



Influence of groundwater on streambank soil moisture content, storm runoff production and sediment production in a semi-arid watershed, southwest Montana
by Jon Matthew Aspie

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences
Montana State University
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Abstract:

Localized groundwater-seepage areas are a source of variability in streambank soil moisture content, storm runoff production and sediment production within the semi-arid Cottonwood Creek watershed (210 ha) in southwest Montana. This variability needs to be understood in order to better assess the impacts various cattle-grazing management practices have on streambank stability and sediment production along different reaches of the stream.

Soil samples were collected along the length of the stream to assess spatial variability of streambank soil moisture contents. Groundwater-seepage areas were found to have persistently higher streambank soil moisture contents than non-seepage areas with the exception of one zone within the study basin. Within this anomalous zone a shallow groundwater table, 0.5 to 0.8 meters below ground surface, was the cause of the persistently high moisture contents.

Where the groundwater table was greater than 1 meter deep, soil moisture contents were low.

Storm runoff within the study basin was derived mostly from direct precipitation into the stream channel and overland flow occurring from saturated-seepage areas. During large, low-intensity storm events saturated-seepage areas expanded, which increased the runoff-contributing area. During high-intensity storm events Horton overland flow is thought to have occurred from dry-ground areas within the riparian zone, but the actual location of this overland flow is not known. The total contributing area for storm runoff generation was less than one percent of the basin for storms occurring in 1987, with more than one-half of the storm runoff generated from the stream channel.

Sediment production was measured in different areas of the watershed using overland flow sediment traps. Cattle paths produced the most sediment of any area, an order of magnitude more than perennial-seepage areas. Perennial-seepage areas produced up to an order of magnitude more sediment than intermittent-seepage areas and dry-ground areas. Intermittent-seepage areas and dry-ground areas produced about the same amount of sediment. Factors which have a large influence on sediment production are thought to include: the ability of an area to produce overland flow, vegetation cover, topographic position and the amount of cattle-induced soil disturbance.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Localized groundwater-seepage areas are a source of variability in streambank soil moisture content, storm runoff production and sediment production within the semi-arid Cottonwood Creek watershed (210 ha) in southwest Montana. This variability needs to be understood in order to better assess the impacts various cattle-grazing management practices have on streambank stability and sediment production along different reaches of the stream.

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INTRODUCTION

The Problem

Sediment pollution is a major water quality concern in United States waterways (Duda, 1985). While streamflow in western rivers comes mainly from forested mountains, sediment influx is derived mainly from rangelands (Branson and others, 1981). Livestock grazing on rangelands in poor condition is considered to be the main contributor of increased sediment loads from these areas (Environmental Protection Agency/Bureau of Land Management, 1979). Sediment sources include streambank and channel erosion and inputs from sheet, rill and gully erosion (Vanoni, 1975). On western rangelands sheet and rill erosion is thought to be more dominant than channelized erosion (Lusby, 1963; Leopold and others, 1966), but sediment derived from upland sources is not as well documented as sediment derived from streambank, gully and channel erosion (Gifford, 1980).

Recent studies of cattle-induced streambank damage and potential sediment influx to streams at Montana Agricultural Experiment Station's Red Bluff Research Ranch has indicated that bank damage and instream sediment loads are greater in spring and early summer when the soil moisture contents of the streambanks are relatively high (Pogacnik, 1985; Marlow and Pogacnik, 1985; Marlow and others, 1987). As soil moisture contents declined through the summer, streambank damage and instream sediment loads also declined.

A problem arises with this generality as there are groundwater-seepage areas and springs spaced intermittently along the length of the study stream (Pogacnik, 1985). These seepage areas may be localized areas where soil moisture remains high throughout the year. Seeps were not monitored for moisture content by Pogacnik (1985) because he used a Troxler Neutron Probe for moisture measurements. If these seepage areas have continually high soil moisture contents, they would be important to identify for streambank stability studies. Saturated zones (seeps) are often the most sensitive to mechanical damage due to low soil strength within these zones (Moore and others, 1988).

Groundwater also contributes to streambank damage as seepage pressure is a major force in causing sloughing, flow slides, and erosion of soil (Springer and others, 1985; Henderson, 1986). Thus, there may be differences in soil moisture content and streambank stability between dry areas and groundwater-seepage areas. Differences in streambank stability may lead to differences in sediment production from different sections of the stream.

While streambanks are an important source of sediment, upland sediment sources also need to be considered in studies of sediment production. Overland flow is considered to be the dominant mechanism delivering sediment to the stream from upland sources (Heede, 1984; Pathack and others, 1984). Thus, areas which generate overland flow should be the areas from which sediment is delivered to the stream. However, the process of sediment delivery is often of a "black box" nature (Walling, 1983) because upland erosion is linked to basin sediment yields with little emphasis on the way the processes interact

(Campbell, 1985). Sediment delivered from upland sources needs to be studied more intensively (Dickinson and Wall, 1977; Walling, 1983) and needs to be put into context with runoff processes and runoff-generating areas (Lane and others, 1978; Dunne, 1983; Campbell, 1985).

Runoff generation is spatially variable within a drainage basin (Dunne and Leopold, 1978). Saturated zones are often the only areas in a watershed which will produce overland flow (Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Bevin, 1978; Pilgrim and others 1978). If overland flow is generated solely from the saturated areas, sediment delivery to the stream from upland areas may also occur mostly from the seepage areas.

Seepage areas can be expected to fluctuate in size either seasonally or due to climatic factors (Dunne and Black, 1970a, 1970b; Hewlett and Nutter, 1970). The nature of this fluctuation, both spatially and temporally, is of concern because the changing conditions controlling the seep size may also control soil moisture content as well as runoff production and sediment delivery.

Purpose

Groundwater-seepage areas have the potential to dominate many aspects of studies dealing with streambank stability and sediment yields. These seeps are hypothesized to have higher soil moisture contents than other areas along the stream, and thus have greater potential for streambank damage. Seepage areas may also produce more surface runoff (via overland flow) and deliver more sediment to a stream than other areas.

The purpose of this thesis is to test these hypotheses at the Red Bluff Research site by answering the following questions:

- 1) Are there areas along the stream with consistently high soil moisture contents? If so, are they controlled by groundwater-seepage areas?
- 2) Do groundwater-seepage areas fluctuate in size through time?
- 3) What are the dominant runoff processes within the basin which contribute to storm flow?
- 4) Do groundwater-seepage areas produce more runoff than "dry" areas?
- 5) Do groundwater-seepage areas have the potential for greater sediment production than other areas?

Runoff Processes and Contributing Areas

As upland sediment delivery to a stream is of importance in water quality studies, the concept of runoff generation is important to understand. The processes by which water flows from a hillside to a stream will greatly affect the efficiency of sediment delivery to a stream. Three main processes of storm runoff have been documented in the literature: Horton overland flow, saturation overland flow and subsurface storm flow. Direct precipitation into the stream channel can also be an important source of storm runoff (Dunne and Black, 1970a, 1970b; Bevin, 1978). However, this flow component does not move from the hillslope to a stream so will not influence sediment delivery. Many excellent reviews of the runoff processes are found in papers and

text books such as Freeze (1974), Dunne and others (1975), Ward (1975), Dunne (1978, 1983) and Dunne and Leopold (1978). The runoff processes will be reviewed here as they pertain to this thesis.

Horton Overland Flow

Horton overland flow occurs when dry soil becomes saturated at the surface as rainfall intensity exceeds the infiltration capacity of the soil and detention storage is filled (Horton, 1933). Horton overland flow moves to the stream with sufficient speed to cause rapid rises in streamflow associated with storm runoff (Freeze, 1974; Dunne, 1978).

Horton overland flow is considered the main runoff process in arid and semi-arid watersheds (Arteaga and Rantz, 1973; Freeze, 1974; Dunne, 1978; Lane and others, 1978; Branson and others, 1981; Pilgrim, 1982), and has been observed in many areas with low infiltration capacities and minimal vegetative cover (Dunne and others, 1975; Dunne, 1978; Dunne and Leopold, 1978; Pilgrim, 1982). In humid areas, Horton overland flow is considered to occur only over disturbed areas and roads (Dunne, 1978; Dunne and Leopold, 1978; Heede, 1984) and occasionally forest litter (Pierce, 1967; Ragan, 1968). Within arid and semi-arid areas Horton overland flow is commonly perceived to be generated over an entire drainage basin (Pilgrim, 1982; Dunne, 1983). However, infiltration capacities are spatially variable within a basin due to changes in slope, soil type and antecedent moisture content (Musgrave and Holtan, 1964; Dunne and others, 1975). Thus, Horton overland flow is often generated over only a portion of the drainage basin. The notion that overland flow occurs only from a small part of the drainage basin was termed the partial area concept by Betson

(1964). The partial area concept has been tested on ephemeral drainages in Arizona (Arteaga and Rantz, 1973; Lane and others, 1978). Runoff there was found to be generated from only 12 to 64 percent of the drainage basin.

Saturation Overland Flow

Saturation overland flow differs from Horton overland flow in that saturation overland flow occurs when rain falls onto soil which is saturated from below by either the perennial groundwater table (Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Bevin, 1978; Ando and others, 1985) or a shallow perched water table (Bonnel and others, 1982). These saturated areas are generally located in stream bottoms and convergent hollows (Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Bevin, 1978; Pilgrim and others, 1978; Ando and others, 1985) though saturated areas may not be located along the entire stream (Betson and Marius, 1969; Pilgrim and others, 1978). Sideslope areas may also become saturated where soils are thin or a shallow water table exists, but these areas may not be connected to the stream (Ammerman, 1965; Betson and Marius, 1969). As a result, these areas may not contribute overland flow to the stream except possibly during large storm events when the flow generated exceeds the infiltration capacity of the unsaturated area between the saturated zone and the stream.

Saturation overland flow has been documented as the major source of overland flow generation in areas of humid climate (Hewlett and Hibbert, 1967; Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Hewlett and Nutter, 1970; Bevin, 1978; Pilgrim and others, 1978; Ando and others, 1985; Bonell and others, 1985). However, total storm

runoff is sometimes produced by a combination of saturation overland flow and subsurface flow in the lower reaches of the hillslope, mostly from saturated zones (Hewlett, 1974; Bevin, 1978; Dunne, 1978). The notion that runoff is generated only from saturated areas which may change in size through time, both seasonally and during storm events, has been termed the variable source area concept by Hewlett and Hibbert (1967).

Subsurface Storm Flow

Storm runoff does not always flow overland, and may follow subsurface routes. Subsurface storm flow (interflow) occurs as rain infiltrates into the soil and water percolates laterally through the soil over a zone of low permeability above the water table (Hewlett and Hibbert, 1963; Whipkey, 1967; Weyman, 1973; Bonell and others, 1982) or from the perennial groundwater body (Ragan, 1968; Sklash and Farvolden, 1979) and discharges directly from the soil to the stream. Subsurface flow is an important contributor to storm runoff in areas with highly permeable soils, and dense vegetation. These conditions most commonly occur in humid regions (Dunne, 1983). High water tables, low permeability zones within a stratified soil, and high soil moisture contents favor subsurface flow (Weyman, 1973; Mosley, 1979; Bonell and others, 1982). If there is no stratigraphic layering within the soil, water will move dominantly vertically until it reaches the water table as there is little horizontal percolation under unsaturated conditions (Weyman, 1973). In many areas (including humid climates) subsurface flow is considered to be too slow and too insensitive to rainfall variations to contribute to the storm hydrograph (Dunne and Black,

1970a, 1970b; Weyman, 1973) though subsurface flow may be a large contributor to dry-weather baseflow (Hewlett and Hibbert, 1963; Weyman, 1973; Pilgrim and others, 1978).

Subsurface flow may also contribute to saturation overland flow when subsurface flow moves to the ground surface before reaching the stream channel (Dunne and Black, 1970a, 1970b). This "return flow" travels at velocities 100 to 500 times as fast as subsurface flow and can contribute to the storm hydrograph.

Role of Partial-Variable Source Area Concept in Water Quality

Knowledge of runoff processes and areas of runoff generation within a watershed are important for hydrologic modeling (Ammerman, 1965; Hewlett and Nutter, 1970; Engman, 1974; Freeze, 1974; Bevin and Kirkby, 1979; Dunne, 1983) as well as for water quality concerns (Engman, 1974; Dunne and others, 1975; Hewlett and Troendle, 1975; Dickinson and Wall, 1977; Dunne and Leopold, 1978; Dunne, 1983; Campbell, 1985; Reckhow and others, 1985). Kunkle (1970), Hewlett and Troendle (1975) and Dunne and Leopold (1978) have used the variable source area concept to delineate areas of nonpoint-source pollution from bacteria, herbicides and fertilizers. While the need to study sedimentation from the perspective of the partial-variable source concept has been stressed, field studies still need to be performed to determine the role of these areas for sediment generation and delivery to streams (Dickinson and Wall, 1977; Dunne, 1983; Campbell, 1985).

Patterns of runoff and sediment yield are commonly treated as separate components, if not separate processes (Campbell, 1985). The

sediment-contributing area is often assumed to be the entire watershed (Hewlett and Troendle, 1975; Kirkby, 1978; Campbell, 1985) and the runoff process involved is assumed to be Horton overland flow. Such assumptions are often incorrect and can pose many problems in sedimentation and sediment yield studies (Dunne, 1983), and complicate determination of the effects of management practices on sediment yields. Knowledge and documentation of erosion processes in relation to runoff processes would greatly enhance the understanding of sediment yields (Branson and others, 1981; Dunne 1983).

Field studies have identified sediment sources such as streambank, stream channel, gully and sheet flow erosion, forest roads and cattle paths (Hadley and Schumm, 1961; Lusby, 1970; Campbell, 1977; Fortier and others, 1980; Heede, 1984). However, all sediment produced within a watershed does not necessarily reach a stream (Hadley and Schumm, 1961; Dickinson and Wall, 1977; Walling, 1983; Heede, 1984). As a result, sediment delivery ratios have been calculated from erosion studies of hillsides and instream sediment yield measurements in an effort to deduce the amount of sediment which reaches the stream and is transported out of a basin (Walling, 1983; Campbell, 1985). Dickinson and Wall (1977) point out many paradoxes associated with this practice and suggest that sediment delivery processes from different landscape elements should be studied more intensively. Campbell (1985) stresses the need to study sediment source areas in relation to partial-variable source areas.

Studies have been undertaken which differentiate soil erosion from sediment delivery and sediment yields in light of the partial-variable

source area concept. Dickinson and others (1985) have incorporated "field proximity to stream" into simple computer models which target erosional areas as potential sediment source areas for sediment yields of watersheds. Snell (1985) incorporated the concept of "hydrologically active areas" (i.e., runoff-generating areas) into a regional targeting program for delineation of potential nonpoint-source sediment loading into streams. Moore and Burch (1986) used a computer model based on three-dimensional topographic analysis to determine areas of erosion and sediment deposition within a watershed through the use of factors such as slope and overland flow generation from saturated areas. These studies, among others, show the importance runoff-generating areas have in sediment delivery and sediment yield studies.

If runoff is produced from only a small part of the watershed it follows that sediment will be delivered to the stream from either all or part of this small area. However, streamside areas (i.e., riparian zones) with their lush growth of vegetation, even in semi-arid climates, are excellent protectors of water quality (Lowrance and others, 1985). Healthy riparian zones filter out sediments and nutrients before the contaminants reach the stream channel. Forest hydrologists also recognize the importance of riparian zones in protecting water quality. Buffer zones along streams are incorporated into Best Management Practices for protecting water quality in logging areas (Lynch and others, 1985). Mitigation and sound management practices should effectively protect water quality if sediment delivery and runoff processes are understood.

Site Description

Study Area

This study was conducted in the headwaters of the Cottonwood Creek watershed (Fig. 1). The watershed is part of the Montana Agricultural Experiment Station's Red Bluff Research Ranch. This is the same watershed monitored by Marlow and Pogacnik (1985), Pogacnik (1985), and Marlow and others (1987), and is currently being monitored by Dr. Clayton Marlow (Department of Animal and Range Sciences, Montana State University) to determine the effects various cattle-grazing management practices have on streambank stability and sediment production. Cottonwood Creek is a small tributary of the Madison River and joins the Madison River in Beartrap Canyon approximately 16 km southeast of Norris, Montana.

The study area is on the upstream segment of the north fork of Cottonwood Creek (Fig. 1). Watershed area is approximately 210 ha. This study, along with Dr. Marlow's grazing study, concentrated on a fenced area along the lower reach of the stream within the watershed (Fig. 2). Instrumentation and measuring points are located within the grazing study area and include rain gauges, streamflow recorders, groundwater-monitoring wells, sediment traps, stream channel transects, and soil moisture sampling sites.

Stream length within the study basin (Fig. 2) is approximately 1.7 km, including 0.7 km within the grazing study area. The stream is perennial and is fed by a large seep in the headwater area and several seeps and springs along its length. Streamflow (baseflow) at the lower end of the study area fluctuates from less than 1 liter per second

(1/s) to 53 1/s based on Parshall flume data from 1981-87 (Marlow, 1988).

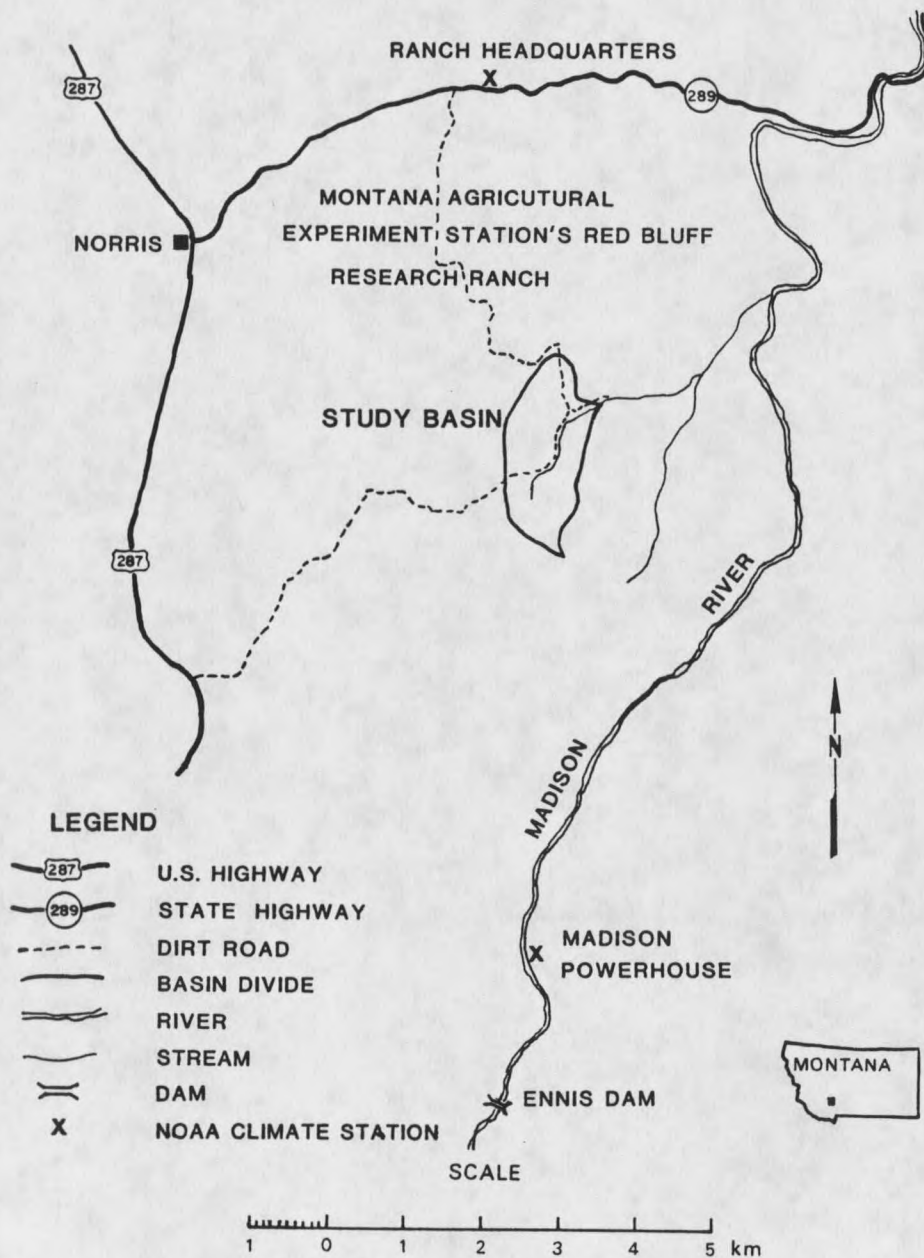


Figure 1. Location map of the study basin on the north fork of Cottonwood Creek.

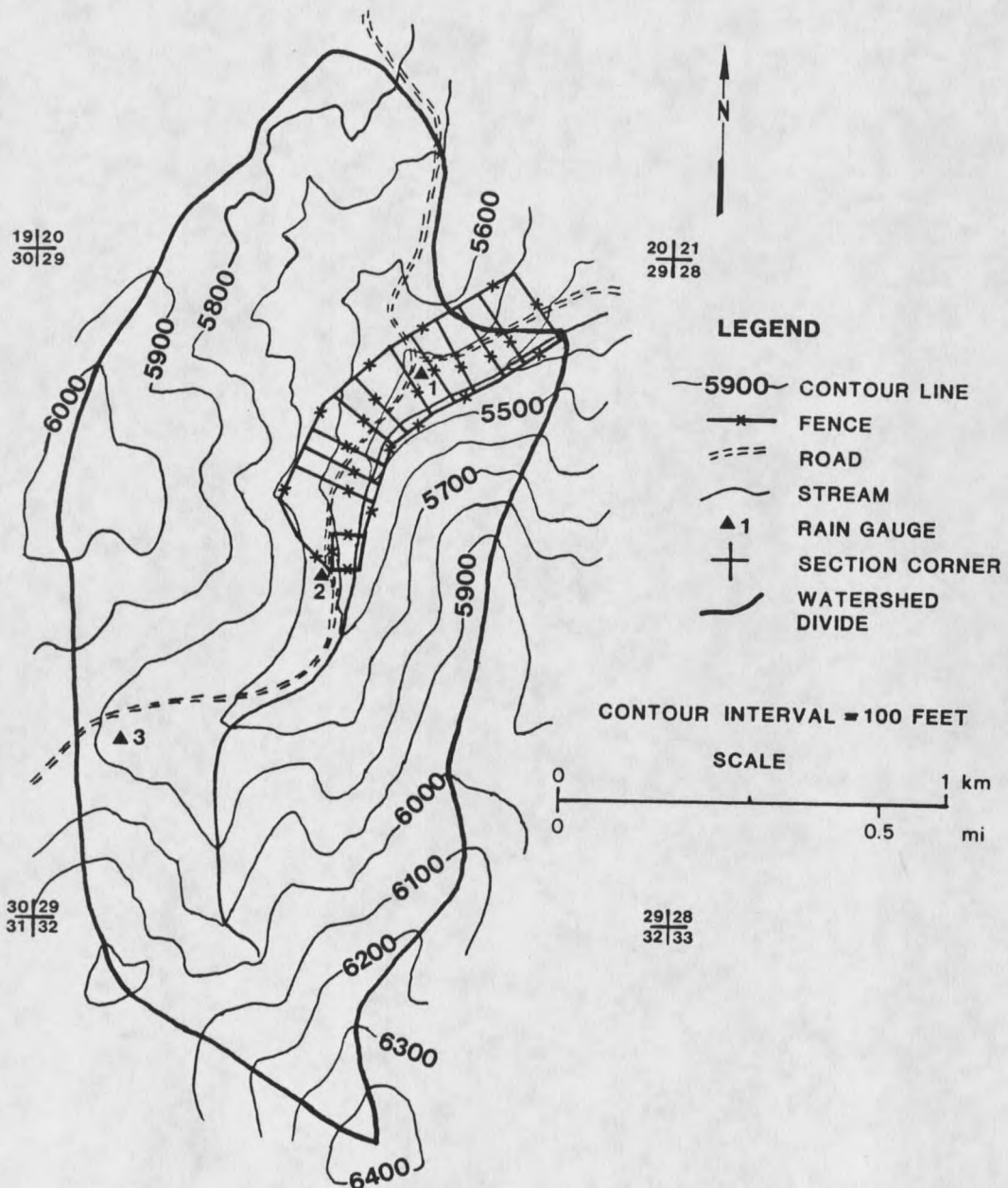


Figure 2. Map of the study basin showing the approximate location of fencelines encompassing the grazing study area and rain gauge placement in 1981 and 1982. Numbers in section corners indicate section numbers in T3S R1E Montana Principal Meridian.

Geology

Bedrock in the watershed contributing to the study reach consists predominantly of Archean quartzo-feldspathic gneiss interlayered with amphibolite and hornblende gneiss (Chadwick, 1984). One outcrop of quartzite with green mica (fuchsite) forms a ridge along the eastern divide near the drainage outlet of the study basin. Outcrops of gneiss are highly fractured and jointed, and are generally weathered to gruss.

Hydrologically, although foliated, the unweathered bedrock can be considered to be essentially homogeneous with low permeability. However, seepage along fractures and joints can be observed in various mine addits in the area. Weathering of the outcrops may lead to greater permeability of outcrops at the surface. Thus, recharge of groundwater may occur in areas of grussified metamorphic rock outcrop, and fracture or joint zones. Runoff from such areas will probably be less than otherwise expected from metamorphic rock outcrop (Fetter, 1980).

Soils

The Soil Conservation Service (SCS) (1985) has divided the soils in the area into two dominant complexes: Oro Fino-Poin complex, and Shurley-Rock Outcrop complex, but the soils have not been mapped in detail at this time. Soils of both complexes are dominated by coarse sandy loam textures which are well drained but can be locally susceptible to erosion problems (Veseth and Montagne, 1980).

Regionally, the Oro Fino-Poin complex consists of 50 percent Oro Fino gravelly loam on hillsides and footslopes, 30 percent Poin very flaggy sandy loam on hilltops and ridges, and 20 percent rock outcrop

and Adel silt loam mainly on ridgetops (SCS, 1985). The Oro Fino gravelly loam is deep, well drained, and forms in colluvium.

Permeability is moderate (1.5-5 cm/hr) to moderately rapid (5-15 cm/hr) at depth. The Poin sandy loam is shallow, well drained, and also forms in colluvium. Permeability is moderately rapid (5-15 cm/hr). The Adel silt loam is well drained with moderate permeability (1.5-5 cm/hr).

Regionally, the Shurley-Rock Outcrop complex consists of 40 percent Shurley very flaggy, coarse, sandy loam on rough broken slopes, 40 percent outcrop mainly in small scattered areas on ridgetops, and 20 percent small areas composed of Yental loamy sand on small fans and footslopes, and moderately sloping Nuley clay loam (SCS, 1985). The Shurley sandy loam is deep, well drained, and forms in colluvium. Permeability is moderately rapid (5-15 cm/hr) to rapid (15-50 cm/hr) at depth. The Yental loamy sand is deep, excessively drained, and forms in alluvium. Permeability is rapid (15-50 cm/hr). The Nuley soil is deep, well drained, and forms in colluvium and regolith. Permeability is moderate (1.5-5 cm/hr) to rapid/moderately rapid (15-50 cm/hr/5-15 cm/hr) at depth.

Soil pits within the study area were described by Pogacnik (1985). Soil on a lower portion of a north facing slope was described as loamy-skeletal, mixed Typic Cryorthents. Soil on a lower portion of a south facing slope was described as loamy-skeletal, mixed Typic Cryoboroll. Alluvial soil within the riparian zone was described as fine-loamy, mixed Argic Cryoboroll. Depth to the water table in the riparian zone varies from a few centimeters to greater than one meter. Streambank

soil textures along the length of the stream are predominantly sandy loam with areas of sandy clay loam.

Topography and Geomorphology

Elevation within the study area ranges from 1640 to 1980 m. Local relief from the stream channel to the ridgetops ranges from 75 to 145 m throughout most of the study basin (Fig. 2). Watershed topography away from the streamside area is characterized by moderate to steep slopes (15-50 percent). A steep ridge with 30 to 50 percent slopes borders the stream to the south while more rolling hills with 15 to 30 percent slopes borders the stream to the north. Slopes within the riparian area range from 10 to 30 percent. Stream gradient averages approximately 9 percent but varies from 3 to 15 percent.

Small alluvial fans are found at the mouths of draws along the footslope of the stream valley. One large alluvial fan is located approximately at the center of the grazing study area and extends to the stream channel. This large fan has its debris source in a series of larger draws forming a small basin on the north slope. Cottonwood Creek flows across the toe of fan and has incised the toe of the fan. Streambanks through this section are steep and high (2-3 m). Elsewhere, Cottonwood Creek is incised approximately 0.2 to 1.5 m.

Small streambank slumps (up to 15 m across) and flow slides are common along the length of the stream. The slumps and flow slides appear to be located in groundwater-seepage areas though sloughing of dry streambanks due to stream undercutting is also present.

Climate

A National Oceanographic and Atmospheric Administration (NOAA) weather reporting station was operated at the Red Bluff Research Station headquarters (Norris 3 ENE) sporadically from 1958 to September, 1982 (NOAA, 1982). The headquarters are 4.4 km north of the study basin (Fig. 1). Records were not kept at station headquarters long enough to establish long term averages for precipitation and temperature (NOAA, 1982). A reporting station is also located at Montana Power's Madison Powerhouse located near the Ennis dam on the Madison River (Norris Madison PH) (Fig. 1). The dam is at the south end of Beartrap Canyon approximately 7 km south of the study basin. Elevation at the Madison Powerhouse is approximately 1445 m and is 200 to 500 m lower than that of the study area.

Average annual precipitation at Madison Powerhouse is 458 mm. On average, 34 percent of the precipitation falls in May and June while only 15 percent occurs from November to February (NOAA, 1981). The average annual temperature is 8.3 degrees Centigrade ($^{\circ}\text{C}$). Temperature extremes at the ranch headquarters in 1981 were 35 $^{\circ}\text{C}$ and -38 $^{\circ}\text{C}$ (NOAA, 1981).

For the Red Bluff Research Ranch, Pogacnik (1985) reports annual precipitation of 400 mm to 510 mm, with 1200 mm of snow. The snow collects in drifts mainly in draws and in the stream channel. Snow generally persists until May.

METHODS

In order to test the hypothesis that groundwater-seepage areas are zones with consistently high soil moisture contents and are dominant areas of runoff production and sediment production, several factors need to be assessed. The methods used in testing the hypothesis are described in the following sections. Many of the methods used in this study make use of the equipment and/or follow procedures established by Dr. Clayton Marlow as part of his research in the study basin so that data from various parts of the study are comparable.

Mapping Base

Field mapping and geomorphic analysis of the watershed was based on a topographic map and aerial photographs. The topographic map has a scale of 1:24000 with a 20 ft (6.1 m) contour interval (Bureau of Reclamation, 1948). Stereo pair, false color infrared aerial photographs at a scale of approximately 1:4800 were taken of the watershed in July, 1986. The true scale of each photograph was established in the field by measuring the horizontal distance between two points on the ground which were easily recognized on the aerial photograph. A fiberglass tape was used for distance measurement and the angle from horizontal was measured with a Brunton compass.

One aerial photograph encompassing the main study area was enlarged to a scale of 1:1672 for detailed field mapping of seepage areas. A level survey was conducted with this enlarged photo as a base to

establish reference points for mapping and to establish elevations of groundwater-monitoring wells (Wright, 1982). A Topcon AT-F6 automatic level was used for surveying. Precision in surveying was ± 0.01 m for elevation measurements and ± 0.1 m for distance measurements. Twenty-one survey stations were used to survey 141 points. A topographic map with a 3 m contour interval was produced from the aerial photograph and surveyed points as an approximation of the topography within the study area (Fig. 3). Elevations are referenced to an arbitrary datum because the nearest monumental federal benchmark is approximately 4.5 km from the study area. The datum point was set below the study area to the east, so this point is not referenced on Figure 3. Closure error of the survey is unknown as the survey was open ended (Wright, 1982).

Precipitation Measurements

Rainfall in the watershed was measured with two rain gauges, a tipping-bucket, recording rain gauge and a non-recording gauge. Both gauges measure precipitation to ± 0.01 mm. These gauges were located next to each other near the lower end of the watershed, approximately in the middle of the grazing study area (Fig. 4). As rainfall is measured at only one point in the watershed, the amount of rain received at this point is assumed to have fallen over the entire watershed. This same assumption was used by Arteaga and Rantz (1973) in a similar sized basin (132 ha). A multiple rain gauge system was established in the study basin in 1981 and 1982 (Fig. 2). Results from this study indicate most points in the basin receive nearly the same amount of rainfall during storm events (Table 1). Generally, all rain

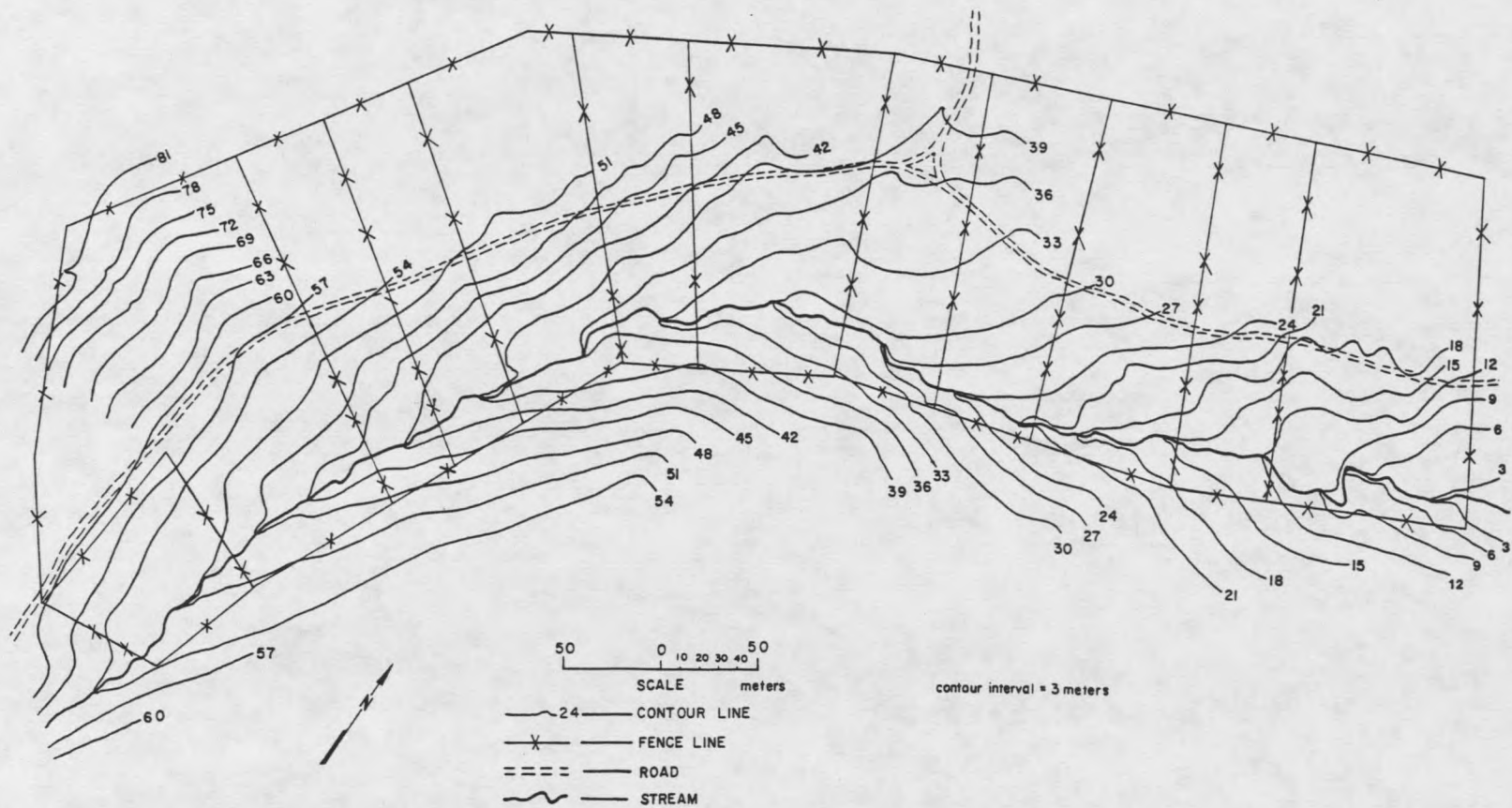


Figure 3. Contour map of grazing study area produced from survey data.

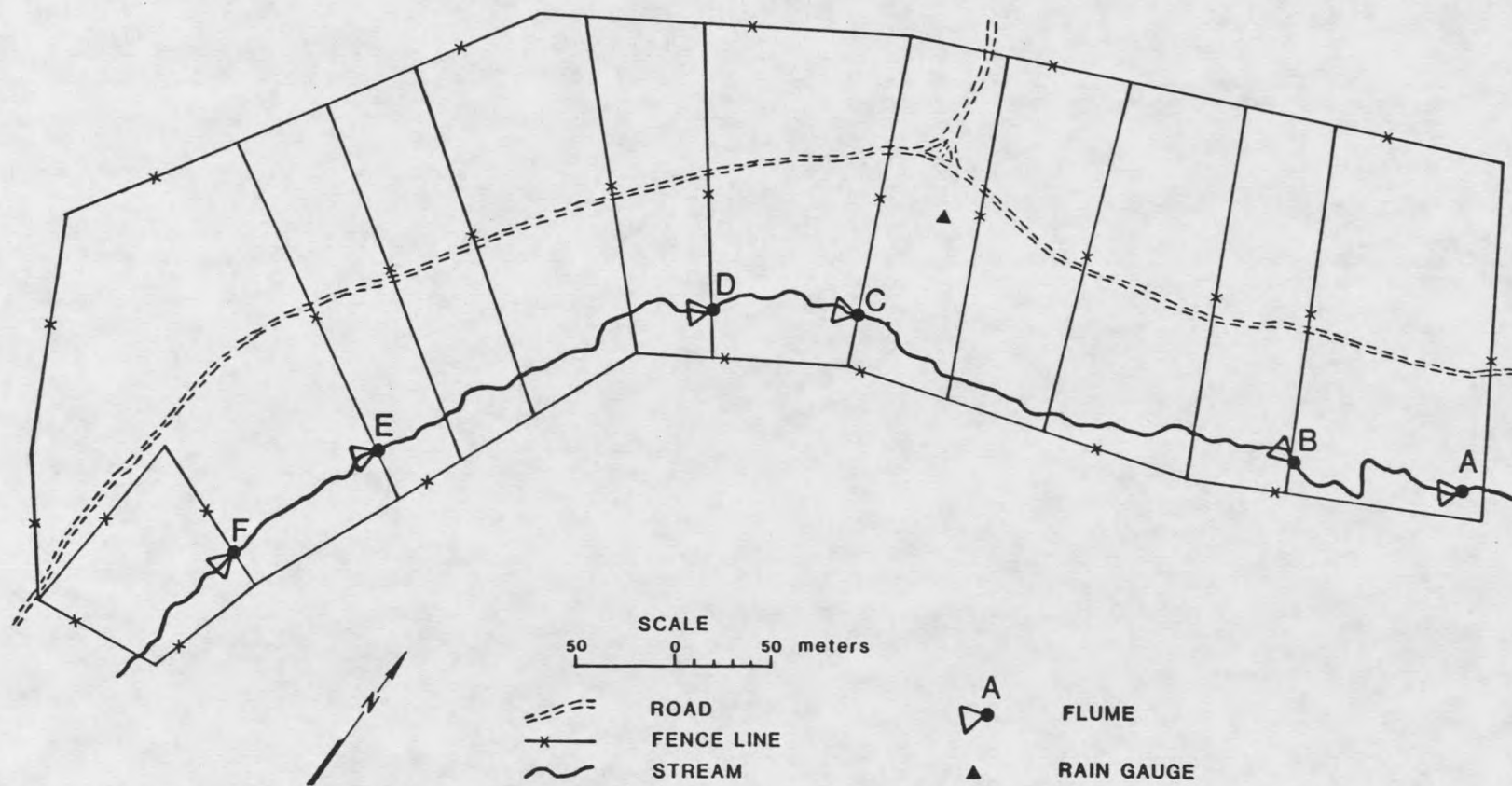


Figure 4. Map of grazing study area with locations of rain gauge and Parshall flumes. Flume location is denoted by black dot.

Table 1. Differences in rainfall between three points within the study basin for 1981 and 1982. Rainfall gauge locations are shown in Figure 2.

Date	Rainfall (mm)		
	#1	#2	#3
<u>1981</u>			
May 6	*		
May 8		*	
May 19	77.2	82.0	*
May 23	61.5	68.0	nd
Jun 8	40.6	40.2	36.0
Jun 13	36.1	40.0	30.8
Jun 26	1.0	0.0	0.1
Jul 16	nd	6.0	4.0
Jul 22	23.1	25.0	22.0
Aug 6	6.4	9.0	5.6
Aug 21	6.9	5.8	5.2
Sep 22	3.1	2.2	nd
Sep 29	28.7	29.8	27.2
Oct 6	16.5	17.6	14.0
Oct 8	5.6	5.6	5.8
Oct 17	24.4	27.6	20.8
Oct 22	1.8	3.2	nd
<u>1982</u>			
May 13	*	*	*
May 20	24.0	22.6	21.6
Jun 1	23.0	21.3	21.6
Jun 3	1.1	1.3	1.1
Jun 7	20.2	19.1	19.8
Jun 8	26.8	27.9	27.4
Jun 14	5.2	5.6	7.1
Jun 15	1.6	1.6	nd
Jun 17	5.0	5.8	5.2
Jun 18	2.8	3.1	2.9
Jun 21	3.8	4.1	5.2
Jun 24	3.8	4.3	2.8
Jun 28	11.4	13.5	12.2
Jul 26	2.6	2.3	1.3
Aug 5	2.2	2.0	1.8
Aug 6	0.8	1.0	1.1
Aug 23	7.2	8.4	7.6
Sep 20	54.6	54.6	42.0
Oct 5	22.8	23.6	nd
Oct 12	8.8	9.1	8.6
Oct 21	2.4	3.3	1.1

* = date of gauge placement

nd = no data

gauges collected rainfall amounts which were within a few millimeters of the others, although differences as great as 20% were measured. No pattern to the variation is apparent in the 1981-1982 data at the 95% confidence level between gauges 1 and 2 and between gauges 1 and 3 based on a Friedman rank test (Conover, 1980). Gauge 1 (Fig. 2, Table 1) is in the same location as the rain gauges used in this study (Fig. 4).

Groundwater-Seepage Area Size

Saturated-seepage area size was determined by mapping in the field using a mylar overlay, with plotted survey points, on the enlarged aerial photograph following procedures outlined by Dunne and others (1975). The saturated-seepage area at the time of mapping was determined by noting the occurrence of standing or flowing water on the ground surface and by noting standing water in cattle hoofprints. Flagging was used to mark saturated area boundaries in order to check the progress of saturated area expansion and contraction. Cattle hoofprints breaking the ground surface could often be used as an indicator of the maximum extent of the seepage area boundaries. Also, seepage area boundaries often were marked by the occurrence of slump scarps.

Saturated-seepage area mapping in 1986 was performed only at the beginning and end of the field season, because other projects were prioritized above seep mapping at this time. Mapping in 1987 was undertaken five times, additional observations were made during the summer while doing other projects and were recorded in a field

notebook. Accuracy in mapping seep locations was approximately ± 3 m using the enlarged air photo.

The areas of the mapped seeps were measured using the computerized digitizer in the Earth Sciences Department at Montana State University. Measurement error of the digitizer was consistently within 1 percent, as determined by repeated measurements.

Stream Channel Area

Precipitation directly into the stream channel can supply much of the total storm runoff generated in small headwater streams (Dunne and Black, 1970a, 1970b; Bevin, 1978). Stream channel area needs to be determined if total storm runoff is to be measured and used in part to determine the occurrence of other runoff processes in the basin. Stream channel area was determined as the plan view area of the channel bottom (i.e., the area of the stream channel between the stream banks). While the active channel often occupied only a portion of the channel bottom, channel areas generally expand during a runoff event due to the increase of flowing water (Hewlett and Hibbert, 1967; Bevin, 1978). In addition, the water table is assumed to be close to the ground surface in the channel bottom and the soil moisture deficit is small, so the entire channel bottom will often contribute to storm runoff.

Area was determined by measuring the width of the channel bottom in the field at various points. Measurements were made on both the active channel width and the total channel width between the streambanks (Fig. 5). On average, at low flow, the active channel occupied about 50% of the channel bottom. Within the grazing study area, width was

determined at channel transect points where width was repeatedly measured for Dr. Marlow's research (Fig. 7). Points upstream of the grazing study area were chosen where there appeared to be a change in channel width. Longitudinal distance between measurement points upstream of the grazing study area varied from 15 to 75 m, but commonly was in the range from 18 to 36 m. Length of the stream was measured from aerial photographs. Total area was determined by averaging the width of the stream channel between measurement points and multiplying the average width by the length of the stream along the reach between measurement points.

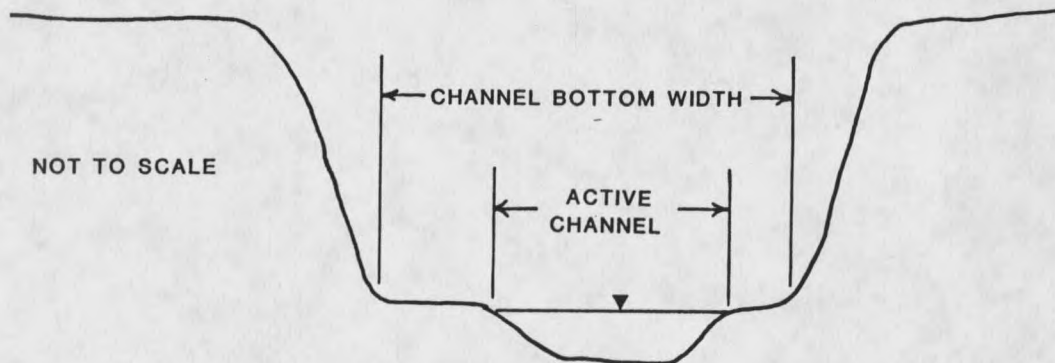


Figure 5. Typical stream channel cross-section showing measurement points used to determine stream channel areas.

Groundwater Monitoring

In an effort to determine the depth to the water table, 65 groundwater-monitoring wells were placed within the grazing study area (Fig. 6). Placement of the wells was based on visual field reconnaissance. An attempt was made to place the wells such that a three-dimensional model of the groundwater table could be constructed. Wells were drilled using a hand auger and cased using PVC pipe. Size

of the auger was either 5.1 cm or 15.2 cm depending on the size of the casing to be installed. Casing size was either 3.8 cm or 10.2 cm. Wells were drilled to a depth where drilling was stopped by rocks which could not be picked up by the auger. This generally occurred at a depth of 1-2 m, though some wells could be drilled to a depth of nearly 3 m. For sites where deeper wells were needed (>2 m), a Giddings Soil Sampler was used for drilling. This hydraulic drill was able to reach to depths of nearly 6 m before being hindered by the nature of the subsurface material. Both a coring tube and auger bit with diameters of 6.4 cm were used for drilling. Due to the nature of the earth materials, amount of groundwater in storage and drilling methods, most attempts at placing a well within the phreatic zone at upland sites were unsuccessful. Relevant measurements of all wells are reported in Appendix A.

As depth to the water table (not a piezometric surface) was desired, well casings were perforated. Casings were generally slotted from the bottom of the casing up to a point above the saturated zone at the time of drilling. Slots were made with a hand-held, cross-cut saw, and were spaced approximately 1-2 cm. At first, the wells installed were left open ended. Later in the installation process wells were capped at the bottom with duct tape in an attempt to reduce sediment clogging.

Wells were numbered using a two number system. The first number designated the grazing study paddock (1 through 12). The numbers do not necessarily conform to current paddocks (Fig. 6), as the final paddock configuration still had to be established at the time of well

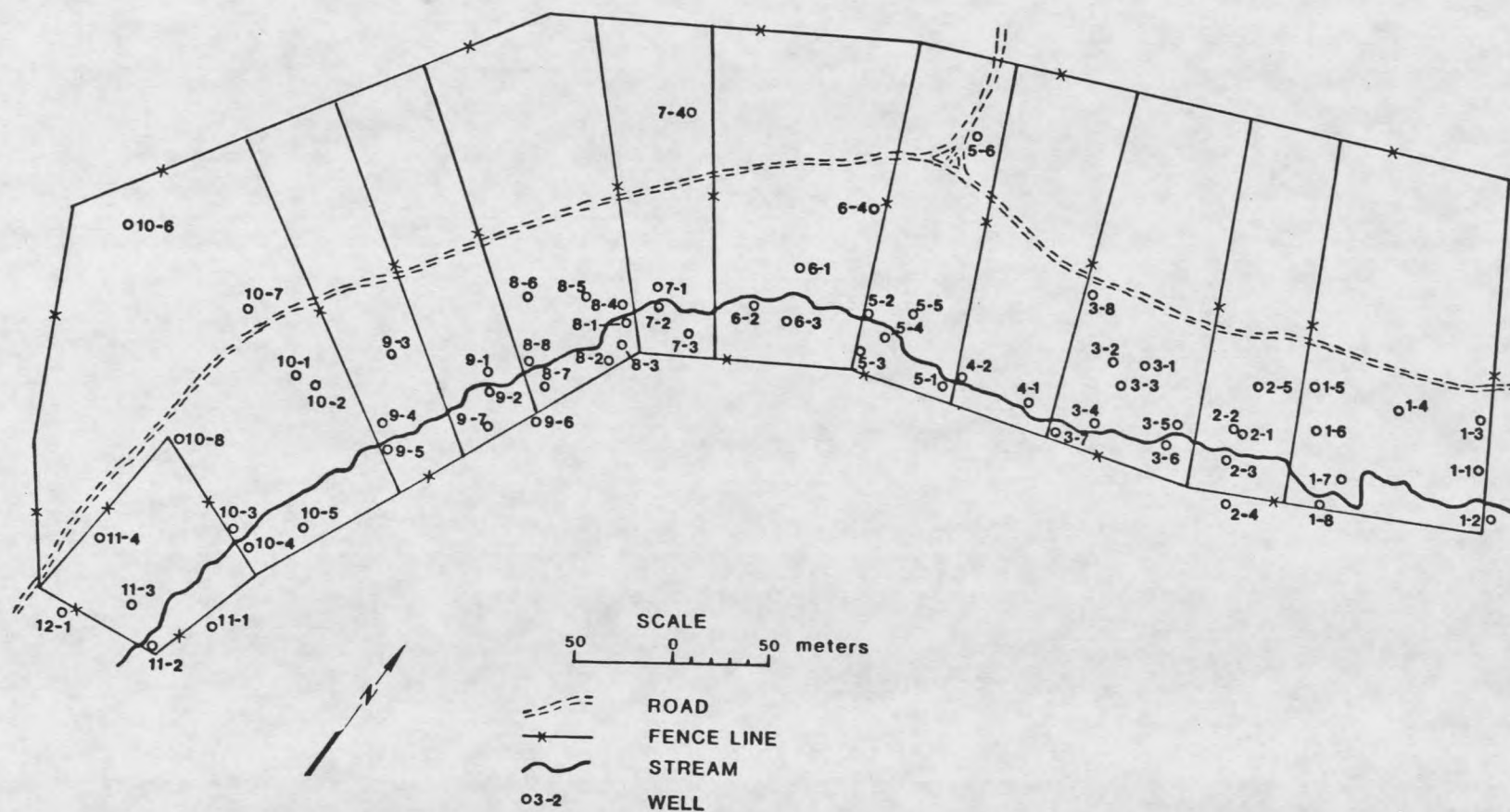


Figure 6. Map of grazing study area with location of groundwater-monitoring wells.

placement. The second number designated the order in which the wells were installed.

Depth to the water table was measured as the distance from the top of the well casing to the surface of standing water within the well. Measurements were made with a steel tape to the nearest 0.25 cm. An attempt was made to measure from the same point on the casing each time. The point on the casing nearest to the stream was chosen for the measuring point. The height of the casing above ground surface at this point was measured and recorded. This measurement was then subtracted from the total depth to the water table to determine the depth of the water table below the ground surface. The elevation of the ground surface was surveyed at each well. Depth to water table measurements were made at intervals of 1 to 4 weeks depending on moisture conditions and available time.

Hydraulic Conductivity

Hydraulic conductivity of the earth material within the saturated zone was measured by conducting slug (bail) tests. Only the wells with larger casings were tested, as materials were readily available to construct a bailing device for these larger wells. Also, the water surface could be seen in the larger casing wells at all times which aided in the speed and accuracy of taking measurements. Of the wells available, 11 were selected for testing based on depth of water within the well, potential variability of earth materials based on crude well logs, and the ability to get the bailing device into the well. Wells with various well depths and water table depths were tested to check

for possible differences in hydraulic conductivity with depth. If hydraulic conductivities decrease with depth, a layer or zone may be present on which subsurface storm flow may occur. Analysis of results was based on techniques by Hvorslev (1951), Bouwer and Rice (1976), and Pandit and Miner (1986).

All tests were conducted in riparian zone wells because: 1) all large casing wells were located in the riparian zone; 2) hydraulic conductivity was tested in part to determine the potential for subsurface flow as a major component in the storm hydrograph of the stream based on a model by Freeze (1972); 3) this is the region where wells successfully penetrated the water table.

Well tests were performed by bailing a well and measuring water levels with a steel tape. A stop watch was used to time the tests. A bailing device was constructed by stacking and wiring together two coffee cans. Volume of the bailer was 2 liters (1). Static water levels, well depths, and perforated length of well casings were determined at the same time the tests were performed. Only one well was tested with a capped end, as most wells which fit the testing criteria had open ends.

Soil Moisture Measurements

Soil moisture data was collected by obtaining soil cores in the field with a king tube. Samples were taken extending from the ground surface to a depth of 30 cm. Soil in the surface zone (0-30 cm) is most likely to be damaged by cattle. Samples were collected throughout the grazing season (June through October) to monitor the change in

moisture content through the season. Sampling intervals varied somewhat depending on available time.

Samples were collected and placed in plastic ziplock storage bags. As much air as possible was removed from the sample bags before sealing. Storage time between sampling and laboratory analysis was generally less than one week. Samples stored for this period of time will generally have negligible losses of moisture (Reynolds, 1970b).

Soil moisture content was determined by the gravimetric method (Reynolds, 1970a; Hillel, 1982). Moisture content was determined with the samples in collection bags due to the loss of water from the soil sample to the inside of the bag when samples were in transport or storage. Soil samples were first weighed wet on an analytical balance to the nearest 0.01 g. The samples were then dried in an oven at 80 to 90 °C until reaching a constant weight. This generally took 72 to 96 hours. An arbitrary sample was weighed periodically during drying to determine whether samples were dry. After drying, samples were again weighed on an analytical balance to the nearest 0.01 g.

Gravimetric moisture content was determined by the following equation:

$$\text{moisture content} = \frac{(\text{wet sample mass} - \text{dry sample mass})}{(\text{dry sample mass} - \text{bag mass})} \quad (1)$$

Soil moisture samples were collected at stream channel transect sites established for livestock-grazing impact studies (Fig. 7) (Pogacnik, 1985; Marlow and others, 1987). These transect sites have variable spacing along the stream but generally occur every 10 to 20 m within the grazing study area. Samples were collected within 1 m of the permanent transect location stakes. These stakes are within 0.5 m of the edge of the streambank (Pogacnik, 1985). Samples were collected

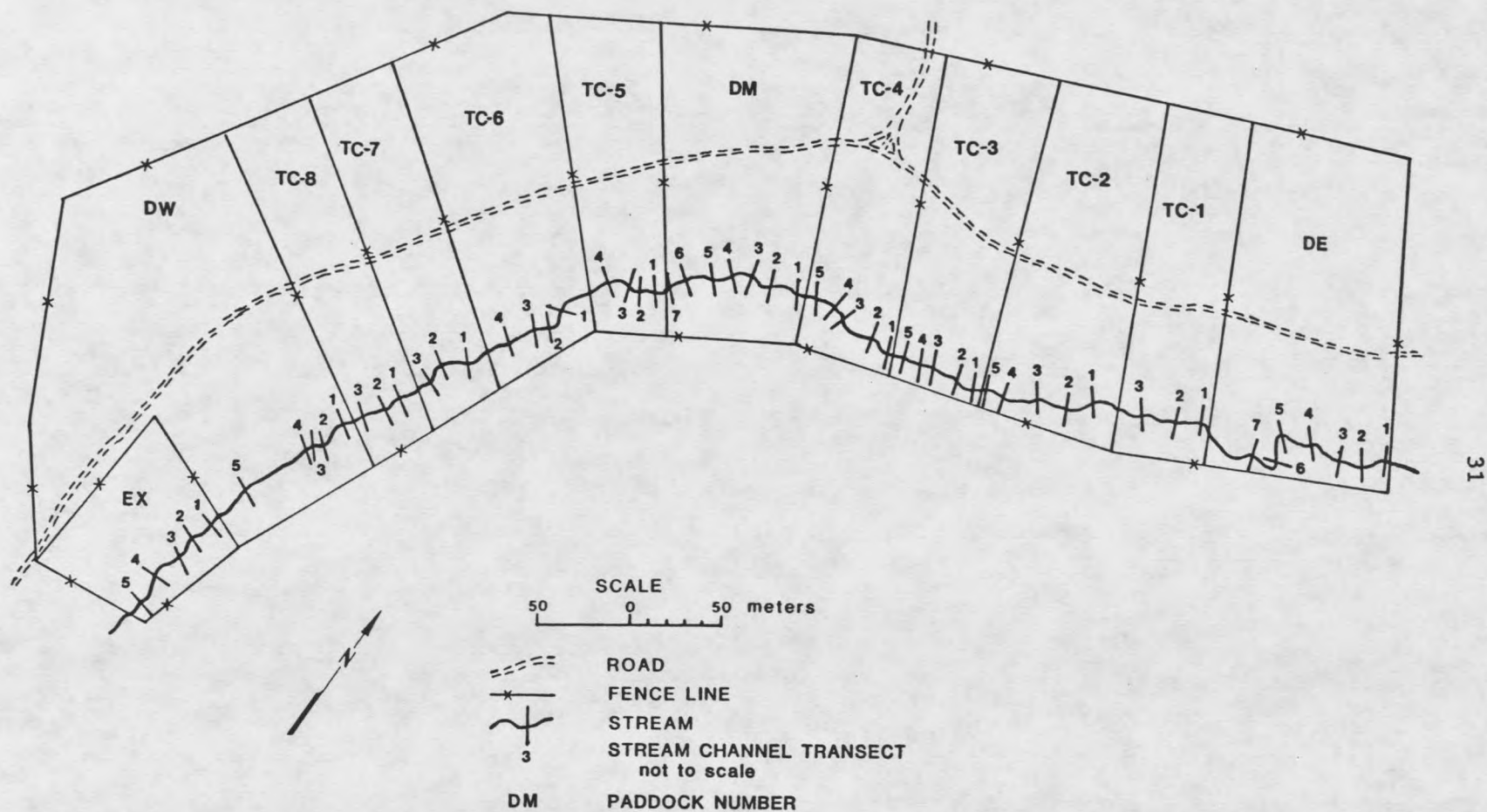


Figure 7. Map of grazing study area with location of stream channel transects. These transects were used to locate soil moisture sampling sites.

on the stream side of these stakes. A total of 56 transects were used as sampling sites. Soil moisture samples were collected from both streambanks along the transect (a total of 112 samples per sampling period). The number of transects within grazing paddocks varied from 3 to 7, as stream length varied between different paddocks. Transects are located in both dry areas and seepage areas. Thus, sampling locations allow for measuring differences in soil moisture content between dry ground and seepage areas along the entire reach of the stream within the grazing study area (Fig. 7).

All streambank soil moisture measurements are numbered according to the paddock and transect numbering scheme used by Dr. Clayton Marlow (Fig. 7), as these data will also be used in his research on the effects cattle-grazing management practices have on streambank stability.

Soil Texture

Differences in soil texture from site to site can cause differences in soil moisture content (Reynolds, 1970c; Knapp, 1978; Hillel, 1982; Price and Bauer, 1984). Textural analysis of streambank soils within the grazing study area was conducted by Dr. Marlow. Soil texture was determined using the hydrometer method for both the north and south streambank of each grazing paddock. Samples for analysis were taken from soils collected for moisture content measurements after drying.

Stream Discharge Measurements

Stream discharge was measured with Parshall flumes at two points in 1986, and at six points in 1987 (Fig. 4). Gauging points were determined by Dr. Marlow for use in his grazing studies. In 1986, gauging points essentially coincided with the upstream and downstream boundaries of the grazing study area. In 1987, the grazing study area was enlarged and the emphasis of the study was changed to monitor different types of grazing management practices. The location of gauging points were changed to fit with the new study plan. Parshall flumes were located at the downstream boundary of the study area and at various points within the study area on the border of paddocks separating different grazing management practices (Fig. 4).

Two sizes of Parshall flumes are installed on Cottonwood Creek. One flume with a 6 in (15.24 cm) throat (58 l/s capacity) is located at the downstream boundary of the study area (Flume A, Fig. 4). All other flumes have a 3 in (7.62 cm) throat (25 l/s capacity). Stage height within the flumes was monitored continuously by mounting Stevens Type F model 68 recorders to the stilling well of the flumes. Measurement precision of the recorders is ± 0.01 ft (0.30 cm).

Discharge was determined through use of the stage height records. Stage-discharge relations for the Parshall flumes in English units are as follows (Bureau of Reclamation, 1984):

$$6 \text{ in} : Q \text{ (cfs)} = 2.06 H^{1.58} \quad (2)$$

$$3 \text{ in} : Q \text{ (cfs)} = 0.992 H^{1.55} \quad (3)$$

where Q is discharge (ft^3/sec) and H (ft) is stage height recorded on the upstream end of the flume.

Conversion from stage to discharge hydrographs was conducted by computerized digitizing of the stage hydrographs and applying the conversion formulas to the digitized data. Discharge was then converted to liters per second to accommodate use of metric units. Liters per second were chosen due to the low discharge of the stream.

Of the six flumes operating in 1987, only flumes B and F (Fig. 4) were used for analysis of storm runoff for the following reasons: Flumes A and E are located in the middle of groundwater-seepage areas, making it difficult to determine contributing areas for storm runoff from the seeps to the flumes; the recorder on flume C was working poorly for many of the storms; and, flume D appears to operate under a submerged flow condition (Bureau of Reclamation, 1984). This condition requires another record of stage height at the lower end of the flume. This second record is not available at this time. Flumes B and F can be used to deduce differences in runoff production between stream reaches with varying amounts of influence from groundwater-seepage areas. The stream reach above flume F has little influence from groundwater-seepage areas. The reach between flumes B and F has greater influence from groundwater-seepage areas.

Storm Runoff

An objective of this thesis was to test if groundwater-seepage areas produced more runoff than dry areas during storm events. Storm runoff processes and runoff-contributing areas were determined by direct field observation and through hydrograph analysis. Direct field observations were gathered in the field during storm events by noting runoff processes and areas which produce overland flow. However, not

all storms were witnessed and subsurface storm flow cannot be observed in the field.

The field observations made were used to supplement inferences about runoff processes made through hydrograph analysis. The predominance of overland flow or subsurface storm flow in the drainage basin may be detected by characteristics of the storm hydrograph (Hewlett and Nutter, 1970; Bevin, 1978; Dunne, 1978). These characteristics include responsiveness to rainfall (Dunne and Black, 1970a, 1970b; Weyman, 1973; Bevin, 1978; Dunne, 1978) and the nature of the recession limb of the storm hydrograph (Hewlett and Nutter, 1970; Bevin, 1978; Dunne, 1978). A dominance of overland flow and runoff from direct precipitation into the stream channel, as expected in the study basin, will show a flashy hydrograph (Fig. 8, upper basin hydrograph). Storm hydrographs will be highly responsive to precipitation and fluctuations in rainfall intensity, and will have steep recession limbs. Weak response to rainfall and rainfall intensity fluctuations, and long, low-slope recession limbs would indicate a predominance of subsurface storm flow. If subsurface flow dominates storm runoff, there may be a second peak in the storm hydrograph which is not directly related to precipitation at the time of the second peak (Fig. 8, lower basin hydrograph).

In addition to hydrograph analysis, Freeze (1972) developed a model to test the volume of subsurface flow in the storm runoff hydrograph from hillslopes with steep convex slopes and a deeply incised stream channel, considered to be the ideal morphology for subsurface flow to occur. The most important control on the volume of subsurface flow was

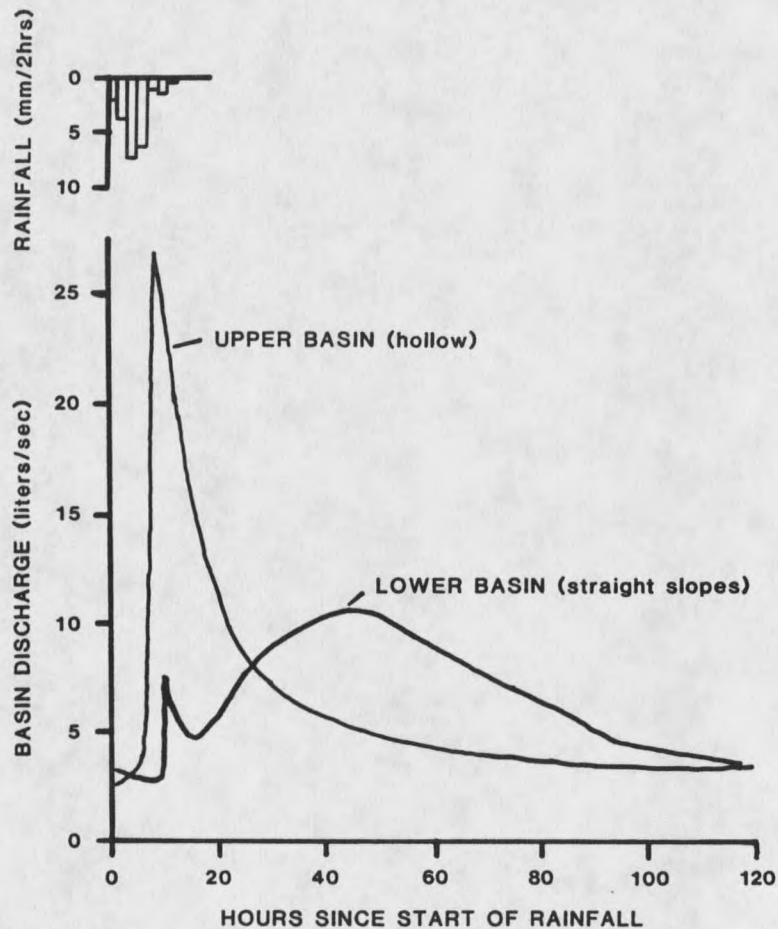


Figure 8. Storm runoff hydrographs from two basins within the same watershed. The upper basin hydrograph is highly responsive to rainfall and is produced mostly by saturation overland flow. The lower basin hydrograph is double peaked and is produced mostly by subsurface storm flow (after Calver and others, 1972, as cited in Dunne, 1978).

the hydraulic conductivity of the soil within the basin. Hydraulic conductivity of the soils within the study basin was measured and will be compared to values tested by Freeze (1972) to get a qualitative estimate of the occurrence of subsurface flow within the study basin. The antecedent moisture condition is also a very important control on

the amount of subsurface flow produced during a storm (Weyman, 1973; Dunne, 1978; Knapp, 1978).

If storm runoff processes and contributing areas can be determined, the volume of runoff expected for a storm can be calculated. The runoff processes and contributing areas deduced for the study basin will be tested against the storm runoff volumes measured with the Parshall Flumes. Observed storm runoff volumes were obtained by calculating the area under the storm hydrograph curve with a computer-driven digitizer. Storm runoff implies that the baseflow is separated out of the storm hydrograph such that only the excess runoff contributable to a storm is measured.

Separation of baseflow from a storm hydrograph has long been a problem in hydrology (Dunne and Leopold, 1978). Elaborate methods of hydrograph separation have been devised through arbitrary classification of source areas and flow rates of storm runoff (Hewlett and Hibbert, 1967). While many techniques exist for hydrograph separation, most are based on empirical methods that may not properly define the different runoff components of the hydrograph (Ward, 1975). Hewlett and Hibbert (1967) have developed a method for separating the hydrograph into components which they term quick flow and delayed flow (Fig. 9). The process essentially separates the hydrograph into streamflow which responds quickly to a storm event, quick flow, and flow which supplements the longer term recession of stream discharge, delayed flow. In more general terms, quick flow is associated with storm runoff while delayed flow is associated with baseflow. This method of separation is independent of storm runoff process and

potential baseflow increases during a runoff event. The method was devised to allow for uniform hydrograph separation in different basins which may have different runoff processes occurring within them. Although hydrograph separation is generally a somewhat arbitrary process, an arbitrary method should be able to be applied consistently to several different areas. If the same method of hydrograph separation is used throughout a study, usable results should be obtained (Ward, 1975; Dunne and Leopold, 1978).

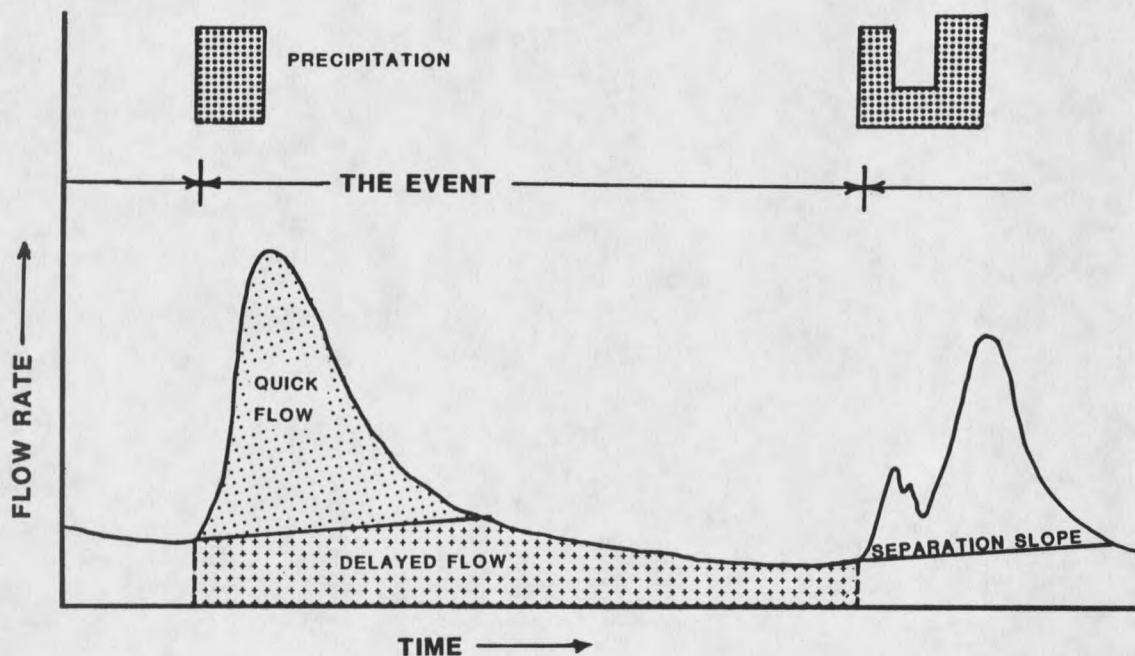


Figure 9. Hydrograph showing components of quick flow and delayed flow along with the separation slope (from Hewlett and Hibbert, 1967).

Hewlett and Hibbert (1967) separated hydrographs by use of a line of constant slope projected from the beginning of a storm induced rise in the hydrograph to a point where this line intersects the falling limb of the hydrograph (Fig. 9). They selected a slope value of 0.05

cubic feet per square mile per hour (0.55 liters per square kilometer per hour) as it was greater than the normal diurnal fluctuation of flow and permitted separation of runoff events which were close together (2 to 3 days). This technique was established for use with a digital computer on watersheds in the southeastern United States. This technique has also been used in other geographic areas though the slope of the separation line has been altered (Ward, 1975).

The Hewlett and Hibbert (1967) technique was also applied to hydrograph separation in this study, but the slope of the separation line was not based on the slope defined by Hewlett and Hibbert (1967). Instead, a line separating storm runoff from baseflow was established by observing hydrograph characteristics. The most important factor in this process is determination of when storm runoff ends and normal baseflow again dominates the hydrograph. Diurnal fluctuations in the hydrograph both before and after a storm help to distinguish when baseflow dominates the hydrograph. Separation lines are shown on all hydrographs in the following chapter.

Sediment Production

Sediment transport over the ground surface was measured using overland flow sediment traps (Goudie, 1981; Bush, 1985). The sediment traps collect sediment which has been transported by overland flow from above the trap, and raindrop splash from around the trap. Sediment traps will also collect sediment which has been transported by wind (Marlow, 1988). The amount of sediment trapped due to each process cannot be separated from the total. Overland flow should have the

ability to transport more sediment than raindrop splash or wind in the study basin. Thus, differences in sediment production are assumed to be differences due to overland flow transport.

To test for differences in sediment production from seepage areas and dry ground, traps were placed in each type of ground surface. Dry-ground traps were placed along both "flat" streambanks and in small gullies. Two traps were also placed in cattle paths which cut into the streambank and did not extend more than one meter beyond the top of the streambank. Except for the traps located within the cattle paths, all traps were placed above the streambank (i.e., above the break in slope which was formed by the active stream channel).

Thirty sediment traps were obtained from Dr. Marlow for use in this study and were installed in 1987. The first sediment traps were installed on May 23, 1987. Installation of all traps was completed by June 30, 1987. The traps were cleaned on four occasions in 1987 based on storm frequency and time available for cleaning.

Traps are V-shaped and are 61 cm long, 10.1 cm wide, and 7.6 cm deep. A small trench was made in the ground surface with a shovel, and the traps were installed so the lip of a trap was flush with the ground surface. An attempt was made to orient the traps perpendicular to the slope of the ground surface. Traps were placed in each grazing paddock, on both north and south streambanks, in order to determine sediment production from a variety of positions along the length of the stream (Fig. 10). Visual reconnaissance was conducted for each paddock to determine the location in which traps might operate most effectively. Few channels extend from the hillslopes to the stream

channel, so field determination of the sites which may contribute or concentrate runoff for sediment delivery was difficult. Traps were numbered using the same system used for the groundwater-monitoring wells. A two number system was set up in which the first number depicts the grazing paddock and the second number indicates the order in which the trap was installed.

Overland flow sediment traps operate most efficiently when placed on slopes which exceed 10 percent (Bush, 1985). Slopes within the streamside zone of Cottonwood Creek vary from 10 to 25 percent based on a computerized slope map prepared from the 1:24000 topographic map by Dr. Ian Moore at the University of Minnesota.

Paired sediment trap configurations (one trap topographically above another but along the same drainage line) were positioned in four different areas. In two areas, paired traps were set up in dry ground locations. One pair was placed in a small, vegetated, gullied area (traps 1-4, 1-5) (Fig. 10) and one pair was placed in an area which was partly terraced (traps 2-5, 2-6). In both cases the lower trap was positioned near the stream channel. A paired trap configuration was also installed in one seep (traps 2-3, 2-4). The lower trap was positioned in a main runoff channel near the stream while the upper trap was installed above the slope of the streambank though still located within the same runoff channel. One other paired trap configuration was situated in a broad, vegetated gully within the streambank (traps 4-1, 4-2). There is a seep along the lower portion of the gully. The upper trap was positioned above the seep while the lower trap was located within the seep.

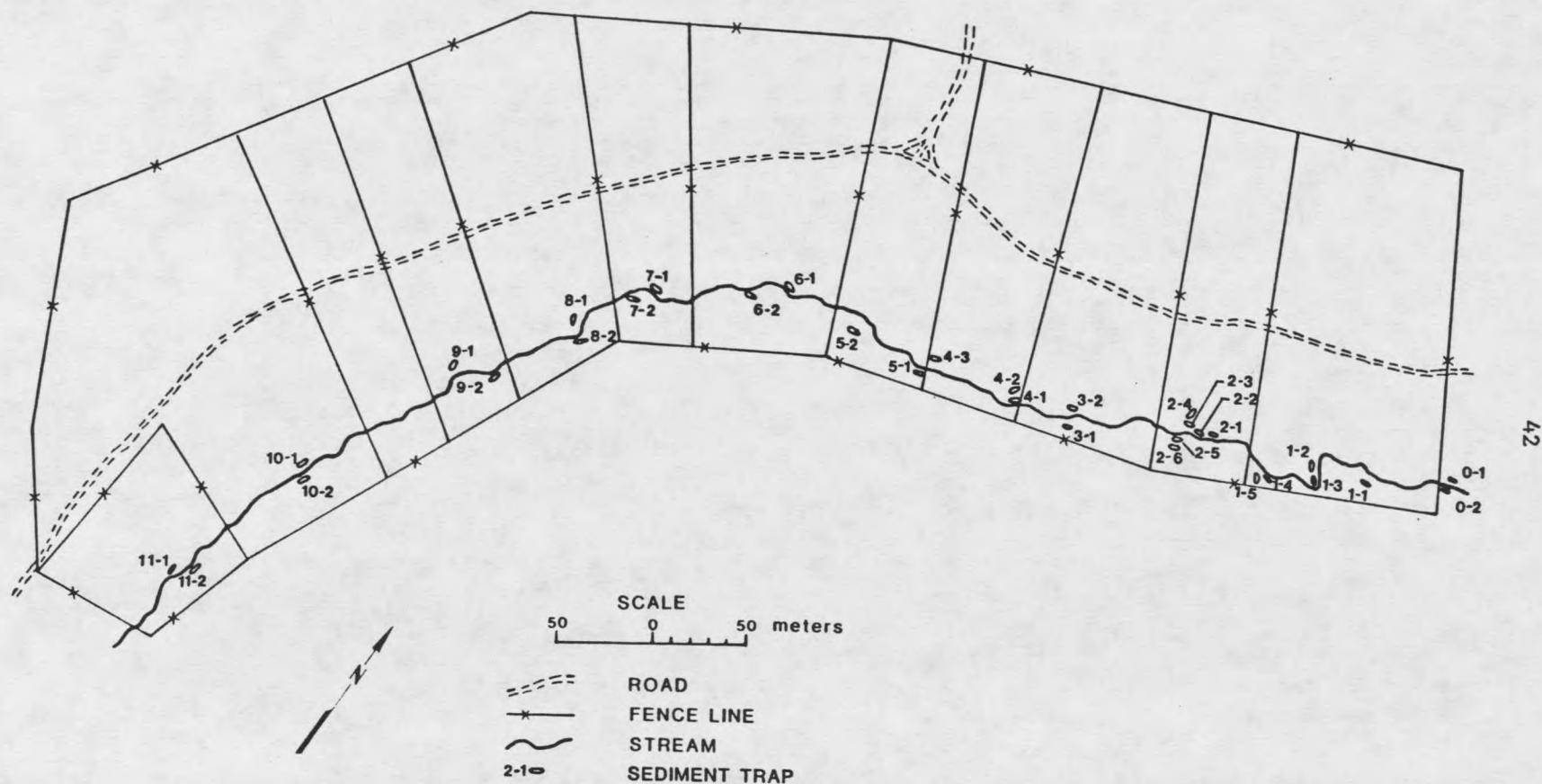


Figure 10. Map of grazing study area with location of sediment traps. Sediment trap sizes are not shown to scale.

The amount of sediment transported from an area was determined by the weight of sediment collected in the traps. Sediment within the traps was collected by first spooning as much sediment as possible out of a trap, then flushing the trap with water and collecting the water in the trap with a turkey baster. Contents of the trap were placed in plastic whirlpack and ziplock bags. Pieces of vegetation and insects collected in the trap were discarded.

Laboratory analysis consisted of emptying and flushing the bags into aluminum baking tins and drying the samples in an oven at 80 to 100 °C for 2 to 3 days. Each dry sample was then weighed on an analytical balance to the nearest 0.01 g.

To test for differences in sediment production, ground surface types were separated into four different categories. These include: dry-ground areas, perennial-seepage areas, intermittent-seepage areas and cattle paths. The type of ground surface is listed with each trap in the results section. Comparisons were made between the average amount of sediment collected per mm of rain, per trap, from each ground surface type.

Statistical analysis was performed on the data even though the number of samples was relatively small. Student t-tests (Freedman and others, 1978) were run testing for the significance of differences between the average amount of sediment collected per mm of rain, per trap, from the different location types. Tests for differences of means were run for sediment amounts (g/mm of rain, per trap) collected during each sampling period and for the yearly average of sediment collected (g/mm of rain, per trap) for each location type. Student

t-tests were also run on the paired trap configurations to test for the significance of differences between the amount of sediment trapped (g/mm of rain) from each of the traps in each pair.

RESULTS

Precipitation

Precipitation is the driving influence of hydrologic processes (Ward, 1975). As hydrologic monitoring of the Cottonwood Creek watershed was performed during only two years for this study, some determination as to whether or not precipitation patterns were "normal" is necessary to allow the data to be extrapolated to other years for management considerations. Precipitation patterns recorded at the study site were compared to data recorded at the NOAA station located at the Madison Powerhouse (Norris Madison P H) (Figs. 11, 12) as it was the closest station with a long continuous record. Comparisons were made for precipitation received in both areas and to the thirty year average (1951 to 1980) listed for the Madison Powerhouse station (NOAA, 1986, 1987). Precipitation data were recorded at the study area from April through October in both 1986 and 1987.

For 1986 and 1987, monthly precipitation records for Madison Powerhouse and the study site compare favorably ($r^2=0.88$), with the exception of records for April and May, 1986 (Fig. 11). During April and May, 1986, only a non-recording rain gauge was in use at the study site and was checked only periodically, so these data may be suspect. A recording rain gauge was in operation for the rest of the study period, both 1986 and 1987. Generally, the Cottonwood Creek watershed received more monthly rainfall than the Madison Powerhouse (Figs. 11,

12). The regression equation comparing the two sites is:

$$Y = 1.21X + 2.15 \quad (4)$$

where Y is monthly precipitation (mm) at Cottonwood Creek and X is monthly precipitation (mm) at Madison Powerhouse.

Monthly precipitation at the Madison Powerhouse did not vary greatly from the thirty year average in 1986, though rarely was it the same as the average (Fig. 11). The average deviation from normal was 30% during the period when monitoring was conducted at Cottonwood Creek. The greatest deviations from normal occurred in August (141% of normal) and October (42% of normal). Total precipitation at Madison Powerhouse for 1986 was 97% of normal (NOAA, 1986).

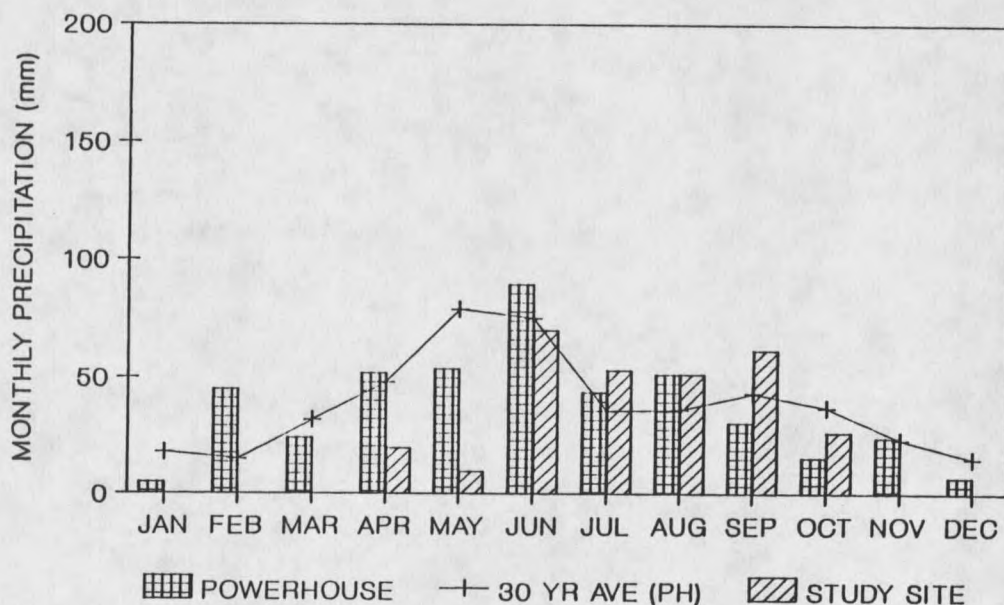


Figure 11. Precipitation patterns for 1986, for Madison Powerhouse (NOAA, 1986), Cottonwood Creek study basin and the 30 year average (normal) for Madison Powerhouse (NOAA, 1986).

Monthly precipitation in 1987 at the Madison Powerhouse deviated greatly from the normal pattern (Fig. 12). Precipitation from January

through April, and September through October was only 42% of normal. Precipitation was above normal in May (138% of normal), July (324% of normal) and August (214% of normal). However, total precipitation for 1987 at Madison Powerhouse was 99% of normal (NOAA, 1987). The large amount of precipitation from May to August occurred when most hydrologic monitoring took place, so the patterns recorded in 1987 may be abnormal.

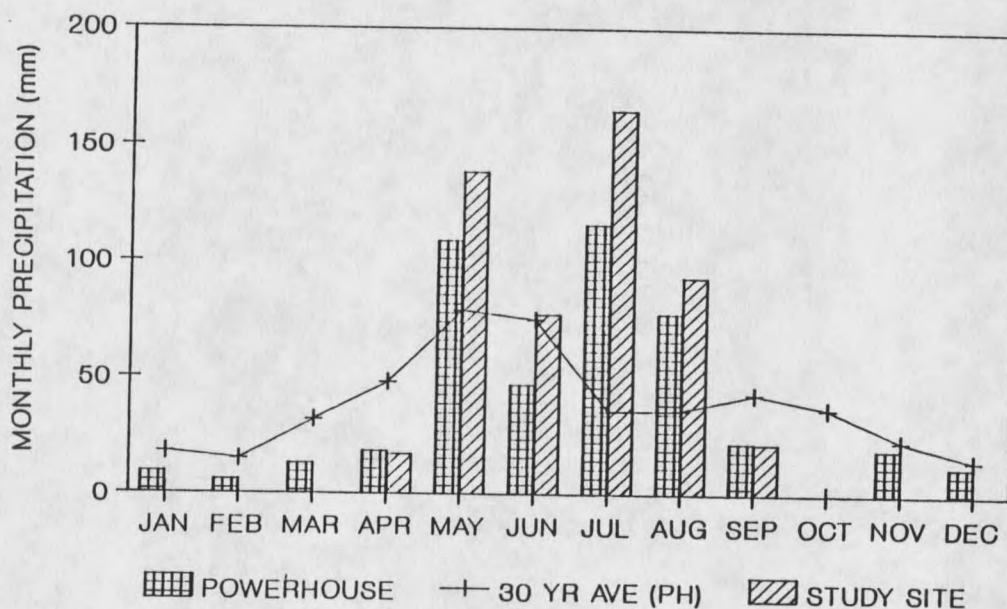


Figure 12. Precipitation patterns for 1987, for Madison Powerhouse (NOAA, 1987), Cottonwood Creek study basin, and the 30 year average (normal) for Madison Powerhouse (NOAA, 1987).

Snow cover and snowmelt patterns are also important in soil moisture and groundwater recharge behavior (Dunne and Leopold, 1978). Generalizations about snowpack distribution and timing of snowmelt were recorded in field notes. Snow did not persist as a continual ground cover within the study basin, instead snow accumulated in drifts located in draws, gullies, wooded areas and the stream channel. The

timing of snowmelt was different in 1986 than in 1987. Snow persisted until mid-June in 1986, whereas all snow was essentially gone from the watershed by the end of April in 1987. Snowmelt was not measured or calculated because no runoff events were analyzed during snowmelt periods.

Groundwater-Seepage Areas

Locations of groundwater-seepage areas were mapped and monitored for changes in saturated area in order to evaluate the control these areas exert on soil moisture content, runoff production and sediment production. Above the study area the watershed contains only two seeps, one in a streamside slump and one near the headwater spring. Although these two seeps were not mapped for size variation, the sizes were small compared to the seeps mapped within the grazing study area. The two seeps also tended to be wet whenever they were observed.

Five major groundwater-seepage areas are located within the grazing study area (Fig. 13). The map presented in Figure 13 shows only the minimum and maximum sizes of the different seepage areas mapped during 1986 and 1987, and the assigned numbers of the seeps used for reference. Saturated-seepage area size within the grazing study area varied during the study period (Fig. 14). Maps showing the fluctuation of saturated areas for seeps S1 through S5 are presented in Appendix B. Saturated-seepage area size fluctuations in 1986 showed a trend opposite that of 1987 (Fig. 14). Although rainfall did occur in 1986, it was much less than that of 1987. The largest saturated-seepage area sizes mapped in 1986 occurred in June while the smallest sizes were

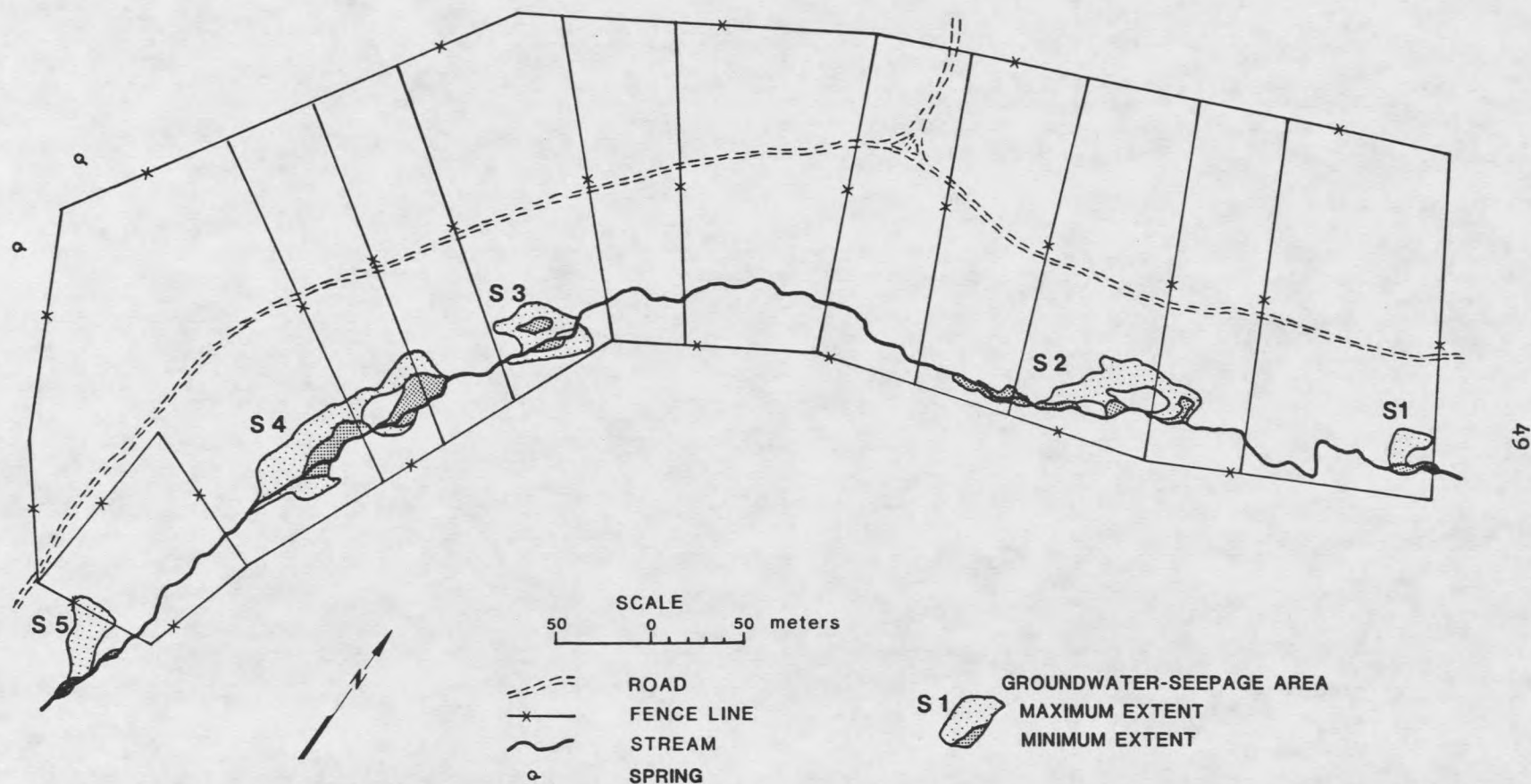


Figure 13. Map of grazing study area with locations of groundwater-seepage areas, showing both the maximum and minimum sizes mapped in 1986 and 1987.

mapped in September. The size of the saturated areas mapped in June, 1986 were approximately the same size as those mapped in September, 1987 (Fig. 14). Size of the saturated areas in September, 1986 were roughly the same size as those found in April, 1987.

There is a general increase in saturated area size through time in 1987 except for the decrease in size from May 17 to June 13 (Fig. 14). Changes in saturated area size during storm events were not mapped, and observations made during small storm events indicate no major change in saturated-seepage area size during a single small event. However, the saturated-seepage area sizes on May 17 were mapped during a time in which 91 mm of rain fell from May 15 to May 22. Approximately 35 mm of rain fell before mapping took place, and saturated area sizes at the beginning of this period are not known.

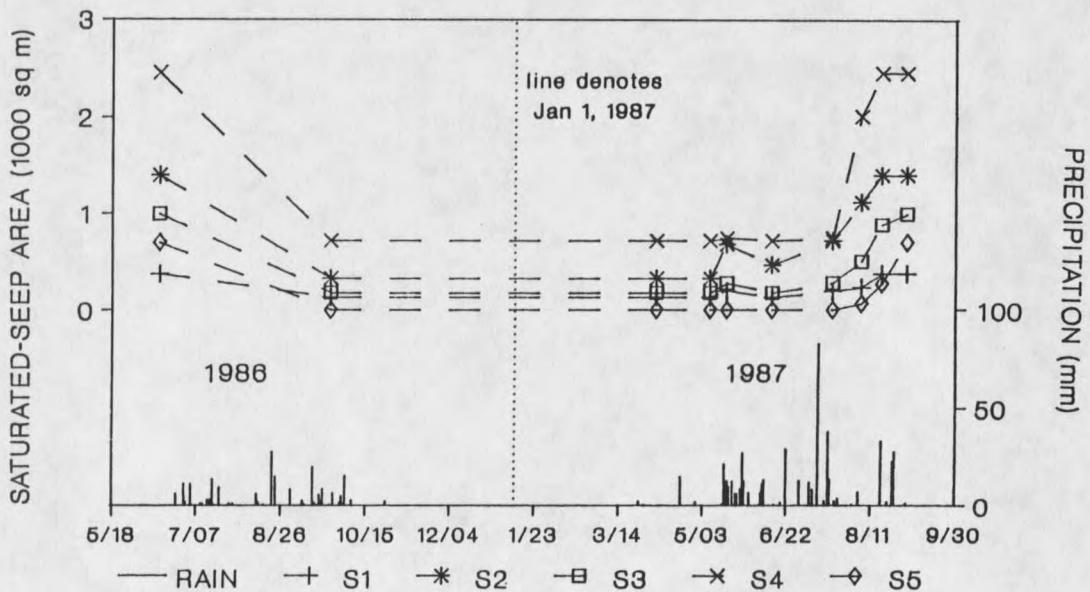


Figure 14. Graph of saturated-seepage area size fluctuation in 1986 and 1987 for the five mapped seeps in Figure 13, along with daily precipitation amounts.

There are upland springs on the hillside north of the grazing study area. Two springs are located in a large draw feeding seepage area S4 (Fig. 13) and one spring is located just north of the map area near the road leading north out of the middle of the grazing study area. All springs flow overland in small channels for a short distance but reinfiltrate before reaching Cottonwood Creek. Springs are differentiated from seeps as water flow from springs occurs from a more distinct discharge area than from seeps, and flow from the springs is channelized and moves more swiftly than flow from the seeps (Todd, 1980).

Groundwater

Groundwater levels in monitoring wells were measured to determine the depth to the water table and to monitor water level fluctuations through time. All water level measurements are reported in Appendix C. Water level fluctuations throughout the study period were generally less than 0.5 m in most wells. Trends in water level fluctuations were different in 1986 than 1987.

In 1986, there was a general, small decline in water levels through the year (Fig. 15). Observations of water level fluctuations due to precipitation events were not possible because measurements of water levels were made infrequently. There was an occasional rise in water level observed in some wells during the summer of 1986 (Fig. 15), but rises were sporadic and were observed in few wells.

Water level fluctuations were greater in 1987 than 1986, and appear to be related to large precipitation events (Fig. 16). Water levels

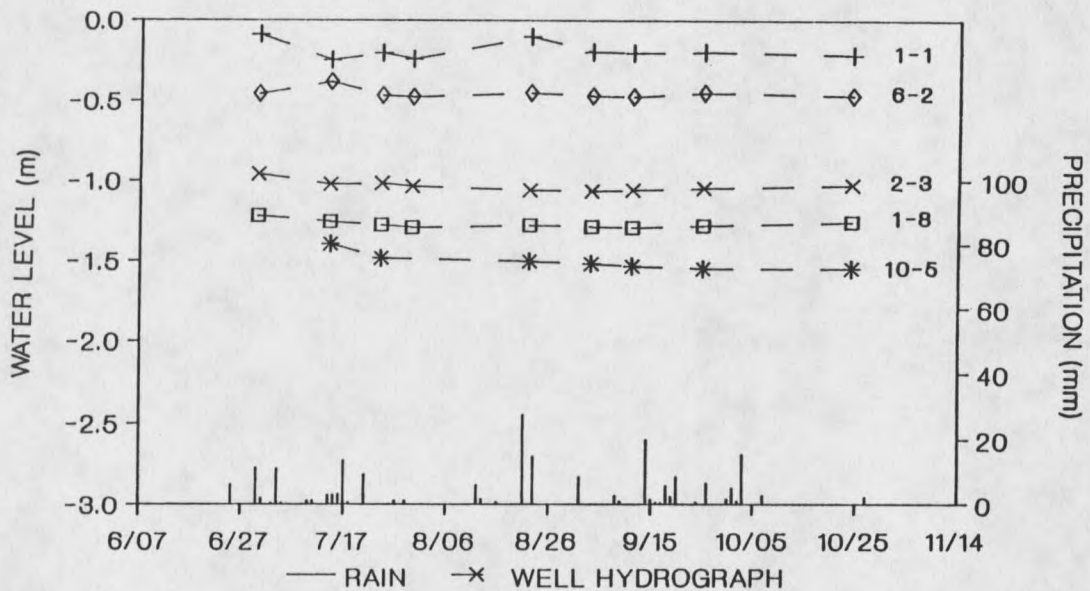


Figure 15. Hydrographs of selected wells showing fluctuations in water levels (as depth below ground surface) and daily precipitation amounts in 1986. Well number is shown with each hydrograph. Well location is shown in Figure 6.

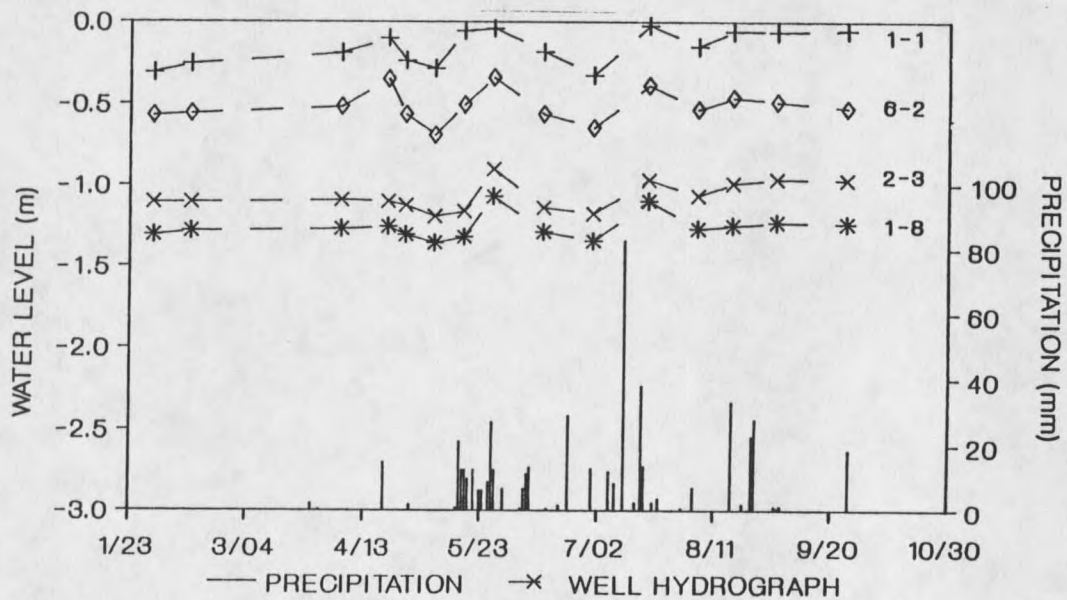


Figure 16. Hydrographs of selected wells showing fluctuations in water levels (as depth below ground surface) and daily precipitation amounts in 1987. Well number is shown with each hydrograph. Well location is shown in Figure 6.

were high for measurements made on May 27, 1987 and July 19, 1987. Large amounts of precipitation fell during a two week period preceding these two measurements, 110 mm of rain fell before May 27 and 142 mm fell before July 19. No other two week period, either in 1986 or 1987, had this much precipitation during the period studied.

Hydraulic Conductivity

Hydraulic conductivity (K) of the soil was measured in an effort to determine whether or not subsurface storm flow is a part of the storm hydrograph. All measured hydraulic conductivities fall within the range 0.5×10^{-4} to 2.8×10^{-3} cm/sec (Table 2). There appears to be no systematic relationship between K and depth (Table 2). No layers of potentially low-K materials were noticed during well drilling, so no low-K layer is thought to exist above unweathered bedrock. The K values do show some heterogeneity but no pattern has been recognized.

Table 2. Hydraulic conductivity values and well information.

Well	Hydraulic conductivity	Total well depth	Depth to the water table
	($\times 10^{-4}$ cm/sec)	(cm)	(cm)
1-1	2.0	147	18
1-6	24.7	128	90
1-8	27.9	175	145
2-1	0.9	147	74
2-2	0.5	90	45
2-3	1.3	151	114
3-5	7.0	79	51
4-1	0.9	114	101
6-2	2.4	140	64
8-1	1.7	201	125
10-3	0.9	196	143

Soil Moisture

Spatial Variability of Streambank Soil Moisture Content

Areas of high streambank soil moisture content were expected to be controlled by groundwater-seepage areas. High soil moisture contents are arbitrarily defined here as having greater than 40% water content by weight (gravimetric moisture content). The 40% moisture content was chosen as this content was the lowest observed in any seepage area. Use of the 40% division allows for determination of whether or not non-seepage areas have lower moisture contents than seepage areas. All areas with high streambank soil moisture content are in groundwater seepage areas, with one exception (Fig. 17). There is one anomalous zone spanning parts of paddocks DM and TC-5 that is not a seepage area but has high streambank soil moisture contents. A complete table of all soil moisture measurements is provided in Appendix D.

Analysis of the spatial distribution of soil moisture (Fig. 17) was based on the average moisture content for each site, calculated from the eight measurements made during the summers of 1986 and 1987. The average over the two summers was used to find areas which had continually high streambank soil moisture contents. This approach, with its greater number of measurements, also reduced any errors associated with the sampling technique (Reynolds, 1970c). Maps showing the spatial distribution of soil moisture content made separately for 1986 and 1987 show the same pattern as that seen in Figure 17.

All soil moisture samples were collected at stream channel transect sites, but the ends of the transect lines and position of soil moisture

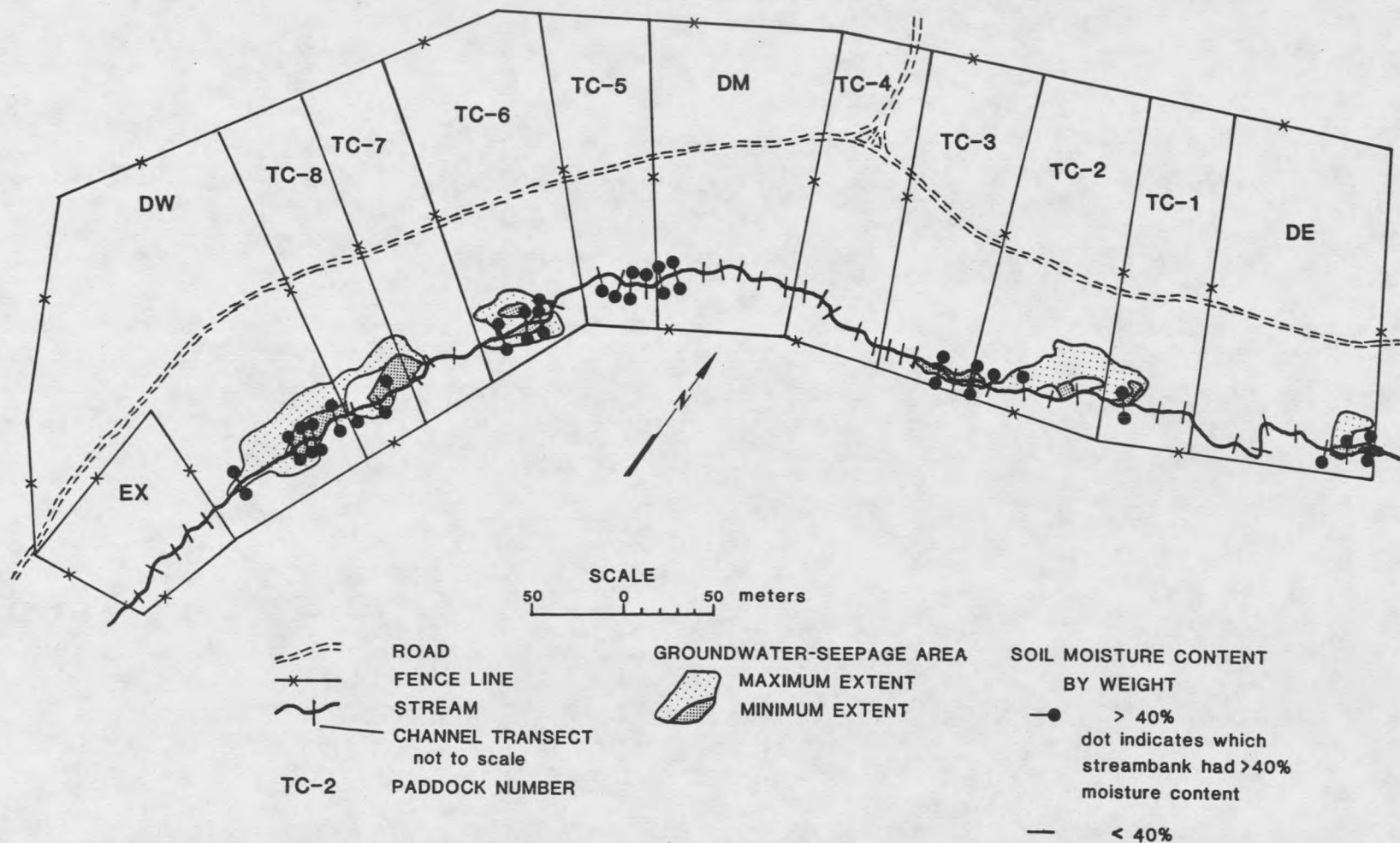


Figure 17. Map of grazing study area with locations of groundwater-seepage areas, soil moisture sampling sites (stream channel transects), and soil moisture highs (>40% moisture content).

content symbols do not show the exact location of soil moisture sampling sites along the transects (Fig. 17). The line indicating the location of any transect is not to scale, as map scale is too small to show the actual length of a transect. Location of any transect with respect to the stream channel, seepage areas and other transects are accurate.

Temporal Variability of Streambank Soil Moisture Content

This study assessed temporal changes in soil moisture at different sites to determine whether dry areas had high moisture contents, or wet areas had low moisture contents at any point in time. Moisture contents did vary through time at individual sites, however, fluctuations in moisture content were sporadic (Figs. 18, 19). Some sites increased in moisture content while other sites decreased in moisture content over any given period of time. Plots of soil moisture fluctuations for twelve different sites in both 1986 and 1987 indicate that while moisture contents do vary over time, dry sites tend to remain dry while wet sites tend to remain wet (Figs. 18, 19). Though only twelve of the sampling sites are plotted, all sampling sites follow this general pattern.

Soil Texture

Soil textures were analyzed to determine whether there were differences in texture along the length of the stream within the grazing study area. A table listing the results of the textural analysis is provided in Appendix E. Textures of soils taken from soil

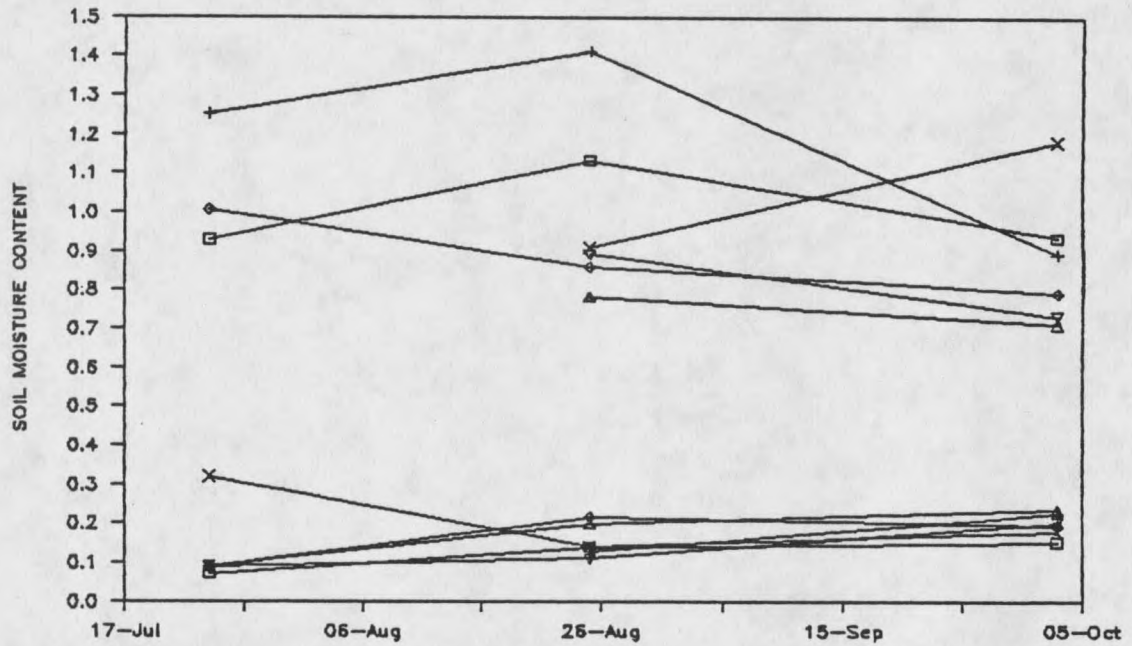


Figure 18. Soil moisture fluctuations in 1986 for the six wettest and the six driest sampling sites in 1986.

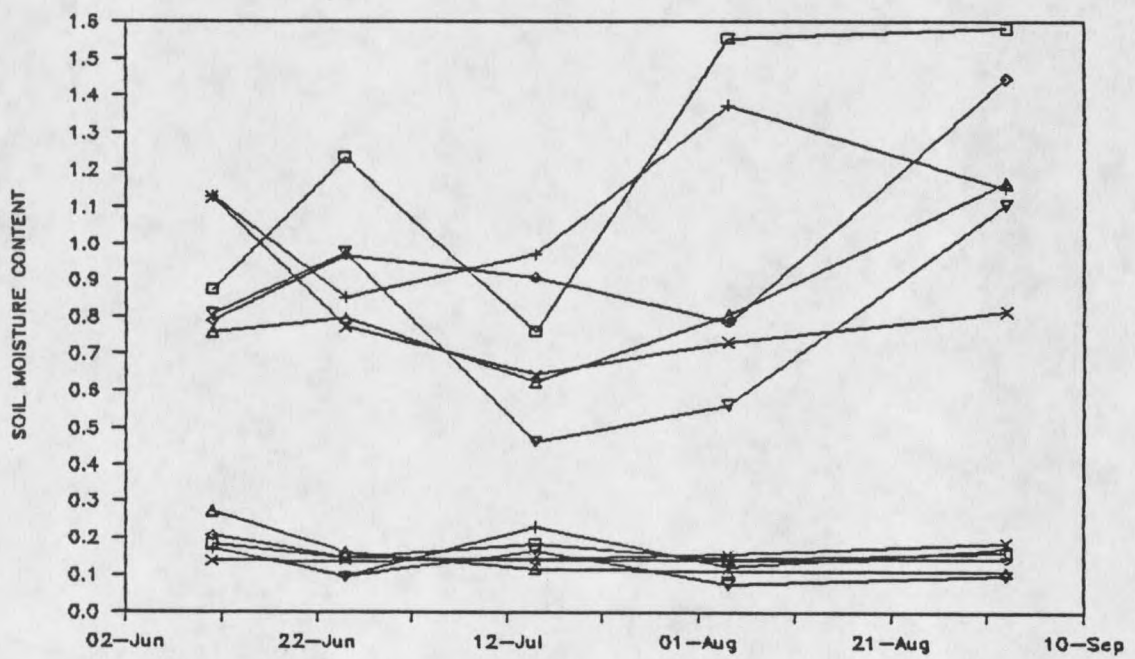


Figure 19. Soil moisture fluctuations in 1987 for the six wettest and the six driest sampling sites in 1987.

moisture sampling cores are sandy loam and sandy clay loam (Fig. 20). Though plotted textures cross nomenclature boundaries, textures along the length of the stream group together well on the ternary diagram. There is no pattern of textural change along the length of the stream (Appendix E).

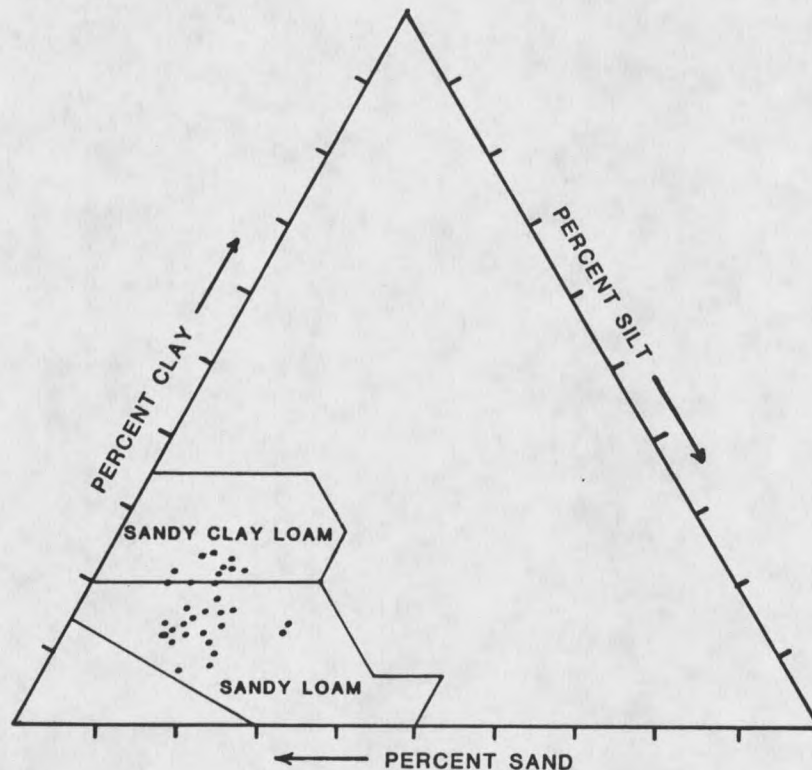


Figure 20. Soil texture diagram with plots of streambank soil textures within the grazing study area ($n = 31$) (after Soil Conservation Service, 1970).

Storm Runoff

Storm runoff processes and runoff-contributing areas can be deduced in part through field observations. Field observations were not made during most storm events. Many events occurred at night or at times when I could not be in the field. Some field observations were made

during multiday events though precipitation intensities were generally quite low during these storms.

Overland flow was witnessed to occur only over groundwater-seepage areas and on the road surface within the watershed. However, overland flow was also seen from groundwater-seepage areas during most dry periods. No quantification of overland flow from groundwater-seepage areas was possible at any time. Overland flow occurring on the road surface did not reach the stream within the study area. This flow was observed to either stay on the road or infiltrate quickly into the ground upon leaving the road surface. There is one gully which leads from the road to the stream in the upper part of the watershed (above flume F). At this point there is some evidence indicating overland flow does reach the stream, as rills in the soil reach the stream channel. The quantity of overland flow through this gully is unknown as observations or quantification of this occurrence were never made. There is a sediment dam made up of hay bails in this gully which may hinder some overland flow from reaching the stream. The onset (though not the entire storm) of the high-intensity storm event of June 8 (16 mm/hr) was witnessed by Dr. Clayton Marlow. He saw overland flow occurring only on the road surface and stated no overland flow was observed on the hillslopes. No observations were made in the stream bottom during this event.

As most storm events were not witnessed, storm hydrographs and corresponding hyetographs were analyzed in this study to help deduce runoff volumes and runoff processes by noting the responsiveness and shape of the storm hydrograph (Figs. 21 through 29). Hyetographs were

not available for all storms analyzed though the total amount of precipitation received during all storms was recorded.

No large storm events were available for runoff analysis for 1986, mainly due to faulty recorders. In 1987, records were available to analyze 15 separable runoff events. Selection of an event for analysis was based on the quality of a storm hydrograph as recorded by the Stevens Recorders and the quality of the corresponding precipitation record. Selected events cover different periods of time coinciding with fluctuating conditions in soil moisture contents, groundwater levels and groundwater-seepage area sizes. These storm events were also of various sizes and intensities.

Streamflow appears to be highly responsive to both the beginning and end of precipitation events and to fluctuations in precipitation intensity at both flumes B and F (Figs. 21, 22, 23, 26, 29).

Streamflow rises are rapid and generally occur shortly after the onset of precipitation or increases in precipitation intensity. Streamflow drops quickly following the end of precipitation or a drop in rainfall intensity.

The recession limb of the storm hydrographs generally show two segments (Figs. 23 through 26, 28, 29). The first segment is quite steep and tends to follow lulls in precipitation intensity, or the end of a precipitation event. The last segment of a recession limb has a much more gentle slope that often falls off rapidly at the end of this segment. After this rapid drop, streamflow again rises somewhat (Figs. 21 through 29) and normal diurnal fluctuations in the hydrograph can be seen.

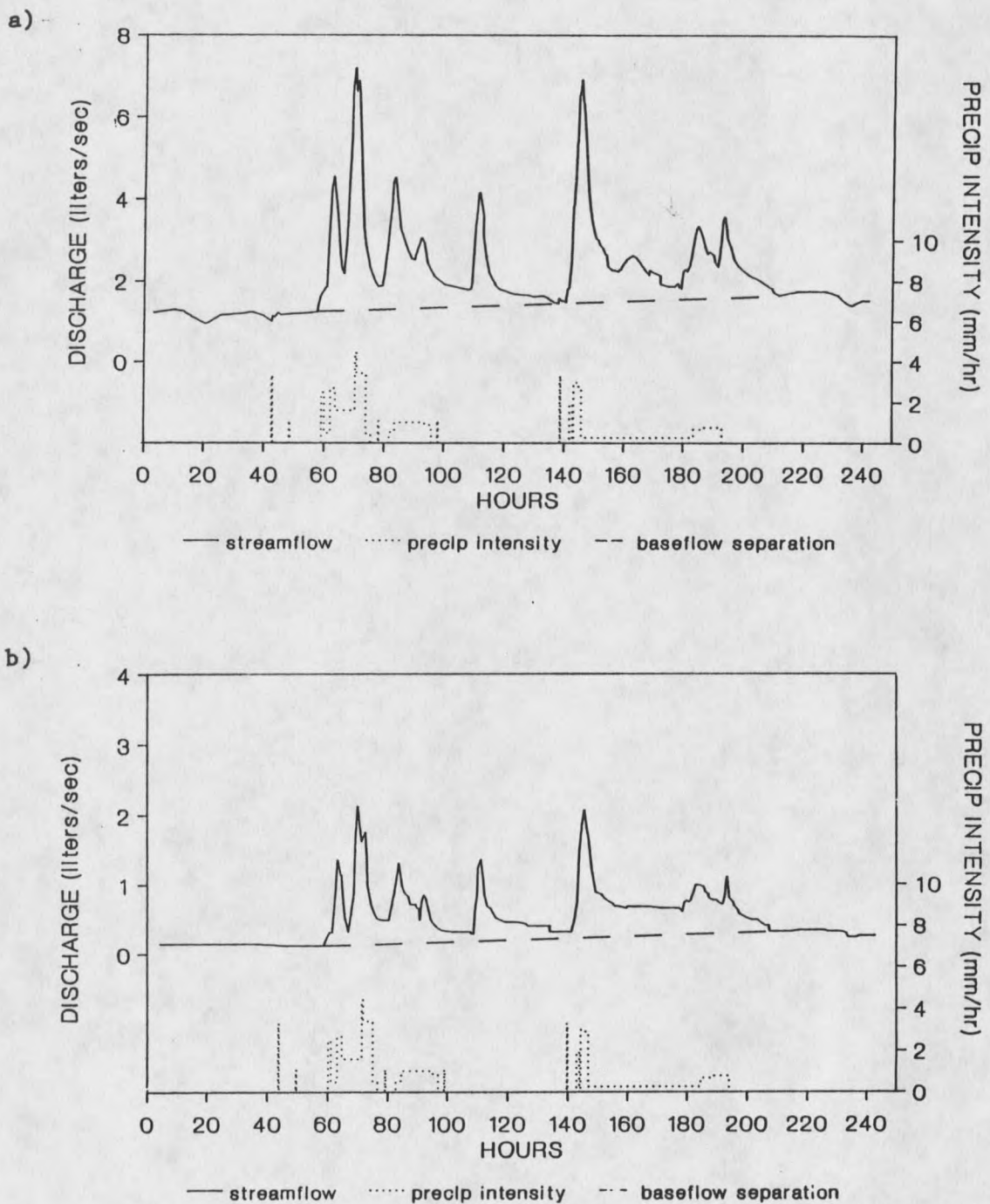


Figure 21. Storm runoff hydrographs for flumes B (a) and F (b), with hyetographs, for the storm event of May 15-22, 1987.

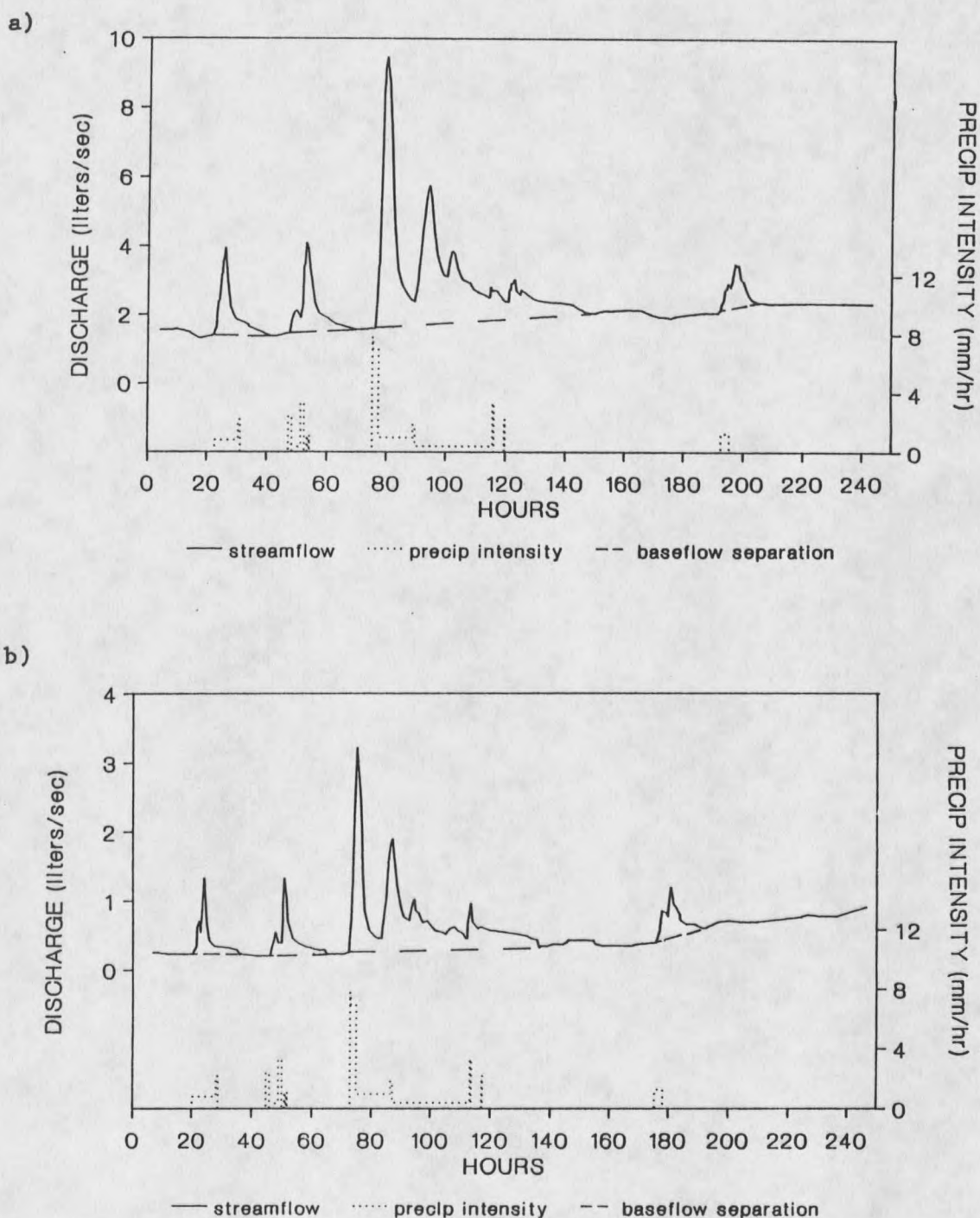
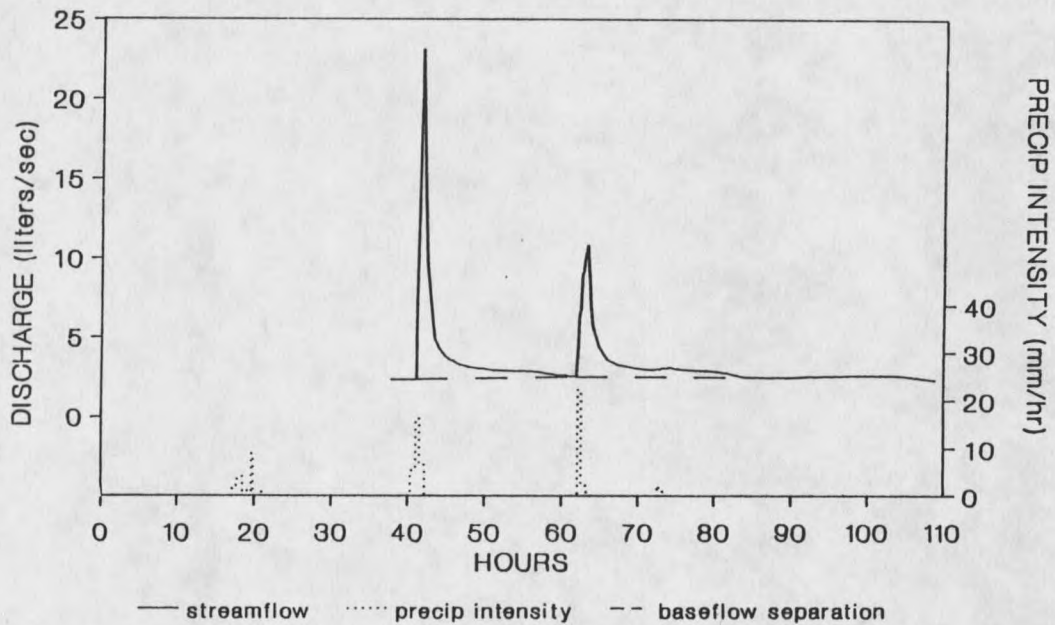


Figure 22. Storm runoff hydrographs for flumes B (a) and F (b), with hyetographs, for the storm events of May 25, 26, 27-29 and 31, 1987.

a)



b)

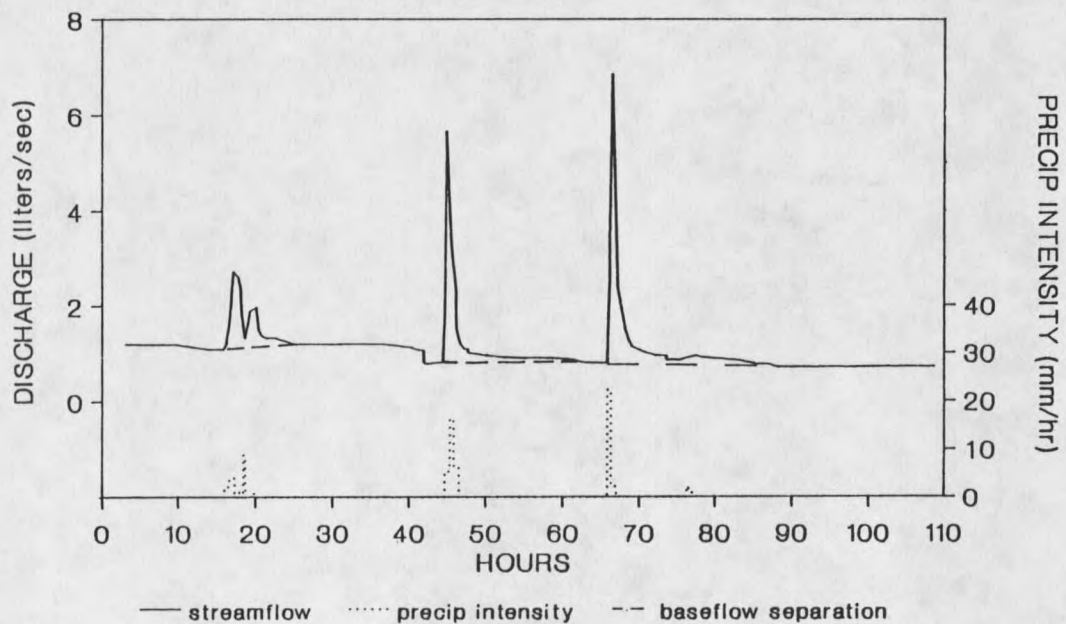
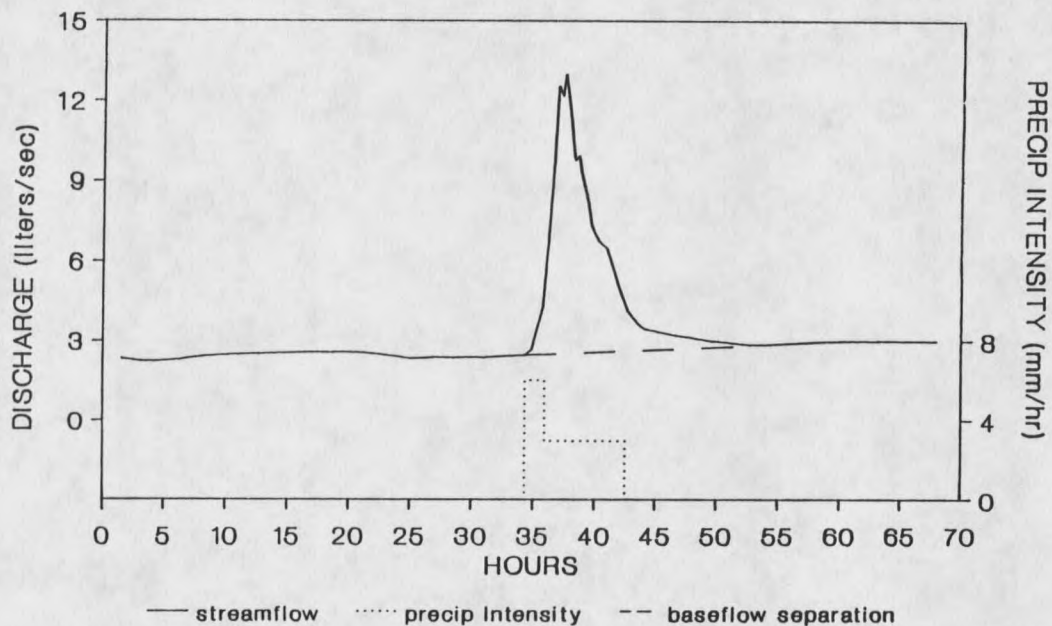


Figure 23. Storm runoff hydrographs for flumes B (a) and F (b), with hyetographs, for the storm events of June 6, 8 and 9, 1987. No record available for June 6 at flume B.

a)



b)

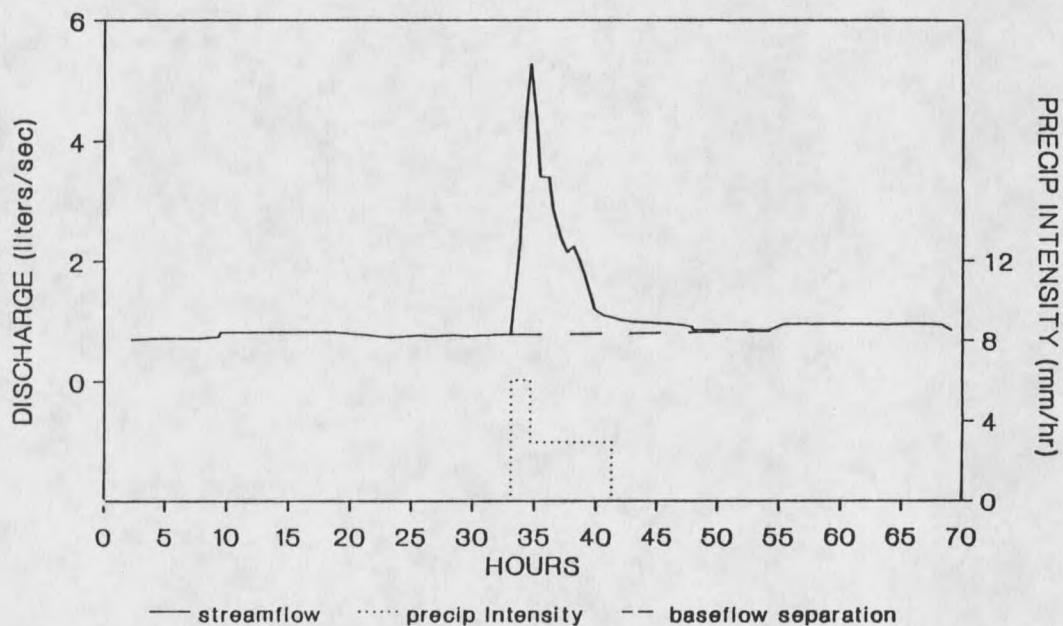


Figure 24. Storm runoff hydrographs for flumes B (a) and F (b), with hyetographs, for the storm event of June 21, 1987.

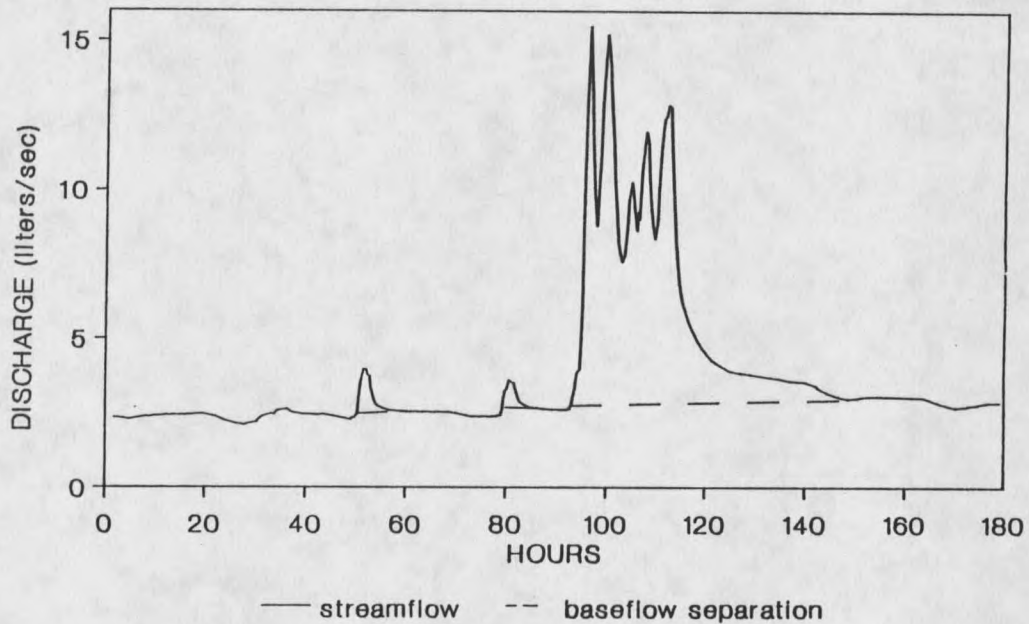


Figure 25. Storm runoff hydrographs for flume B for the storm events of July 8 and 10-11, 1987. The recording rain gauge was not working properly during these storm events. Also, the streamflow recorder at flume F was not working properly.

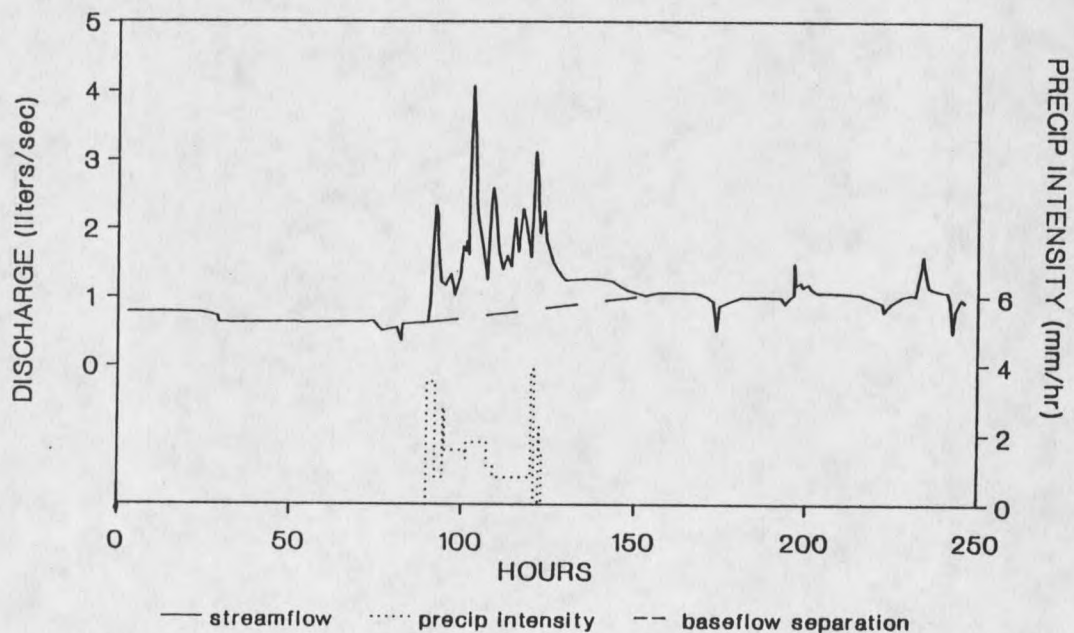
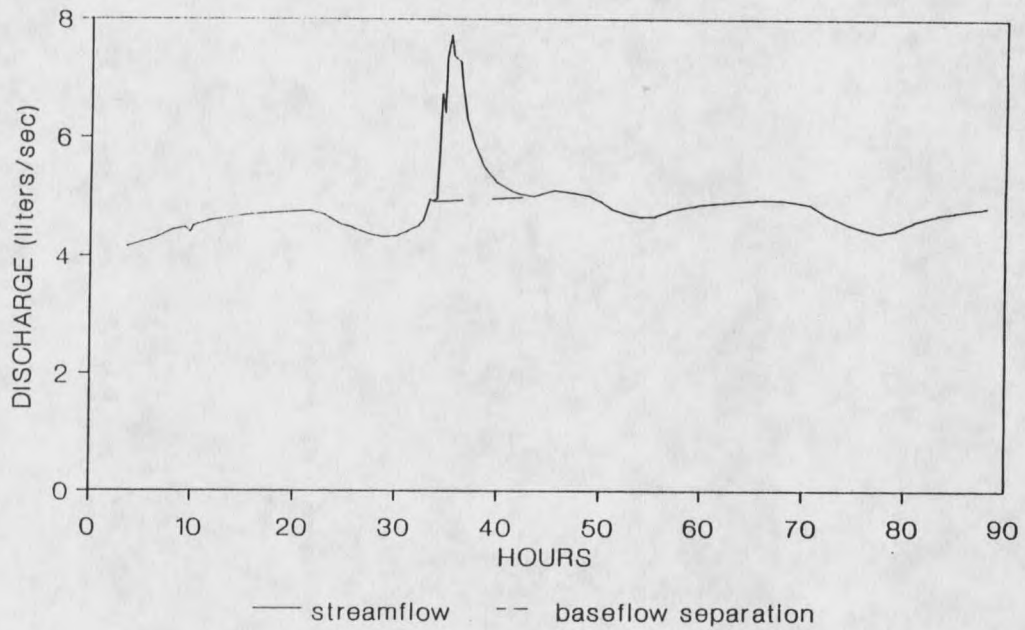


Figure 26. Storm runoff hydrograph for flume F, with hyetograph, for the storm event of July 17-18, 1987. The streamflow recorder at flume B was not working properly during this event.

a)



b)

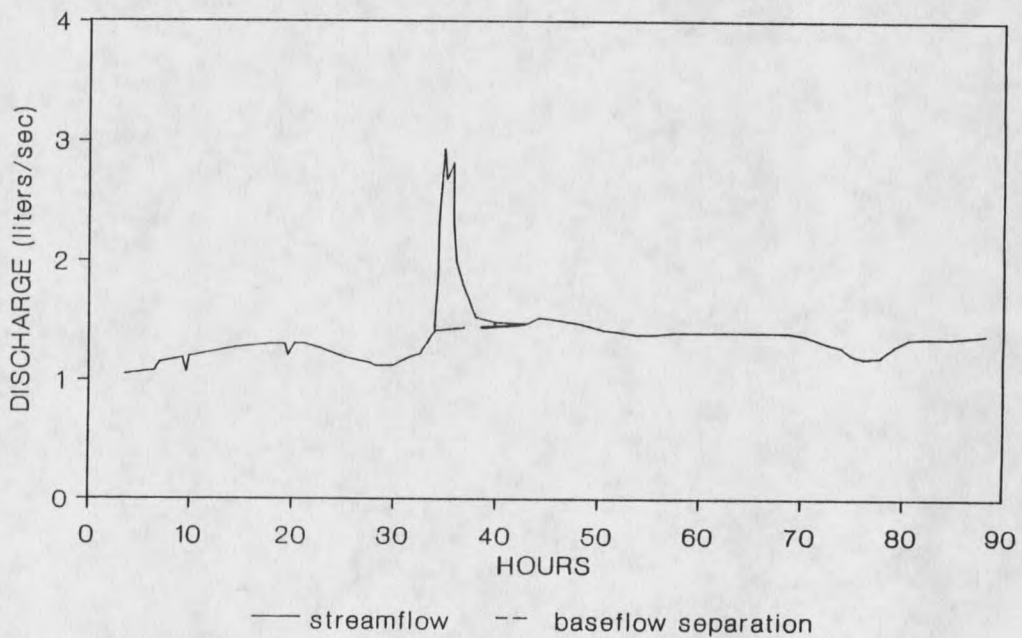
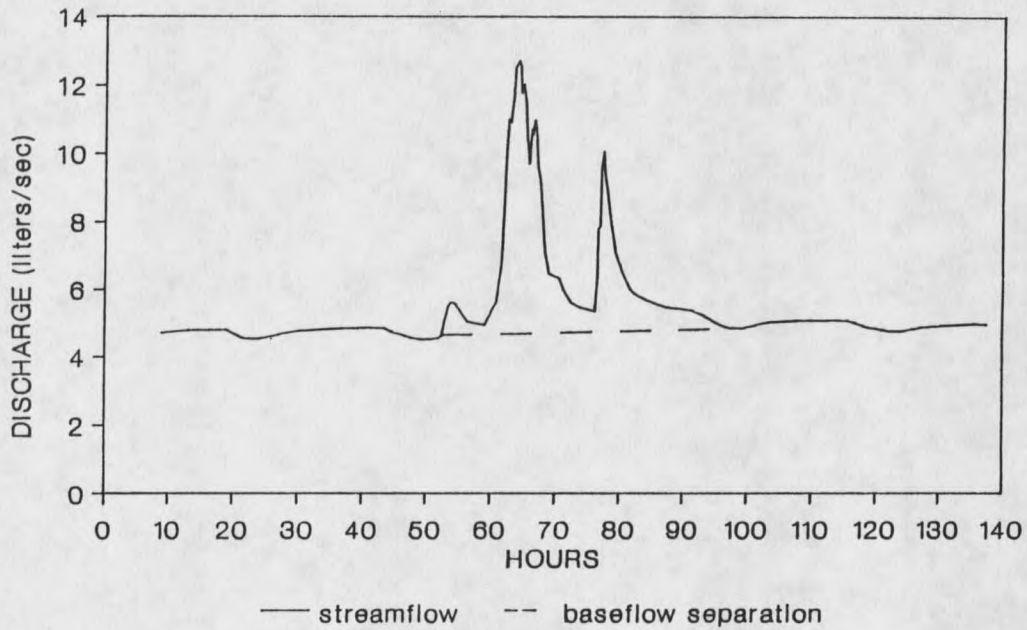


Figure 27. Storm runoff hydrographs for flumes B (a) and F (b) for the storm event of August 6, 1987. The recording rain gauge was not working properly during this storm event.

a)



b)

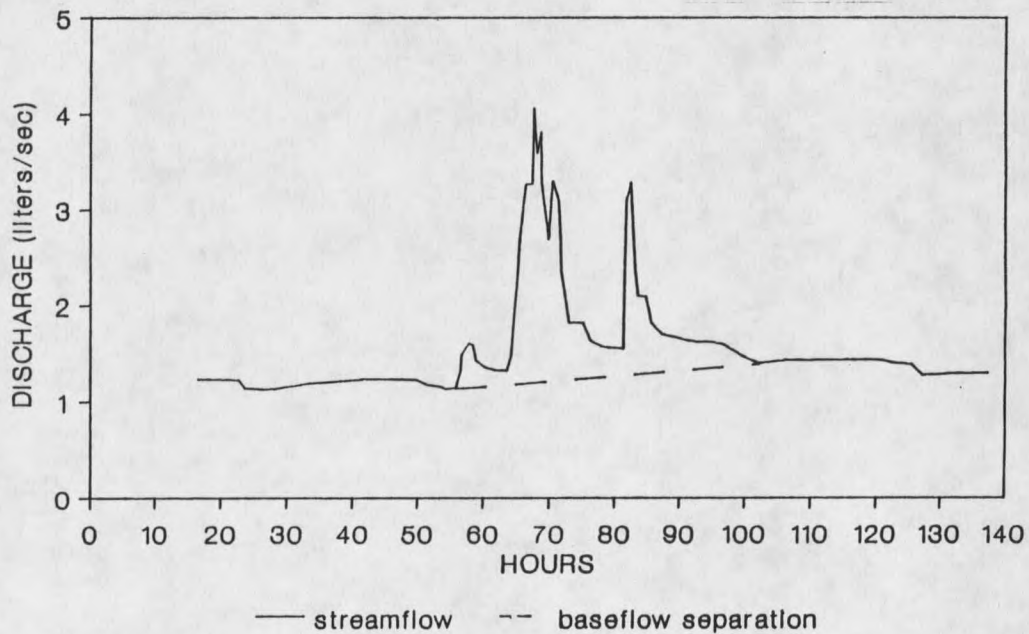
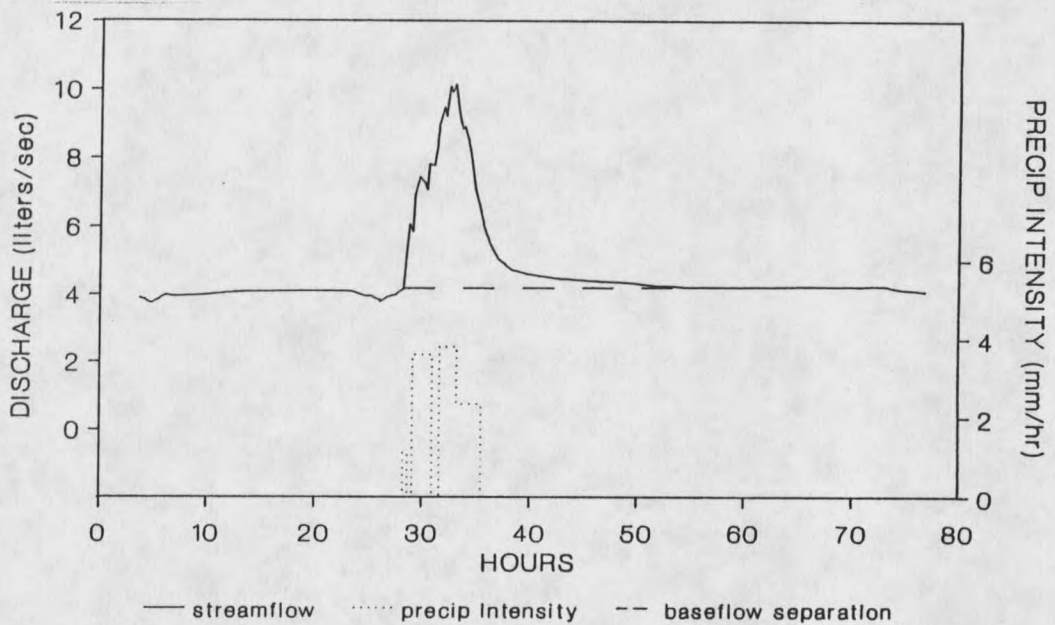


Figure 28. Storm runoff hydrographs for flumes B (a) and F (b) for the storm event of August 14-15, 1987. The recording rain gauge was not working properly during this storm event.

a)



b)

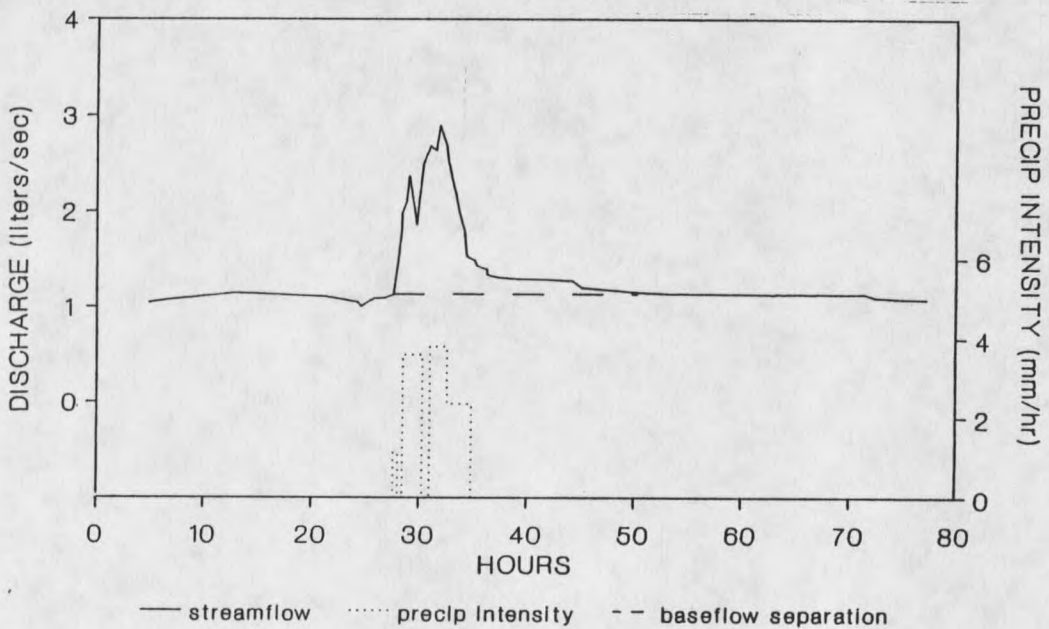


Figure 29. Storm runoff hydrographs for flumes B (a) and F (b), with hyetographs, for the storm event of September 26, 1987.

Problems do exist in matching rainfall intensity fluctuations with hydrograph fluctuations. Hyetographs do not always show peak intensities or fluctuating intensities during storm events as the pen on the recorder often stuck during an event for a period of time. For this reason, an average intensity of a storm during a period of time when the pen was stuck had to be calculated. This may or may not show the true intensity or fluctuations in intensity of a storm, particularly at times when there are long flat sections in the storm hyetograph. Sharp rises in intensity generally reflect real changes.

Also, the streamflow recorders and precipitation recorder generally did not match in their timing. One problem follows from the fact that several individuals changed the charts on the recorders. Times were not always written down on the precipitation charts, or the true beginning or end of the record was not marked or observed due to faulty equipment. At times the pen was placed on the chart and then moved into position to start the record. These starts can sometimes be deciphered or assumed to match the clock numbers on the chart. Thus, a timed record is available but actual times are not always known. The beginning of a precipitation event is artificially matched with the beginning of an event recorded for streamflow. The timing of the rest of the hyetograph is not altered so fluctuations in precipitation intensities can be matched with fluctuations in streamflow. Due to the artificial matching of hyetographs with hydrographs, lag times between precipitation and streamflow cannot be calculated.

The separation of baseflow from storm runoff can be interpreted for these hydrographs. The baseflow separation lines are included in

all figures for information at this point. The interpretation of these baseflow separation lines will be discussed in the next chapter.

Sediment Production

Sediment production was monitored in several locations within the grazing study area, through the use of sediment traps in an attempt to determine whether groundwater-seepage areas produced more sediment than other areas. Traps were cleaned and sampled on four different occasions in 1987: June 19, June 24, July 24 and September 1. The length of time between sampling periods varied considerably as did the amount of sediment collected from the traps on different dates. Sediment collection could not be made from all traps for all sampling dates. Not all traps were in place for the first two sampling dates and cattle often knocked traps out of the ground or filled traps with fecal matter at various times during the summer. Nearly all traps showed indications of some degree of cattle disturbance. Attempts were made to replace or clean traps if a cattle disturbance was found. Data of sediment collected from each trap for all dates are listed in Appendix F.

Because of the discrepancies in the data for different dates, an attempt was made to normalize the amount of sediment collected from the traps on the different dates (Table 3). Normalization of the data was achieved by calculating the amount of rainfall received over the collection period, then dividing the total amount of sediment collected by the total amount of rainfall received. Other factors such as

rainfall intensity and duration are probably very important in sediment transport but the overall precipitation record involving intensity measurements is spotty, and accurate calculation of these factors would be tenuous at best.

Table 3. Amount of sediment collected from each sediment trap (g/mm of rain), for each collection period and for the yearly average. Trap locations are shown in Figure 10.

Ground surface	Trap number	Collection date				
		6/19	6/24	7/24	9/01	Average
Cattle path	2-2	8.9	1.2	6.3		5.4
	1-3	3.8	2.4	3.1		3.1
Perennial seepage area	2-3	0.30	0.37	0.99	0.80	0.61
	8-1				0.45	0.45
	2-4	0.250	0.14		0.55	0.32
	4-1		0.19		0.36	0.27
Intermittent seepage area	0-1	0.160	0.058	0.032	0.107	0.089
	3-2	0.037	0.029	0.163		0.077
	10-2			0.054	0.060	0.057
	10-1			0.008	0.045	0.026
	8-2			0.015	0.011	0.013
Dry ground	1-4	0.031	0.090	0.070	0.082	0.068
	2-5	0.031	0.077	0.069	0.066	0.061
	5-2		0.048			0.048
	2-6		0.042	0.045	0.043	0.043
	4-3		0.026	0.006	0.094	0.042
	2-1	0.057	0.026			0.042
	4-2		0.045	0.029		0.037
	1-2	0.031	0.035	0.038	0.044	0.037
	7-1			0.023	0.015	0.019
	6-1		0.010	0.021	0.020	0.017
	0-2	0.008	0.013	0.007	0.031	0.015
	9-1				0.015	0.015
	11-2			0.019	0.009	0.014
	7-2			0.015	0.013	0.014
	3-1	0.017	0.016	0.006	0.014	0.013
	5-1		0.016	0.006	0.003	0.008
	1-1	0.009	0.013		0.002	0.008
	11-1			0.004	0.009	0.007
	1-5	0.006	0.003	0.005	0.009	0.006
	6-2			0.004		0.004
	9-2					

The results show that traps located in cattle paths collected the greatest amount of sediment on all sampling dates (Table 3). Traps located in perennial-seepage areas collected more sediment than traps located in intermittent-seepage areas and in dry-ground areas. Traps located in dry-ground areas collected about the same amount of sediment as traps located in intermittent-seepage areas.

Though sample populations (n) are small (Table 4), a two-tailed t-test was performed on the data to determine whether the differences found in sediment production between one ground surface type and another are significant. The null hypothesis for these tests is: there is no significant difference in the amount of sediment produced from one ground surface type to another. The alternate hypothesis is: there is a significant difference in sediment production from one ground surface type to the next. As sample populations (n) are small (Table 4), the 90% confidence level was chosen as the base to reject the null hypothesis. A modified standard error (SE+) needs to be calculated for t-tests when n is small (Freedman and others, 1978). The SE+ is determined as the standard error from a modified standard deviation (SD+). The data used in the statistical analyses are listed in Table 4. The average amount of sediment collected per mm of rain, per trap, for each ground surface type was tested against all other ground surface types, for each sampling date and for the yearly average (Table 5). The confidence level for differences in sediment produced from the different ground surface types is listed as $((1-p \text{ value}) \times 100\%)$.

Two-tailed tests made for difference of means between the ground surface types sampled June 19, indicate significant differences only

Table 4. Values used for statistical analysis of sediment production data. All values, except n, indicate the amount of sediment trapped (g/mm of rain).

Collection date	Ground surface ¹	Statistical values ²				
		AVE	SD	SD+	SE+	n
June 19	CP	6.4	2.52	3.56	2.52	2
	PS	0.28	0.026	0.036	0.026	2
	IS	0.099	0.062	0.087	0.062	2
	DR	0.024	0.016	0.017	0.006	8
June 24	CP	1.8	0.63	0.89	0.63	2
	PS	0.23	0.100	0.123	0.071	3
	IS	0.044	0.015	0.021	0.015	2
	DR	0.033	0.025	0.026	0.007	14
July 24	CP	4.70	1.57	2.22	1.57	2
	PS	0.99				1
	IS	0.054	0.057	0.063	0.028	5
	DR	0.023	0.021	0.022	0.006	16
September 1	CP	all traps in CP destroyed				
	PS	0.540	0.163	0.188	0.094	4
	IS	0.056	0.034	0.039	0.020	4
	DR	0.029	0.028	0.029	0.007	16
Yearly average	CP	4.3	1.15	1.63	1.15	2
	PS	0.41	0.133	0.153	0.077	4
	IS	0.052	0.029	0.032	0.014	5
	DR	0.026	0.019	0.020	0.004	20

¹ CP = cattle paths
 PS = perennial-seepage areas
 IS = intermittent-seepage areas
 DR = dry-ground areas

² AVE = yearly average
 SD = standard deviation
 SD+ = modified standard deviation for use when n is small
 SE+ = modified standard error for use when n is small
 n = sample population

for cattle paths versus dry-ground areas and perennial-seepage areas versus dry-ground areas (Table 5). Tests made for difference of means between the ground surface types sampled June 24, July 24, and September 1 show significant differences between all ground surface types except between traps located in dry-ground areas and traps

located in intermittent-seepage areas. Due to cattle disturbances, sediment amounts from traps located in perennial-seepage areas on the July 24 sampling date and from traps located in cattle paths for the September 1 sampling date were not available for statistical analysis. Tests made for difference of means on the yearly averages indicate significant differences in sediment production at the 90% confidence level between all ground surface types.

Table 5. Level of significance for the difference of means for two tailed t-test, shown as (1-p value) x 100%.

Group tested	Ground surface ¹			
		PS	IS	DR
June 19	CP	85%	85%	95%
	PS	-	87%	99%
	IS	-	-	<80%
June 24	CP	90%	89%	98%
	PS	-	91%	98%
	IS	-	-	<80%
July 24	CP	nd	97%	99%
	PS	-	nd	nd
	IS	-	-	<80%
September 1	CP	nd	nd	nd
	PS	-	99%	99%
	IS	-	-	<80%
Yearly average	CP	97%	99%	99%
	PS	-	99%	99%
	IS	-	-	90%

¹ CP = cattle path
 PS = perennial-seepage area
 IS = intermittent-seepage area
 DR = dry-ground area

nd = no data

Paired Sediment Traps

Paired sediment traps were used to determine if there was a difference in sediment production along a single drainage line. The

amount of sediment collected in traps located nearest to the stream (low) is greater than that collected in traps located in topographically higher areas (hi) for each paired trap configuration for each sampling date (Table 6). Differences in sediment collected between the upper and lower trap were significant only for paired traps located in the small vegetated gully (traps 1-4, 1-5) and in the small draw in which the lower trap (4-1) is in a perennial-seepage area and the upper trap (4-2) is located in a dry-ground area. The paired trap configurations located in the perennial-seepage area (S2) (2-3, 2-4) and in the dry terraced streambank (2-5, 2-6) show no significant difference in the average amount of sediment trapped between the upper and lower traps. Statistical tests were run only on the average amount of sediment collected (g/mm of rain), per trap, over the entire monitoring period as many data points are missing due to disturbance of the traps.

Table 6. Statistical values and test results for paired sediment trap configurations. All values, except significance level and n, are for the amount of sediment collected in each trap (g/mm of rain). Location of each trap is shown in Figure 10.

Location	Gully		Seep		Terraced		Seep / Dry	
	low	hi	low	hi	low	hi	low	hi
Trap	1-4	1-5	2-3	2-4	2-5	2-6	4-1	4-2
Date								
June 19	0.031	0.006	0.30	0.25	0.031	nd	nd	nd
June 24	0.090	0.003	0.37	0.13	0.077	0.042	0.185	0.045
July 24	0.070	0.005	0.98	nd	0.069	0.045	nd	0.029
September 1	0.082	0.009	0.79	0.55	0.066	0.043	0.360	nd
Yearly ave	0.068	0.006	0.61	0.31	0.061	0.043	0.273	0.037
SD ¹	0.026	0.003	0.33	0.21	0.020	0.002	0.124	0.011
SE+ ²	0.013	0.001	0.16	0.12	0.010	0.001	0.087	0.007
Sig level ³	98%		80%		<80%		90%	
n	4		3		3		2	

¹SD = standard deviation

²SE+ = modified standard error for use when n is small

³Sig level = Level of significance for difference of means for two tailed t-test, ((1-p value) x 100%), between low and hi traps in each location.

nd = no data

DISCUSSION

The objective of this thesis is to determine the influence groundwater-seepage areas exert on soil moisture, storm runoff production and sediment production within the Cottonwood Creek watershed. The results of the field measurements and observations indicate that seepage areas are sites with high soil moisture contents, and are areas of overland flow production and sediment production. However, further discussion of these processes is needed to understand the role groundwater plays in the hydrologic aspects of the watershed.

Spatial And Temporal Variability of Streambank Soil Moisture

One of the questions to be answered in this thesis is: are there areas along the stream with consistently high streambank soil moisture contents? If so, are they controlled by groundwater-seepage areas? In order to properly address the question, soil moisture variability needs to be assessed in both a spatial and temporal framework.

Spatial Variability Of Streambank Soil Moisture Content

Streambank soil moisture contents were expected to be spatially variable along the length of Cottonwood Creek due to the presence of groundwater seeps in localized areas. Seepage areas generally had higher streambank soil moisture contents than dry streambank areas with the exception of one zone within the grazing study area (Fig. 17).

This anomalous zone had high streambank soil moisture contents, but was not in a seepage or saturated area.

Differences in the depth to groundwater throughout the watershed are thought to be the cause of the spatial variability in moisture content (Wind, 1961 as cited in Ward, 1975; Anat and others, 1965; Reynolds, 1970a; Ripple and others, 1972), but this spatial variability may also be influenced by other factors such as soil textural differences (Reynolds, 1970b; Price and Bauer, 1984) and errors inherent in the gravimetric method of moisture sampling (Reynolds, 1970a; Hillel, 1982). Streambank soil textures are fairly uniform throughout the study area (Fig. 20) and the small differences found in soil texture do not relate well to the differences in soil moisture content. Errors in the sampling technique should be within ± 5 to 10% when the moisture content is calculated from 8 samples (Reynolds, 1970b). Also, Reynolds (1970c) identified differences in moisture content between areas with 10 measurements from each area over a period of one year. Thus, measured differences in soil moisture content at Cottonwood Creek are expected to be real. As groundwater does control areas of high moisture content within the seepage areas, groundwater may also control the high streambank soil moisture contents measured in the anomalous zone.

The anomalous zone has characteristics which suggest that groundwater influences the high moisture content. This zone is located just downstream of a groundwater-seepage area (S3) (Fig. 17), and through this zone the stream is very narrow (0.3 m) and is not deeply incised (0.2 m). Just below this anomalous zone the stream drops over

a small (0.4 m) waterfall (knickpoint), and streambank soils downstream of this waterfall are dry (<40 % soil moisture content). Greater incision by the stream can lead to a lowering of the water table within the streamside area (David and Ledger, 1988). The lowering of the water table in the riparian zone downstream of the waterfall may be a cause of the lower streambank soil moisture contents measured there. As the stream is not deeply incised through the anomalous zone, the water table may be close to the ground surface.

To assess the relation between soil moisture content and the depth to groundwater, a longitudinal profile of the ground surface along with the depth to the groundwater table was constructed for the streamside zone within the grazing study area (Fig. 30). The ground surface elevation and depth to groundwater are represented on different vertical scales in Figure 30, and the depth to groundwater is not a profile in the same sense as the ground surface profile. Depth to groundwater is read as the distance below the ground surface, so actual elevation of the groundwater table is not given. The depth to groundwater is shown for measurements made on September 1, 1987. Water levels in the monitoring wells were fairly high at this time, and this date was chosen because there was water in most monitoring wells. During periods with lower water levels, many of the monitoring wells contained no water, and the depth to the water table could not be measured.

A profile is presented only for the north streambank (Fig. 30) because well control on depth to the water table is much better for the north streambank than for the south streambank (Fig. 6). The accuracy

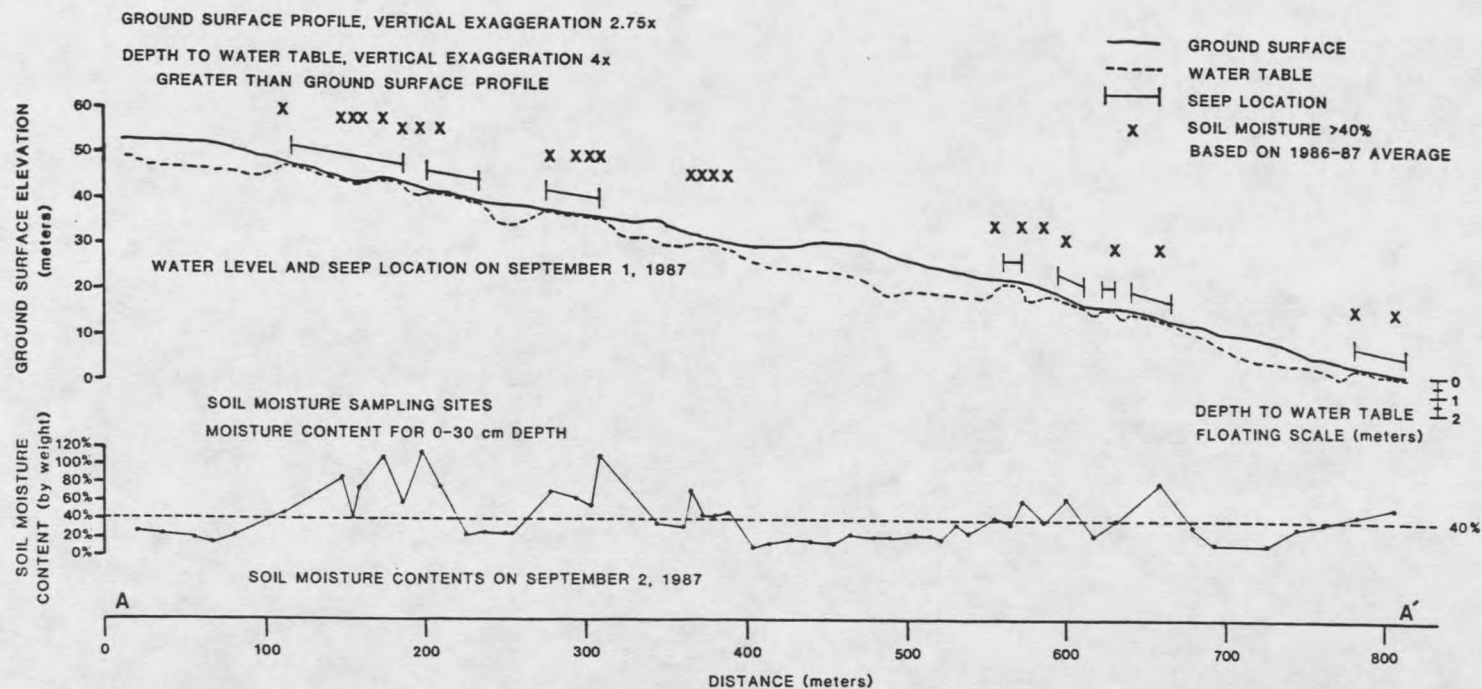


Figure 30. Long profile of ground surface along the north streambank within the grazing study area, showing the depth to groundwater, seep locations and soil moisture content of sampling sites. Location of profile is shown in Figure 31, contours from depth to groundwater map control water table profile (Fig. 32).

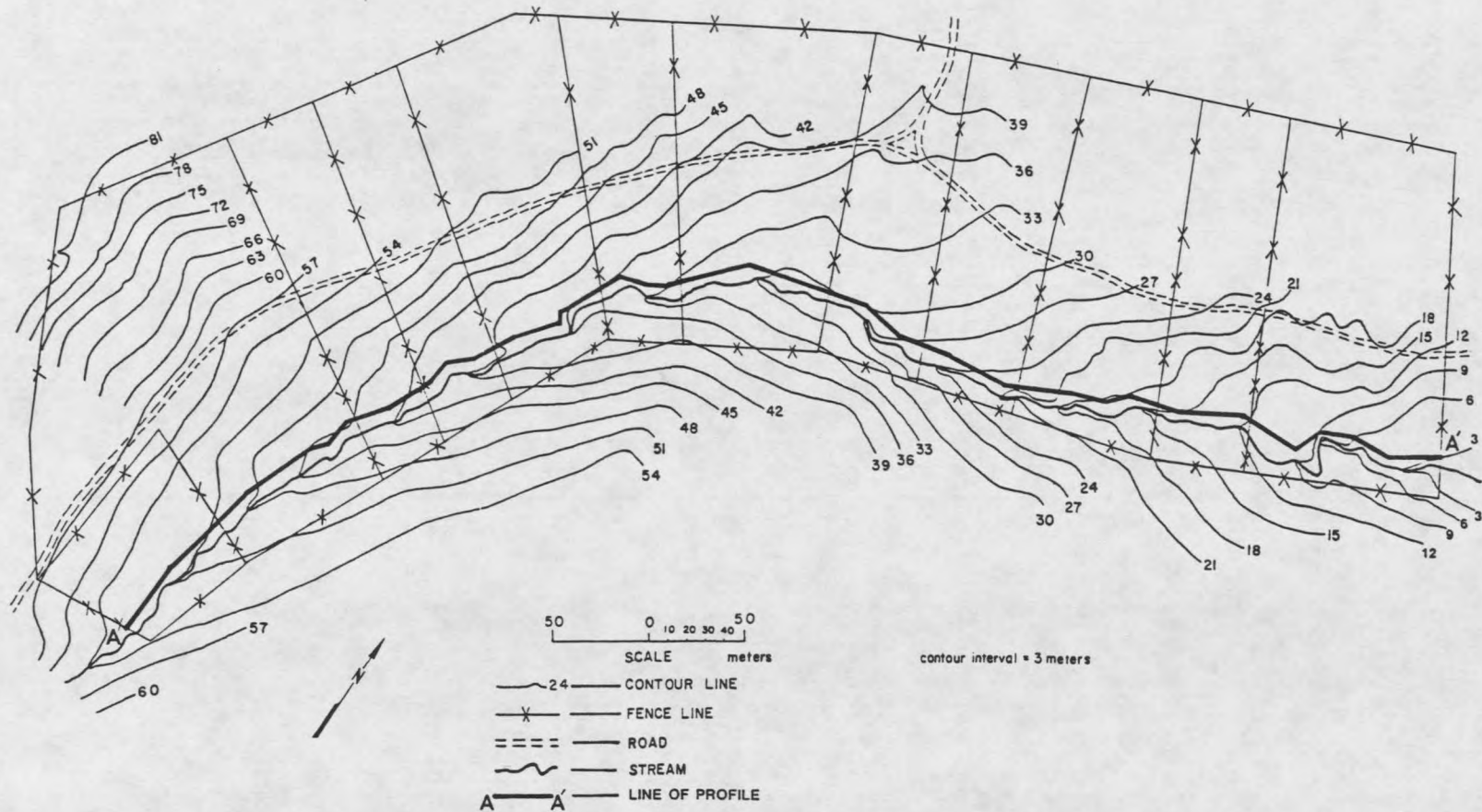


Figure 31. Location map of profile line for Figure 30.

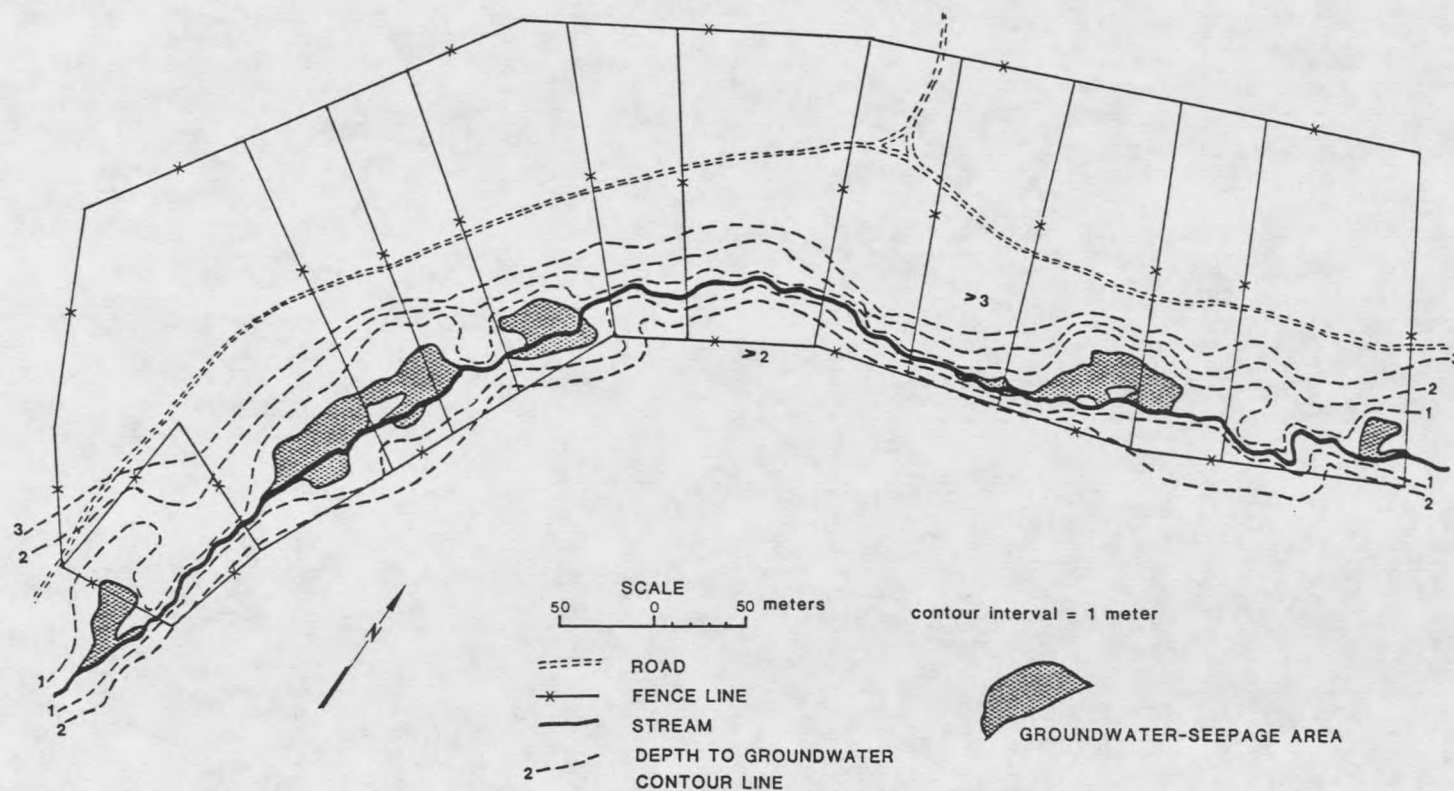


Figure 32. Map of seepage area location and depth to groundwater within the riparian zone of the grazing study area on September 1, 1987.

of the profile is limited by the number of groundwater-monitoring wells, the number of surveyed points of the ground surface and the precision of the survey technique. Water levels do fluctuate so the depth to the water table will change depending on moisture conditions within the basin. This fluctuation may induce changes in soil moisture content and saturated-seepage area size. Fluctuation of water levels within the monitoring wells were found to be as large as 0.5 m during the summer seasons, though many wells showed water level fluctuations of 0.3 m or less, particularly in seepage areas (Figs. 15, 16). Due to the scale and accuracy of the map, the line of the profile was not drawn through the exact location of the soil moisture sampling points. The sampling site locations and seepage area locations along the streambank were extrapolated to the profile location line. As a result, small discrepancies may exist when comparing the location of the soil moisture sample sites and the depth to groundwater.

There appears to be a good relation between soil moisture content and the depth to groundwater (Fig. 30). Soil moisture contents are found to be high in seepage areas where saturation of the soil was observed due to the presence of a very shallow groundwater table (Fig. 30). However, saturated areas of the seeps did fluctuate in size through time (Fig. 14). Saturation was not always observed at the ground surface within the seepage areas, but soil moisture contents remained high (Figs. 17, 18, 19) due to the persistent presence of a shallow groundwater table. The anomalous zone of high soil moisture content but no seepage is also in an area with a shallow groundwater table (0.5 m below the ground surface for the water level measured on

September 1, 1987) (Fig. 30). The areas with the lowest soil moisture contents occur where the groundwater table is well below the ground surface (>1 m) (Fig. 30). Patterns seen for high soil moisture areas based on the average moisture content over the two year period (Fig. 17) are the same as found on September 1, 1987 (Fig. 30). This favorable comparison is expected as the moisture content of any site was found to either stay wet or stay dry (Figs. 18, 19).

The sustained high moisture contents of the soils within groundwater-seepage areas are the result of either direct contact with the water table, or capillary action drawing water through soil pores to the soil surface a short distance above the groundwater table (Ward, 1975; Hillel, 1982). Within the groundwater-seepage areas the water table seems to be continually within 0.2 m of the ground surface. This allows capillary action to keep soils in a nearly saturated condition.

The anomalous zone of high streambank soil moisture content is located in an area with a shallow groundwater table (Fig. 30) but may be slightly above the capillary fringe. The water table within this zone is at a depth of about 0.5 m (Fig. 30) but may fluctuate to a depth of about 0.8 m. Even with a water table at this depth, one explanation for the high soil moisture content may be capillary rise. Moisture from the groundwater zone will migrate upward in the unsaturated zone in response to capillary forces which are influenced by evapotranspiration and the vertical suction gradient (Wind, 1961 as cited in Ward, 1975; Anat and others, 1965; Ripple and others, 1972). The ability of the groundwater zone to vertically recharge soil moisture lost to evapotranspiration at the ground surface is dependent

upon the unsaturated hydraulic conductivity of the soil and the depth to the groundwater table. For the coarse-textured soil within the study area (Fig. 20), the surface soil moisture should be efficiently recharged from the groundwater zone where the groundwater table is within approximately 0.8 m of the surface (Wind, 1961 as cited in Ward, 1975). As a result, the soil moisture within the anomalous zone might be expected to be affected by the groundwater table even though seepage is not evident. Dry zones are typically in areas where the depth to groundwater is greater than 1 m (Fig. 30), thus, groundwater probably has no effect on the surface soil moisture content in these dry areas.

Temporal Variability of Streambank Soil Moisture Content

Streambank soil moisture contents were found to fluctuate sporadically through time (Figs. 18, 19). However, a pattern is evident. Wet areas tended to remain wet while dry areas tended to remain dry throughout the study period. This is a very important point to be considered if soil moisture contents are to be correlated to streambank stability and cattle-grazing management practices along different sections of the stream. As wet areas remain wet through time, these wet areas will continue to be sensitive to damage from activities such as cattle trampling at all times. In addition, streambank slumps and flow slides within the study basin occur dominantly in seepage areas. These movements may cause changes in streambanks regardless of management practices. If not taken into account, the discrepancy in moisture content and streambank strength along different reaches of the stream may override experiments designed

to evaluate relationships between streambank damage and different management practices. Dry streambank areas may become dry enough during certain periods to withstand activities such as cattle trampling and sustain little damage (Pogacnik, 1985).

Although wet areas tend to be persistent, there is some variation in the data. This variation does not invalidate the data as the variation may be explained. Much of the temporal variability in streambank soil moisture may stem from sampling technique. Only one sample was taken from each sampling site for each sampling period. Due to the destructive nature of the sampling technique, the same point could not be sampled each time. When only one sample is used to determine the soil moisture content of a site, the error associated with the measurement may be $\pm 10\%$ or greater (Reynolds, 1970b). As a result, fluctuations in moisture content may be due to measurement error and not actual changes in moisture content. Samples with a high soil moisture content are susceptible to greater error than samples with a low moisture content (Reynolds, 1970b) which may explain the larger variations in moisture content in the wet areas than in the dry areas (Figs. 18, 19). Sampling was done infrequently so changes in soil moisture due to precipitation events cannot be determined. The soils in the study area are coarse textured and drain rapidly (SCS, 1985) so the moisture content in soils within dry areas may quickly achieve field capacity (Knapp, 1978). This may be the moisture content at which many dry samples were collected. Though the sampling procedure may not be able to decipher small-scale changes in moisture content through time, the overall pattern of wet areas staying wet due

to the presence of a shallow groundwater table, and dry areas staying dry due to removal of moisture through drainage and evapotranspiration is not negated.

The soil moisture fluctuation pattern for dry areas found in this study did not conform to the pattern found by Pogacnik (1985) in 1981 and 1982. In both 1981 and 1982 soil moisture contents were highest in June (16 to 17%), and then declined rapidly until the end of July (10 to 11%). The lowest moisture contents were measured at the beginning of September (<10%) (Pogacnik, 1985). Though the sampling procedure used in this study is not sensitive to small changes in moisture content, the changes noted by Pogacnik (1985) should have been large enough or persistent enough to recognize. One explanation for the difference in results may be that precipitation and snowmelt conditions were quite different during this study and the study of Pogacnik (1985). Precipitation patterns in 1987 did not follow the normal precipitation pattern through the year. In 1987, snowpack was low and summer precipitation was very high and late compared to normal (Fig. 12). Generally the summer months experience low precipitation which would cause a decline in soil moisture from wet spring conditions. In 1986 soil moisture measurements were not made until July so moisture contents may have been higher earlier in the year following snowmelt. Conditions were much wetter in 1981 and 1982 during the study of Pogacnik (1985). Streamflow (baseflow) was the highest recorded for Cottonwood Creek in the spring of 1981 when Pogacnik (1985) measured a discharge of 53 l/s, this discharge is much larger than the maximum flow of 8 l/s recorded in the spring of 1986, and 5 l/s in the fall of

1987. The study of Pogacnik (1985) indicates that soil moisture in dry areas may seasonally fluctuate due to changes in moisture conditions. However, these patterns may not be noted in years which have different weather conditions such as 1986 or 1987 (Figs. 18, 19). The soil moisture content in wet areas is expected to remain high irrespective of wet or dry weather because the nature of the soil moisture recharge is different for wet areas than that for dry areas.

Storm Runoff Production

Another hypothesis of this thesis is that groundwater-seepage areas produce more storm runoff than non-seepage areas. To test this hypothesis, predicted runoff-producing zones and runoff processes were used to calculate runoff volumes for naturally occurring storms. These calculated volumes were then compared to observed runoff volumes to determine the validity of the predictions.

Runoff Process Identification

Storm runoff is believed to be dominated by saturation overland flow and direct precipitation into the stream channel, based on field observations and hydrograph analysis. The storm runoff hydrographs analyzed from the study period are highly responsive precipitation events and to fluctuations in rainfall intensity (Figs. 21, 22, 23, 26, 29). This observation indicates that direct precipitation into the stream channel and/or overland flow rather than subsurface storm flow are the major sources of storm runoff from the drainage basin (Dunne and Black, 1970a, 1970b; Bevin, 1978; Dunne, 1978). The initial steep slope of the recession limb of storm hydrographs (Figs. 21

through 29) also indicates overland flow is a major contributor to storm runoff (Dunne, 1978).

Field observations indicate that the overland flow consists of saturation overland flow from the saturated-seepage area zones. No Horton overland flow was witnessed from dry areas other than the road surface within the study basin, but overland flow was observed from saturated-seepage areas during rainstorms. However, only low intensity events were witnessed in detail so these observations are not conclusive.

Hydrologic properties of the soils within the basin also indicate that Horton overland flow is not a major source of storm runoff. Soil permeabilities are high, 15-500 mm/hr (SCS, 1985) and infiltration capacities for the soil measured on hillslope areas above the riparian zone are in excess of 100 mm/hr (Marlow, 1988). The highest rainfall intensity recorded during the study period was only 22 mm/hr. The infiltration rates for dry soil are generally much higher than rainfall rates observed so little Horton overland flow generation is expected.

Subsurface storm flow is expected to be a minimal component of runoff in the Cottonwood Creek watershed. However, there is a second segment of the recession limb which has a low slope followed by a sharp drop in flow at the end of this low-slope segment (Figs. 23 through 26, 28, 29). The low-slope segment of the recession limb of the storm hydrograph may be inferred to be caused by either subsurface flow (Hewlett and Nutter, 1970; Freeze, 1972, 1974; Dunne, 1978) or slow drainage of water detained within seepage areas and the stream channel

(Pilgrim, 1966; Dunne, 1978). Water detention is caused by impedance of flow due to vegetation and other roughness elements as the flow becomes lower and slower. The very abrupt drop off of flow at the end of this low-slope segment on the storm hydrograph seems to indicate that slow drainage from seep and channel storage may be responsible for this part of the hydrograph. Subsurface flow is generally slow and attenuated and should not produce as precipitous a drop in the hydrograph as that observed (Hewlett and Nutter, 1970; Pilgrim and others; 1978).

Though direct measurements of subsurface flow were not made during this study, subsurface flow is not considered to be an important source of storm runoff in semi-arid drainage basins (Dunne, 1978; Dunne and Leopold, 1978; Pilgrim and others, 1978; Pilgrim and others, 1982; Pilgrim, 1983). A possible way to test for the occurrence of subsurface flow is to measure the hydraulic conductivity of the soil within the drainage basin. Measured hydraulic conductivities within the streamside area of the study basin range from 0.5×10^{-4} cm/sec to 2.8×10^{-3} cm/sec (Table 2). These values compare favorably with the values listed by the SCS (1985) for expected permeabilities of soil types found in the study basin, 4.2×10^{-4} cm/sec to 1.4×10^{-2} cm/sec. A computer model developed by Freeze (1972) indicated that subsurface flow was nearly nonexistent in the storm hydrograph for a hillslope with soil hydraulic conductivity of 4.4×10^{-3} cm/sec, even with a hillslope morphology considered the most conducive for the occurrence of subsurface storm flow. This model suggests little subsurface storm flow should be expected in the Cottonwood Creek watershed. A study by

Dunne and Black (1970a, 1970b) in Vermont also showed that subsurface storm flow is not a major contributor to the storm hydrograph in a basin with reported soil hydraulic conductivity of 9.5×10^{-3} cm/sec. Pilgrim and others (1978) found subsurface flow to be a very small part of the hydrograph for storms occurring on a hillslope in California with reported soil hydraulic conductivities of 2.5×10^{-2} cm/sec. Also, saturated or near saturated conditions are needed before much subsurface flow is expected to occur (Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Hewlett and Nutter, 1970; Weyman, 1973; Bevin, 1978; Bonell and others, 1985). Hillslopes within the study basin generally are dry and the water table is very deep, except in small areas of the riparian zone. These dry conditions would hamper generation of subsurface flow, particularly for inclusion in storm runoff. For these reasons little subsurface storm flow is expected in the Cottonwood Creek watershed and the low-slope segment of the storm hydrograph is thought to be dominated by drainage of rainwater detained in seepage areas and the stream channel.

Runoff Volume Calculations

To further test the hypothesis that storm runoff is produced mainly by direct precipitation onto saturated groundwater-seepage areas (saturation overland flow) and into the stream channel, predicted storm runoff was compared to observed storm runoff for 15 natural storms which occurred in the study basin during 1987. Results were compared both graphically and statistically, through the use of simple linear regression. As all storms analyzed in this section occurred in 1987, the year is not attached to storm dates in the following discussion.

To test the importance groundwater-seepage areas have on runoff production, the drainage basin was divided into two runoff reaches based on the location of the Parshall Flumes chosen for this study (flumes B and F) (Fig. 4). The drainage basin above flume F has a small total area of groundwater seepage and the expected storm runoff contributing area is dominated by the stream channel. Only one major groundwater-seepage area is located above flume F (seepage area S5) (Fig. 13). The major portion of the saturated area within seep S5 was not connected to the stream during most storms analyzed in this study, except for the storm which occurred September 26. For this reason, the saturated area of seep S5 was not included in calculations of storm runoff production except for the storm which occurred September 26. The drainage basin between flumes B and F has a much larger area of groundwater seepage (Fig. 13) so both the stream channel and saturated-seepage areas are expected to contribute to storm runoff.

Predicted runoff volumes were calculated by multiplying the total amount of precipitation received in a storm by the total area expected to produce runoff (precipitation (m) x contributing area (m^2) = runoff volume (m^3)). Expected runoff-producing zones are the stream channel and saturated zones of the groundwater-seepage areas at the time of a storm. Saturated-seepage area sizes were not mapped at the beginning of each storm so the expected saturated area of the seeps was assumed to be the same as that mapped on the date closest to the date of a storm. The stream channel may physically change during a storm event, causing changes in channel area, and potentially in contributing area. Continuous monitoring of stream channel change by Dr. Clayton Marlow

showed essentially no change of the stream channel during 1986 and 1987. For this reason channel areas are assumed constant. All data pertinent to runoff calculations are reported in Appendix G.

To determine observed storm runoff volumes, the observed storm hydrograph must be separated into baseflow and storm runoff components. A method of hydrograph separation similar to that of Hewlett and Hibbert (1967) was used for this study. However, some interpretation is needed based on individual hydrograph characteristics. The technique used simply involves drawing a straight line from the point on the hydrograph where storm flow rises above the normal diurnal fluctuation, to the point where the hydrograph is again noted to rise following the recession limb of the storm hydrograph (Figs. 21 through 29). The rise in the hydrograph following the storm runoff recession is interpreted to be diurnal fluctuation of baseflow. As a result, the separation line connects the two known points of baseflow on the storm hydrograph. If there are large baseflow increases during storm runoff, the large increases may be interpreted as storm runoff via subsurface flow even if the origin of the runoff is from the perennial groundwater body (Ragan, 1968; Sklash and Farvolden, 1979). The volume of runoff measured through use of this separation process should include the total volume of storm runoff observed for the basin regardless of the actual runoff processes occurring in the basin. This will serve as a test for prediction of runoff processes. Observed runoff volumes were obtained by measuring the area under the storm hydrograph above the baseflow separation line.

Observed storm runoff is expected to be somewhat less than predicted for several reasons. Interception of rainfall by vegetation will allow less rain to fall into the stream channel and onto seepage areas than that measured at the rain gauge (Ando and others, 1985; Moore and others, 1986). Depression storage of rainfall is also expected, primarily in seepage areas. Seepage areas are generally in slightly depressed areas and a small(?) amount of rainfall will be necessary to raise water levels before release of water from depression storage can occur. Cattle hoofprints are also very common in seepage areas. These hoofprints create many small depressions which can also catch and hold rain water. Water loss from the stream channel to the streambanks (bank storage) can also occur along the stream, particularly in areas where streambanks are dry (Pilgrim and others, 1982). The amount of rain water which will be lost to these processes is unknown at this time, but the concept that rain water will be lost from total runoff is important to realize when comparing predicted storm runoff volumes to observed runoff volumes.

Many measurements and assumptions are used in this part of the study, which leads to many potential sources of error. Observed storm runoff error is associated with the stage-discharge relationship of the flumes and measurements made with the Steven's recorders, along with error introduced when transferring data from a stage to a discharge hydrograph. The error associated with the observed storm runoff volume is determined to be ± 6.2 percent using methods outlined by Kulin (1975).

Determination of error in predicted storm runoff is not as straight forward. Errors associated with rainfall measurements, saturated-seepage area size measurements, and channel area determination all need to be estimated before a total error can be estimated. Estimation of error in rainfall measurements is 9 percent and is based on errors noted when calibrating the recording rain gauge and differences noted between the two rain gauges operating during the study period. The total error attributed to saturated-seep area is about 11 percent and involves error associated with mapping of the saturated area within seeps (5%), determination of the area of the saturated zones (1%) and the assumptions made concerning saturated area at the time of a storm (10%). Estimated error associated with stream channel area determination is 10% based on mapping error and assumptions made concerning the width of the stream channel between the streambanks (Fig. 5). The total error for calculation of predicted runoff volumes is 17.5 percent as determined by taking the square root of the sum of the squares of all error estimations (Kulin, 1975). The error associated with the predicted runoff volume is just an estimation and is assumed to be the maximum error which may apply to the calculation.

Comparison of Predicted and Observed Storm Runoff

Runoff Production Above Flume F. Most of the runoff production above flume F is predicted to be generated by direct precipitation into the stream channel. Graphical comparison of predicted storm runoff volumes versus observed storm runoff volumes for the stream reach above flume F is shown in Figure 33. Regression analysis of the data yields

an r^2 value of 0.94 indicating a close correlation of predicted to actual conditions. Direct precipitation into the stream channel does seem to account for the storm runoff volumes measured for this section of stream. Only one storm, that of June 9, produced more runoff than expected within the error limits. Most storms produced slightly less runoff than predicted, though this result was anticipated.

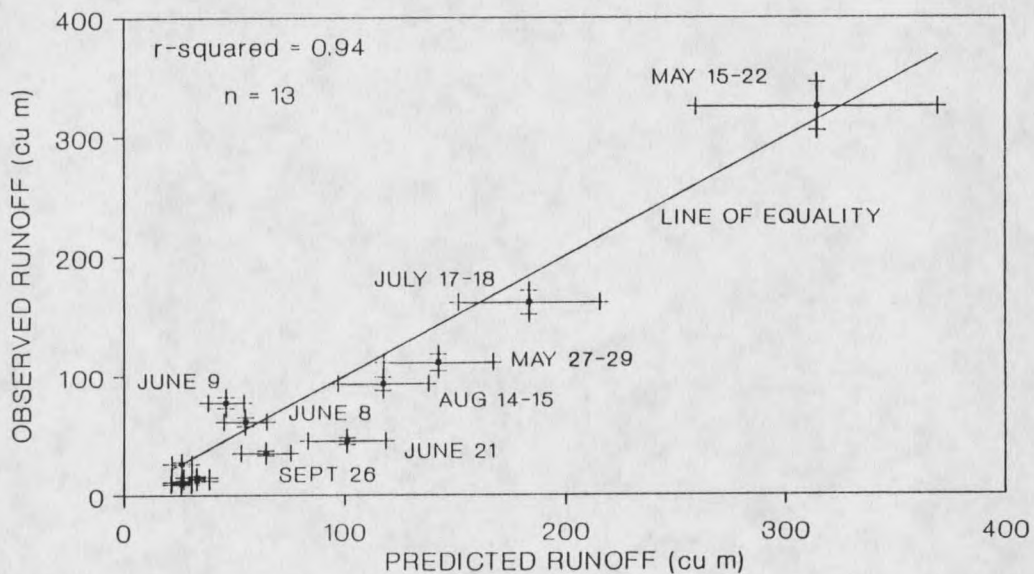


Figure 33. Graph of predicted versus observed storm runoff volumes, with error bars, for the study basin above flume F. Dates are shown for all but the five smallest storms in 1987 for reference.

Runoff Production Above Flume B. Runoff production above flume B is predicted to be generated by both direct precipitation into the stream channel and saturation overland flow, as groundwater-seepage areas occupy a significant area of the riparian zone between flumes B and F. Comparisons of predicted storm runoff volumes versus observed storm runoff volumes for the entire length of stream above flume B (Fig. 34) are different from those obtained above flume F (Fig. 33).

Many storms produced greater observed runoff than predicted above flume B, though less observed storm runoff than predicted was expected (Fig. 34). These storms occurred May 15-22, June 8, June 9, and July 10-11. Regression analysis of the data yields an r^2 value of 0.92 which indicates there is a strong linear correlation between predicted and observed runoff though data points do not fall where expected.

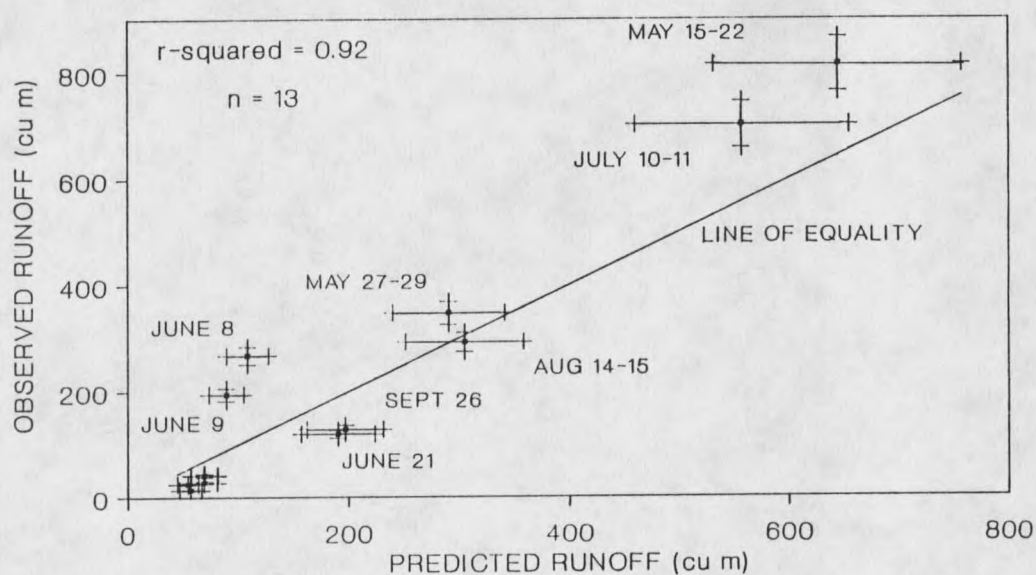


Figure 34. Graph of predicted versus observed storm runoff volumes, with error bars, for the study basin above flume B. Dates are shown for all but the five smallest storms in 1987 for reference.

The section of stream above flume B for these measurements also includes the section of stream above flume F. Thus, the total runoff-producing area is dominated by direct precipitation into the stream channel (53% to 94%, most commonly 75% to 80%, depending on saturated-seepage area size at the time of a storm) (Table 7). In order to get a better idea of groundwater-seepage area influence on storm runoff, the total volume of storm runoff and total area of the expected

runoff-producing zones measured above flume F were subtracted from measurements made for the total storm runoff and contributing area above flume B. This subtraction should give the runoff production only for that section of stream between flumes B and F (Ragan, 1968; Atkinson, 1978).

Table 7. Percentage of the total runoff predicted to be contributed by overland flow from groundwater-seepage areas. The remaining percentage is expected to be contributed from the stream channel area.

Events in 1987	Above flume B		Above flume F		Between flumes B and F	
	1	2	1	2	1	2
May 15-22	24%	47%	0%	17%	47%	68%
May 25	24%	47%	0%	17%	47%	68%
May 26	24%	47%	0%	17%	47%	68%
May 27-29	24%	47%	0%	17%	47%	68%
May 31	24%	47%	0%	17%	47%	68%
Jun 6	-	-	0%	17%	-	-
Jun 8	20%	47%	0%	17%	41%	68%
Jun 9	20%	47%	0%	17%	41%	68%
Jun 21	20%	47%	0%	17%	41%	68%
Jul 8	20%	47%	-	-	-	-
Jul 10-11	20%	47%	-	-	-	-
Jul 17-18	-	-	0%	17%	-	-
Aug 6	40%	47%	0%	17%	65%	68%
Aug 14-15	40%	47%	0%	17%	65%	68%
Sep 26	47%	47%	17%	17%	68%	68%

1 = Percentage when only saturated areas of seeps predicted to contribute to storm runoff.

2 = Percentage when entire area within the maximum extent of seeps predicted to contribute to storm runoff.

Graphical comparison of predicted storm runoff volumes versus observed storm runoff volumes for the stream section between flumes B and F is shown in Figure 35. Observed runoff volumes are often much greater than predicted, particularly for storms occurring May 15-22, May 27-29, June 8, and June 9. Regression analysis yields an r^2 of 0.81. This value is much lower than when the runoff-producing area is dominated by the stream channel area to a greater extent ($r^2 = 0.92$)

(Fig. 34). Between flumes B and F, saturated-seepage areas account for 41% to 68% of the expected runoff-producing area, though commonly the value is 41% to 47%, depending on saturated-seepage area size during a storm (Table 7). This indicates the stream channel itself is still an important contributing area to storm runoff. Predicted contributions to storm runoff from the stream channel were close to observed contributions above flume F (Fig. 33). Thus, the decline in correlation coefficient for runoff comparisons below flume F with seepage areas accounted for may imply that groundwater-seepage areas are indeed very important runoff-producing zones during storm events.

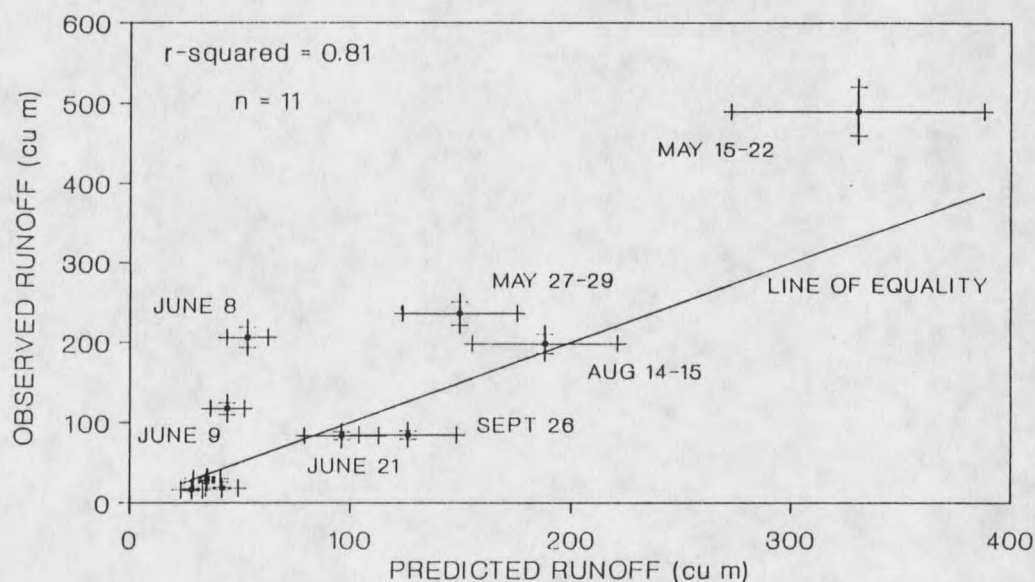


Figure 35. Graph of predicted versus observed storm runoff volumes, with error bars, for the study basin area between flumes B and F. Dates are shown for all but the four smallest storms in 1987 for reference.

As observed runoff is greater than expected for some storms there may be processes other than overland flow from mapped saturated-seepage areas and direct precipitation into the stream channel which

influence storm runoff. More runoff than expected was produced mostly in the region where seepage areas exist. The saturated areas may generate subsurface storm flow as well as overland flow. However, Dunne and Black (1970a, 1970b) suggest that only large storms of low frequency may produce much subsurface storm flow. Horton overland flow may also be an important contributor to storm runoff for the stream between flumes B and F, though it appears to be insignificant for the stream above flume F. As Horton overland flow and subsurface storm flow are considered to be negligible in the study basin, the process of saturated-seepage area expansion may influence storm runoff.

Saturated-Seepage Area Fluctuation During Storm Events. Saturated-seepage areas may expand during a storm event, which would cause the poorer correlation found between predicted and observed storm runoff volumes for the stream reach between flumes B and F. The prediction of runoff volumes did not account for varying saturated areas during storm events. Saturated area size fluctuations during storms have been noted by Betson and Marius (1969), Dunne and Black (1970a, 1970b), Bevin (1978), Pilgrim and others (1978), and Bonell and others (1984). Saturated-seepage areas within the study basin were not observed to expand during storm events, but some evidence exists indicating that saturated-seepage area does expand during large storm events. Mapping of saturated-seepage area sizes on May 17, 1987 took place during the large event of May 15-22. Saturated-seep areas were greater on May 17 than sizes mapped or observed both preceding (May 7) and following (June 13) the storm event (Fig. 14). This observation suggests that saturated area may fluctuate during a storm event. Also, groundwater

levels were found to rise during, or shortly after (depending on the time of measurement) the large storm events which occurred at the end of May and around July 10-11 (Fig. 16). This rise in groundwater levels may be an indication of saturated area expansion (Ragan, 1968; Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Sklash and Farvolden, 1979).

If saturated-seepage areas do indeed grow in size during a storm event, the runoff-producing area during a storm would also expand. This expansion would cause underestimation of predicted runoff volumes if this expanded area was not taken into consideration. Also, only the saturated zones of groundwater-seepage areas were mapped and considered to be runoff-contributing areas. The soils in the "dry" zones of the seepage areas (along the streambanks) were found to have high soil moisture contents throughout the year, even when the areas were not saturated at the surface (Figs. 17, 30). The soil moisture deficit in these areas would not be great and infiltration capacities would probably be low (Betson and Marius, 1969; Dunne and Black, 1970a, 1970b; Knapp, 1978). Inputs from precipitation may easily cause saturated conditions, which may make "dry" areas of the seeps conducive to overland flow.

Field evidence indicates that groundwater-seepage areas do achieve a maximum size within the study basin, even under wet conditions. The maximum seepage area sizes mapped in 1986 and 1987 were roughly the same, though the conditions which caused the maximum saturated-seepage area extent were different. In 1986, the maximum saturated area extent was mapped in June (Fig. 14) following snowmelt and spring rains. In

1987, snowfall was light during the winter and the saturated-seepage area was smallest in late winter and spring. Precipitation was greater than normal during the summer of 1987 (Fig. 12) and the maximum extent of the saturated-seepage area was mapped in September (Fig. 14). Also, beyond the boundary of the maximum observed extent of the seepage area there are no deep cattle hoofprints. Within the maximum extent of the seepage areas such hoofprints are seen even within intermittently saturated areas. In some areas there is an abrupt topographic change from the seepage area edge to dry ground. This change is often caused by slumping of the streambanks within the seepage areas. There also appears to be a change in vegetation type from seepage area to dry ground, again indicating that the maximum extent of the seepage areas remains constant. Willows and sedges grow in seepage areas but do not appear in dry-ground areas. However, this observation needs to be confirmed through vegetation transects.

Though only saturated areas were mapped and considered zones of runoff production in previous tests, the entire area encompassed by the maximum extent of the groundwater-seepage areas may contribute to storm runoff by the end of a large storm. In reality, the extent of the seepage area contributing to storm runoff may be controlled by the size of the saturated area at the beginning of a storm, moisture conditions preceding a storm, the size of a storm, and the extent of the increase of the saturated area during a storm.

To further test this possibility, predicted storm runoff volumes were retested against observed storm runoff volumes based on a new assumption that the entire zone within the maximum extent of

groundwater-seepage areas contributed runoff during a storm. Observed runoff volumes are anticipated to be less than predicted due to factors such as depression storage, rainfall interception and bank storage.

Also, some precipitation will fill moisture deficits within "dry zones" of seepage areas to cause expansion or saturation, and will not occur as runoff. As seepage areas are of limited extent above flume F, this assumption will not be tested for runoff volumes above flume F.

Instead, the prediction was tested for the stream reach between flumes B and F.

Graphical comparison of predicted storm runoff versus observed storm runoff from the expanded saturated zone and the stream channel is presented in Figure 36. As anticipated, observed storm runoff volumes are less than expected with the exception of two storms, those which occurred June 8 and June 9. Graphically, the comparison between predicted and observed storm runoff is much better when the entire seepage area zone is expected to be contributing (Fig. 36) than when only the saturated area at the beginning of a storm is expected to contribute (Fig. 35). Regression analysis yields an r^2 of 0.88 for the data presented in Figure 36. The modified approach yields a slightly better correlation than that found for the data in which only saturated areas were expected to contribute to storm runoff ($r^2 = 0.81$) (Fig. 35). If saturated-seepage area expansion does occur during large storm events as implied by the data, intermittently saturated seepage areas also are important in storm runoff production via overland flow even when the areas are unsaturated at the surface before a storm.

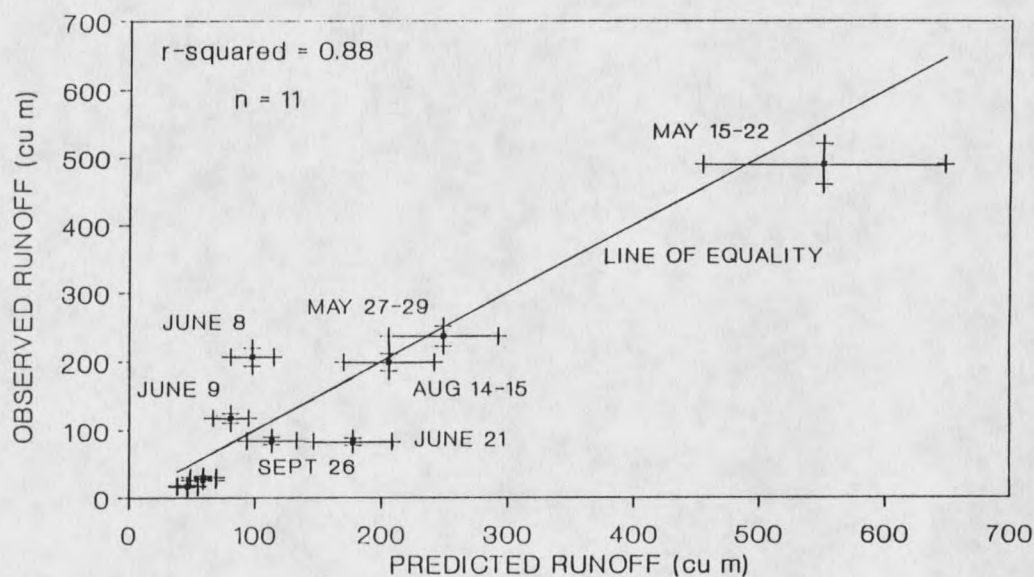


Figure 36. Graph of predicted versus observed storm runoff volumes, with error bars, for the study basin area between flumes B and F when the entire area within the maximum extent of the groundwater-seepage areas is expected to contribute to storm runoff. Dates are shown for all but the four smallest storms in 1987 for reference.

Runoff Processes and Contributing Areas

While direct precipitation onto mapped saturated areas (saturation overland flow) and into the stream channel predict storm runoff well for most storms, saturation overland flow from the area within the maximum extent of groundwater-seepage areas was required to predict storm runoff for larger events. Five storms in 1987 produced more runoff than predicted for the contributing area above flume B based on the original predictions (i.e., predicted runoff = direct precipitation onto mapped saturated areas and into the stream channel) (Figs. 34, 35). These storms occurred May 15-22, May 27-29, June 8, June 9, and July 10-11. When the entire area within the maximum extent of the groundwater-seepage areas was expected to contribute to storm runoff,

the storms of May 15-22, May 27-29, and July 10-11, fit the prediction much better (Fig. 36). The improved correlation indicates that the greater runoff than originally predicted was produced from the zone within the maximum extent of the groundwater-seepage areas. The storms which occurred June 8 and June 9 had more runoff than predicted even when the area within the maximum extent of the groundwater-seepage areas was expected to contribute.

All storms, except that of May 27-29, which produced greater storm runoff than originally predicted (Figs. 34, 35) had longer return periods than storms which produced runoff nearly as expected (Table 8). This suggests that only large storm events may produce runoff from areas other than saturated areas of seeps and the stream channel. The lower return period storms later in the summer (after July 10) (Table 8) occurred when saturated-seepage areas were nearing their maximum size and little saturated area expansion would be needed for the storms to produce the volumes of runoff observed. Also, storms with smaller return periods may not cause saturated area expansion (Dunne and Black, 1970a, 1970b). The storm of May 27-29 occurred shortly after the large storm of May 15-22 and many smaller storms occurred between these two events. Thus, the expanded saturated area caused by the May 15-22 storm may have still been large when the May 27-29 storm occurred.

Return periods for the storms were estimated from regional maps and charts published by the U.S. Weather Bureau (1955, 1961) as precipitation data for the Cottonwood Creek watershed are insufficient to determine site specific return periods. The expected return period for most storms was estimated from U.S. Weather Bureau (1961) maps

based on the total precipitation and duration of the storms (depth-duration) as measured intensities were generally low (Table 8).

However, the storms of June 8 and June 9 were of low rainfall but of higher intensity. In these two cases, the return period listed (Table 8) is for the intensity-duration of the storm based on U.S. Weather Bureau (1955) charts. The recording rain gauge was not recording properly for many of the storms so no data are available concerning intensity and duration. The storm of July 10-11 is of great interest as it was very large. The recording rain gauge was not recording properly at this time. The amount of rainfall was recorded in a non-recording gauge. The duration of the storm was inferred by taking measurements from the streamflow hydrograph.

Table 8. Storm characteristics and return periods (U.S. Weather Bureau, 1955, 1961).

Events in 1987	Total precip mm	Storm duration hrs	Intensity		Return period yrs
			peak mm/hr	duration min	
May 15-22	90.7	150.5	4.6	30	25
May 25	9.7	8.7	2.3	40	<2
May 26	9.7	16.7	3.3	70	<2
May 27-29	40.9	44.5	7.9	15	<2
May 31	7.6	2.7	1.3	162	<2
Jun 6	7.4	4.0	8.9	20	<2
Jun 8	16.0	1.9	16.3	30	* <5
Jun 9	13.2	11.2	22.4	30	* 5
Jun 21	29.2	8.2	6.1	96	<2
Jul 8	8.4	nd	nd	nd	nd
Jul 10-11	82.3	(estimated 63-76 mm in 24 hrs)			75-100
Jul 17-18	51.3	33.6	13.5	15	2
Aug 6	7.6	nd	nd	nd	nd
Aug 14-15	33.8	nd	nd	nd	nd
Sep 26	18.5	7.3	3.8	96	<2

* = return period for intensity-duration, others for amount-duration
nd = no data

The storms of June 8 and June 9 which produced more runoff than expected, even when the maximum extent of the seepage areas were predicted to contribute runoff (Fig. 36), each had a higher intensity level than other storms during the study period, 16.3 and 22.4 mm/hr, respectively (Table 8). If permeability of the soil is considered to be near the minimum infiltration capacity (Betson and Marius, 1969), these two storms may have generated Horton overland flow. The SCS (1985) reports permeabilities of 15 to 500 mm/hr for soil types within the study basin, indicating infiltration capacity of the soil may have been exceeded by these storms in some areas. Horton overland flow generation from areas outside the groundwater-seepage areas would explain observed runoff being greater than predicted. Areas which may generate Horton overland flow in the Cottonwood Creek watershed are not known as the occurrence of Horton overland flow was not witnessed. Mapping the infiltration capacities of the soils within the drainage basin might help define areas which produce Horton overland flow during more intense rainstorms (Dunne and others, 1975). These measurements were not made during this study. Defining areas which produce Horton overland flow could be of importance in sediment delivery studies.

While the specific areas which produce Horton overland flow are not known, the size of the contributing area may be estimated. Total contributing area to storm runoff was calculated by the Tennessee Valley Authority (1970, as cited in Dunne and others, 1975) by dividing the observed storm runoff volume by the total rainfall received during a storm ($\text{area (m}^2\text{)} = \text{storm runoff (m}^3\text{)} / \text{rainfall (m)}$). Overland flow is expected to be generated from the area within the maximum extent of

the groundwater-seepage areas, so this area, along with the stream channel area, was subtracted from the total calculated contributing area to determine the area from which Horton overland flow may have been generated (Table 9).

The maximum area calculated to produce Horton overland flow from the study basin above flume F is about 1650 m^2 (Table 9). This area is less than one-half the area occupied by the stream channel (3465 m^2) indicating Horton overland flow occurs from only a very small area in this part of the drainage basin. The maximum area calculated to produce Horton overland flow from the drainage basin between flumes B and F is about 6800 m^2 (Table 9). This calculated area is greater than the area occupied by the stream channel and the maximum extent of the groundwater-seepage areas combined (6073 m^2). Thus, Horton overland flow can be a large contributor to storm runoff for the stream reach between flumes B and F during intense storms.

Though the specific areas of Horton overland flow production are not known, Horton overland flow contributing to storm runoff probably occurs in riparian areas. Horton overland flow was not observed on hillslope areas during the June 8 storm (Marlow, 1988) and overland flow generated from hillslope springs and the road surface has been observed to infiltrate quickly after leaving these areas and did not reach the stream channel. Similar observations were noted by Ammerman (1965). The storms which produced Horton overland flow during the study period had return periods of about five years (Table 8). As Horton overland flow generation is somewhat uncommon,

Table 9. Predicted and observed runoff-contributing areas (m²).

Events 1987	Flume	Predicted area		Observed area		
		1	2	3	4	5
May 15-22	B	7102	10235	8982	-1253	0.5%
May 25	B	7102	10235	4384	-5852	0.2%
May 26	B	7102	10235	4254	-5981	0.2%
May 27-29	B	7102	10235	8476	-1760	0.4%
May 31	B	7102	10235	3259	-6976	0.2%
Jun 8	B	6760	10235	16678	6443	0.8%
Jun 9	B	6760	10235	14698	4462	0.7%
Jun 21	B	6760	10235	4368	-5851	0.2%
Jul 8	B	6760	10235	1618	-8617	0.1%
Jul 10-11	B	6760	10235	8530	-1706	0.4%
Aug 6	B	9027	10235	3717	-6520	0.2%
Aug 14-15	B	9027	10235	8635	-1601	0.4%
Sep 26	B	10235	10235	6415	-3821	0.3%
May 15-22	F	3465	4162	3581	-581	0.3%
May 25	F	3465	4162	1247	-2601	0.1%
May 26	F	3465	4162	1561	-2915	0.1%
May 27-29	F	3465	4162	2713	-1450	0.2%
May 31	F	3465	4162	1156	-3007	0.1%
Jun 6	F	3465	4162	3487	-675	0.3%
Jun 8	F	3465	4162	3791	-372	0.3%
Jun 9	F	3465	4162	5811	1648	0.5%
Jun 21	F	3465	4162	1537	-2626	0.1%
Jul 17-18	F	3561	4162	3135	-1123	0.3%
Aug 6	F	3465	4162	1394	-2769	0.1%
Aug 14-15	F	3465	4162	2766	-1396	0.2%
Sep 26	F	4162	4162	1879	-2281	0.1%
May 15-22	B-F	3637	6073	5401	-672	0.7%
May 25	B-F	3637	6073	3137	-2937	0.4%
May 26	B-F	3637	6073	2694	-3380	0.3%
May 27-29	B-F	3637	6073	5763	-310	0.7%
May 31	B-F	3637	6073	2104	-3970	0.3%
Jun 8	B-F	3295	6073	12888	6814	1.6%
Jun 9	B-F	3295	6073	8888	2814	1.1%
Jun 21	B-F	3295	6073	2831	-3233	0.3%
Aug 6	B-F	5562	6073	2323	-3751	0.3%
Aug 14-15	B-F	5562	6073	5868	-206	0.7%
Sep 26	B-F	6073	6073	4536	-1540	0.5%

1 = Stream channel area and saturated-seepage areas.

2 = Stream channel area and maximum extent of seepage areas.

3 = Total contributing area calculation as described by TVA (1970).

4 = Calculated contributing area (3) - predicted maximum contributing area (2) (negative indicates 3 > 2).

5 = Calculated contributing area (3) as percentage of the total drainage basin area.

groundwater-seepage areas are the dominant areas from which overland flow generation occurs during most storm events.

Though the area from which Horton overland flow can be delivered as storm runoff is significant when compared to groundwater-seepage area and stream channel area, it is still a very small portion of the total drainage basin area. The largest total runoff-contributing area (for all runoff processes combined) calculated for the study period is only 0.8% of the total watershed area above flume B, and 1.6% of the total watershed area between flumes B and F (Table 9). The riparian area, particularly groundwater-seepage area, is small compared to the entire basin area, but is very important when put in the perspective of where water comes from to generate storm runoff.

Runoff-contributing areas in small, first to third order, drainage basins in humid regions seem to commonly comprise 5% to 20% of the total basin area, though contributing areas can be greater than 50% of the watershed area (Dunne and Black, 1970a, 1970b; Weyman, 1973; Dunne and others, 1975; Pilgrim and others, 1982; Ando and others, 1985). The contributing area expressed as a percentage of the total drainage basin is generally an indicator of the size of the saturated area and stream channel area within the basin. Drainage basins in semi-arid regions have been reported to have runoff-contributing areas which comprise 12% to 64% of the total basin area (Arteaga and Rantz, 1973; Lane and others, 1978) but may reach up to 100% in some areas (Pilgrim, 1982). However, these estimates are for basins in which Horton overland flow is considered the primary storm runoff mechanism. Low infiltration capacities of the soils in these areas are the main reason

runoff is generated over a large area. The basins in semi-arid regions previously reported in the literature have been ephemeral or intermittent in nature. A dry basin with permeable soils and a perennial stream, such as the Cottonwood Creek watershed, produces much less storm runoff than other semi-arid basins reported, and illustrates the importance of soil permeability when assessing runoff production in semi-arid basins. In semi-arid basins with greater soil permeabilities, rainfall is absorbed into the soil and subsurface percolation of water appears to be too slow to produce storm runoff. However, subsurface flow is probably an important contributor to dry-weather baseflow and recharge to groundwater-seepage areas (Hewlett and Hibbert, 1963; Dunne and Black, 1970a, 1970b; Weyman, 1973; Bevin, 1978; Pilgrim and others, 1978).

Sediment Production

As groundwater-seepage areas were hypothesized to produce greater overland flow than dry areas, groundwater-seepage areas were also hypothesized to have the potential to produce more sediment than dry areas within the study basin. The areas within a watershed which produce overland flow should be areas over which sediment is transported (Dunne and others, 1975; Hewlett and Troendle, 1975; Dickinson and Wall, 1977; Dunne and Leopold, 1978; Lane and others, 1978; Dunne, 1983; Istok and Kling, 1983; Heede, 1984; Campbell, 1985). Zones of perennial groundwater seepage were found to produce more sediment due to overland processes than areas of dry ground away from cattle paths (Table 3). This result is consistent with the results

which indicate runoff generated by overland flow is contributed dominantly from groundwater-seepage areas within the study basin (Fig. 35). However, sediment traps were placed in the watershed in order to get only a first approximation of sediment-producing areas within the streamside environment. This is the area which has the greatest potential to contribute sediment to the stream (Dickinson and others, 1985, Snell, 1985). Answering the question; "Do groundwater-seepage areas have the potential for greater sediment production than other areas?" is problematic, though patterns do exist.

Sediment production from ground surface types consistently followed the order: cattle paths > perennial seeps > intermittent seeps $\geq$ dry ground (Table 3). Intermittent seeps and dry-ground areas generally produced nearly the same amount of sediment, though the lowest sediment amounts were observed from traps located in dry-ground areas.

Statistical analysis generally revealed significant differences in sediment production between the ground surface types, except for differences between intermittent seeps and dry-ground areas (Table 5).

However, not all statistical tests indicated that there was a significant difference in sediment production between ground surface types, particularly for the June 19 and June 24 sampling dates (Table 5). The statistical analysis used (two-tailed t-test) is sensitive to the size of the populations sampled (Freedman and others, 1978). The discrepancies noted in the statistical analysis probably are indicative of the small sample sizes, lack of data from all traps for all collection periods, and the large variations in sediment amounts

observed in the traps, both at a trap through time and between traps within a given ground surface type.

Although variability is present, the data do indicate that sediment production is different between ground surface types, despite the discrepancies in the statistical analysis. Sediment amounts (g/mm of rain) collected in traps within each ground surface type are within the same order of magnitude on all sampling dates, except for sediment amounts trapped in intermittent-seepage areas (Table 3). As these similarities do exist, it is feasible to compare sediment production between the ground surface types.

Differences in sediment amounts (g/mm of rain) between ground surface types generally differed by an order of magnitude or more (Table 3). Differences of this magnitude were found on every sampling date between cattle paths and all other ground surface types, and between perennial-seepage areas and dry-ground areas (Table 3). Intermittent-seepage areas generally produced sediment amounts which were similar to dry-ground areas, but two of the traps (0-1 and 3-2) sporadically collected larger amounts of sediment (Table 3).

As differences in sediment production are an order of magnitude or more between ground surface types, and sediment amounts within ground surface types are within the same order of magnitude, the differences in sediment production between ground surface types should be greater than the range of error. Thus, differences in sediment production between ground surface types documented in this study should indicate

that these differences are significant, except for differences between intermittent-seepage areas and dry-ground areas.

While differences in sediment production between ground surface types are significant, there are some differences in sediment production within the different ground surface types. Differences between sediment amounts within intermittent-seepage areas and dry-ground areas are significant, though sediment amounts are generally within the same order of magnitude within the ground surface types. Some of this variation may be the result of errors evident in the use of overland flow sediment traps to document sediment production. Cattle disturbances of sediment traps may have skewed the data. Most traps were stepped on or kicked out of the ground at one time or another. The amount of sediment which may have been kicked and/or dropped in a trap from a bovine hoof is unknown. Disturbances caused by placing a trap in the ground can also affect the amount of sediment collected in a trap. Often vegetation was inadvertently removed from the area around the lip of a trap during installation. Sediment transported by rainsplash or wind could easily be deposited in the trap from this disturbed area next to the trap and may account for most of the sediment observed in traps within dry-ground and intermittent-seepage areas. Due to the small amounts of sediment collected in many of the traps, errors in the amount of sediment produced from a given area may be quite large. Despite the errors, there are processes that control the amount of sediment transported to the traps which can explain the differences in sediment production between ground surface types.

Controls on Sediment Production

The portion of a watershed which has the characteristics necessary to produce overland flow is the area from which erosion and transport of sediment is most likely to occur (Dickinson and Wall, 1977; Lane and others, 1978; Dunne, 1983; Istok and Kling, 1983; Heede, 1984; Campbell, 1985). Overland flow is considered to occur dominantly from groundwater-seepage areas within the study basin. This suggests greater sediment production from groundwater-seepage areas than dry-ground areas. However, intermittent-seepage areas produced less sediment than perennial-seepage areas, and two of the sediment traps located in intermittent-seepage areas also collected less sediment than many of the traps located in dry-ground areas (Table 3).

Several processes may explain why intermittent-seepage areas produce small amounts of sediment. Unless saturated, intermittent seeps generally do not produce overland flow, except possibly during large storm events. Also, vegetation cover appears to be thicker in intermittent-seepage areas than in perennial-seepage areas but this was not measured. The amount of vegetation or bare ground is important as vegetation limits sediment production (Gifford, 1980). Little bare ground can be seen in intermittent-seepage areas. While perennial-seepage areas have much vegetation, there are areas of bare ground visible. Perennial-seepage areas also seem to have more cattle induced soil and vegetation disturbance than areas within intermittent seeps where sediment traps are located. Perennial-seepage areas generally have a continuous flow of water, even during periods of dry weather. This may cause perennial seeps to produce more sediment than

intermittent seeps. The amount of sediment trapped may not indicate storm-induced sediment production, but rather that sediment is in transport and will increase total sediment production.

Very small amounts of sediment were observed in traps within dry-ground areas, and these amounts were found to be significantly different from sediment amounts observed in traps within perennial seeps and cattle paths (Table 5). Overland flow occurrence on dry-ground areas is rare in the Cottonwood Creek watershed and the areas over which Horton overland flow may be generated are not known. Few sediment traps were in place and functioning during the high-intensity storm events of June 8 and June 9, 1987 when Horton overland flow is thought to have occurred. However, the amount of sediment collected in the traps which were in place at this time was often less than that collected at other times of the year (Table 3) so the traps were probably not located in areas of Horton overland flow generation. Processes other than Horton overland flow must account for the sediment observed in traps within dry-ground areas. Cattle paths within dry-ground areas can produce and concentrate overland flow which would increase erosion and sediment production to a greater extent than non-trampled areas (Fortier and others, 1980). The trampling and increased overland flow production probably accounts for the large amount of sediment production observed from cattle paths.

Differences in the amount of sediment observed between traps located within dry-ground areas are small, but were found to be significant. There is a large amount of error in this part of the study which may account for the differences, but the amount of error is

unknown. Aside from the errors, differences in sediment production may arise because vegetation cover may not be the same around each trap and raindrop splash would be greater in areas of less vegetation (Branson and others, 1981). Another cause of the sediment variation between traps may be due to differences in the amount of sediment deposited by wind and cattle into the traps. Differences in cattle management practices may induce differences in cattle trampling and sediment production (Marlow, 1988). Topographic position may also influence sediment production from dry-ground areas. The paired sediment traps located in a small, dry, vegetated gully (traps 1-4, 1-5) (Fig. 10) show a significant difference in sediment produced between the lower and upper sections of the gully (Table 6). However, trap 5-1 (Fig. 10), located at the base of a large, dry, vegetated gully in the hillslope collected very little sediment (Table 3). An important point to consider for this study is that dry-ground areas produce very small amounts of sediment, largely because overland flow does not occur from these dry areas.

To answer the question posed as to whether or not groundwater-seepage areas have the potential for greater sediment production than other areas, a first approximation can be inferred from the data available. Within the riparian area studied, zones of perennial groundwater seepage do produce significantly greater amounts of sediment than dry-ground areas in which there are no cattle paths, though sediment amounts are small. Intermittent-seepage areas do not produce significantly greater amounts of sediment than dry-ground areas. Cattle paths produce the greatest amount of sediment of all the

areas tested in this study. The ability of an area to generate overland flow is considered to be an important point in the production of sediment though other factors, such as vegetation cover, topographic position, and cattle disturbance are probably important as well. Further study is required to better assess sediment production within the drainage basin, and other methods may need to be utilized. Also, instream sediment loads need to be measured in order to determine the impact different sediment-producing areas have on water quality. These aspects will be discussed in the suggestions for further study section.

The results of a study by Istok and Kling (1983) indicate the importance of saturated areas to sediment yield within a basin. Three small watersheds in Oregon were monitored for runoff and sediment yield for two years. All watersheds had saturated areas in the near-stream area due to the presence of perched water tables during rainy periods. These saturated areas were responsible for much of the surface runoff from the watersheds. Subsurface drains were installed in one watershed to lower the water table. The drains effectively reduced the saturated area on the watershed while the saturated areas remained on the undrained watersheds. Runoff was reduced by 65% and sediment yield was reduced by 55% on the drained watershed. The reduction in saturated area was responsible for reducing the amount of overland flow generated on the watershed. As a result, erosion and sediment transport was also reduced. The study of Istok and Kling (1983) supports the hypothesis set forth in this thesis that saturated-seepage areas have the potential to greatly influence sediment production due to the production of overland flow from the saturated areas.

SUMMARY

Groundwater-seepage areas play a major role in the hydrologic response of the Cottonwood Creek watershed. These areas are important sites of high soil moisture contents, and are important zones of runoff and sediment production. Such seepage areas may need to be looked at more closely when determining the effects of management practices on water quality within the watershed.

Persistently high streambank soil moisture contents can lead to weak streambanks which are vulnerable to mechanical damage through activities such as cattle trampling. Zones with high streambank soil moisture contents were found to be controlled by the presence of a shallow groundwater table. Areas with shallow groundwater tables generally occur as seepage areas, but there is one area in the study basin which appears dry at the surface and contains sites of high moisture content due to a shallow groundwater table. Saturated zones of groundwater-seepage areas fluctuated in size through time but the unsaturated areas of the seeps always had high moisture contents. A shallow groundwater table persisted in the seepage areas even when saturation was not observed at the ground surface.

The saturated areas of groundwater seeps were important sites of overland flow generation. These saturated areas are considered to be the only sites of overland flow generation except during large storm events. For large, low-intensity storms the entire area encompassed by the maximum extent of the groundwater-seepage areas are considered

to be sites of overland flow generation. During more intense storms, Horton overland flow is thought to occur from a small area of the watershed. The location of Horton overland flow generation contributing to storm runoff is not known, but it is believed to occur in the streamside zone. Overland flow occurring in areas higher on the hillside appear to infiltrate before reaching the stream. Though overland flow does occur in the watershed, direct precipitation into the stream channel accounts for more than one-half of the total storm runoff from the study basin. Overall, the total contributing area to storm runoff was found to be less than one percent of the study basin for 1987.

As overland flow is not generated equally from all points within the watershed, or from the streamside zone, sediment production is not produced equally from all points within the watershed. Sediment production not derived from the stream channel area is greater from groundwater-seepage areas than dry-ground areas which do not contain cattle paths. Aside from the cattle paths in dry-ground areas, soil disturbances are greater in saturated areas. When overland flow is generated from these saturated zones, the flowing water may more easily pick up sediment from the disturbed areas. The greater overland flow and sediment production capabilities of groundwater-seepage areas, coupled with the tendency for streambanks to be more easily damaged within seepage areas make these zones very important in studies which examine potential sediment yields from the basin. Managers and researchers should be aware of how seepage areas may affect water quality and the stream environment.

Suggestions for Further Study

The research for this thesis was conducted in part to determine if groundwater-seepage areas have the potential for greater streambank instability and overland sediment production than dry areas.

Hydrologic processes such as groundwater recharge of soil moisture and overland flow production are greater in seepage areas than in dry areas. These processes need to be understood before determining the influence cattle-grazing management practices have on streambank instability and sediment production on different sections of the study stream. The nature of the management practices was not taken into account in this study. To further determine the actual influence cattle-grazing practices have on streambank instability and sediment production, future studies must incorporate hydrologic factors. Many of these factors have been identified in this thesis.

Areas with consistently high streambank soil moisture contents should be separated from areas with consistently dry streambanks to determine the influence moisture content exerts on streambank instability under different grazing management schemes. If soil moisture is a factor which can be used to empirically determine relative streambank stability in response to cattle grazing, further study of streambank alteration should be conducted with a more rigorous soil moisture measurement scheme. Closely spaced measurements in time, or continuous monitoring, may help to define a critical moisture level at which banks are considered stable for activities such as cattle grazing.

Marlow and others (1987) comment that high streamflow along with high soil moisture and grazing activity were responsible for the highest degree of streambank alteration. Streamflow, precipitation intensity and snowmelt runoff should be included as factors in future research on streambank stability. High magnitude discharge events, or lack thereof, during a monitoring period will have a large influence on the amount of stream channel and streambank alteration (Dunne and Leopold, 1978; Heede, 1980) and hence on conclusions regarding grazing impact.

The nonhomogenous nature of the study basin indicates that sediment production will be different from different areas of the watershed regardless of the management practices imposed upon them. Some determination of the potential for an area to produce sediment needs to be assessed before determining the impacts different cattle-grazing management practices have on sediment production. Factors such as vegetation cover and topography need to be evaluated for areas of the watershed where different management practices are utilized (Lusby, 1970). Use of rainfall simulators may help determine the relative potential different areas have to produce sediment from raindrop splash, sheet and rill erosion (Marston and Dolan, 1988). Computer modeling of erosional and depositional areas in the drainage basin (Moore and Burch, 1986) may also help delineate differences in sediment production, provided the model is calibrated correctly. In addition, the movement of sediment should be assessed. Much of the sediment produced will be stored in depositional areas of the watershed above the stream channel (Walling, 1983; Heede, 1984). The presence of

alluvial fans at the base of gullies within the Cottonwood Creek watershed indicate that sediment produced from these gullies is in storage and has not been delivered to the stream.

Sediment production was monitored in the riparian area of the study basin but actual sediment delivery to the stream was not measured. The amount of sediment which reaches the stream is important to water quality. Cattle paths and perennial-seepage areas, which were found to produce the greatest amounts of sediment in the study area, are directly connected to the stream. Overland flow is also generated from these areas. This would imply that sediment produced in these areas has a high probability of reaching the stream. Sediment derived from dry areas may not reach the stream as there is generally no delivery mechanism. Horton overland flow may occur over some dry areas during intense storms but the location of these areas is not known. Areas where Horton overland flow does occur will be sites where sediment may be produced and delivered to the stream. Further study of overland flow processes during intense storm events may help delineate areas where Horton overland flow might occur. This may be done through field observation or through detailed field mapping of infiltration capacities (Dunne and others, 1975). Rainfall simulators can be used to map infiltration capacities as well as sediment-producing areas (Marston and Dolan, 1988). This approach would also help determine precipitation intensity thresholds for runoff and sediment production.

Monitoring instream sediment loads both above and below different areas might give an indication of the amount of sediment which reaches the stream from these areas. To be successful, however, the sediment

influxes must be large enough to be detectable as statistically significant increments. Dr. Marlow is currently monitoring instream sediment loads through the use of continuous recording turbidity meters. Continuous records will allow analysis of the amount of sediment transported in the stream channel during storm events, when most sediment is transported (Loughran and others, 1986). However, in addition to sediment from overland sources, sediment can also be derived from streambanks and the stream channel. Sediment picked up from the channel and banks may give a false indication of sediment derived from overland sources. Sediment may also be deposited and stored in the stream channel which would decrease sediment concentrations. Although there are a large number of factors which influence sediment transport (Heede, 1980), measurement and observation of several of the factors, in both upland areas and the stream channel, may indicate where sediment is being supplied from, and what factors influence sediment production.

Degradation and aggradation of the stream channel and streambanks is currently being monitored by Dr. Marlow and should indicate whether sediment is derived from or deposited in the stream channel. Away from stream channel monitoring points (transects) certain aspects of the stream channel and streambanks may be observed as an indication of whether sediment is being supplied from or being deposited in the stream channel between sediment measurement points. Bare and/or slumped or sloughed streambanks will increase sediment as will knickpoints in the stream channel. Thick vegetation, woody debris and other roughness elements will generally decrease instream sediment

loads through deposition of sediment (Beschta and Platts, 1986; DeBano and Heede, 1987). These elements may also stabilize the stream channel and banks. For this reason, low sediment production and stable streambanks may be influenced by factors other than management practices. The effects management practices have on variables which influence streambank stability and sediment production could be monitored and may be as informative as actually measuring sediment yields. During the course of a short study, events which move significant amounts of sediment may not occur. The differences between the results of Pogacnik (1985) and this study and the differences between 1986 and 1987 point out the need for monitoring over time periods that encounter many runoff conditions. As the hydrologic system is complex, determination of sediment sources and the effects management practices have on water quality is difficult but may be addressed if several steps are taken.

Many of the problems encountered in this thesis were the result of faulty equipment or lack of field observations during storm events. More reliable equipment would be beneficial to future studies in the Cottonwood Creek watershed. Personnel who are available to live on site and carefully observe runoff and sediment production at all times would be extremely helpful. Observation of phenomena during natural storm events would aid greatly in the understanding of runoff and sediment production processes. On site personnel could also maintain equipment to assure that important data for isolated, high-intensity storms are not missed.

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APPENDICES

APPENDIX A

GROUNDWATER-MONITORING WELL INFORMATION

Table 10. Groundwater-monitoring well information.

Well number	Casing information				Capped bottom	Depth to water at time of drilling*
	Diameter (cm)	Length (total) (cm)	Above ground (cm)	Slotted length (cm)		
1-1	10.2	147.3	14.0	124.5	no	25.4
1-2	10.2	111.8	21.6	111.8	no	67.3
1-3	3.8	239.1	12.7	109.2	no	nw
1-4	3.8	281.0	14.0	157.5	no	nw
1-5	3.8	236.9	14.6	66.0	no	nw
1-6	10.2	127.0	17.8	81.3	no	50.8
1-7	3.8	208.3	12.7	91.4	no	152.4
1-8	10.2	182.9	21.6	137.2	no	127.0
2-1	10.2	137.2	12.7	106.7	no	68.6
2-2	10.2	106.7	15.2	76.2	no	0.0
2-3	10.2	152.4	15.2	121.9	no	106.7
2-4	3.8	182.9	14.0	76.2	no	nw
2-5	3.8	204.5	12.7	30.5	no	nw
3-1	3.8	132.1	13.3	50.8	no	50.8
3-2	3.8	116.8	14.6	30.5	no	nw
3-3	3.8	116.8	12.7	50.8	no	19.1
3-4	3.8	118.1	16.5	50.8	no	10.2
3-5	10.2	139.7	12.7	91.4	no	15.2
3-6	10.2	94.0	15.2	61.0	no	88.9
3-7	3.8	71.1	10.2	15.2	no	nw
3-8	3.8	395.0	17.8	91.4	yes	nw
4-1	10.2	134.6	15.2	76.2	no	45.7
4-2	3.8	130.8	10.2	38.1	no	68.6
5-1	3.8	190.5	10.2	30.5	no	116.8
5-2	3.8	144.8	11.4	111.8	no	68.6
5-3	3.8	129.5	11.4	30.5	no	nw
5-4	3.8	129.5	10.2	58.4	no	55.9
5-5	3.8	505.5	20.3	121.9	yes	396.2
5-6	3.8	193.0	19.1	55.9	yes	nw
6-1	3.8	213.4	14.0	134.6	no	111.8
6-2	10.2	161.3	11.4	88.9	no	124.5
6-3	3.8	256.5	15.2	134.6	no	175.3
6-4	3.8	378.5	20.3	78.7	yes	nw
7-1	3.8	236.2	16.5	157.5	no	111.8
7-2	3.8	142.2	21.6	22.9	yes	114.3
7-3	3.8	195.6	20.3	116.8	no	114.3
7-4	3.8	213.4	17.8	33.0	no	nw
8-1	10.2	223.5	16.5	114.3	no	177.8
8-2	10.2	106.7	11.4	68.6	no	22.9
8-3	3.8	116.8	10.2	66.0	yes	83.8
8-4	3.8	152.4	16.5	33.0	no	111.8
8-5	3.8	190.5	11.4	111.8	yes	94.0
8-6	3.8	313.7	15.2	88.9	yes	205.7
8-7	3.8	238.8	14.0	88.9	yes	132.1
8-8	10.2	132.1	15.2	73.7	no	50.8
9-1	3.8	149.9	21.6	22.9	yes	114.3

Table 10. (continued).

Well number	Casing information					Depth to water at time of drilling*
	Diameter	Length (total)	Above ground	Slotted length	Capped bottom	
	(cm)	(cm)	(cm)	(cm)		(cm)
9-2	3.8	142.2	15.2	50.8	yes	63.5
9-3	3.8	195.6	16.5	116.8	yes	116.8
9-4	3.8	128.3	12.7	78.7	yes	88.9
9-5	3.8	148.6	14.0	55.9	yes	83.8
9-6	3.8	142.2	21.6	30.5	yes	nw
9-7	3.8	161.3	16.5	61.0	yes	96.5
10-1	3.8	135.9	11.4	96.5	no	nw
10-2	3.8	274.3	15.2	91.4	yes	180.3
10-3	10.2	213.4	25.4	139.7	yes	96.5
10-4	10.2	193.0	15.2	91.4	yes	114.3
10-5	3.8	228.6	14.0	88.9	yes	152.4
10-6	3.8	247.7	15.2	91.4	yes	160.0
10-7	3.8	473.7	19.1	121.9	yes	345.4
10-8	3.8	495.3	20.3	81.3	yes	419.1
11-1	3.8	212.1	14.0	53.3	yes	nw
11-2	10.2	228.6	25.4	119.4	yes	154.9
11-3	10.2	210.8	22.9	124.5	yes	129.5
11-4	3.8	200.7	19.1	73.7	no	104.1
12-1	10.2	148.6	20.3	73.7	no	63.5

* = water depth below ground surface

nw = no water in well

APPENDIX B

SATURATED-SEEPAGE AREA MAPS

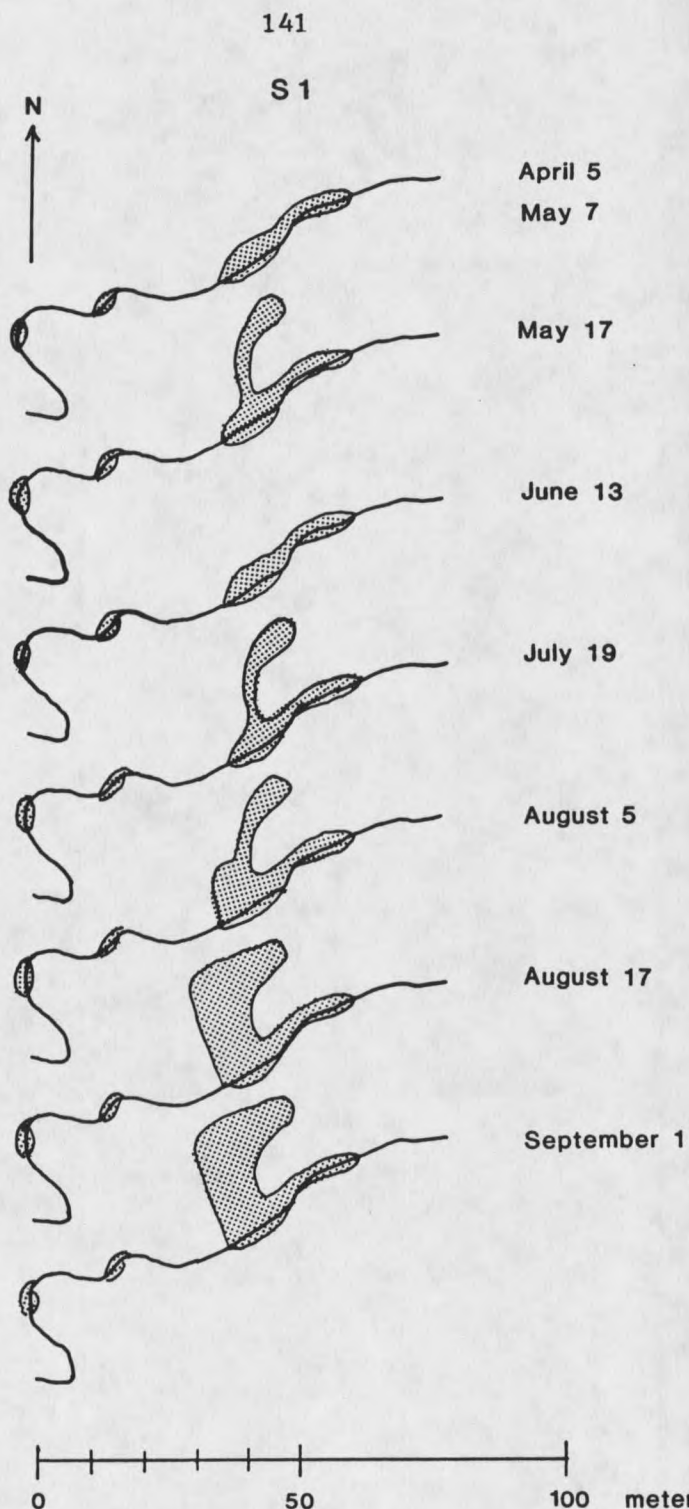


Figure 37. Maps of saturated area size for seep S1 on eight dates in 1987. More than one date on a map indicates no change in size between the dates shown. Location of seepage area is shown in Figure 13, measurements for April 5 match the minimum seepage area and measurements for September 1 match the maximum seepage area shown in Figure 13.

S2

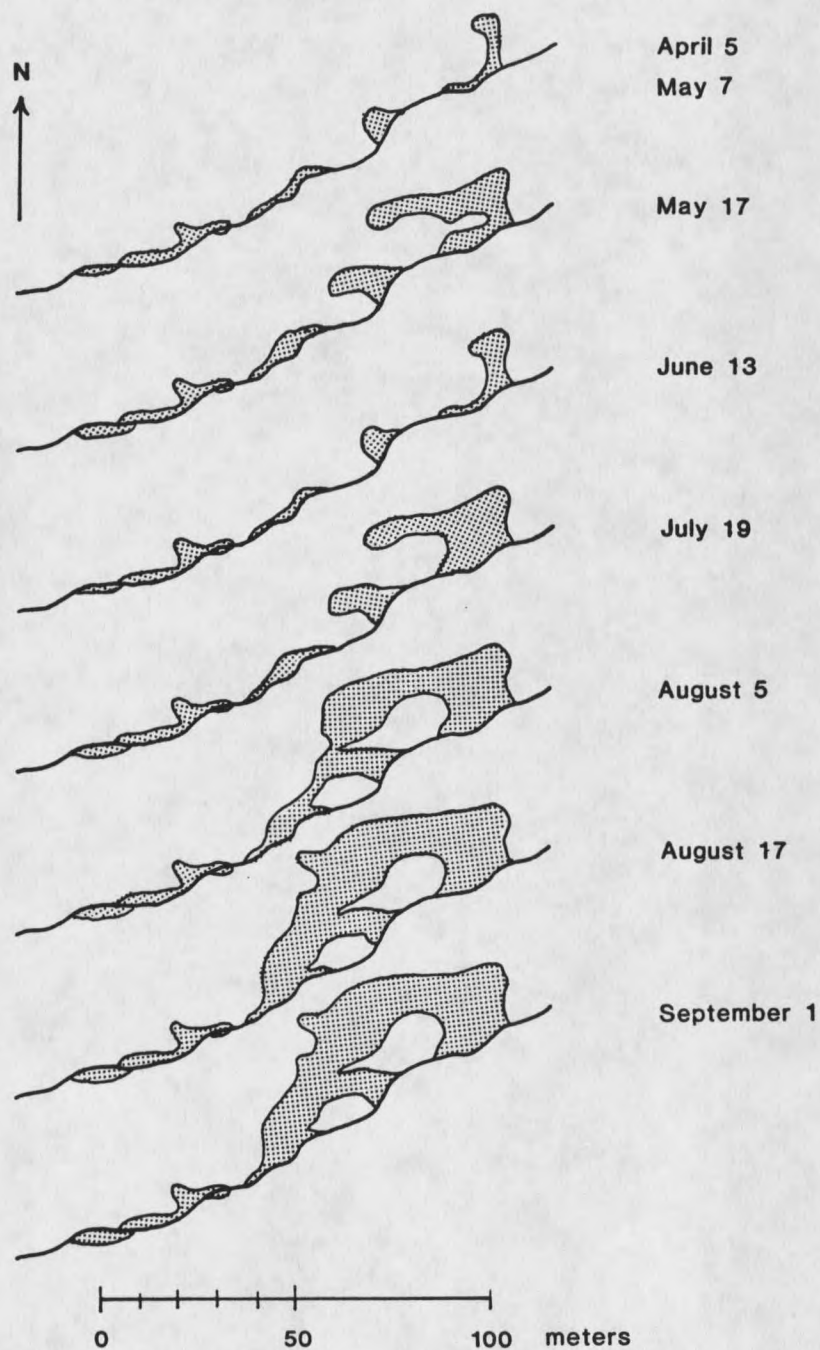


Figure 38. Maps of saturated area size for seep S2 on eight dates in 1987. More than one date on a map indicates no change in size between the dates shown. Location of seepage area is shown in Figure 13, measurements for April 5 match the minimum seepage area and measurements for September 1 match the maximum seepage area shown in Figure 13.

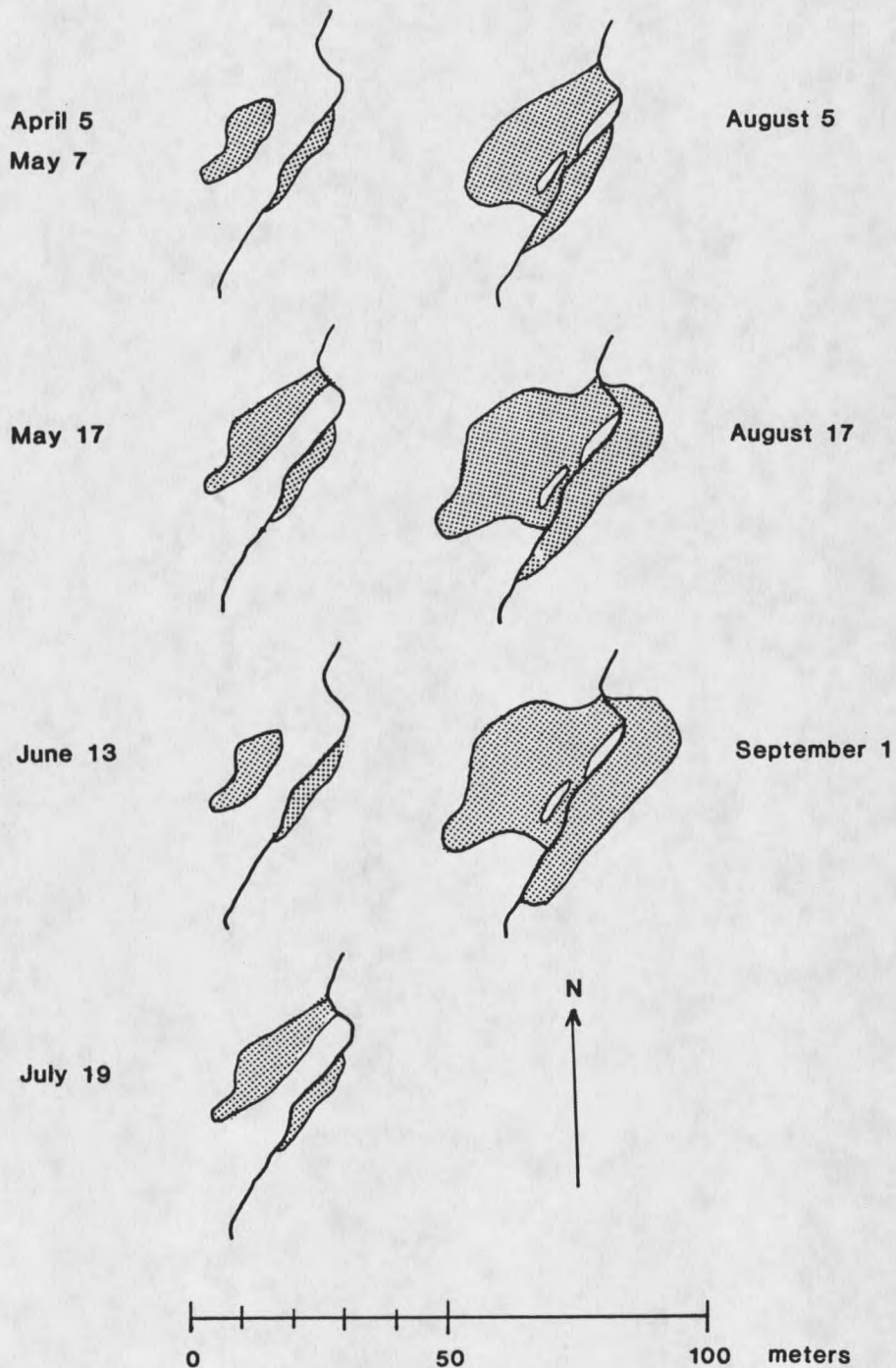


Figure 39. Maps of saturated area size for seep S3 on eight dates in 1987. More than one date on a map indicates no change in size between the dates shown. Location of seepage area is shown in Figure 13, measurements for April 5 match the minimum seepage area and measurements for September 1 match the maximum seepage area shown in Figure 13.

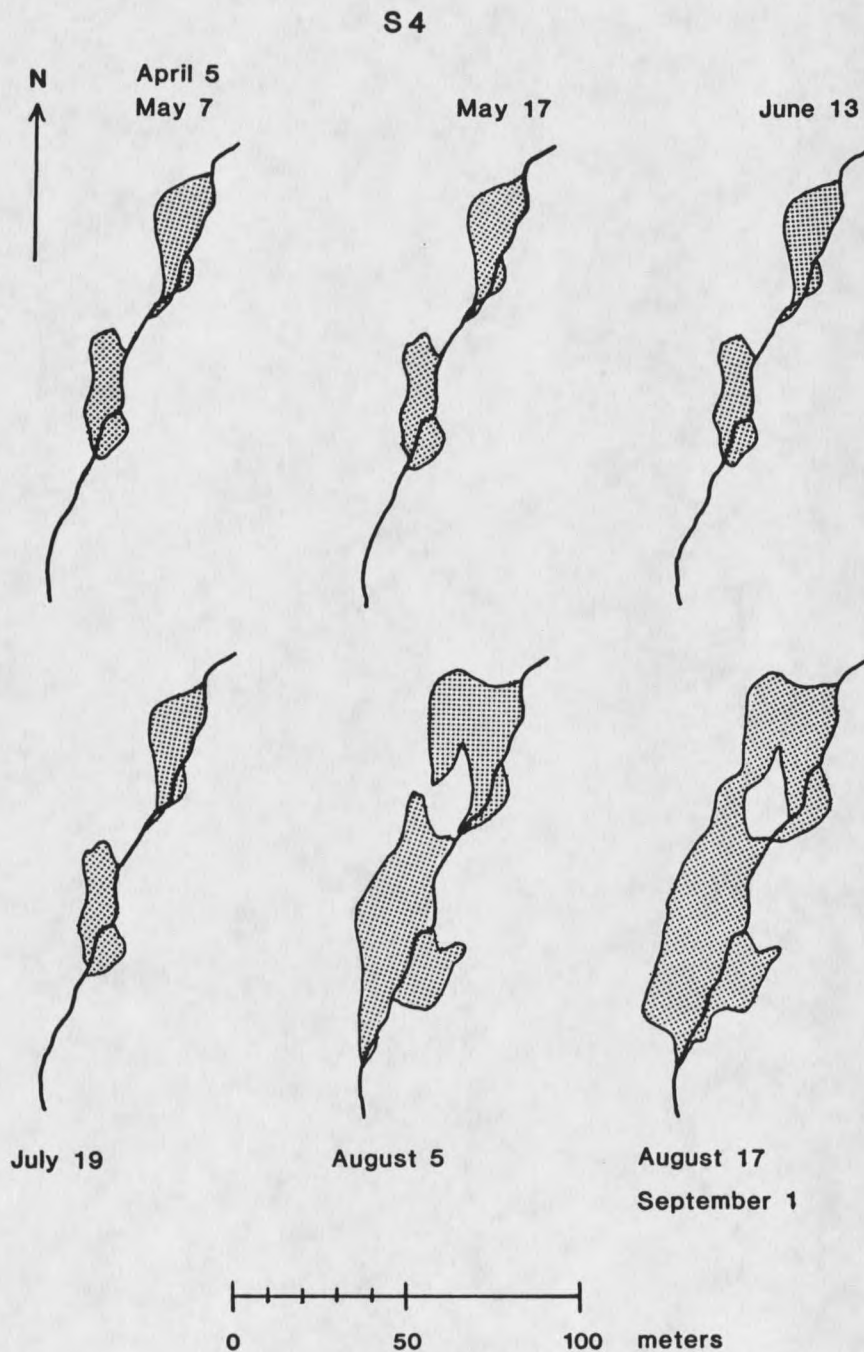


Figure 40. Maps of saturated area size for seep S4 on eight dates in 1987. More than one date on a map indicates no change in size between the dates shown. Location of seepage area is shown in Figure 13, measurements for April 5 match the minimum seepage area and measurements for September 1 match the maximum seepage area shown in Figure 13.

145

S5



April 5

May 7

May 17

June 13

July 19

August 5

August 17

September 1

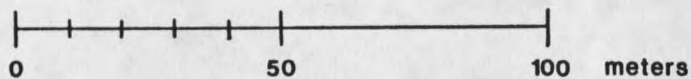


Figure 41. Maps of saturated area size for seep S5 on eight dates in 1987. More than one date on a map indicates no change in size between the dates shown. Location of seepage area is shown in Figure 13, measurements for April 5 match the minimum seepage area and measurements for September 1 match the maximum seepage area shown in Figure 13.

APPENDIX C

DEPTH TO GROUNDWATER

Table 11. Depth to groundwater (cm) for all wells which reached the water table. Well information is given in Table 10. Well locations are shown in Figure 6. No data generally implies water levels fell below the bottom of the well, though some wells were not measured on all dates. Water levels are listed as the depth below ground surface, not as depth below the top of the well casing.

Date	Well									
	1-1	1-2	1-6	1-7	1-8	2-1	2-2	2-3	3-1	3-3
	water level below ground surface (cm)									
30-Jun-86	9	57	58	132	122	86	28	96	42	25
14-Jul-86	25	64	62	140	126	84	28	102	46	29
24-Jul-86	20	64	65	145	128	78	30	102	48	32
30-Jul-86	24	65	71	141	129		30	104	51	36
22-Aug-86	10	62	73	138	128	84	25	106	63	59
03-Sep-86	20	66	77	134	129	76	33	107	69	64
11-Sep-86	20	65	79	143	130	76	32	106	74	64
25-Sep-86	20	64	79	139	128	76	33	105	82	
24-Oct-86	22	64	81	140	126	83	38	103		
31-Jan-87	31	70		140	131			110		
13-Feb-87	26	69	86	141	128	93	34	110		
05-Apr-87	19	67	89	141	127	71	24	109		
21-Apr-87	10	66	90	141	126	77	33	110		
27-Apr-87	24	71	94		131	83	37	113		
07-May-87	29	74	97	142	136	86	35	119		
17-May-87	6	70	95	141	132	62	28	116		
27-May-87	4	51	70	127	107	66	28	90		
13-Jun-87	18	69	84	146	129	68	30	114		
30-Jun-87	33	73	87	150	135	67	29	118		
19-Jul-87	3	56	65	124	110	65	33	97		
05-Aug-87	15	66	67	157	127	62	26	107	63	60
17-Aug-87	6	60	64	131	125	62	27	99	55	55
01-Sep-87	6	59	64	132	123	52	31	97	56	61
25-Sep-87	5	60	67	134	124	55	35	97	67	82

Table 11. (continued).

Date	Well									
	3-4	3-5	3-6	4-1	4-2	5-1	5-2	5-4	5-5	6-1
	water level below ground surface (cm)									
30-Jun-86	13	28	75	66	72	132	50	65		122
14-Jul-86	14	29	74	72	79	144	52	60		121
24-Jul-86	16	29		78	85	161	53	70		137
30-Jul-86	19	31	75	84	97	161	56		486	145
22-Aug-86	30	32	76	81	99		56		467	
03-Sep-86	39	41		83	103		58		470	
11-Sep-86	43	42	79	84	118	180	60	69	472	161
25-Sep-86	45	43		96	109	184	59	74	464	172
24-Oct-86	54	47		96	109	188	60	74	452	
31-Jan-87			77						434	
13-Feb-87		54							427	
05-Apr-87	77	76		100	102	184	67	84	437	
21-Apr-87	86	74		98	127		67	84	437	
27-Apr-87	90	91					70	85		
07-May-87							70	93		
17-May-87		60		95			68	87	393	
27-May-87		57					63			
13-Jun-87	74	59		90	109	185	64	77	424	
30-Jun-87	69	59		90	110	185	65	79	417	
19-Jul-87	53	44		89	91	164	58	67	415	
05-Aug-87	25	35		70	69	138	54	64	417	147
17-Aug-87	21	31		68	72	139	54	62	417	145
01-Sep-87	22	31	76	70	77	146	54	63	417	145
25-Sep-87	31	36	76	79	90	160	56	65	419	156

Table 11. (continued).

Date	Well									
	6-2	6-3	7-1	7-2	7-3	8-1	8-2	8-3	8-4	8-5
	water level below ground surface (cm)									
30-Jun-86	46	179	114	112	119	94	25	81	116	69
14-Jul-86	38	193	126	116	141	95	25	66	118	70
24-Jul-86	47	199	124	118	142	102	34	75	118	76
30-Jul-86	48	201		119	141	105	37	75		74
22-Aug-86	45					93	48	71		83
03-Sep-86	47		142			104	56	79		86
11-Sep-86	48	224			172	105	65	81		88
25-Sep-86	45	226	154		184	104	56	78		85
24-Oct-86	47		164		174	108	59	81		87
31-Jan-87	57		196			123	88			95
13-Feb-87	56		185		175	122	86	76		95
05-Apr-87	52		181		173	114	79	78		92
21-Apr-87	35		183		180	77	76	32		92
27-Apr-87	57		183			119	98	79		98
07-May-87	69		187			124	103	81		104
17-May-87	50		189			69	103	56		96
27-May-87	34									
13-Jun-87	56		165			112	84	80		89
30-Jun-87	65		174			121	108	83		95
19-Jul-87	39		144		153	74	61	75		77
05-Aug-87	53	220	140		146	104	60	78		78
17-Aug-87	46	219	135		142	87	50	77		76
01-Sep-87	49	217	132	122	141	97	42	76		75
25-Sep-87	53	222	148		154	104	50	76		80

Table 11. (continued).

Date	Well									
	8-6	8-7	8-8	9-1	9-2	9-3	9-4	9-5	9-7	10-2
	water level below ground surface (cm)									
30-Jun-86	211	124	33	114	69	90	93		99	
14-Jul-86	216	121	28	114	76	98		58	103	192
24-Jul-86	226	124	38	119	81	110	100	58	110	204
30-Jul-86	227		37		79	112	100	52	81	203
22-Aug-86		138	43	122		133	88	68	93	
03-Sep-86	244	141	45			130	100	64	96	
11-Sep-86	247	141	47		97	129	105	61	116	225
25-Sep-86	242	138	44			126	95	56	113	
24-Oct-86	244	139	46			129	97	55	118	
31-Jan-87	254		70					65		
13-Feb-87	259		69	126				64	118	
05-Apr-87	260	150	77	131		135	84	62	118	
21-Apr-87	259	156	54			138	72	60	119	
27-Apr-87	260	157	66			140	106	67	122	
07-May-87	264	163	74			145	109	74	121	
17-May-87	267	161	59			146	52	75	128	
27-May-87										
13-Jun-87	244	149	61			125	105	64	119	
30-Jun-87	248	149	67			133		75	124	
19-Jul-87	227	133	47	122	75	108	79	47	104	215
05-Aug-87	219	128	46	123	85	105	109	62	106	190
17-Aug-87	217	123	41	120	74	99	83	53	102	187
01-Sep-87	217	121	37	118	72	92	83	53	105	182
25-Sep-87	226	127	46	127	91	102	88	56	110	204

Table 11. (continued).

Date	Well									
	10-3	10-4	10-5	10-6	10-7	10-8	11-2	11-3	11-4	12-1
	water level below ground surface (cm)									
30-Jun-86										
14-Jul-86	100	113	140	163			145	131	105	52
24-Jul-86	103	114	149	166	385		147	134	115	56
30-Jul-86	104	114			383		148	136	115	57
22-Aug-86	114	122	151	177	325	473	157	138	124	66
03-Sep-86	117	124	152	180	347	477	160	142		74
11-Sep-86	119	126	154				163	143	144	76
25-Sep-86	121	128	155	165	399		164	142	142	76
24-Oct-86	129	134	155				163	144		83
31-Jan-87	144	149	166		399					
13-Feb-87	145	150	167					150	150	
05-Apr-87	138	146	165	155	410		179	147	154	107
21-Apr-87	141	149	166	142	395		179	149		99
27-Apr-87	141	148	167	169			179	148		104
07-May-87	144	149	167	185			180	153		
17-May-87	145	153	170	197	399		179	151		
27-May-87										
13-Jun-87	131	138	159	152	378		168	147		
30-Jun-87	137	141	161	178	389		170	150		
19-Jul-87	116	124	147	110	354	447	149	126	130	77
05-Aug-87	117	128	146	156	352	439	154	142	114	66
17-Aug-87	109	122	145	142	359	470	147	131	112	63
01-Sep-87	105	120	145	140	363	471	148	131	111	61
25-Sep-87	113	126	150	150	381	471	157	139	128	71

APPENDIX D

SOIL MOISTURE CONTENTS

Table 12. Gravimetric soil moisture content of the top 30 cm of soil for all sampling sites (stream channel transects). Actual date of sample collection is listed. All dates are listed to show the time within the sampling period the sample was collected. Transect locations are shown in Figure 7.

Sampling date	Paddock designation									
	DE	DE	DE	DE	DE	DE	DE	DE	DE	DE
	Transect number									
	1	1	2	2	3	3	4	4	5	5
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
	soil moisture content by weight									
07/24/86	0.48	0.54	1.25	0.51	0.31	0.64	0.28	0.33	0.35	1.01
07/28/86										
07/31/86										
08/01/86										
08/04/86										
08/25/86	0.40	0.63	1.41	0.26	0.31	0.74	0.23	0.25	0.20	0.86
08/26/86										
10/03/86	0.50	0.34	0.89	0.29	0.31	0.23	0.26	0.30	0.42	0.79
10/07/86										
10/09/86										
10/14/86										
10/16/86										
Ave 1986	0.46	0.50	1.19	0.36	0.31	0.54	0.26	0.29	0.32	0.89
06/11/87	0.46	0.47	1.13	0.41	0.37	0.41	0.25	0.31	0.30	0.79
06/13/87										
06/14/87										
06/25/87	0.43	0.52	0.85	0.34	0.24	0.29	0.27	0.33	0.30	0.97
06/26/87										
06/29/87										
07/15/87	0.77	0.58	0.97	0.35	0.31	0.52	0.64			0.91
08/04/87	0.48	0.51	1.37	0.43	0.30	0.44	0.39	0.21	0.35	0.78
08/05/87										
09/02/87	0.57	0.60	1.15	0.34	0.48	0.42	0.40	0.28	0.35	1.44
Ave 1987	0.54	0.54	1.09	0.37	0.34	0.42	0.39	0.28	0.32	0.98
Average										
1986-87	0.51	0.52	1.13	0.37	0.33	0.46	0.34	0.29	0.32	0.94

Table 12. (continued).

Sampling date	Paddock designation									
	DE	DE	DE	DE	TC-1	TC-1	TC-1	TC-1	TC-1	TC-1
	Transect number									
	6	6	7	7	1	1	2	2	3	3
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86	0.14	0.30	0.14	0.13	0.15	0.11	0.08	0.19	0.75	0.58
07/31/86										
08/01/86										
08/04/86										
08/25/86	0.14	0.17	0.16	0.30	0.16	0.15	0.18	0.23	0.99	0.73
08/26/86										
10/03/86	0.26	0.24	0.28	0.20	0.32	0.24	0.30	0.35	0.70	0.62
10/07/86										
10/09/86										
10/14/86										
10/16/86										
Ave 1986	0.18	0.24	0.19	0.21	0.21	0.16	0.19	0.26	0.82	0.65
06/11/87	0.27	0.27	0.20	0.28	0.22	0.23	0.21	0.32	0.63	0.57
06/13/87										
06/14/87										
06/25/87	0.09	0.44	0.23	0.25	0.26	0.21	0.18	0.28	0.80	0.56
06/26/87										
06/29/87										
07/15/87	0.28					0.31	0.28	0.30	0.91	0.84
08/04/87	0.30	0.39	0.07	0.45	0.20	0.14	0.16	0.22	0.61	0.49
08/05/87										
09/02/87	0.25	0.32	0.15	0.43	0.18	0.29	0.35	0.27	0.83	0.73
Ave 1987	0.24	0.36	0.16	0.35	0.21	0.24	0.24	0.28	0.76	0.64
Average 1986-87	0.22	0.30	0.18	0.29	0.21	0.21	0.22	0.27	0.78	0.64

Table 12. (continued).

Sampling date	Paddock designation									
	TC-2	TC-2	TC-2	TC-2	TC-2	TC-2	TC-2	TC-2	TC-2	TC-2
	Transect number									
	1	1	2	2	3	3	4	4	5	5
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86	0.35	0.15	0.21	0.11	0.51	0.20	0.40	0.23	0.48	0.21
07/31/86										
08/01/86										
08/04/86										
08/25/86	0.41	0.19	0.23	0.17	0.37	0.26	0.56	0.23	0.66	0.56
08/26/86										
10/03/86	0.30	0.21	0.30	0.35	0.40	0.30				
10/07/86							0.41	0.34	0.54	0.56
10/09/86										
10/14/86										
10/16/86										
Ave 1986	0.35	0.18	0.25	0.21	0.43	0.25	0.46	0.27	0.56	0.44
06/11/87	0.27	0.27								
06/13/87			0.37	0.17	0.40	0.31	0.47	0.30	0.31	0.30
06/14/87										
06/25/87	0.29	0.16	0.29	0.18	0.50	0.30	0.72	0.28	0.53	0.28
06/26/87										
06/29/87										
07/15/87	0.51	0.30	0.29	0.17	0.35	0.35	0.59	0.28	0.52	0.38
08/04/87	0.51	0.29	0.28	0.23	0.44	0.30	0.46	0.27	0.48	0.42
08/05/87										
09/02/87	0.40	0.25	0.23	0.14	0.64	0.37	0.40	0.27	0.61	0.47
Ave 1987	0.40	0.25	0.29	0.18	0.46	0.32	0.53	0.28	0.49	0.37
Average 1986-87	0.38	0.23	0.27	0.19	0.45	0.30	0.50	0.28	0.52	0.40

Table 12. (continued).

Sampling date	Paddock designation									
	TC-3	TC-3	TC-3	TC-3	TC-3	TC-3	TC-3	TC-3	TC-3	TC-3
	Transect number									
	1	1	2	2	3	3	4	4	5	5
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86	0.35	0.52	0.47	0.21	0.21	0.31	0.12	0.19	0.12	0.07
07/31/86										
08/01/86										
08/04/86										
08/25/86	0.43	0.37	0.34	0.51						
08/26/86					0.19	0.40	0.14	0.25	0.17	0.14
10/03/86										
10/07/86	0.28	0.36	0.41	0.32	0.20	0.40	0.15	0.25	0.22	0.15
10/09/86										
10/14/86										
10/16/86										
Ave 1986	0.35	0.42	0.40	0.35	0.20	0.37	0.13	0.23	0.17	0.12
06/11/87										
06/13/87	0.46	0.33	0.52	0.74			0.26	0.29	0.21	0.18
06/14/87										
06/25/87	0.28	0.29	0.37	0.35	0.17	0.30	0.45	0.21	0.23	0.15
06/26/87										
06/29/87										
07/15/87	0.33	0.38	0.48	0.49	0.24	0.35	0.37	0.18	0.21	0.18
08/04/87	0.40	0.31	1.04	0.45	0.26	0.35	0.39	0.36	0.16	0.14
08/05/87										
09/02/87	0.38	0.42	0.42	0.54	0.27	0.47	0.38	0.32	0.20	0.16
Ave 1987	0.37	0.35	0.57	0.51	0.23	0.37	0.37	0.27	0.20	0.16
Average										
1986-87	0.37	0.37	0.51	0.45	0.22	0.37	0.28	0.26	0.19	0.15

Table 12. (continued).

Sampling date	Paddock designation									
	TC-4	TC-4	TC-4	TC-4	TC-4	TC-4	TC-4	TC-4	TC-4	TC-4
	Transect number									
	1	1	2	2	3	3	4	4	5	5
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86	0.14	0.33								
07/31/86			0.11	0.34	0.08	0.19	0.06	0.13	0.08	0.17
08/01/86										
08/04/86										
08/25/86										
08/26/86	0.19	0.42	0.25	0.46	0.14	0.21	0.20	0.21	0.13	0.21
10/03/86										
10/07/86	0.20	0.38	0.16	0.43	0.16	0.26	0.18	0.28	0.12	0.22
10/09/86										
10/14/86										
10/16/86										
Ave 1986	0.18	0.38	0.17	0.41	0.13	0.22	0.15	0.21	0.11	0.20
06/11/87										
06/13/87	0.27	0.35	0.26	0.37	0.20	0.28	0.18	0.26	0.19	0.27
06/14/87										
06/25/87	0.21	0.39								
06/26/87			0.17	0.37	0.15	0.20	0.24	0.34	0.01	0.53
06/29/87										
07/15/87	0.30	0.39	0.39	0.37	0.19	0.26	0.22	0.32	0.22	0.54
08/04/87	0.20	0.43	0.28	0.40	0.16	0.18	0.22	0.31	0.20	0.42
08/05/87										
09/02/87	0.24	0.43	0.24	0.31	0.23	0.26	0.22	0.39	0.25	0.50
Ave 1987	0.24	0.40	0.27	0.36	0.19	0.24	0.22	0.32	0.17	0.45
Average 1986-87	0.22	0.39	0.23	0.38	0.16	0.23	0.19	0.28	0.15	0.36

Table 12. (continued).

Sampling date	Paddock designation									
	DM	DM	DM	DM	DM	DM	DM	DM	DM	DM
	Transect number									
	1	1	2	2	3	3	4	4	5	5
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
	soil moisture content by weight									
07/24/86										
07/28/86										
07/31/86	0.04	0.10	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.11
08/01/86										
08/04/86										
08/25/86										
08/26/86	0.14	0.15	0.15	0.16	0.18	0.11	0.22	0.20	0.11	0.20
10/03/86										
10/07/86	0.11	0.25	0.21	0.29	0.22	0.29	0.20	0.24		
10/09/86									0.20	0.28
10/14/86										
10/16/86										
Ave 1986	0.10	0.17	0.15	0.18	0.16	0.16	0.17	0.17	0.13	0.20
06/11/87										
06/13/87	0.16	0.26	0.19	0.27	0.20	0.28	0.21	0.27		
06/14/87										
06/25/87										
06/26/87	0.10	0.18	0.14	0.18	0.19	0.17	0.15	0.16	0.10	0.19
06/29/87										
07/15/87	0.33	0.22	0.21	0.19	0.25	0.19	0.14	0.12	0.17	0.29
08/04/87										
08/05/87	0.07	0.17	0.13	0.15	0.22	0.15	0.14	0.11	0.07	0.22
09/02/87	0.16	0.18	0.19	0.22	0.20	0.25	0.14	0.11	0.10	0.19
Ave 1987	0.16	0.20	0.17	0.20	0.21	0.21	0.16	0.15	0.11	0.22
Average 1986-87	0.14	0.19	0.16	0.19	0.19	0.19	0.16	0.16	0.12	0.21

Table 12. (continued).

Sampling date	Paddock designation									
	DM	DM	DM	DM	TC-5	TC-5	TC-5	TC-5	TC-5	TC-5
	Transect number									
	6	6	7	7	1	1	2	2	3	3
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
	soil moisture content by weight									
07/24/86										
07/28/86										
07/31/86										
08/01/86					0.20	0.64	0.49	0.49	0.39	0.20
08/04/86										
08/25/86										
08/26/86	0.32	0.82	0.54	0.68	0.49	0.30	0.30	0.24	0.14	0.37
10/03/86										
10/07/86										
10/09/86	0.39	0.62	0.47	0.61	0.52	0.30	0.28	0.41	0.22	0.36
10/14/86										
10/16/86										
Ave 1986	0.35	0.72	0.51	0.65	0.40	0.41	0.36	0.38	0.25	0.31
06/11/87										
06/13/87	0.44	0.56	0.49	0.63						
06/14/87					0.71	0.28			0.25	0.37
06/25/87										
06/26/87	0.40	0.58	0.40	0.33	0.53	0.32	0.46	0.28	0.39	0.65
06/29/87										
07/15/87	0.51	0.91	0.53	0.56	0.51	0.43	0.52	0.23	0.37	0.63
08/04/87										
08/05/87	0.33	0.59	0.63	0.65	0.50	0.30	0.26	0.79	0.32	0.59
09/02/87	0.49	0.73	0.44	0.48	0.48	0.31	0.71	0.83	0.31	0.30
Ave 1987	0.43	0.67	0.50	0.53	0.55	0.33	0.49	0.53	0.33	0.51
Average										
1986-87	0.41	0.69	0.50	0.56	0.49	0.36	0.43	0.47	0.30	0.43

Table 12. (continued).

Sampling date	Paddock designation									
	TC-5	TC-5	TC-6	TC-6	TC-6	TC-6	TC-6	TC-6	TC-6	TC-6
	Transect number									
	4	4	1	1	2	2	3	3	4	4
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86										
07/31/86										
08/01/86			0.23	0.20	0.12	0.47	0.31	0.51		
08/04/86										
08/25/86										
08/26/86	0.37	0.45	0.90	0.38	0.65	0.38	0.48	0.66	0.74	0.56
10/03/86										
10/07/86										
10/09/86	0.26	0.37	0.61	0.34	0.65	0.33	0.28	1.00	0.78	0.44
10/14/86										
10/16/86										
Ave 1986	0.31	0.41	0.58	0.31	0.47	0.39	0.36	0.72	0.76	0.50
06/11/87										
06/13/87										
06/14/87	0.26	0.41	0.64		0.50	0.39		0.62	0.59	0.45
06/25/87										
06/26/87	0.27	0.31	0.59	0.32						
06/29/87					0.91	0.55	0.42	0.98	0.45	0.72
07/15/87	0.47	0.34	0.50	0.34	0.55	0.46	0.46	0.80	0.75	0.53
08/04/87										
08/05/87	0.15	0.54	0.43	0.39	0.43	0.50	0.44	0.63	0.39	0.65
09/02/87	0.39	0.63	1.40	0.36	0.58	0.41	0.64	0.59	0.70	0.67
Ave 1987	0.31	0.45	0.71	0.35	0.59	0.46	0.49	0.72	0.58	0.60
Average 1986-87	0.31	0.44	0.66	0.33	0.55	0.44	0.43	0.72	0.63	0.57

Table 12. (continued).

Sampling date	Paddock designation									
	TC-7	TC-7	TC-7	TC-7	TC-7	TC-7	TC-8	TC-8	TC-8	TC-8
	Transect number									
	1	1	2	2	3	3	1	1	2	2
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86										
07/31/86										
08/01/86	1.00	0.32	0.75	0.52	0.43	0.93				
08/04/86							0.12	0.14	0.22	0.48
08/25/86										
08/26/86	0.16	0.14	0.20	0.33	0.21	0.34	1.17	1.13	0.78	0.39
10/03/86										
10/07/86										
10/09/86	0.19	0.18	0.29	0.61	0.28	0.33				
10/14/86							0.66	0.94	0.71	0.36
10/16/86										
Ave 1986	0.45	0.21	0.41	0.49	0.30	0.53	0.65	0.74	0.57	0.41
06/11/87										
06/13/87										
06/14/87	0.16	0.14	0.23	0.28	0.15	0.30	0.92	0.87	0.76	0.36
06/25/87										
06/26/87										
06/29/87	0.14	0.14	0.24	0.52	0.25	0.30	0.70	1.23	0.80	0.36
07/15/87	0.19	0.14	0.29	0.36	0.22	0.49	0.65	0.76	0.62	0.35
08/04/87										
08/05/87	0.12	0.16	0.19	0.31	0.17	0.36	0.88	1.55	0.80	0.42
09/02/87	0.25	0.19	0.29	0.34	0.24	0.41	0.75	1.58	1.16	0.37
Ave 1987	0.17	0.15	0.25	0.36	0.21	0.37	0.78	1.20	0.83	0.37
Average										
1986-87	0.28	0.18	0.31	0.41	0.24	0.43	0.73	1.03	0.73	0.39

Table 12. (continued).

Sampling date	Paddock designation									
	TC-8	TC-8	DW	DW	DW	DW	DW	DW	DW	DW
	Transect number									
	3	3	1	1	2	2	3	3	4	4
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86										
07/31/86										
08/01/86										
08/04/86	0.18	0.33								
08/25/86										
08/26/86	0.24	0.59	0.89	0.33	0.83	0.79	0.73	0.91		
10/03/86										
10/07/86										
10/09/86										
10/14/86	0.17	0.57	0.73	0.41	0.71	0.59				
10/16/86							0.39	1.18	0.71	1.32
Ave 1986	0.20	0.50	0.81	0.37	0.77	0.69	0.56	1.05	0.71	1.32
06/11/87										
06/13/87										
06/14/87	0.36	0.43	0.81	0.49	0.76	0.44	0.36	1.13		
06/25/87										
06/26/87										
06/29/87	0.31	0.67	0.97	0.51	0.72	0.59	0.41	0.77	0.56	0.49
07/15/87	0.43	0.76	0.46	0.52	0.61	0.44	0.41	0.64	0.47	0.49
08/04/87										
08/05/87	0.51	0.87	0.56	0.79	0.45	0.52	0.66	0.73	0.79	0.54
09/02/87	0.59	0.81	1.10	0.56	0.73	0.71	0.42	0.81	0.89	0.50
Ave 1987	0.44	0.71	0.78	0.57	0.66	0.54	0.45	0.82	0.68	0.50
Average 1986-87	0.35	0.63	0.79	0.52	0.69	0.58	0.48	0.88	0.68	0.67

Table 12. (continued).

Sampling date	Paddock designation									
	DW	DW	EX-I	EX-I	EX-I	EX-I	EX-I	EX-I	EX-I	EX-I
	Transect number									
	5	5	1	1	2	2	3	3	4	4
	Streambank (North or South)									
	N	S	N	S	N	S	N	S	N	S
soil moisture content by weight										
07/24/86										
07/28/86										
07/31/86										
08/01/86										
08/04/86										
08/25/86										
08/26/86	0.70	0.48	0.37	0.23	0.13	0.22	0.13	0.23	0.30	0.31
10/03/86										
10/07/86										
10/09/86										
10/14/86										
10/16/86	0.64	0.54	0.16	0.26	0.22	0.33	0.25	0.23	0.42	0.30
Ave 1986	0.67	0.51	0.27	0.25	0.18	0.27	0.19	0.23	0.36	0.30
06/11/87										
06/13/87										
06/14/87		0.48	0.27	0.24	0.17	0.18	0.24	0.21	0.32	0.27
06/25/87										
06/26/87										
06/29/87	0.57	0.50	0.18	0.31	0.10	0.30	0.11	0.13	0.25	0.24
07/15/87	0.76	0.38	0.24	0.25	0.23	0.28	0.20	0.23	0.22	0.29
08/04/87										
08/05/87	0.62	0.47	0.14	0.24	0.12	0.19	0.15	0.11	0.21	0.32
09/02/87	0.49	0.56	0.22	0.28	0.17	0.28	0.21	0.21	0.24	0.20
Ave 1987	0.61	0.48	0.21	0.26	0.16	0.25	0.18	0.18	0.25	0.26
Average 1986-87	0.63	0.49	0.23	0.26	0.16	0.25	0.18	0.19	0.28	0.27

Table 12. (continued).

Sampling date	Paddock designation	
	EX-I	EX-I
	Transect number	
	5	5
	Streambank (North or South)	
	N	S
	soil moisture content by weight	
07/24/86		
07/28/86		
07/31/86		
08/01/86		
08/04/86		
08/25/86		
08/26/86	0.16	0.16
10/03/86		
10/07/86		
10/09/86		
10/14/86		
10/16/86	0.28	0.24
Ave 1986	0.22	0.20
06/11/87		
06/13/87		
06/14/87	0.29	0.21
06/25/87		
06/26/87		
06/29/87	0.18	0.13
07/15/87	0.28	0.26
08/04/87		
08/05/87	0.23	0.19
09/02/87	0.29	0.21
Ave 1987	0.25	0.20
Average		
1986-87	0.24	0.20

APPENDIX E

SOIL TEXTURE ANALYSIS

Table 13. Laboratory analysis of soil texture by hydrometer method.
Sample mass for each analysis was 50 g.

Sample location			Texture			Textural name*
Paddock	Bank	Depth (cm)	Sand	Silt	Clay	
				(% of total)		
DE	N	0-15	69	22	9	SCL
DE	N	15-30	62	22	16	SCL
DE	S	0-15	71	20	9	SL/SCL
DE	S	15-30	72	14	14	SL
TC-1	N	0-15	62	23	15	SCL
TC-1	N	15-30	63	22	15	SCL
TC-1	S	0-15	61	24	15	SCL
TC-2	N	0-15	67	16	17	SL
TC-2	N	15-30	67	17	16	SL
TC-2	S	0-15	72	8	20	SL
TC-2	S	15-30	76	7	17	SL
TC-3	N	0-15	74	13	13	SL
TC-3	N	15-30	75	12	13	SL
TC-3	S	0-15	60	13	27	SL
TC-3	S	15-30	75	12	13	SL
TC-4	N	0-15	65	16	19	SL
TC-4	N	15-30	70	16	14	SL
TC-4	S	0-15	59	14	27	SL
TC-4	S	15-30	68	13	19	SL
DM	N	0-15	65	20	15	SL/SCL
DM	N	15-30	65	24	11	SCL
DM	S	0-15	63	24	13	SCL
DM	S	15-30	68	20	12	SL/SCL
DW	N	0-15	70	12	18	SL
DW	N	15-30	74	14	12	SL
DW	S	0-15	68	16	16	SL
DW	S	15-30	74	12	16	SL
EX	N	0-15	70	13	17	SL
EX	N	15-30	72	13	15	SL
EX	S	0-15	70	15	15	SL
EX	S	15-30	70	16	14	SL

* SL = Sandy loam

SCL = Sandy clay loam

SL/SCL = Sandy loam/sandy clay loam: texture lies directly on nomenclature boundary.

APPENDIX F

AMOUNT OF SEDIMENT TRAPPED

Table 14. Amount of sediment collected from each trap for each sampling date (g). Sediment trap locations are shown in Figure 10.

Ground surface	Trap	Date			
		June 19	June 24	July 24	Sept 1
Cattle	2-2	902.0	36.5	1110.0	nd
path	1-3	390.0	75.4	554.0	nd
Perennial	2-3	30.6	11.5	174.5	76.1
seepage	8-1	nd	nd	nd	43.0
area	2-4	25.4	4.3	nd	53.3
	4-1	nd	5.7	nd	34.5
Intermittent	0-1	16.3	1.8	5.6	10.2
seepage	3-2	3.8	0.9	28.9	nd
area	10-2	nd	nd	9.5	5.7
	10-1	nd	nd	1.4	4.3
	8-2	nd	nd	2.6	1.1
Dry	1-4	3.1	2.8	12.4	7.9
ground	2-5	3.1	2.4	12.3	6.3
	2-6	nd	1.3	8.0	4.1
	1-2	3.1	1.1	6.8	4.2
	4-3	nd	0.8	1.1	9.0
	2-1	5.8	0.8	nd	nd
	4-2	nd	1.4	5.2	nd
	7-1	nd	nd	4.1	1.4
	11-2	nd	nd	3.4	0.9
	6-1	nd	0.3	3.7	1.9
	7-2	nd	nd	2.7	1.2
	5-2	nd	1.5	nd	nd
	9-1	nd	nd	nd	1.4
	0-2	0.8	0.4	1.3	3.0
	3-1	1.7	0.5	1.1	1.3
	11-1	nd	nd	0.7	0.9
	6-2	nd	nd	0.7	nd
	1-5	0.6	0.1	0.9	0.9
	5-1	nd	0.5	1.0	0.3
	1-1	0.9	0.4	nd	0.2
	9-2	nd	nd	nd	nd

nd = no data

APPENDIX G

RUNOFF VOLUMES AND CONTRIBUTING AREAS

Table 15. Storm runoff volumes and contributing areas.

Event Date: 1987	Flume	Total precip (mm)	Observed runoff (cu m)	Predicted runoff components*				
				Total (cu m)	Stream channel		Seepage area sat (cu m)	area max (cu m)
					act (cu m)	tot (cu m)		
May 15-22	B	90.7	815	644	206	490	154	438
May 25	B	9.7	42	69	22	52	16	47
May 26	B	9.7	41	69	22	52	16	47
May 27-29	B	40.9	347	290	93	221	69	198
May 31	B	7.6	25	54	17	41	13	37
Jun 8	B	16.0	267	108	36	86	22	77
Jun 9	B	13.2	194	89	30	71	18	64
Jun 21	B	29.2	128	197	66	158	40	141
Jul 8	B	8.4	14	57	19	45	11	40
Jul 10-11	B	82.3	702	556	187	445	112	398
Aug 6	B	7.6	28	69	17	41	28	37
Aug 14-15	B	33.8	292	305	77	183	122	163
Sep 26	B	18.5	119	190	42	100	90	90
May 15-22	F	90.7	325	314	163	314	0	63
May 25	F	9.7	15	33	17	33	0	7
May 26	F	9.7	12	33	17	33	0	7
May 27-29	F	40.9	111	142	74	142	0	29
May 31	F	7.6	9	26	14	26	0	5
Jun 6	F	7.4	26	26	13	26	0	5
Jun 8	F	16.0	61	55	29	55	0	11
Jun 9	F	13.2	77	46	24	46	0	9
Jun 21	F	29.2	45	101	53	101	0	20
Jul 17-18	F	51.3	161	183	94	183	0	36
Aug 6	F	7.6	11	26	14	26	0	5
Aug 14-15	F	33.8	93	117	61	117	0	24
Sep 26	F	18.5	35	77	33	64	13	13
May 15-22	B-F	90.7	490	330	42	176	154	375
May 25	B-F	9.7	30	35	5	19	16	40
May 26	B-F	9.7	26	35	5	19	16	40
May 27-29	B-F	40.9	236	149	19	79	69	169
May 31	B-F	7.6	16	28	4	15	13	32
Jun 8	B-F	16.0	206	53	7	31	22	66
Jun 9	B-F	13.2	117	44	6	26	18	55
Jun 21	B-F	29.2	83	96	14	57	40	121
Aug 6	B-F	7.6	18	42	4	15	28	32
Aug 14-15	B-F	33.8	198	188	16	66	122	140
Sep 26	B-F	18.5	84	112	9	36	76	76

* act = Active stream channel area.

tot = Total stream channel bottom area (used for calculation of total predicted runoff volume).

sat = Saturated area of groundwater seeps (used for calculation of total predicted runoff volume).

max = Area of the maximum extent of groundwater-seepage areas.

mm = Rainfall in millimeters.

cu m = Volume in cubic meters.

Table 15. (continued).

Event Date: 1987	Flume	Expected runoff-contributing areas			
		Seepage area		Stream channel	
		maximum (sq m)	saturated (sq m)	total (sq m)	active (sq m)
May 15-22	B	4831	1698	5404	2270
May 25	B	4831	1698	5404	2270
May 26	B	4831	1698	5404	2270
May 27-29	B	4831	1698	5404	2270
May 31	B	4831	1698	5404	2270
Jun 8	B	4831	1356	5404	2270
Jun 9	B	4831	1356	5404	2270
Jun 21	B	4831	1356	5404	2270
Jul 8	B	4831	1356	5404	2270
Jul 10-11	B	4831	1356	5404	2270
Aug 6	B	4831	3623	5404	2270
Aug 14-15	B	4831	3623	5404	2270
Sep 26	B	4831	4831	5404	2270
May 15-22	F	697	0	3465	1803
May 25	F	697	0	3465	1803
May 26	F	697	0	3465	1803
May 27-29	F	697	0	3465	1803
May 31	F	697	0	3465	1803
Jun 6	F	697	0	3465	1803
Jun 8	F	697	0	3465	1803
Jun 9	F	697	0	3465	1803
Jun 21	F	697	0	3465	1803
Jul 17-18	F	697	0	3561	1825
Aug 6	F	697	0	3465	1803
Aug 14-15	F	697	0	3465	1803
Sep 26	F	697	697	3465	1803
May 15-22	B-F	4134	1698	1939	467
May 25	B-F	4134	1698	1939	467
May 26	B-F	4134	1698	1939	467
May 27-29	B-F	4134	1698	1939	467
May 31	B-F	4134	1698	1939	467
Jun 8	B-F	4134	1356	1939	467
Jun 9	B-F	4134	1356	1939	467
Jun 21	B-F	4134	1356	1939	467
Aug 6	B-F	4134	3623	1939	467
Aug 14-15	B-F	4134	3623	1939	467
Sep 26	B-F	4134	4134	1939	467

sq m = Area in square meters.

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