.4 square mile watershed west of Madison, WI. The study also included portions of the Black Earth Creek watershed, to which Garfoot Creek is tributary, and the Sugar River watershed, which is directly to the south. The Garfoot Creek watershed and the upper portion of the Sugar River watershed are entirely in the Driftless Area. Black Earth Creek heads in the Johnstown Terminal Moraine, which forms the eastern edge of the Driftless Area. Figure 1 illustrates the locations of the watersheds.

Like the Driftless Area in general, the topography of the study area consists of rolling uplands, steep hillslopes, and flat valley bottoms. The uplands and valley bottoms are typically farmed; the hillslopes are most often wooded. Bedrock consists of layers of Ordovician and Cambrian dolomites and sandstones (Figure 2). Upland soils, which are developed on loess, are shallow. Soils on the hillsides are developed on colluvium and are also shallow. The hillslopes are dissected by gulleys, which extend from the edge of the farmed uplands to the valley bottoms. There is clear evidence that these gulleys once extended into the uplands, and in fact were caused by agricultural activity. This is consistent with Sartz (1961a), which concludes that Driftless Area gullies are not natural landscape features.

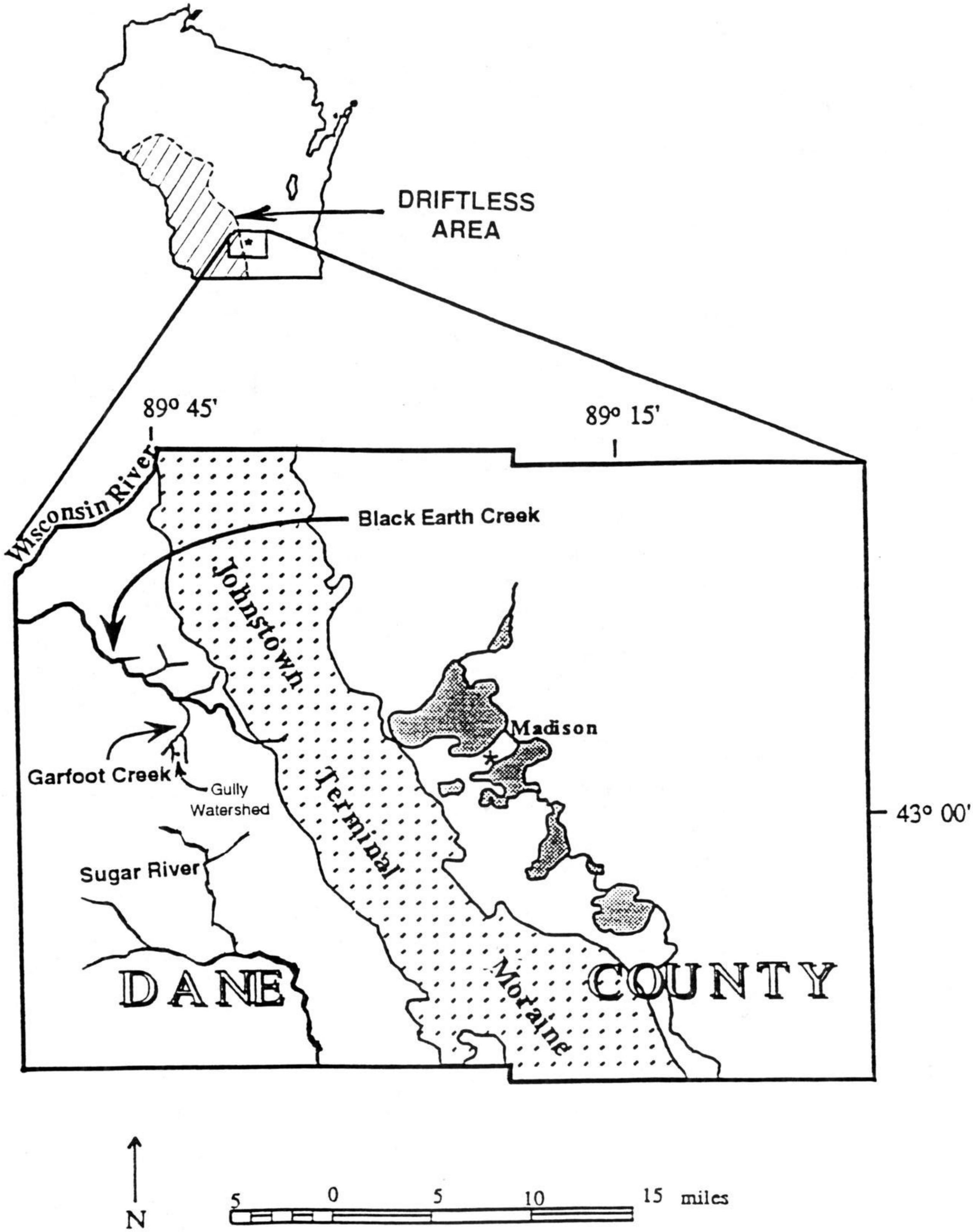

Figure 1. Location of Driftless Area and study sites within Wisconsin.

SYSTEM (age - years)		GROUP	FORMATION		GENERAL LITHOLOGY	THICKNESS (ft)
Quaternary (< 10 000)			Loess Outwash Colluvium Alluvium			
	Middle	SINNIPEE	Galena dolomite Decorah Platteville		dolomite	**120 - 220**
		ANCELL	Glenwood St. Peter sandstone		sandstone	
Ordovician (440 - 500 mil)	Lower	PRAIRIE DU CHIEN	Shakopee Oneota		dolomite	
	Upper	TREMPEALAU	Jordan sandstone St. Lawrence		sandstone	**650 - 1100**
Cambrian (500 - 600 mil)		TUNNEL CITY	Lone Rock Mazomanie			
		ELK MONDE	Wonewoc sandstone Eau Claire sandstone Mount Simone sandstone			
Precambrian (>600 mil)					rhyolit, granit, basalt	

Figure 2. Stratigraphy of the study area.

The valley bottoms contain alluvium of Pleistocene and Recent age. Black Earth Creek was an outwash stream during Wisconsin glaciation; the alluvial fill consists of sands and gravels and is quite thick, exceeding 70 meters (200 feet) in places. The lower portion of Garfoot Creek was affected by the glacial alluviation of Black Earth Creek; except for the upper few meters its alluvium is generally sandy. Just above its confluence with the Black Earth Creek valley bottom, the Garfoot Creek valley fill is over 30 meters (100 feet) thick. In those portions of the three watersheds which were not affected by outwash alluviation, valley fills are typically only a few meters thick and generally fine grained. In the main valley bottom of Garfoot Creek there is meter-hick silty clay layer about one meter below the surface. This layer appears to be continuous, and may represent lacustrine deposits associated with Black Earth Creek during glacial retreat. All valley bottoms in the region have an upper layer of floodplain deposits associated with poor agricultural practices that were characteristic of the Driftless Area from the time of European settlement until the the adoption of soil conservation practices after the late 1930's.

Most of the many springs in the area are located at or near the contact between the valley alluvium and the hillsides. Prior to European settlement the main valley bottoms were dominated by wetlands (Ellarson, 1949), fed by the springs and drained by one or more poorly defined channels. Currently many of the valley bottoms in the Driftless Area are farmed, although they may lie idle in wet years. The upper alluvial layer is generally fine-grained, and may contain clay layers. It is largely a product of the accelerated soil erosion which occurred in the uplands since European settlement. Strong upward gradients are common in the alluvium (Amann, 1993).

The region is in the continental humid temporal climate zone with an annual average air temperature of 8.2 ° C (46.7 ° F). Average monthly temperatures range from -8.4 ° C (16.8 ° F) in January to 22.2 ° C (72.0 ° F) in July. The average annual precipitation from 1948 through 1991 is 79 cm (31 inches). About 60% of the precipitation falls as rain from April through September; the remainder occurs as snow in the winter months. Although much of the precipitation occurs in the summer, most of this moisture is lost to evapotranspiration.

Year-to-year variations in winter climatic conditions probably have the greatest effect on the temporal distribution of groundwater recharge. The ground is generally frozen or covered with snow from December to March, inhibiting infiltration. As the temperature increases in the spring, melting snow and spring rains infiltrate to recharge the aquifer (Cline and Busby, 1963; Cline, 1965). Soil moisture is at a maximum at this time and evapotranspiration is at a minimum. Late autumn rains also contribute to groundwater recharge.

3. GENERAL RESEARCH APPROACH AND PREVIOUS RESULTS

The goal of our research was to improve understanding of the spatial distribution of groundwater recharge in the Driftless Area of Wisconsin. Groundwater recharge is water which infiltrates the ground and then percolates to the water table. For infiltrated water to become recharge it must avoid evaporation from the soil, or capture by plant roots and subsequent transpiration to the atmosphere.

Although the general processes governing groundwater recharge are fairly well understood, it is not generally possible to make accurate estimates of the spatial distribution of recharge in specific applications. This is mainly because of the large number of factors affecting the recharge process, most notably those affecting infiltration and evapotranspiration. These include soil characteristics, vegetation, land use, topography, slope, slope aspect, depth to water table, depth to bedrock, bedrock geology, and climate. These factors can vary widely in space and time. Furthermore, they are commonly interrelated in complex ways. Simulation models have been developed which attempt to account for some of these factors. These include models designed to predict pesticide transport to the groundwater as well as general purpose rainfall-runoff models. However, use of these models to predict the spatial distribution of recharge is hampered by the limited availability of site-specific information about the spatial distribution of the relevant physical factors. More importantly, these models also fail to consider certain processes which often exert a dominant influence on recharge. Examples of such processes include preferential flow and inhibition of infiltration by frost, both of which are important in Wisconsin's Driftless Area.

In view of these problems, we adopted a comprehensive field approach to understanding the spatial distribution of Driftless Area recharge. This approach was characterized by several critical features. First, we made measurements of surface water flows and groundwater levels and analyzed groundwater chemistry at a number of locations throughout the region to gain an initial understanding of the hydrology. We then used a landscape perspective to address the complex spatial distribution of factors affecting recharge. In order to estimate recharge rates for critical landscape elements, we applied a water budget approach at telescoping spatial scales. In making water budget measurements we emphasized the non-growing season, during which recharge is greatest and the complicating effects of evapotranspiration are minimized. We also made synoptic baseflow measurements throughout the region in order to address the question of groundwater divides, which according to Cline (1965) do not necessarily coincide with surface-water divides.

The basic idea of the landscape perspective is that there exist landscape elements such that recharge rates are significantly less variable within elements than they are across elements. Based on our reconnaissance observations and measurements, we hypothesized that at the coarsest level of classification the fundamental landscape elements in the Driftless Area are the uplands, the hillsides, and the valley bottoms (Potter *et al.*, 1995; Olson, 1994). Using these elements, we developed a conceptual model of the hydrology of the study area (Amann, 1993; Olson, 1994, Potter *et al.*, 1995,). This model is consistent with previous hydrological research in the Driftless Area.

In our model we proposed that recharge in the study area occurs primarily on the wooded hillslopes and the farmed uplands, with the former being most important. We also proposed that very little, if any, recharge occurs in the valley bottoms due to the less permeable soils, the presence of fine-grained sediments, and the strong upward gradients.

The proposition that recharge is greater on the wooded hillslopes than on the farmed hilltops is consistent with the results of a number of studies which have demonstrated that wooded areas have significantly higher infiltration and recharge rates than do farmed areas on the same original soils. The most relevant of these studies were conducted by hydrologists at the Coulee Experimental Station in La Crosse, Wisconsin. (See, for example, Sartz, 1961b; Sartz, 1969; Sartz, Curtis and Tolsted, 1977.) Several factors explain the higher infiltration and recharge rates of wooded areas. Farmed soils are periodically compacted by farm equipment, as evidenced by their higher bulk density (Sartz, 1961b). Also, farmed soils generally develop frost which is deeper and more restrictive to infiltration than frost developed in wooded areas (Sartz, 1973). A third factor favoring recharge on the wooded hillslopes is the fact that they receive runoff from upslope farmed hilltops, thus increasing the source of water for recharge.

A primary objective of this study was to test this conceptual model of recharge in the study area. This was done by instrumenting a gulley which drained a farmed upland and wooded hillslope. Over the course of two and a half years flows were measured in this gulley at two locations, enabling us to separate the runoff component from the farmed and wooded areas. Water budget calculations enabled us to estimate recharge in these two areas during recharge events. By focusing on snowmelt events we avoided the necessity to measure evapotranspiration and soil-moisture storage. We also used our recharge and runoff estimates as the basis of water-budget calculations for all of Garfoot Creek. By using U. S. Geological Survey (USGS) flow data on Garfoot Creek we were able to obtain some degree of validation for the general applicability of our recharge model. The results of these calculations are given in the next section.

A second objective of this study was to estimate the areas contributing to baseflow in Garfoot and Black Earth Creeks. Cline (1965) concluded that these contributing areas were greater than the areas of the corresponding surface-watersheds. To aid in this estimation we installed continuous water-level monitoring stations on the primary spring in Garfoot Creek (FF001) and at a location in the Sugar River. The Sugar River watershed is just to the south of Garfoot and Black Earth Creeks, and is the likely additional source of baseflow to these streams. We also made several synoptic measurements of baseflow at sites in the region. All of these data were then used to estimate contributing areas. The analysis and results are presented in Section 5.

4. GULLY MONITORING

Introduction

The goal of this monitoring exercise was to estimate for a number of events the amount of groundwater recharge which occurred on a farmed upland and on a wooded hillslope. This was done by instrumenting a 3.4 ha gully catchment in the Garfoot Creek watershed (See Figure 1 for location.). Runoff data were collected and analyzed during snowmelt periods in 1993, 1994, and 1995. The results were generalized for the entire Garfoot Creek watershed, and compared to independent results based on USGS streamflow data from the Garfoot Creek gage.

Description of Site

The study catchment is on a west facing slope in the Garfoot Creek watershed. The upper 1.6 ha portion of the catchment is an agricultural area of gentle to moderate slope, which has been terraced into two separate fields. The lower 1.8 ha portion of the catchment is a forested hillslope of moderate slope. A gully extends from the lower edge of the tilled upland to the bottom of the hill, providing opportunities for measuring runoff.

The soils of the catchment are Alfisols (Glocker and Patzer, 1978) in the Dunbarton Silt Loam series (Figure 3, Table 1). The Dunbarton soil consists of a silt loam epipedon ranging from 13 to 20 cm deep, underlain by illuviated silty clay loam and silty clay to clay horizons to depths of 30 to 50 cm. Most commonly dolomite underlies the solum. The surface horizon is formed from loess, while subsurface horizons are derived from bedrock residuum. All Dunbarton soils are classified as having been historically eroded. The soils in lower portion of the basin (DuE2) have occasional rock outcroppings.

Table 1. Physical characteristics of the Dunbarton Silt Loam.

	Mapping Symbol		
Characteristic	DuC2	DuD2	DuE2
Slope	6-12%	12-20%	20-45%
Epipedon Depth	17.5 cm	15.0 cm	12.5 cm
Solum Depth	30-50 cm	25-45 cm	20-40 cm
Rock Outcrop*	0%	<1%	1-3%
USDA Capability	IVe-3	VIe-3	VIIe-3

*denotes data from field observation.

The upper portion of the farmed upland was in corn in 1992 and 1993, and in an oat-clover rotation in 1995. The lower field was in alfalfa in 1992, corn in 1993, sorghum in 1994, and an oat-clover rotation in 1995. Vegetation in the forested region consists of dense, mixed deciduous forest. Overstory and understory species include oak, hickory and dogwood. (Table 2).

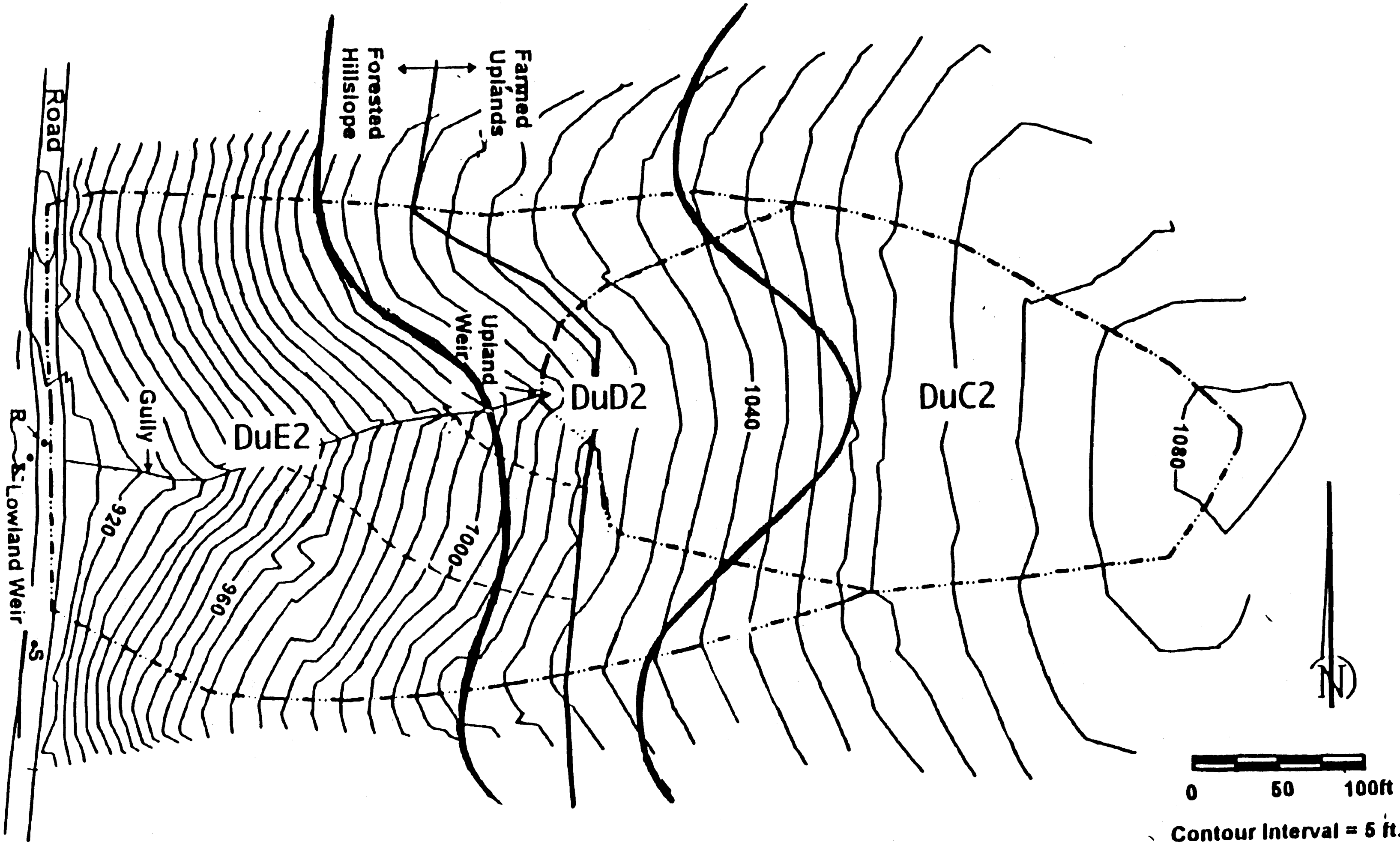

Figure 3. Gully watershed topography and soils.

Table 2. Forest tree species in wooded hillslope (in approximate order of abundance).

Common Name		Scientific Name
	Overstory	
Red Oak		Quercus rubra
Black Oak		Quercus alba
White Oak		Quercus veluntina
Shag Bark Hickory		Carya ovata
Trembling Aspen		Populus tremuloides
	Understory	
Dogwoods (various)		sp. Cornus
Slippery Elm		Ulmus rubra
Buckthorn (various)		sp. Rhamnus
Black Cherry		Prunus serotina

Bedrock consists of dolomites of the Prairie du Chien group overlying Jordan sandstone formation. The Prairie du Chien dolomite is subdivided into the Shakopee and Oneida formations. The Shakopee formation is composed of thin to medium bedded dolomites interbedded with some sand. The Oneota formation is massive and thick bedded. Both formations are fractured. Small seeps along fractures and bedding planes can occur in the Prairie du Chien group. The Jordan sandstone is subdivided into four members. Although the mineralogy of these vary, all are poorly cemented with calcite (Odem and Ostrom, 1978). Typical characteristics of Prairie du Chien group and the Jordan sandstone formations are given in Table 3.

Table 3. Physical characteristics of the bedrock geology.

Characteristic	Bedrock Unit Prairie Du Chien	Jordan
Rock Type	fractured dolomite	sandstone
Mineralogy	Mg Ca 2(CO3)	mixed
Hydr. Conductivity*	2.4 x 10-3 cm/sec	5.8 x 10-3 cm/sec

* Hydraulic Conductivity values from Young (1992).

Methods

Groundwater recharge was estimated by a water balance approach. Consider the control volume shown in Figure 4. Over a time period of duration ΔT, the water budget equation can be written as:

$$\Delta S = P + Q_i + I_i - (Q_o + ET + I_o + R) \qquad 4.1$$

where ΔS is the volumetric change in storage in the control volume, including soil moisture and snow
P is the volume of precipitation
Q_i is the volume of surface runoff into the control volume
Q_o is the volume of surface runoff out of the control volume
I_i is the volume of interflow into the control volume
I_o is the volume of interflow out of the control volume
ET is the volume of evapotranspiration
R is the volume of recharge

Equation 4.1 can be rearranged to give recharge for the period ΔT:

$$R = P + Q_i + I_i - (Q_o + ET + I_o + \Delta S) \qquad 4.2$$

In general, it is difficult to estimate evapotranspiration (ET) and the portion of storage changes due to change in soil moisture. By focusing on snowmelt periods, estimation of these terms is avoided. During snowmelt, evapotranspiration is negligible. At the start of a snowmelt period, it can be assumed that soil moisture is at field capacity, provided there was sufficient rain in the preceding fall to make up for any moisture deficit caused by evapotranspiration. The end of the snowmelt period can be defined as the time at which gravity drainage ceases. With these assumptions, the change in soil moisture is zero, and $-\Delta S$ depends only on loss of surface snow and ice. Denote the latter as M.

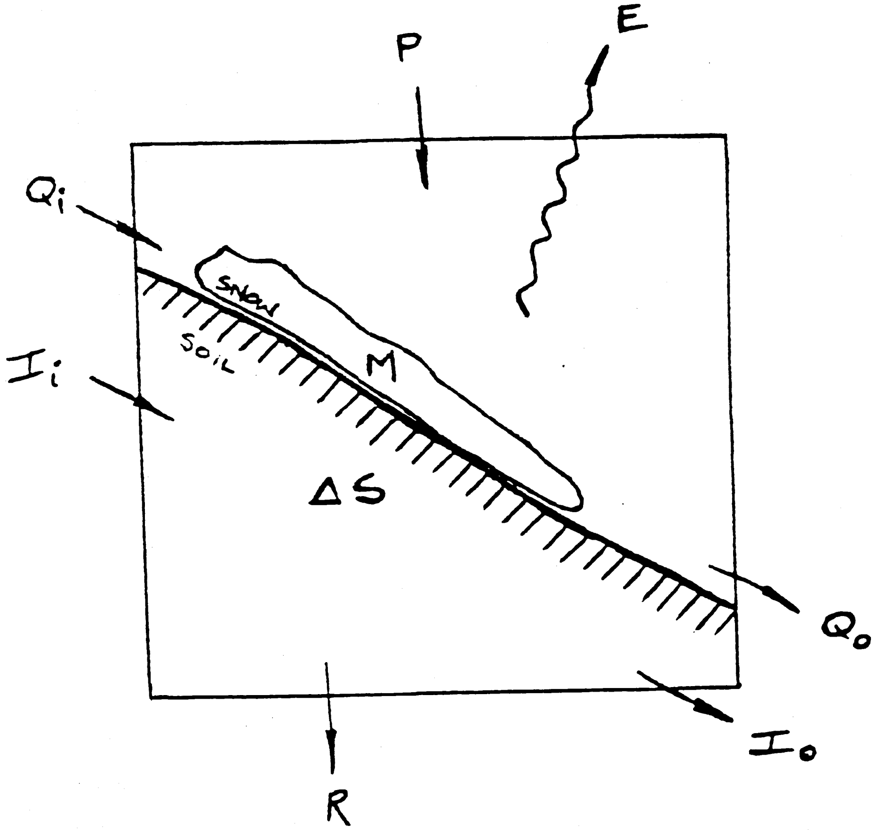

Figure 4. Schematic of the control volume utilized for the gully watershed.

It would also be difficult to measure or estimate interflow. We assumed interflow to be zero, for the following reasons. Our two control volumes were the upper farmed area and the wooded hillslope. The only boundary over which interflow could occur in the upper farmed area is at the boundary with the wooded hillslope. But this boundary is terraced. Any interflow here would appear as runoff, and would be accounted for. In the case of the wooded hillslope, interflow could occur at the lower edge. During snowmelt events we did not see any return flow at the base of the hillslope. It is possible that interflow passed into the alluvium of the valley bottom. If so, it would have become groundwater recharge, and hence accounted for.

With these assumptions, recharge can be written as:

$$R = P + Q_i + M - Q_o \qquad 4.3$$

Monitoring

Based on equation 4.3, we instrumented the gully watershed so that we could estimate recharge for the farmed upland and the wooded hillslope. In order to measure surface runoff, we installed two v-notch weirs, at the upper and lower ends of the gully. The upper weir controlled flows from the farmed upland alone; the lower weir controlled flows from the upland and the wooded hillslope. Contributing areas for each weir were determined from a topographic map based on a leveling survey (Figure 3).

The pool behind each weir was connected to a stilling-well containing a float-pulley-potentiometer system. Potentiometer output was recorded by a data acquisition system (Campbell Scientific Inc., CR-10) at one minute intervals when stage varied more than 0.30 cm and every hour when it did not. Accuracy for the stage measurements was 1.5 mm. Calibration tubes were constructed into each weir plate to facilitate manual stage measurements. Such measurements were made whenever data were downloaded from the data acquisition system, enabling us to reference the stage data. Manual stage measurements were also made during equipment failures, which were common during the snowmelt periods due to sub-freezing conditions at night.

A tipping-bucket rain gage was installed just upslope from the boundary between the farmed upland and the wooded hillslope. The USGS also operated three rain gages in or near the Garfoot Creek watershed. The water content of snow and surface ice was estimated by intensive sampling. Snow samples were taken with U. S. standard snow samplers and field weighed using spring loaded scales (Pesola model 160k). Scales were calibrated in the laboratory before and after snow sampling.

Data and Results

The site was monitored for over three years, which included three snowmelt periods. We also collected data during numerous rainfall events in order to get information about stormflow generation.

Figure 5 summarizes the results of the analysis of the snowmelt data. (Complete hydrographs and summaries are found in the Appendix). There are two important findings. First, note the differing amounts of groundwater recharge in the two landscape units. The wooded hillslope always recharged its entire water supply (precipitation and snowpack), while the farmed upland recharged 20% of its water supply in 1993, 93% in 1994, and 90% in 1995. The low upland recharge value in 1993 was due to January freeze-thaw cycles that created an impermeable dense "concrete" frost. This frost was identified during snow sampling before the recharge event, and has been previously reported in tilled fields (eg. Trimble *et al.*, 1958.) The small amount of upland recharge in 1993 contributed storm runoff to Garfoot Creek, which experienced moderate flooding. Note again that there was no runoff from the wooded hillslope during any of the snowmelt events.

The second important finding is the significant amount of infiltration which occurred in the gully during runoff events. Over the three years of monitoring, this infiltration ranged from 32 to 88 m^3. We estimated that the gulley could continuously infiltrate at a rate of about 160 m^3 /d. This means that it is able to absorb runoff from the 1.6 ha tilled upland at a rate of over 1.0 cm/d. Gully infiltration clearly reduces the volume of runoff from the tilled upland. But perhaps more importantly, it provides this runoff an almost direct pathway to groundwater. Gullies are ubiquitous in the Driftless Area; hence they may be a significant mechanism for groundwater contamination by agricultural chemicals. Note that Prestegaard and McHugh (1990) observed the occurrence of significant amounts of gully infiltration in a small catchment in the Kickapoo River watershed, in the western Driftless Area of Wisconsin.

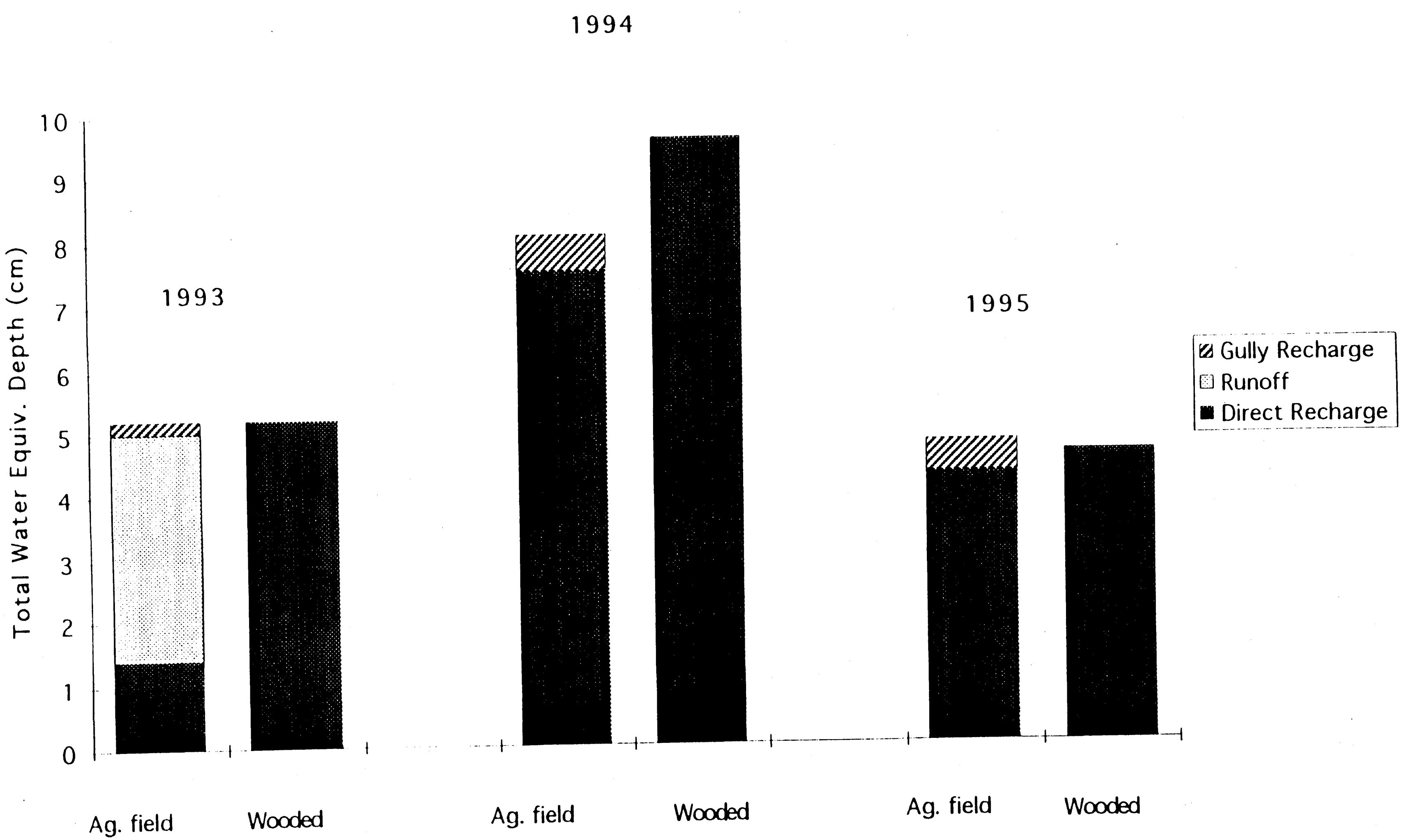

Figure 5. Results of three years of snowmelt monitoring at the gully site.

Over the three year monitoring period, we collected data on 70 non-snowmelt events which produced at least 0.08 cm of precipitation. Appendix 1 gives the data from these events. In only one non-snowmelt event was there flow from either the agricultural upland or the wooded hillslope. That one event, which produced 9.9 cm of rainfall, resulted in 1.08 cm of runoff from the agricultural upland, but no runoff from the wooded hillslope. We anticipated that there would rarely, if ever, be runoff from the wooded hillslope. However, we were surprised by the small amount of non-snowmelt runoff emanating from the farmed upland. We attribute this lack of runoff to the upland terracing and the use of conservation practices.

Garfoot Creek Verification

Our gully monitoring provides data on a 1.6 ha farmed upland and a 1.8 ha wooded hillslope. To determine the representativeness of these data we used them to estimate recharge and runoff for the entire Garfoot Creek watershed, and then compared the results to estimates based on data from the USGS gaging station.

In order to extrapolate our monitoring results to the entire gaged watershed, we needed to estimate the percent of area of the watershed in each of our three landscape units. This was done using digital GIS maps of soil types, land cover, and forest type. All upland wooded areas were classified as wooded hillslope, even if they were on the hilltop. From our GIS analysis were concluded that the watershed was 28.5% (398 ha) agricultural uplands, 50.5% (705 ha) forested hillslopes, and 21.0% (293 ha) bottomlands.

Recharge estimates were made for the 1994 snowmelt event. (We did not use the 1993 event because the estimates of snow cover were less accurate. We could not use the 1995 event because the USGS flow data on Garfoot creek were not yet available.) The unit area recharge amounts calculated from the monitoring data were applied to the entire watershed, based on three landscape units. By using a simple hydrograph separation method on the USGS gaging station data, total basin recharge was calculated.

The results of the independent calculations of recharge, shown in Table 4, are remarkably similar, given that the extrapolation is based on about 0.2% of the watershed. Also note that later in the report we show that the land area contributing groundwater discharge to Garfoot Creek is about 28% larger than the surface drainage. Applying this correction to the data gives an recharge error of about -1%.

Table 4. Comparison of 1994 snowmelt recharge estimates for Garfoot Creek.

	Recharge Estimate	Error*
USGS Gage Data	1,594,000 m^3	NA
Gully Data	1,386,000 m^3	13.0 %
With Areal Adjustment	1,610,000 m^3	-1.0 %

* Error = (Gage - Gully) / Gage

Because our gulley monitoring did not provide any information about runoff from the bottomlands, we were not able to estimate total basin runoff for comparison with estimates from the USGS streamflow data. However, we did use the USGS data to estimate for each storm what the runoff coefficient for the bottomland would have had to have been if the agricultural uplands and wooded hillslopes in the entire watershed would have behaved the same as those elements of our gully catchment.

Runoff estimates were made for five storms in 1993 and 1994. (USGS streamflow data are not yet available for 1995.) For all but the July 7, 1993 event, it was assumed that no runoff was generated on the farmed uplands and wooded hillslopes, as observed at the gully catchment. For the 1993 event, we applied the runoff coefficient derived from the gully data (0.109). Precipitation data were obtained from the three USGS rain gages in and near the watershed. Basin-wide runoff volumes were calculated from the USGS streamflow data, based on simple hydrograph separation. Using the basin-wide precipitation estimates, the assumed runoff coefficients, and the calculated runoff volumes, we estimated the required runoff coefficients for the bottomlands. The coefficients, given in Table 5, range from 0.142 to 0.504. All are consistent with or lower than what would be expected for the bottomland soil types, based on information in the literature. Note that the lower coefficients are due in part to the relatively small amount of rainfall associated with these events.

Because 79% of the Garfoot Creek watershed is in wooded hillslope or farmed hilltop, the total runoff from the watershed is very sensitive to the amount of runoff from these landscape units. Conversely, the total runoff from the watershed is not very sensitive to the amount of runoff from the bottomlands. Even if the runoff coefficient for the bottomlands were zero, the minimum possible value, the runoff coefficients for the combined wooded hillslope and farmed hillslope would need to increase by only 0.04 to 0.13 in order to explain the runoff observed at the Garfoot Creek gage. This is further evidence that the wooded hillslopes and farmed hilltops contribute very little to runoff in the Garfoot Creek watershed.

Table 5. Runoff coefficients for Garfoot Creek.

Event Date	Ppt (cm)	Uplands	Runoff Coefficient Forested Hillslopes	Bottom-lands
7/5/93	9.9	0.109	0.000	0.504
10/9/93	1.26	0.000	0.000	0.307
11/26/93	1.9	0.000	0.000	0.142
8/11/94	6.93	0.000	0.000	0.170
9/14/94	4.53	0.000	0.000	0.274
Literature	Coefficients*	0.000 - 0.400	0.000 - 0.300	0.400 - 0.500

* American Society of Civil Engineers (1969), Rantz (1971) and Sartz (1969)

Summary

Our gully monitoring data strongly support our landscape model of recharge. Wooded hillslopes are sites of high recharge and virtually no surface runoff. Farmed uplands can also have high recharge rates, but may also generate surface runoff in intense rainfalls or during snowmelt events with icy soil conditions. The valley bottoms are primarily runoff-producing areas, providing virtually no recharge. While these conclusions are based primarily on observations at the scale of a single hillslope, they were also supported by analysis of data at a watershed scale of about 10 km^2. Given the relative uniformity of the Driftless Area of Wisconsin, it is not unreasonable to generalize these conclusions to the entire Driftless Area.

5. ESTIMATING AREAS CONTRIBUTING TO BASEFLOW

Introduction

Past analyses of groundwater levels have indicated that the surface and groundwater divides separating the Black Earth Creek and Sugar River watersheds do not coincide. Cline's (1965) water table map of the Black Earth Creek watershed shows the groundwater divide separating the two groundwatersheds to extend well into the surface watershed of the Sugar River. A more recent map (Bradbury *et al.*, 1995) gives a similar interpretation, although with a much smaller portion of the Sugar River watershed contributing to Black Earth Creek. In this section we use streamflow measurements to provide estimates of the surface areas contributing to baseflow at various locations in the two watersheds. The results independently confirm the conclusion that the Black Earth Creek receives baseflow that originates outside the surface water divide.

In conducting this analysis we used USGS streamflow data as well as data we collected. The USGS data are from streamflow gaging stations on Black Earth Creek at Black Earth and Garfoot Creek just above its confluence with Black Earth Creek. On August 1, 1994 we installed a stage recorder on the Sugar River at a location that defines a surface watershed with about the same area as the gaged Black Earth Creek watershed. Since March, 1994 we have also been collecting discharge data on the main spring (FF001) in the Garfoot Creek watershed. On several different occasions we also made discrete current meter measurements at various locations in the Black Earth Creek and Sugar River watersheds.

Methods

Three methods were used to estimate areas contributing to baseflow. Two of these methods use the continuous flow data collected at the four stream gaging sites. One of these is based on average flows; the other on estimates of groundwater recharge during specific recharge events. The third method uses the discrete current meter measurements. The basis of the three methods is explained below.

Consider n stream sites and their corresponding watersheds. Let A_i be the unknown area contributing to baseflow at site i.

For any watershed i, applying conservation of mass over some time period ΔT, we can write

$$\Delta S_i / \Delta T = \overline{R}_i - \overline{Q}_i - \overline{E}_i$$

where ΔS_i is the change in groundwater storage in watershed i;
ΔT is the duration of the time period;
$\overline{R}_i$ is the mean recharge rate for the area contributing to site i;
$\overline{Q}_i$ is the mean baseflow rate at site i.
$\overline{E}_i$ is the evapotranspiration from groundwater over the area contributing to site i.

For a sufficiently long ΔT , $\Delta S_i / \Delta T$ is negligible. We also assume that $\overline{E}_i$ is small compared to $\overline{R}_i$ and $\overline{Q}_i$. (This is likely to be the case unless there are extensive areas of shallow groundwater.) Then

$$\overline{R}_i = \overline{Q}_i$$

For all pairs of i, j where $i \neq j$,

$$\left(\overline{R}_i / A_i\right) / \left(\overline{R}_j / A_j\right) = \gamma_{ij},$$

where γ_{ij} is the ratio of average recharge contributing to site i to that contributing to site j.

In general, γ_{ij} can be estimated from characteristics affecting recharge in each watershed. In our case, for example, we could use the proportion of land area in valley bottom, wooded hillslope, and tilled upland. As a first approximation, we assume that γ_{ij} equals one for all $i \neq j$. This assumption is based on the observation that the proportion of the three landscape units appears to be relatively constant over our region of interest. Based on this assumption,

$$\overline{R}_i / A_i = \overline{R}_j / A_j \text{ for all } i \neq j.$$

Since the recharge per unit area is the same for all watersheds, it must equal the recharge per unit area for the entire area. Hence

$$\overline{R}_i / A_i = \sum_{j=1}^{n} \overline{R}_j \Big/ \sum_{j=1}^{n} A_j \quad \text{for all } i$$

Similarly,

$$\overline{Q}_i / A_i = \sum_{j=1}^{n} \overline{Q}_j \Big/ \sum_{j=1}^{n} A_j \quad \text{for all } i$$

There are n unknown areas contributing to baseflow, A_1, A_2, ..., A_n. Assuming that we can estimate $\overline{R}_i$ or $\overline{Q}_i$ for all i, we have n-1 equations. The nth equation can be obtained by assuming that we know the value of

$$A = \sum_{i=1}^{n} A_i$$

In this study we assume that A equals the sum of the surface drainage areas at all sites. In general, the likelihood of such an assumption increases with the area.

Based on these assumptions,

$$\overline{R}_i / A_i = \sum_{j=1}^{n} \overline{R}_j \Big/ A$$

and

$$\overline{Q}_i / A_i = \sum_{j=1}^{n} \overline{Q}_j \Big/ A$$

Hence,

$$A_i = A\overline{R}_i \Big/ \sum_{j=1}^{n} \overline{R}_j \qquad 5.1$$

and

$$A_i = A\overline{Q}_i \Big/ \sum_{j=1}^{n} \overline{Q}_j \qquad 5.2$$

Our first method for estimating contributing areas uses equation (5.2). Estimates of the various $\overline{Q}_i$ are based on the continuous discharge data from Black Earth Creek, Garfoot Creek, the Sugar River, and the main spring feeding Garfoot Creek.

Method 2 uses equation (5.1). Recharge estimates are based on hydrograph analysis of the continuous discharge data.

Method 3 is based on discrete discharge measurements at a number of sites in the region. It makes indirect use of equation (5.2), as explained below.

Equation (5.2) can be rewritten as

$$A_i = A \Big/ \left(1 + \sum_{j \neq i} \overline{Q}_j / \overline{Q}_i\right)$$

Suppose we substitute concurrent measurements of baseflow, $Q_1, Q_2, \ldots Q_n$, for the mean baseflows $\overline{Q}_1, \overline{Q}_2, \ldots \overline{Q}_n$. How does the ratio Q_j/Q_i compare to the ratio $\overline{Q}_j/\overline{Q}_i$?

To answer this question, we can make use of the common assumption that the logarithms of flows at nearby locations have a multivariate normal distribution. Hence, for locations i and j,

$$\ln Q_j = \alpha_j + \rho(\beta_j/\beta_i)(\ln Q_i - \alpha_i) + (1-\rho^2)^{1/2}\beta_j Z$$

where $\alpha_i = E[\ln Q_i]$, the mean of $\ln Q_i$
$\alpha_j = E[\ln Q_j]$, the mean of $\ln Q_j$
$\beta_i^2 = V[\ln Q_i]$, the variance of $\ln Q_i$
$\beta_j^2 = V[\ln Q_j]$, the variance of $\ln Q_j$
$\rho = E[(\ln Q_i - \alpha_i)(\ln Q_j - \alpha_j)]/\beta_i\beta_j$, the correlation between $\ln Q_i$ and $\ln Q_j$
Z has a normal distribution with zero mean and unit variance.

Based on this model it can be shown that the random variable $\ln Q_j/\ln Q_i$ is lognormally distributed with expected value

$$E[Q_j/Q_i] = (\overline{Q}_j/\overline{Q}_i)\exp(0.5(\beta_i^2 - \beta_i\beta_j\rho))$$

and variance

$$V[Q_j/Q_i] = \exp(2\alpha_j - 2\alpha_i)\left(\exp\left(2\left((\beta_i^2 + \beta_j^2) - 2\beta_i\beta_j\rho\right)\right) - \exp\left(\beta_i^2 + \beta_j^2 - 2\beta_i\beta_j\rho\right)\right)$$

Note that if $\beta_i^2 \approx \beta_j^2$ and $\rho \approx 1$, then

$$E[Q_j/Q_i] \approx \overline{Q}_j/\overline{Q}_i$$

and

$$V[Q_j/Q_i] \approx 0$$

Hence if the logarithms of the baseflows at any two locations are strongly correlated and have nearly equal variances, then the ratio of concurrent measurements of baseflow will about equal the ratio of the mean baseflows. To test this assumption, we analyzed January 1 streamflow data from two nearby Driftless Area streams, the East Branch of the Pecatonica River near Blanchardville (USGS Station #05433000, drainage area of 572 km^2 (221 mi^2)) and the Pecatonica River at Darlington (USGS Station #054325000, drainage area of 707 km2 (273 mi^2)). Based on a period of record from 1940 through 1994, the correlation coefficient (ln-space) is 0.92 and the respective standard deviations (ln-space) are 0.38 and 0.53. Using these values,

$$E[Q_j/Q_i] \approx 0.98\overline{Q}_j/\overline{Q}_i$$

and

$$V[Q_j/Q_i] = 0.06$$

$$\{V[Q_j/Q_i]\}^{1/2} = 0.25$$

Based on these findings we justify the use of concurrent discrete baseflow measurements to estimate areas contributing to baseflow.

Results

The three methods were used to estimate the areas contributing groundwater discharge to Black Earth Creek, Garfoot Creek, and the Sugar

River at their stream gage locations. We also estimated the area contributing to the main spring on Garfoot Creek.

Methods 1 and 2 require continuous streamflow data. Our gage on the Sugar River was installed on August 1, 1994 and is still in operation.

Streamflow data from the USGS gages on the Black Earth and Garfoot Creeks are only available through September, 1994. Hence application of these methods was limited to August and September of 1994. Method 1 was applied using flow data for the full two months. Method 2 was applied to the August 11 rainfall event.

The third method only requires that discrete discharge measurements be made on the same day at all locations. One set of measurements were made on 30 June, 1994. Measurements were made with the Model 1205 Price-type "Mini" Current Meter, and discharges were computed using the midsection method. The results are given in Table 6.

Table 6. Discrete streamflow measurements.

Location	Drainage Area (km^2)	Streamflow (m^3/s)
Sugar River at Valley Road	117	0.829
Garfoot Creek	14.0	0.121
Black Earth Creek	111	1.034

Table 7 gives the estimates of the areas contributing to Black Earth and Garfoot Creeks and the Sugar River, as well as the corresponding surface drainage areas. Note that the results are fairly consistent, given the non-ideal conditions under which the the three methods were applied. Averaging over the results of the three methods, we estimate that Garfoot Creek is receiving flow from an area about 4.1 km^2 (1.6 mi^2) larger than its surface area, while Black Earth Creek is receiving flow from an area about 23 km^2 (8.7 mi^2) larger than its surface area. This latter area is about the same area identified in Cline (1965), but is significantly greater than the area identified in the recent water table map of Bradbury *et al.* (1995). Spring FF001 also appears to be supplied by an area of 4.2 km^2 (1.6 mi^2), which implies that it is receiving water from outside the Garfoot Creek watershed.

Table 7. Estimates of surface area contributing baseflow.

Watershed	Surface Drainage Area (km^2)	Baseflow Contributing Area (km^2) 1	2	3	AVG
Black Earth Creek	118	150	141	130	141
Garfoot Creek	14.0	19.3	19.7	15.3	18.1
Sugar River	117	84.7	94.1	104.7	94.5
Spring FF001	NA	4.2			

When comparing the three estimates of area contributing groundwater discharge to Black Earth Creek, it is important to understand differences in their meaning. Our estimate is based on groundwater discharge into streams, and includes all surface areas contributing to this discharge, regardless of the flow path. Even though Cline (1965) used water levels to develop his water table map for the Black Earth Creek watershed, his estimate of the area contributing to groundwater discharge was based on discharge measurements in the watershed. (Note, however, that Cline (1965) does not provide a description of how the estimation was done.) The contributing area shown on the water table map of Bradbury *et al.* (1995) is based entirely on water table measurements. It shows a total area of about 5.2 km^2 (2 mi^2) of Sugar River watershed contributing to Black Earth Creek. This area represents groundwater flow driven by shallow gradients alone; it does not account for deep circulation. Piezometric data from deep wells in the region indicate that there is such deep circulation, and that Black Earth Creek receives additional water which recharges in the vicinity of the southern flank of Blue Mounds, over 10 km from the surface watershed boundary (Bradbury, 1995).

Also note that there may be errors in our estimate of the area contributing groundwater to Black Earth Creek due to our two critical assumptions. One of these is the assumption that recharge per unit area is the same in the Black Earth Creek and Sugar River watersheds. Although there are many similarities between the two watersheds, there are some important differences. A greater percentage of the bedrock in the Sugar River watershed is in sandstone, rather than in dolomite. This could favor recharge in the Sugar River watershed. Perhaps more importantly, there appears to be a greater proportion of wooded landscape in the Black Earth Creek watershed, which would favor recharge there. Both of these factors need to be considered in future work.

6. SUMMARY OF FINDINGS AND THEIR IMPLICATIONS

In the course of our investigations in the Black Earth Creek and Sugar River watersheds, we were able to draw several conclusions about the hydrology of the region. The principal findings are:

- Black Earth Creek receives groundwater discharge which emanates in the Sugar River watershed. Much of this water recharges well outside of the Black Earth Creek watershed.

- The wooded hillslopes and the farmed uplands are the primary groundwater recharge areas in the region. Recharge rates are highest on the wooded hillslopes, because they have the highest infiltration rates and receive runoff from upslope agricultural areas. Valley bottoms are not important sites for recharge.

- Significant amounts of runoff infiltrate the hillslope gullies, which are ubiquitous in the Driftless Area as a result of many years of abusive agricultural practices.

We did not attempt to determine the general applicability of these findings to the rest of the Driftless Area. However, we do have reasons to believe that at least the last two findings are generally applicable. As a physiographic region, the Driftless Area is relatively homogeneous. There is little reason to expect that our findings on recharge and gully infiltration would not be widely applicable throughout the region. Furthermore, as pointed out earlier, other investigators have made similar observations in other parts of the Driftless Area. For example, Sartz *et al.* (1977) documented high infiltration rates and negligible runoff at the La Crosse Experimental Station. And Prestegaard and McHugh (1990) reported on the significance of gully infiltration in the Kickapoo River watershed in the western Driftless Area.

With respect to the lack of concurrence between surface water and groundwater divides, the picture is not so clear. Both Black Earth Creek and Sugar River were outwash channels during Wisconsin glaciation. It is uncertain how the presence of thick, highly permeable outwash deposits in these watersheds affects groundwater circulation. It may be that their presence is responsible for the movement of groundwater across surface water divides. However, other streams in the Driftless Area, which are not influenced by outwash deposits, also have anomalously high baseflow discharges. One example is Trout Creek, which is about 20 km west of our study region. Additional research will be required to understand the factors contributing to lack of concurrence between surface water and groundwater divides.

Each of our principal findings has important management implications for the area:

- Efforts to protect baseflow-fed trout streams have focused largely on the stream corridor. Clearly attention also needs to be directed to recharge areas, particularly those which lie outside of the surface-water divide.

- Any loss of wooded hillslopes and uplands will decrease groundwater recharge. The cumulative effect of many such losses will be dessication of spring-fed wetlands, reduced baseflows, and decreased groundwater supply. Programs for protecting groundwater recharge must focus on wooded hillslopes and uplands.

- Gullies in the Driftless Area may partially explain the widespread contamination of wells in the region by nitrates and pesticides. The common use of grade stabilization structures to control gully erosion may worsen groundwater contamination by increasing the duration of runoff. (On the other hand, grade stabilization structures may increase groundwater recharge.)

The first two implications could motivate a variety of management strategies to protect the quantity and quality of groundwater recharge. In considering potential strategies, it is important to keep in mind that not all recharge is equally important. In particular, recharge that occurs in a regional recharge area, such as portions of the Sugar River watershed, is in many regards much more critical than recharge that occurs in a regional discharge area, such as the Garfoot Creek watershed. The flow paths associated the former are deeper and much longer than those associated with the later. Hence it is this recharge that primarily contributes to deep groundwater, our most reliable groundwater source. And because of its longer flow paths, the contribution of this recharge to baseflow decreases much less rapidly during dry periods. In fact, during extreme droughts, this water may constitute virtually all of the baseflow. Hence it is essential that management strategies for protecting groundwater recharge focus on regional recharge areas.

The extent to which gullies contribute to groundwater contamination in the Driftless Area is not known. The gulley we monitored was capable of infiltrating significant amounts of runoff. But over a three year period, there were only four events which produced runoff in the gulley. Three of these were snowmelt events. Typically, snowmelt runoff is not likely to be highly contaminated, unless manure was spread during the winter. The fourth event was the 10 cm rainfall event on July 5, 1993. This event produced about 1 cm of runoff from the agricultural upland, at least a third of which infiltrated into the gulley. We did not get a sample of this runoff for laboratory analysis. However, the U. S. Geological Survey (Holmstrom *et al.*,1994) did sample Garfoot Creek on that day, finding measurable concentrations of atrazine (0.9 μg/l), cyanazine (6.1 μg/l), metolachlor (6.0 μg/l), and 2,4-D (0.54 μg/l). If other gullies in the region also infiltrate runoff, then gullies could be a significant source of groundwater contamination by agricultural chemicals.

7. FUTURE WORK

As a result of this study we have improved our understanding of the hydrology of the Black Earth Creek and Sugar River watersheds, as well as of the Driftless Area in general. However, there remain some issues which are critical to wise management of the water resources of the region. In addition, some of the calculations in this report should be refined as additional data become available.

Gullies

It is clear that significant infiltration occurs in our instrumented gully. It is not clear where that water goes and the degree to which it contaminates groundwater. More importantly, it is critical to determine how other gullies in the Driftless Area contribute to groundwater recharge and contamination.

Contributing Areas

Black Earth Creek receives groundwater from the Sugar River watershed. But the exact locus of the recharge area is not precisely known. This is most important for recharge which follows deep flow paths, as this water is most critical to the groundwater system and to the Black Earth Creek.

Our calculations of contributing area need to be refined after USGS streamflow data from 1995 are available. New calculations would also benefit from data on extent of wooded hillslopes and uplands in the Black Earth Creek and Sugar River watersheds.

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APPENDIX: Gully Weir Hydrographs

The following appendix contains the full set of gully weir hydrographs between February 1993 and July 1995. Table 1-1 summarizes these events. Note that the hydrographs are not all to the same scale. Runoff volumes are given on each figure. Annual summaries of the snowmelt events are found in tables 1-2 through 1-4. Calculations within these tables are based on the water budget equations for the gully basin.

Note that two special figures have been added to this appendix. The first (figure 1-9) is the resulting upper weir hydrograph from 900 gallons of water delivered by water truck. This runoff simulation was characteristic of other runoff events. No runoff made it to the lower weir, in fact all runoff infiltrated in the gully no further than 50 m from the upper weir site. The second figure (1-10) shows the 1994 water year hydrograph from the upper weir plotted with the Garfoot hyetograph.

Table 1-1. A summary of the gully weir hydrographs.

Figure Number	Site	Date	Event Type
1-1	Up	3/23-31/93	Snowmelt
1-2	Lo	3/23-31/93	Snowmelt
1-3	Up	7/5/93	Rain
1-4	Lo	7/5/93	Rain
1-5	Up	2/19-20/94	Snowmelt
1-6	Up	3/4-5/94	Snowmelt
1-7	Up	2/21-23/95	Snowmelt
1-8	Up	3/11/95	Snowmelt
1-9	Up	7/14/95	Water Truck
1-10	Up	1994 WY	All

Table 1-2. Summary of the 1993 snowmelt event.

	Upland	Forested Hillslope	
Total Water Equivalent	appr. 5.0 cm	5.2 cm	
Up. Weir Runoff			538 m^3
Lo. Weir Runoff			620 m^3
Runoff Depth	4.0 cm	0.0 cm	
Recharge	1.0 cm	5.2 cm	
Gully Recharge	0.2 cm	NA	

Table 1-3. Summary of the 1994 snowmelt event.

	Upland	Forested Hillslope	
Total Water Equivalent	8.1 cm	9.6 cm	
Up. Weir Runoff			75 m^3
Lo. Weir Runoff			0 m^3
Runoff Depth	0.5 cm	0.0 cm	
Recharge	7.6 cm	9.6 cm	
Gully Recharge	0.5 cm	NA	

Table 1-4. Summary of the 1995 snowmelt event.

	Upland	Forested Hillslope	
Total Water Equivalent	4.8 cm	4.6 cm	
Up. Weir Runoff			64.8 m^3
Lo. Weir Runoff			0 m^3
Runoff Depth	0.5 cm	0.0 cm	
Recharge	4.3 cm	4.6 cm	
Gully Recharge	0.5 cm	NA	

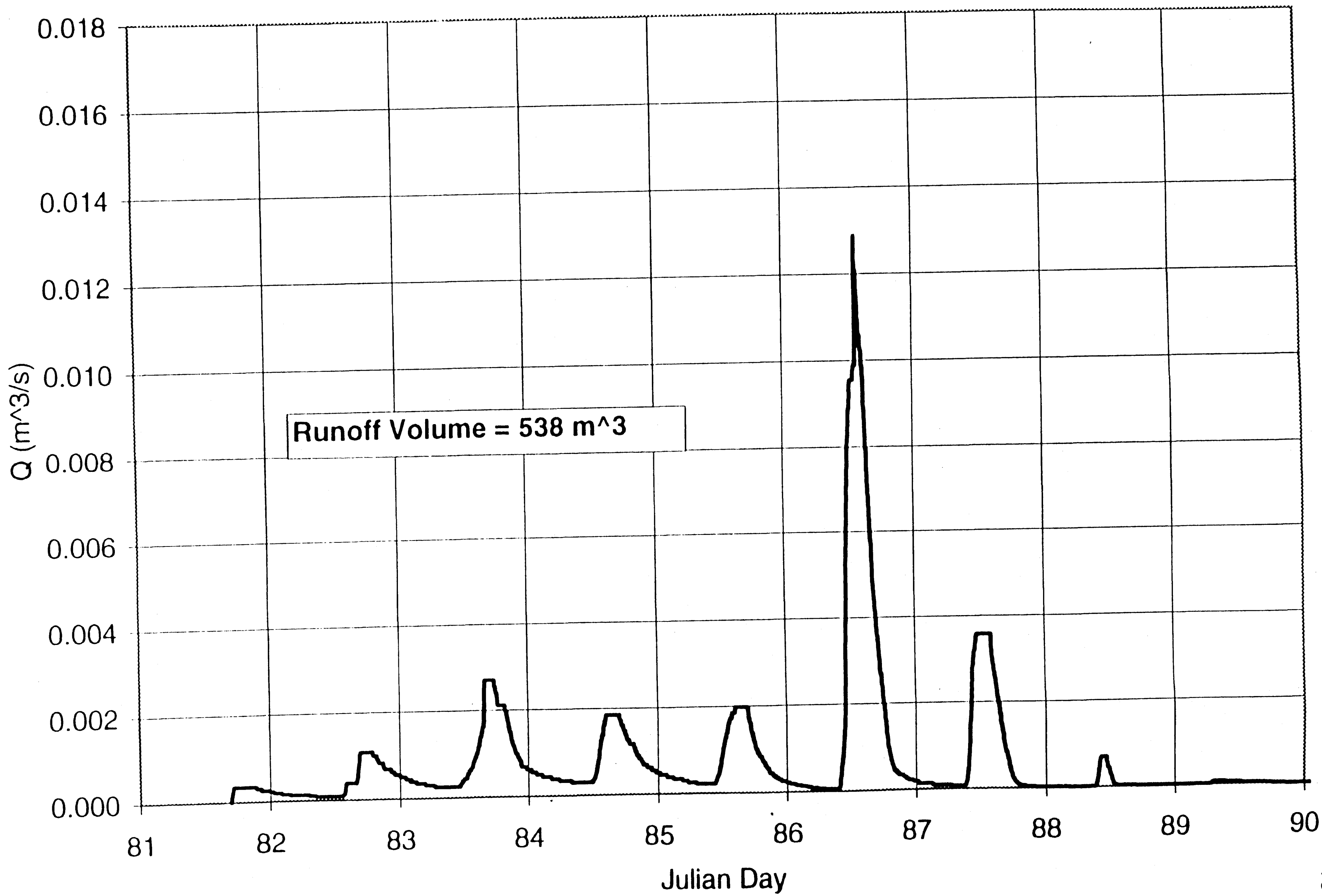

Figure 1-1. Upper gully runoff hydrograph for March 23-31, 1993

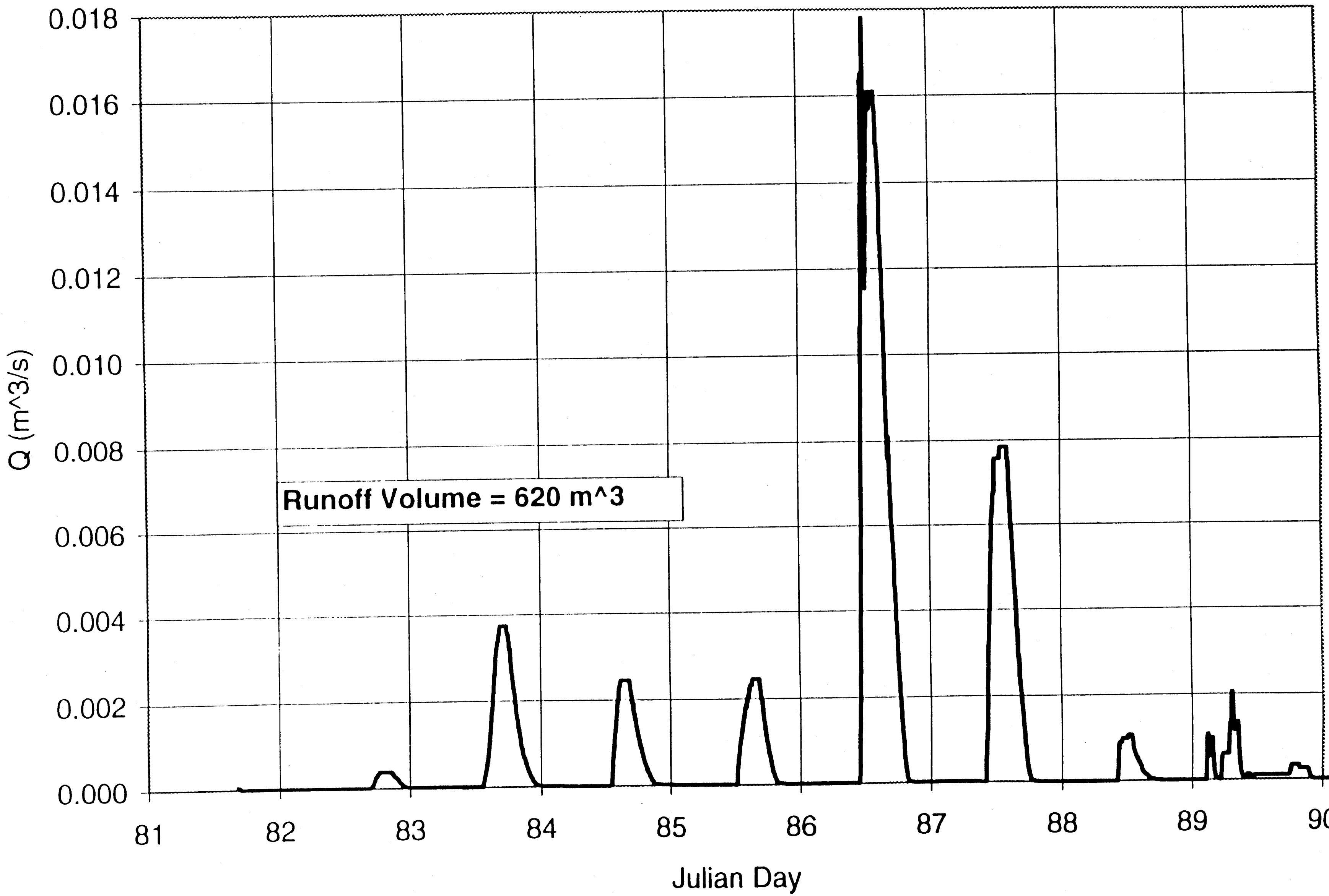

Figure 1-2. Lower gully runoff hydrograph for March 23-31, 1993.

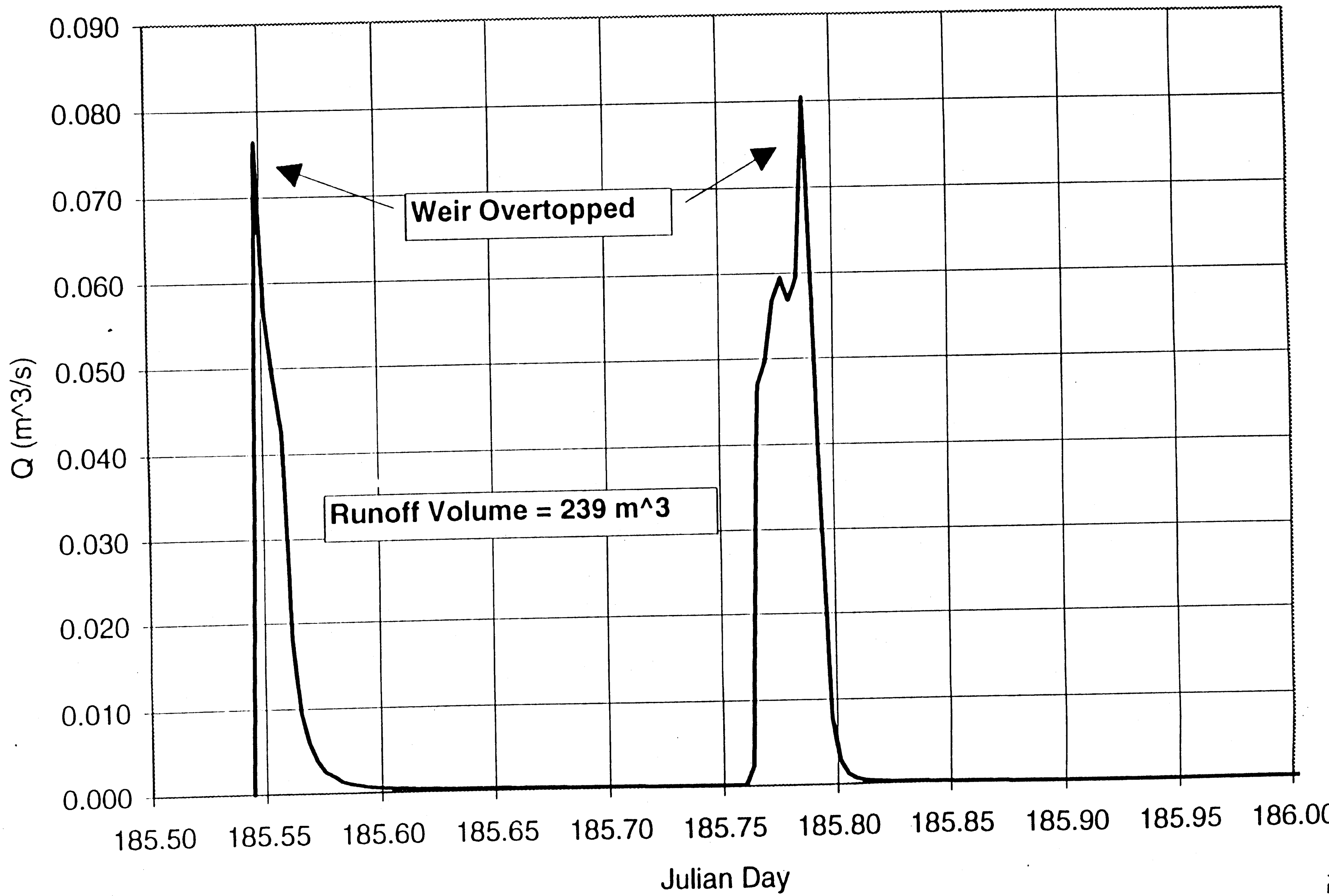

Figure 1-3. Upper gully runoff hydrograph for July 5, 1993.

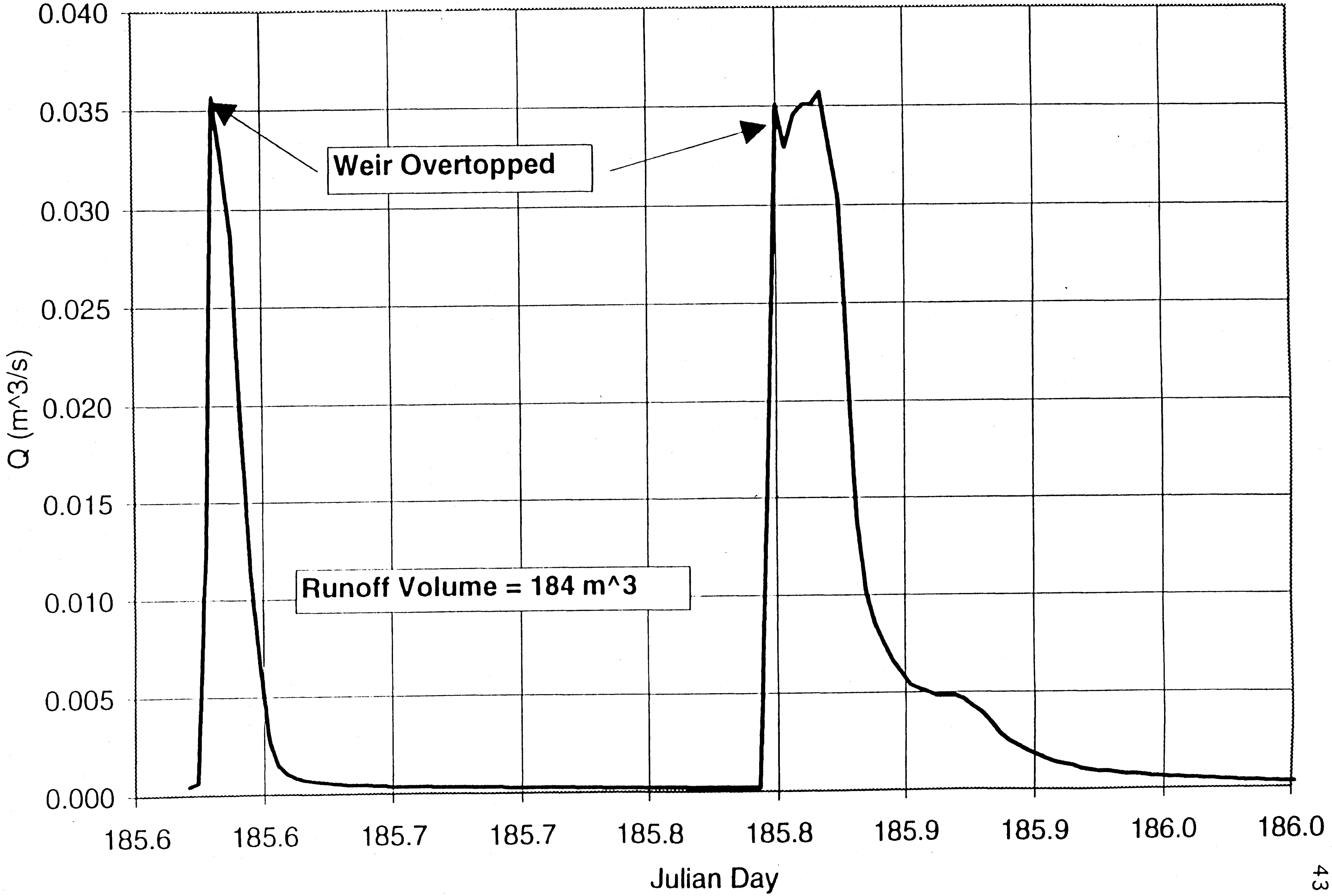

Figure 1-4. Lower gully runoff hydrograph for July 5, 1993.

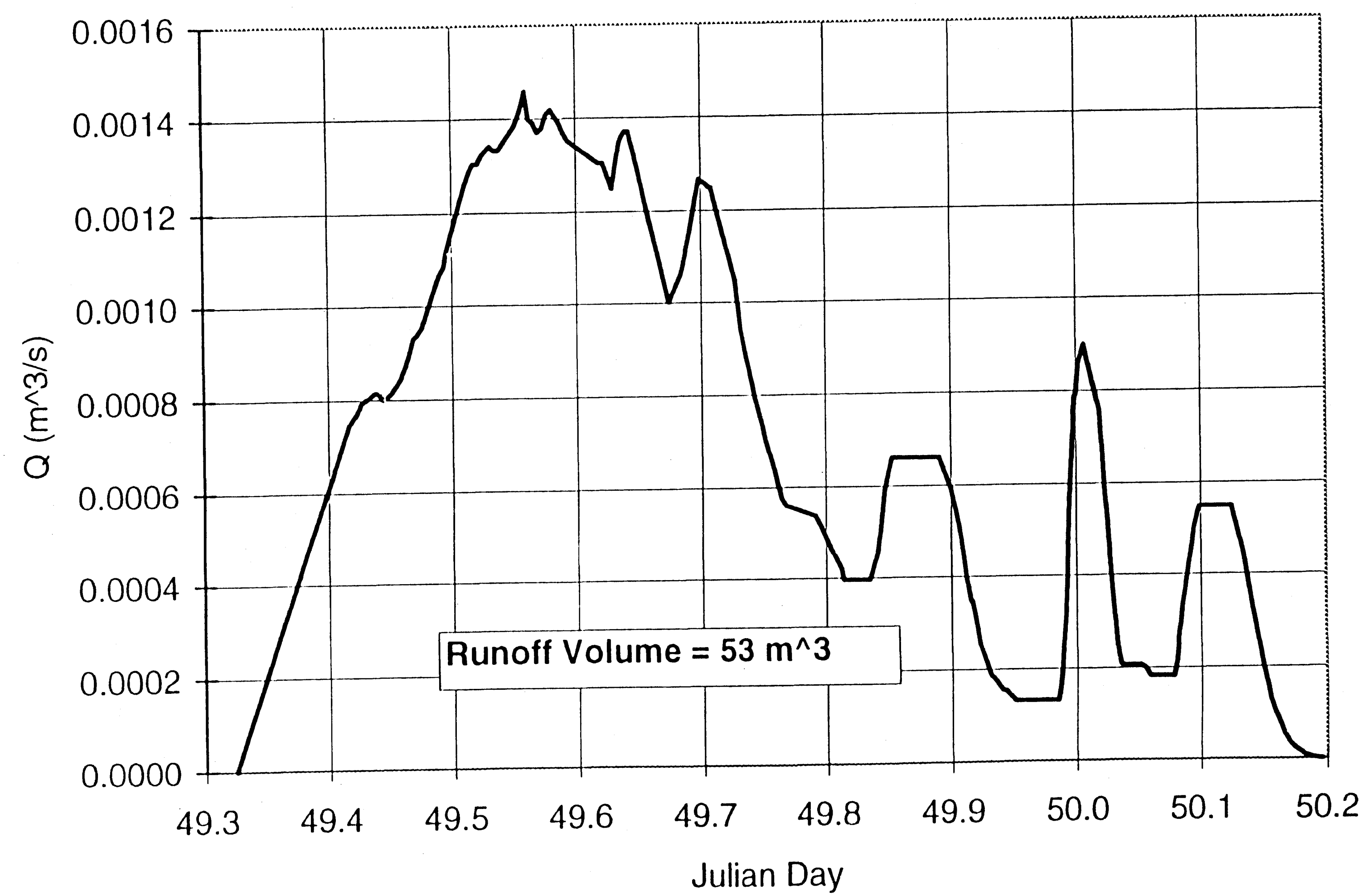

Figure 1-5. Upper gully runoff hydrograph for Febuary 19-20, 1994.

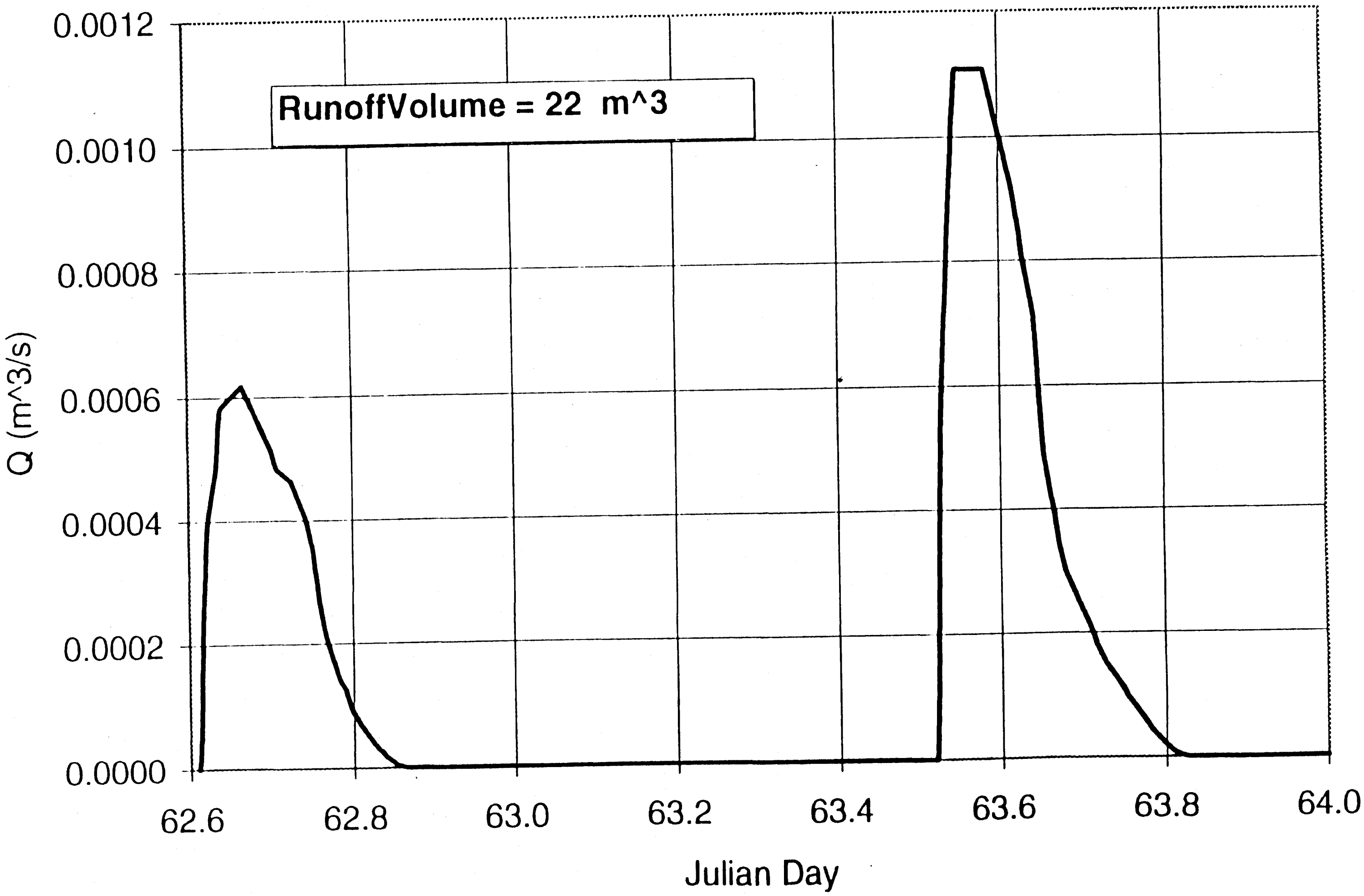

Figure 1-6. Upper gully runoff hydrograph for March 4-5, 1994.

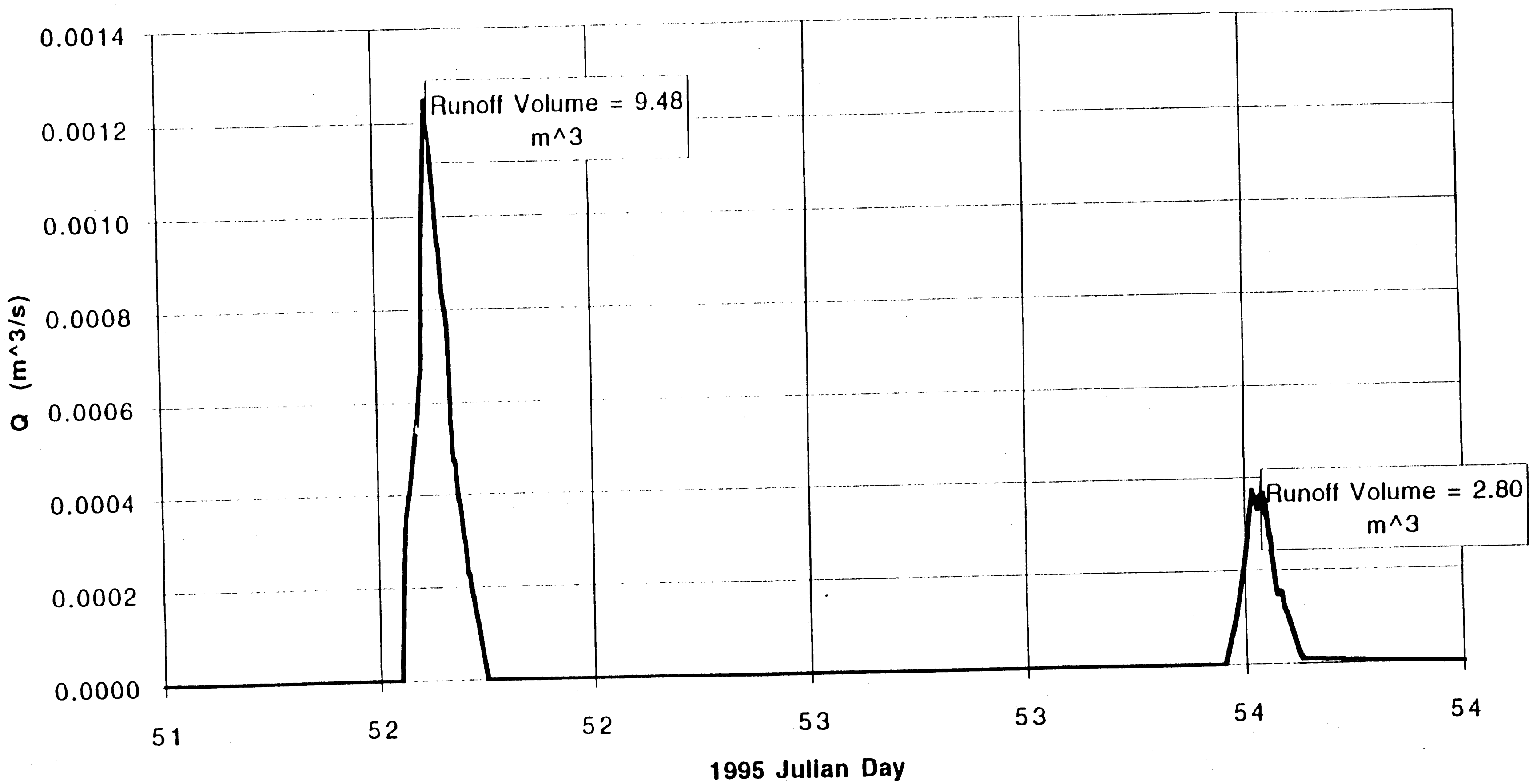

Figure 1-7. Upper gully runoff hydrograph for Febuary 21-23, 1995.

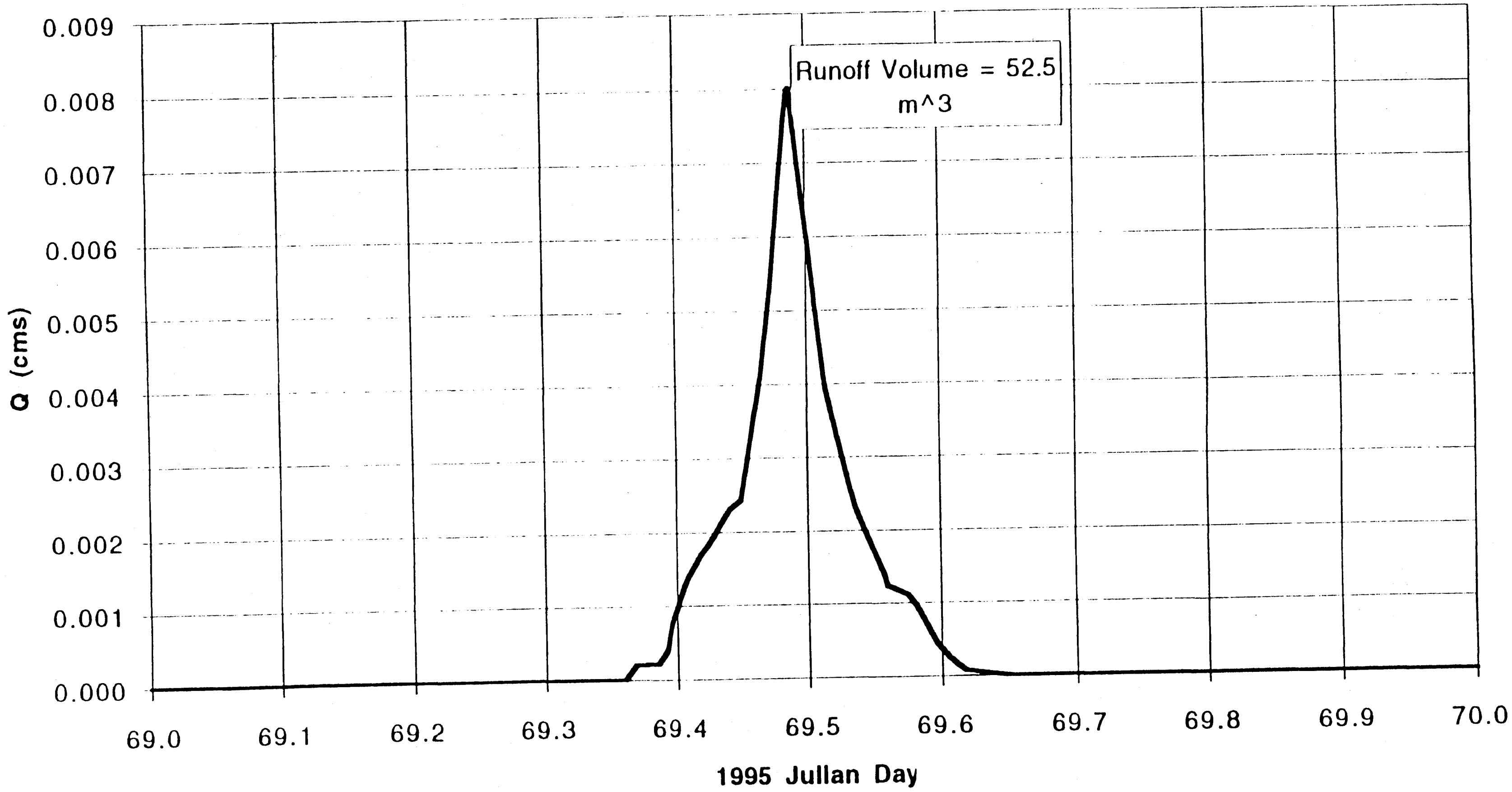

Figure 1-8. Upper gully runoff hydrograph for March 11, 1995.

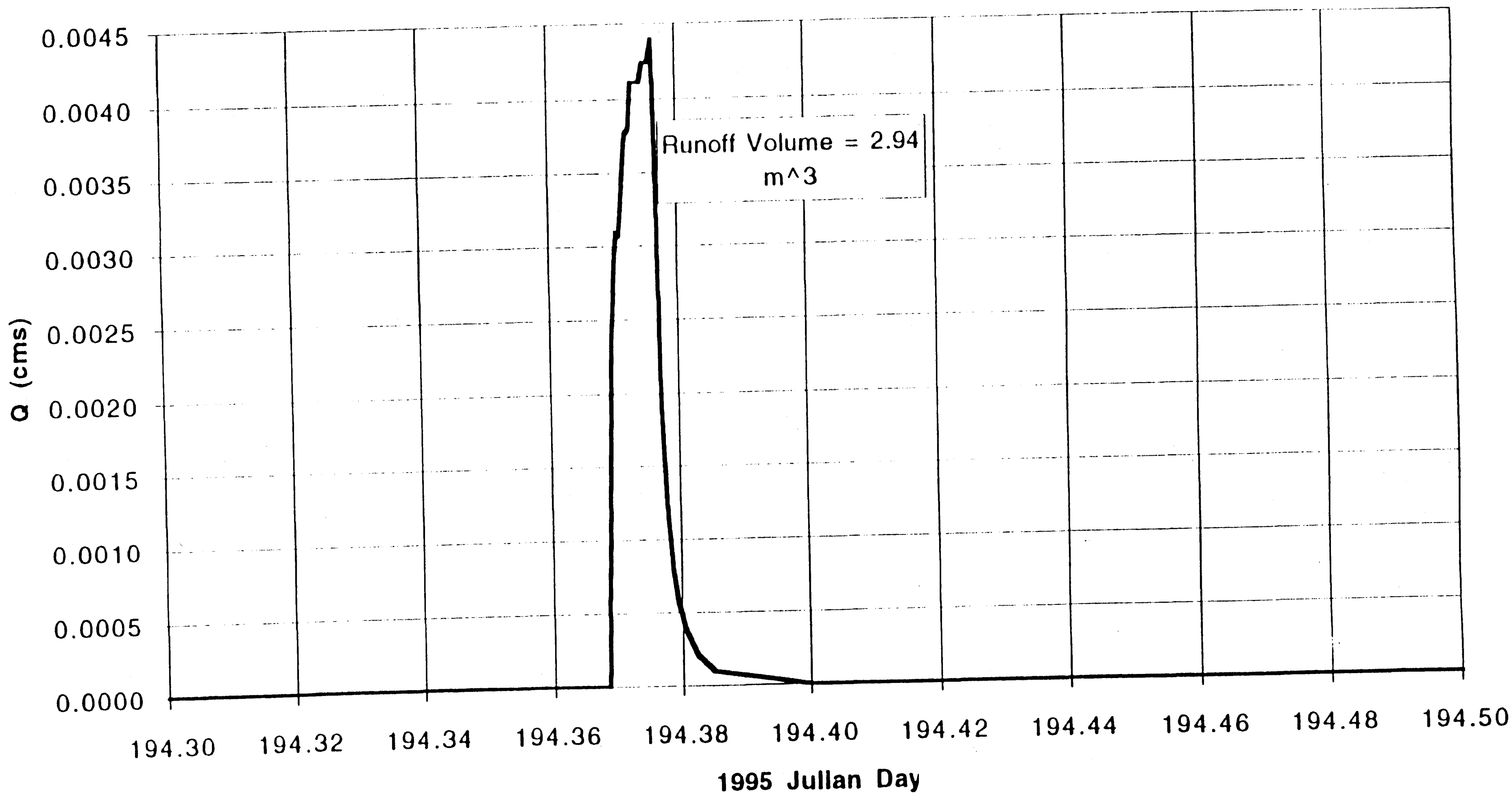

Figure 1-9. Upper gully hydrograph from water truck experiment, July 14, 1995.

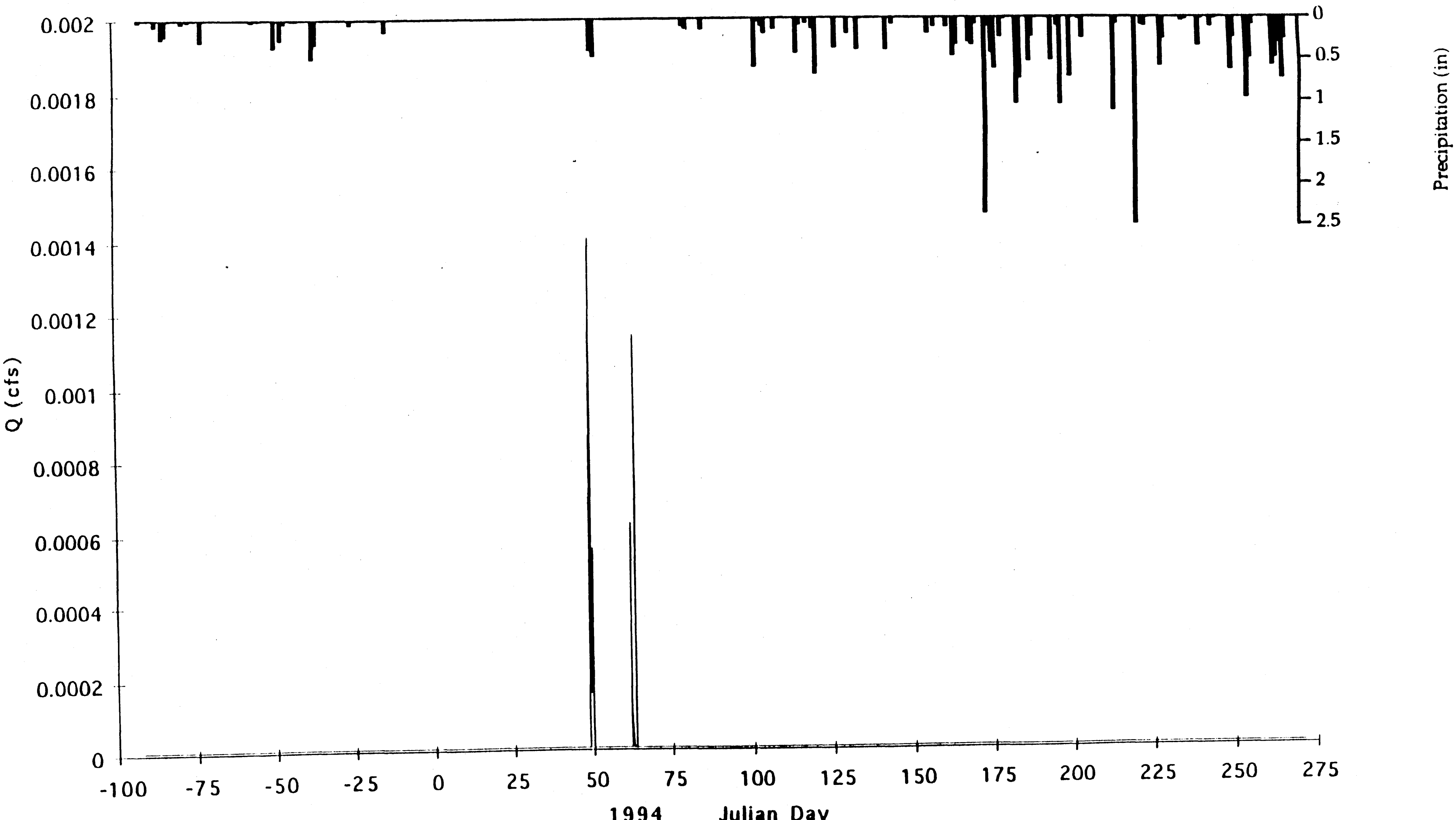

Figure 1-10. Upper gully weir discharge for the 1994 water year (Julian day calculated on calendar year).

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