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).

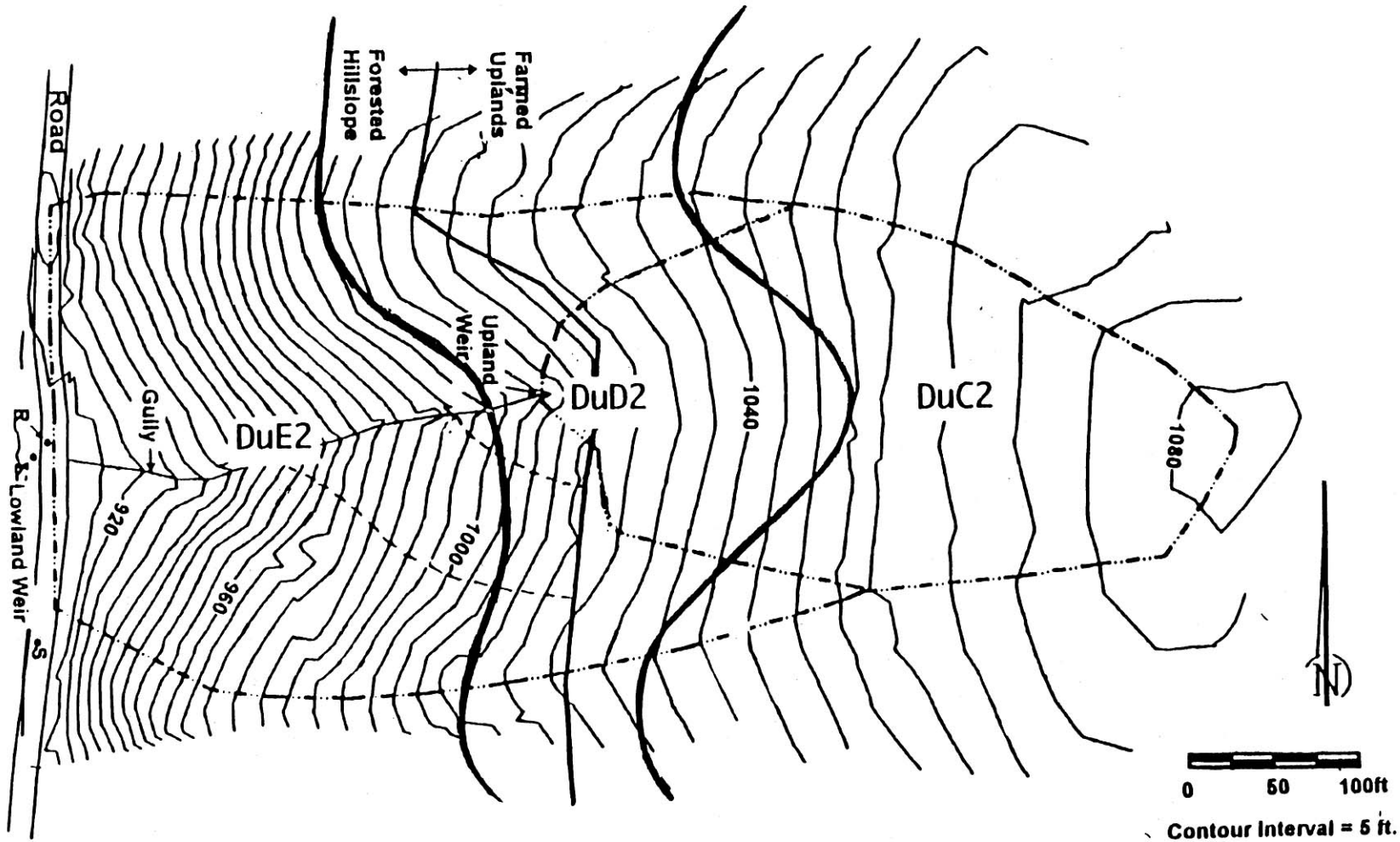

Figure 3. Gully watershed topography and soils.

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.

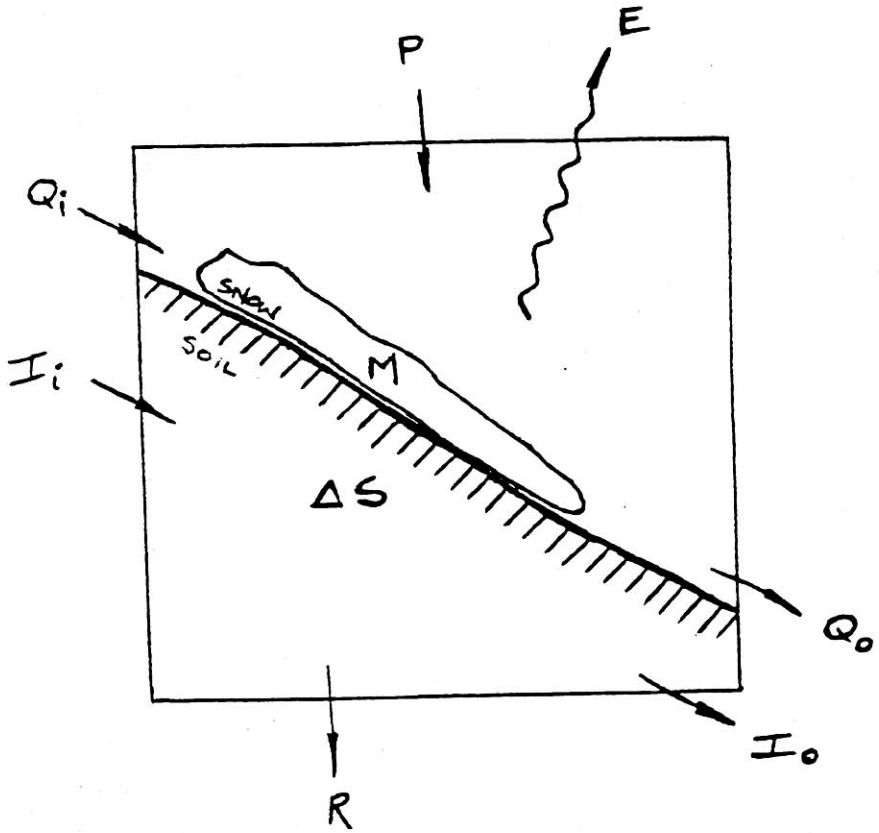

Figure 4. Schematic of the control volume utilized for the gully watershed.

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.

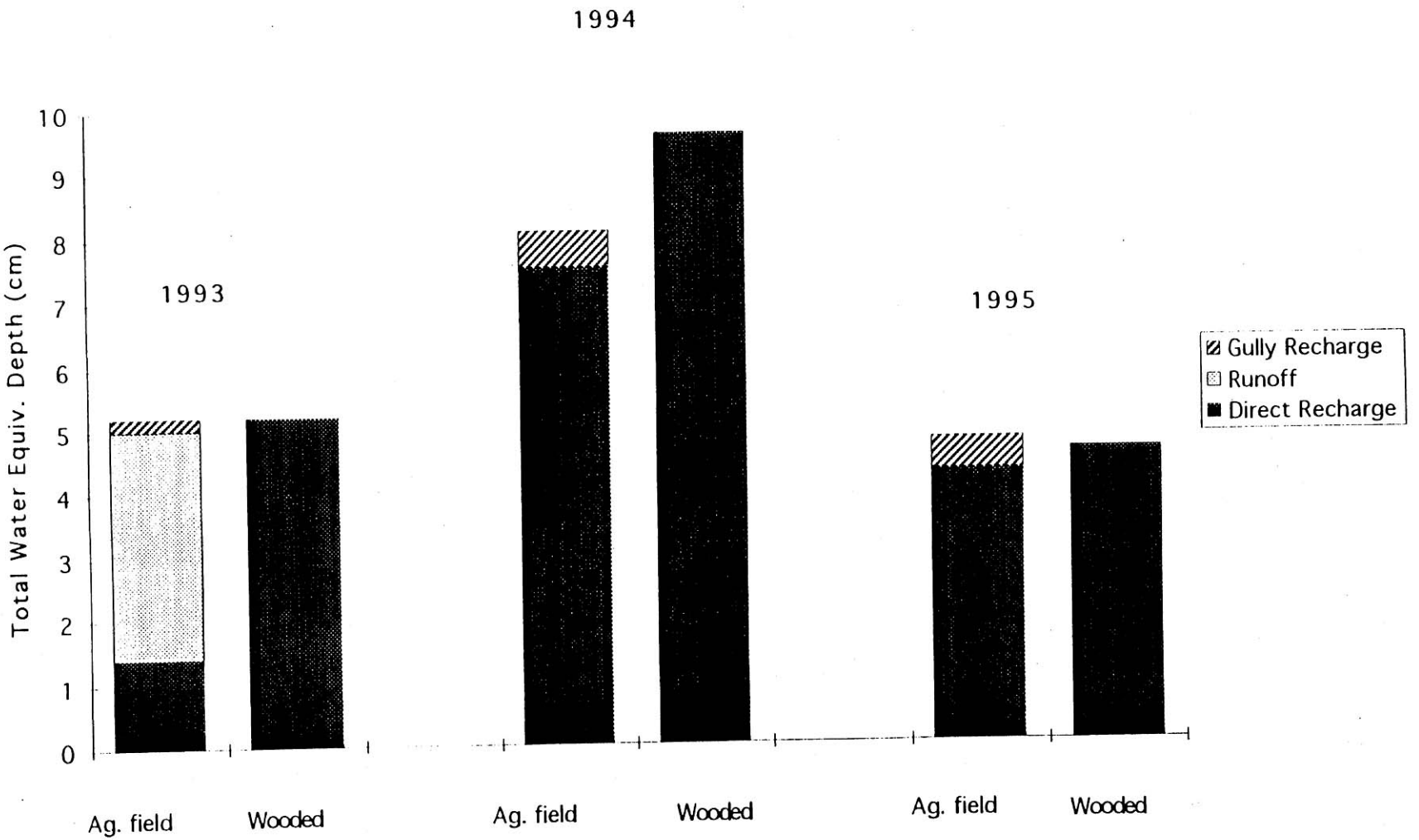

Figure 5. Results of three years of snowmelt monitoring at the gully site.

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)	Runoff Coefficient Uplands	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.