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

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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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 1989

APPROVAL

of a thesis submitted by

Jon Matthew Aspie

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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ACKNOWLEDGMENT

I would like to thank my thesis committee; Dr. Stephan Custer (Committee Chairman) for insight and guidance through the research and writing of this thesis, Dr. William Locke III for help with data crunching, and particularly for statistical help, Dr. John Wilson for writing and organizational comments, and Dr. Clayton Marlow for support and logistical aid while doing field work and laboratory analysis.

Thanks also go out to Chet Clarke for his help with surveying, Jay Erickson for his help with the geophysical survey and Forrest Sanderson for drafting assistance. And, of course, I would like to thank my parents, Estelle and Al Zabrocki, for support and encouragement through my college career.

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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.

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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).

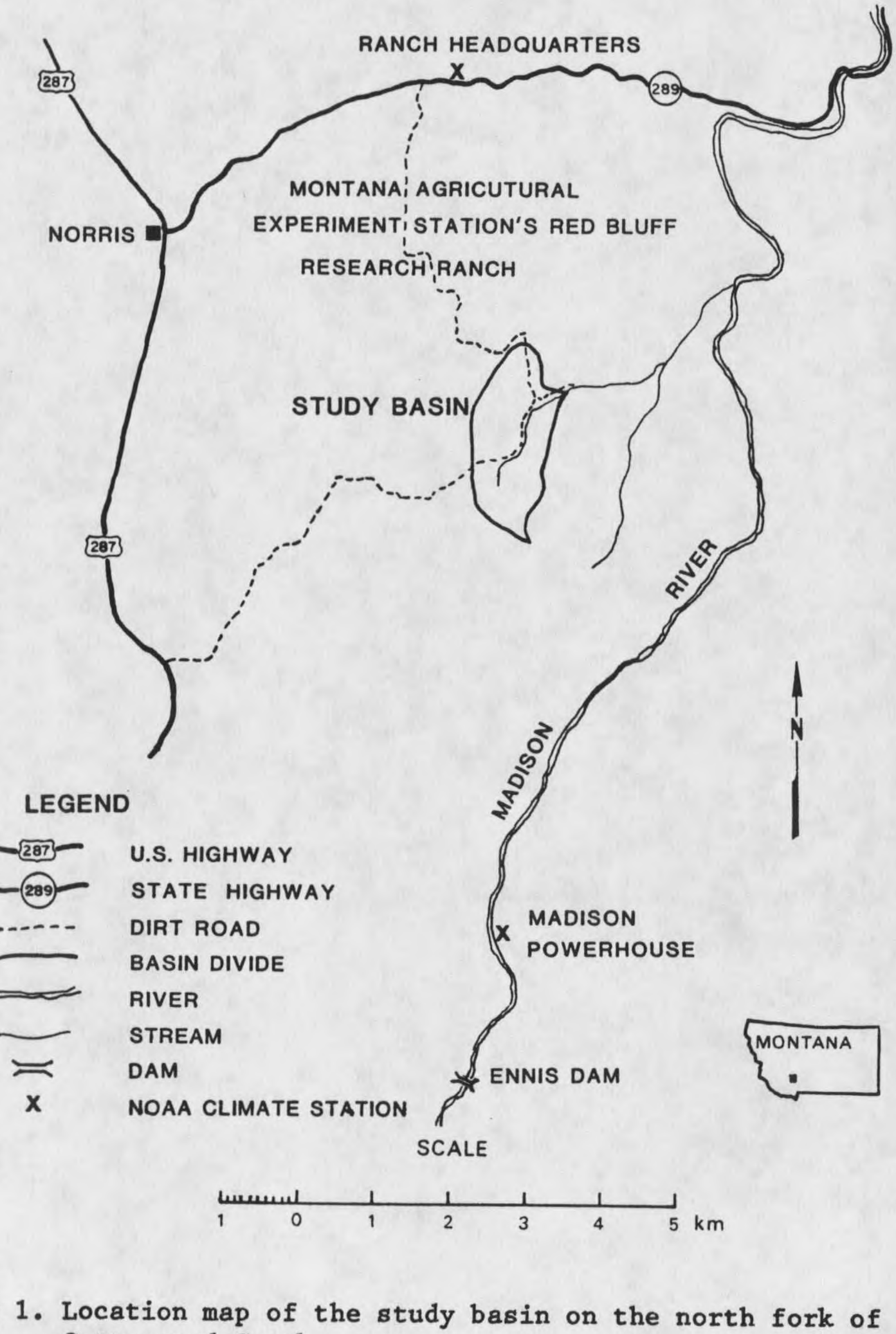

Figure 1. Location map of the study basin on the north fork of Cottonwood Creek.

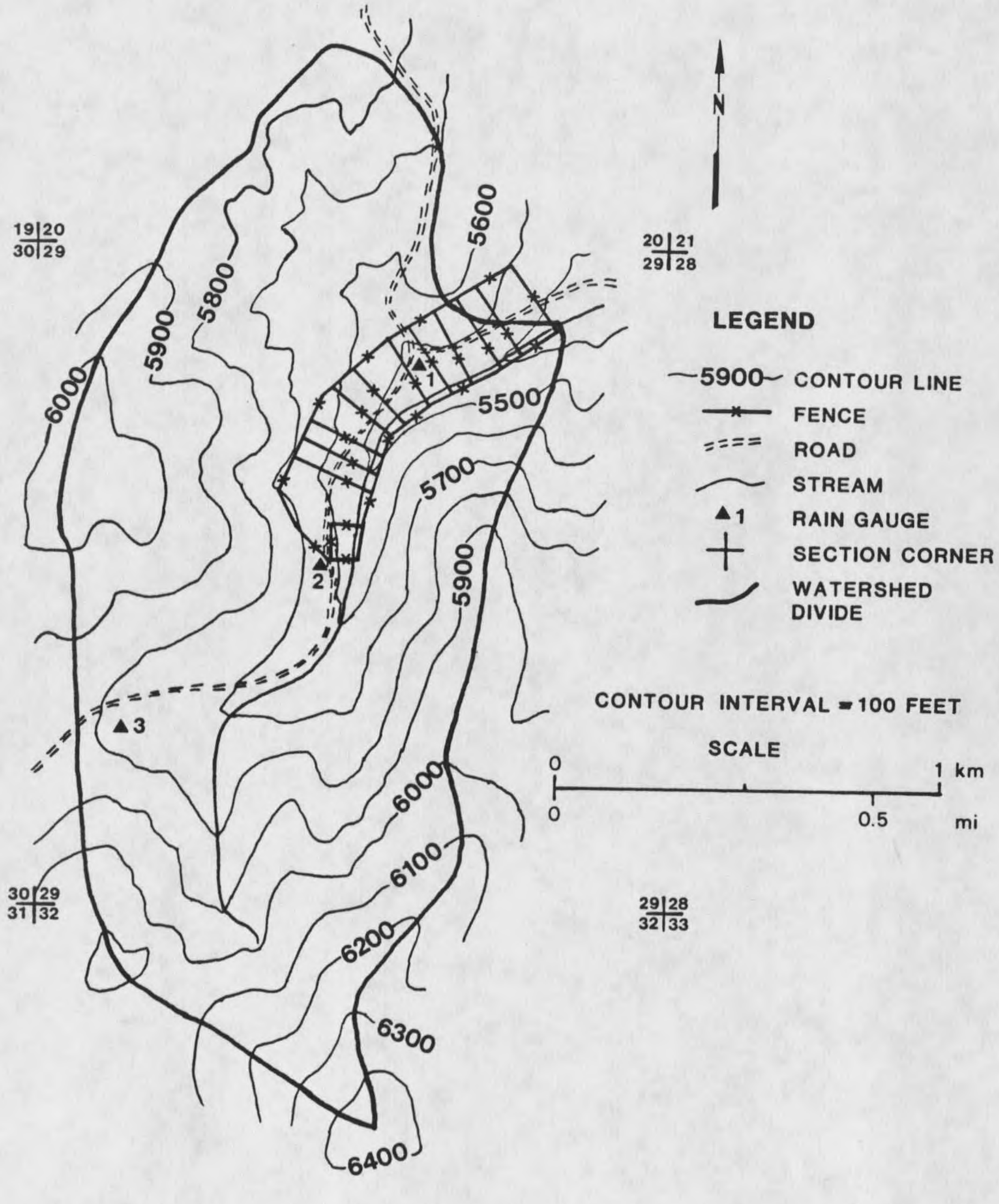

Figure 2. Map of the study basin showing the approximate location of fencelines encompassing the grazing study area and rain gauge placement in 1981 and 1982. Numbers in section corners indicate section numbers in T3S R1E Montana Principal Meridian.

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 (^{o}C). Temperature extremes at the ranch headquarters in 1981 were 35 ^{o}C and -38 ^{o}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