An investigation of groundwater recharge along the western flank of the southern Bridger Range, southwestern Montana
by James Ernest Hay

A thesis submitted impartial fulfillment of the requirements for the degreee of Master of Science in Earth Sciences
Montana State University

Abstract:
Rapid development along the western flank of the southern Bridger Range, Gallatin County, Montana, has heightened the need for information regarding current and future ground water availability. An important aspect of availability is ground water. recharge. This study estimates average annual ground water recharge calculated from a physical water-budget and a chloride mass-balance approach. The water-budget was calculated with measurements of streamflow in and out of the system, and estimates of precipitation, ground water outflow, evapotranspiration, and consumptive water loss related to development. The chloride mass-balance utilized the streamflow data, the precipitation estimate, and measured chloride concentrations in precipitation, ground water, and streamflow to calculate recharge.

The recharge estimates from the water-budget and the mass-balance were 5100 ± 3800 acre-feet and 3000 ± 1700 acre-feet, respectively. The physical water-budget estimate is considered more accurate as it allowed the recognition that the system was not in equilibrium at the time-scale of the study; the chloride mass-balance assumed long-term equilibrium. Consumptive water loss related to development accounted for less than one percent of water leaving the system, suggesting that the impact of development on ground water availability in the area is trivial. Water level monitoring indicates that stream-loss is the dominant source of ground water recharge and revealed seasonal water level fluctuations exceeding 45 feet in the eastern portion of the study area. This is a natural, seasonal fluctuation controlled by the quantity of annual precipitation and subsequent spring runoff infiltration. Long-term fluctuations of greater than 60+ feet are to be expected, particularly in the eastern part of the area, as wet and dry years will significantly affect both the amount of recharge and water levels. Tritium age-dating of water samples suggests that water recharging the eastern third of the study area moves westward via two flowpaths. A significant percentage of the water moves relatively quickly through an unconfined system comprised of the uppermost 150+ feet of alluvial sediments; water at some depth greater than 150 feet appears to move much more slowly. Planners and drillers should consider this information as it has implication for the depth and construction of wells in the area.

AN INVESTIGATION OF GROUNDWATER RECHARGE ALONG THE WESTERN FLANK OF THE SOUTHERN BRIDGER RANGE, SOUTHWESTERN MONTANA

by

James Ernest Hay

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of the requirements for the degreee

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APPROVAL

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James Ernest Hay

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

Rapid development along the western flank of the southern Bridger Range, Gallatin County, Montana, has heightened the need for information regarding current and future ground water availability. An important aspect of availability is ground water recharge. This study estimates average annual ground water recharge calculated from a physical water-budget and a chloride mass-balance approach. The water-budget was calculated with measurements of streamflow in and out of the system, and estimates of precipitation, ground water outflow, evapotranspiration, and consumptive water loss related to development. The chloride mass-balance utilized the streamflow data, the precipitation estimate, and measured chloride concentrations in precipitation, ground water, and streamflow to calculate recharge.

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CHAPTER 1

INTRODUCTION

The western flank of the southern Bridger Range in Gallatin County, southwestern Montana, has experienced rapid growth over the past two decades. There are currently nine subdivisions in and adjacent to the Sypes Canyon and Middle Cottonwood Creek area, with plans to build more in the near future (Figs. 1 and 2). Rapid subdivision has led to concerns regarding the availability of sustainable ground water resources for both current and proposed future development. Although some older, shallow domestic wells in this area have had to be deepened in recent years, insufficient evidence has been collected to date to determine whether this is due to the geologic architecture, natural trends, or withdrawal rates exceeding recharge as subdivisions have been developed.

Several environmental assessments on file with the Gallatin County Planning Office, prepared as part of the subdivision permitting process, provide some characterization of the subsurface water-bearing units and estimate the ground water resources available for domestic use. These reports are subdivision-specific and often rely heavily upon the first extensive ground water investigation of the Gallatin Valley (Hackett and others, 1960). One consulting firm has gone to some effort to investigate the ground water system in a central portion of the area (Morrison-Maierle, 1993a, 1993b). However, recharge estimates have been very generalized and poorly constrained. The

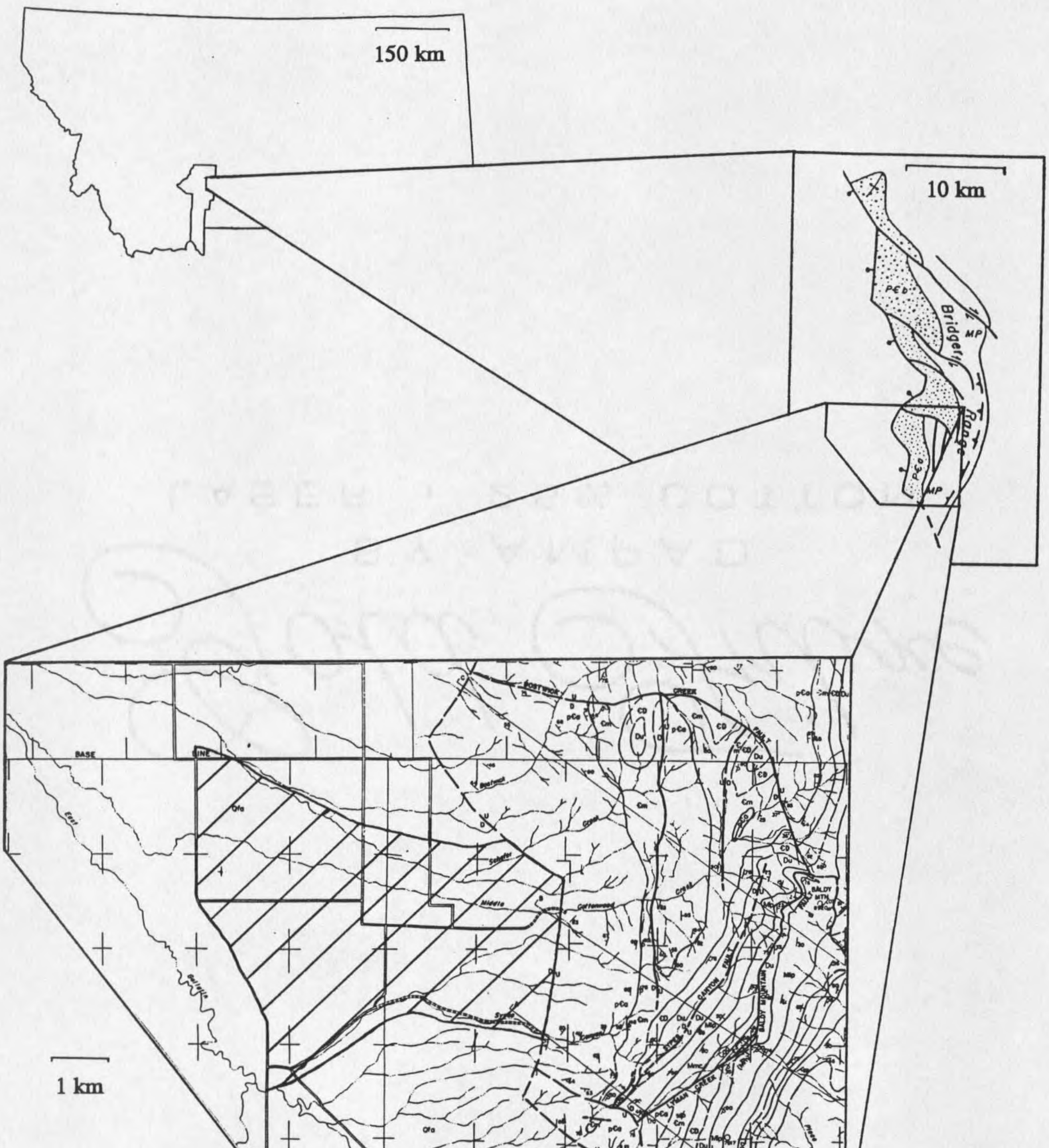
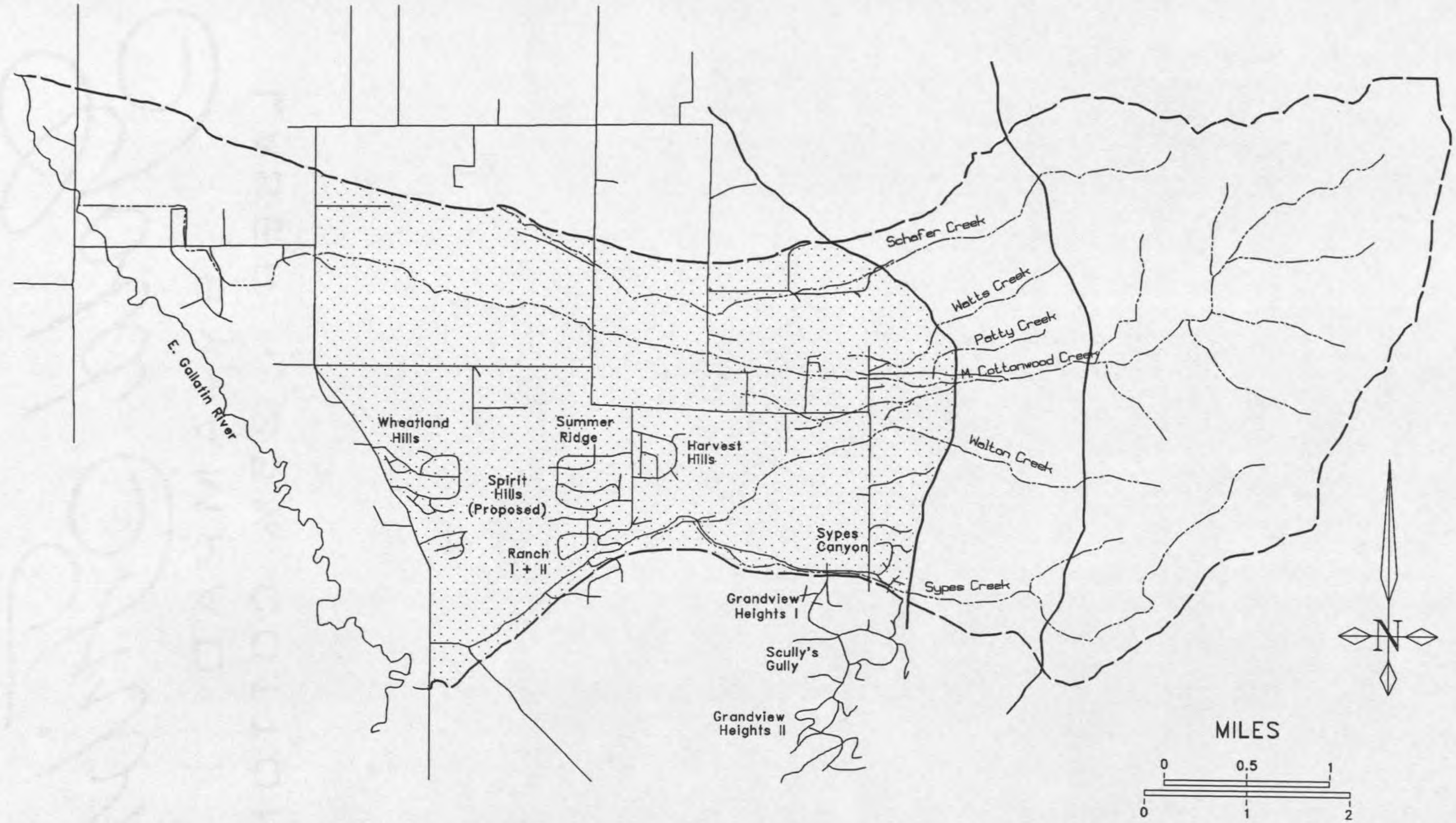


Figure 1. Generalized location map of study area (after McMannis, 1955; Lageson, 1989). Approx. study area shaded; pCa, Archean metamorphic rocks; pCb, pre-Cambrian Belt rocks; Cm, middle Cambrian undiff.; CD, upper Cambrian undiff.; Du, Devonian, undiff.; QTu, Quaternary-Tertiary undiff.



– – – Drainage boundaries

——— Metamorphic rock boundaries

Figure 2. Study area map. Shaded region is study area.

purpose of this investigation is to provide a better constrained estimate of ground water recharge to the study area on the western flank of the southern Bridger Range, Gallatin County, Montana. Utilization of both a classical physical water budget and a chloride mass-balance allows a test of the efficacy of the much less expensive and faster chloride mass-balance approach. Tritium age-dating of water samples was also used to investigate the residence time of water in the subsurface and provide perspective on recharge rates. Monthly monitoring of available wells was performed to investigate the hydraulic gradient, local flow directions, and the relationship between fluctuations in the potentiometric surface and ground water recharge.

Study Area

The study area is in a piedmont setting on the western flank of the southern Bridger Range approximately five miles north of Bozeman in Gallatin County, Montana. The area encompasses roughly 19 square kilometers (7 square miles) and includes Sypes, Walton, Middle Cottonwood, Watts, and Schafer Creek drainages. The area is bounded on the east by the range-front normal fault (Fig. 2). There is a band of metamorphic rocks east of the fault, on the upthrown side. Although the study area does not extend east past the fault, the limits of the contributing drainage basins are indicated for reference and completeness. The western boundary is Spring Hill Road. The East Gallatin River lies outside the study area.

This area was chosen because of heavy current and proposed future residential development. Also, the area lacks internal faulting which both simplifies the water balance by minimizing any ground-water flow along faults into or out of the field area, and minimizes possible sources of chloride contamination.

Geologic History

The Gallatin Valley and Bridger Range experienced a complex structural history from 55 m.a. to the present that includes compression and extension (Kuenzi and Fields, 1971; Lageson, 1989). Approximately 55 m.a., compressional tectonic forces folded the sediments and metamorphic basement rocks into a north-northwest trending anticline. Sometime between 46 m.a. and 15 m.a., the compressional forces were replaced by a Basin-and-Range style extensional regime in which the Bridger range-front listric normal fault developed. The exact age of the beginning of extension depends upon whether one interprets the Renova Formation to be a Laramide basin-fill deposit or a Basin and Range deposit (Lageson, 1989). Regardless of the date, extension caused the crest and west limb of the "Bridger Anticline" to be faulted and dropped relative to the eastern side. This tectonic offset initiated the development of alluvial fans into the Gallatin Valley (Kuenzi and Fields, 1971; Hughes, 1980; Lageson, 1989).

The study site is on a gently west-sloping surface. This surface is composed of Quaternary alluvium which rests unconformably on Tertiary/Quaternary age alluvial material. Most domestic water wells are completed in strata interpreted as either the Tertiary Sixmile Creek Formation or overlying Quaternary units (Kuenzi and Fields, 1971; Hughes, 1980). However, the Quaternary gravel deposits so strongly resemble the Tertiary units (Glancy, 1964) that neither can easily be distinguished in well logs or the few available surface outcrops. Additionally, the fine and coarse-grained units of the near-surface sedimentary rocks are laterally discontinuous and diachronous (Hanneman and Wideman, 1991). The discontinuous nature of these deposits is supported by the fact that individual water-bearing and aquitard layers do not correlate easily across the study area. Also, the delayed-yield behavior observed during aquifer pump tests is better explained by discontinuous units than by continuous, discrete aquifers (Appendix C). Furthermore, the aggradational setting in which these units were deposited has been replaced by an erosional regime and the degree to which the loess deposits, the most laterally extensive aquitards in the area, have been dissected is not known. The resulting "hydrogeologic framework" is complexly stratified (Hackett and others, 1960; Hughes, 1980), and consists of laterally discontinuous stringers of both coarse and fine alluvial material interfingered with very fine eolian deposits (Glancy, 1964; Hughes, 1980; Davis, 1992).

The primary aquifer materials in the eastern portion of the area are visible in road cuts and streambeds and are composed of locally derived metamorphic and sedimentary rock clasts deposited on alluvial fans which originate in the Bridger Range (Hackett and others, 1960; Hughes, 1980). Individual units of coarse sand, gravel, and boulders in these fan materials are likely a few meters in thickness, tens of meters in width, and hundreds of meters in length, based on the size of deposits observed associated with streams such as Middle Cottonwood Creek, and limited observations of outcrops and well logs. These deposits probably trend in a generally east-west direction. The relatively few aquitards in this area are presumably comprised of loess blankets and debris flow lobes rich in silt and clay which abut and surround the channel deposits. Intact loess sheets may be hundreds of square meters in extent; individual debris flow deposits may reach ten meters in width and a hundred meters in length.

Toward the central portion of the area, the fan materials become more extensively reworked by streams. These deposits are of a similar scale and trend as those to the east, with a somewhat greater degree of sorting, although cobbles and boulders are not uncommon, particularly in the streambeds. Loess deposits, which accumulated during a hiatus in the valley filling process, comprise the most significant aquitards and are likely hundreds of square meters in extent.

In the western portion of the area, the fluvial nature of the aquifer materials is even more apparent. Gravel bars and coarse channel fill deposits are present which are one to two meters thick, two to five meters wide, and perhaps hundreds of meters long. Waning energy channel fills of the same dimension and overbank deposits, tens to hundreds of square meters comprise aquitards in this area. The trend of these deposits could be roughly north-south if they were deposited by the ancestral East Gallatin, east-west if deposited by a "major west-flowing stream" draining the Crazy Mountains (Glancy, 1964), or a combination of both if fan material interfingers with the East Gallatin river system.

Regardless of whether the alluvial fan or river deposits dominate the stratigraphy, substantial heterogeneity is indicated. Figure 3 is a conceptual diagram of one possible interpretation of the aquifer architecture in this area. Thus, the study area is better characterized by laterally discontinuous, lenticular deposits of alluvial material than by well-defined, continuous "layer-cake" aquifers.

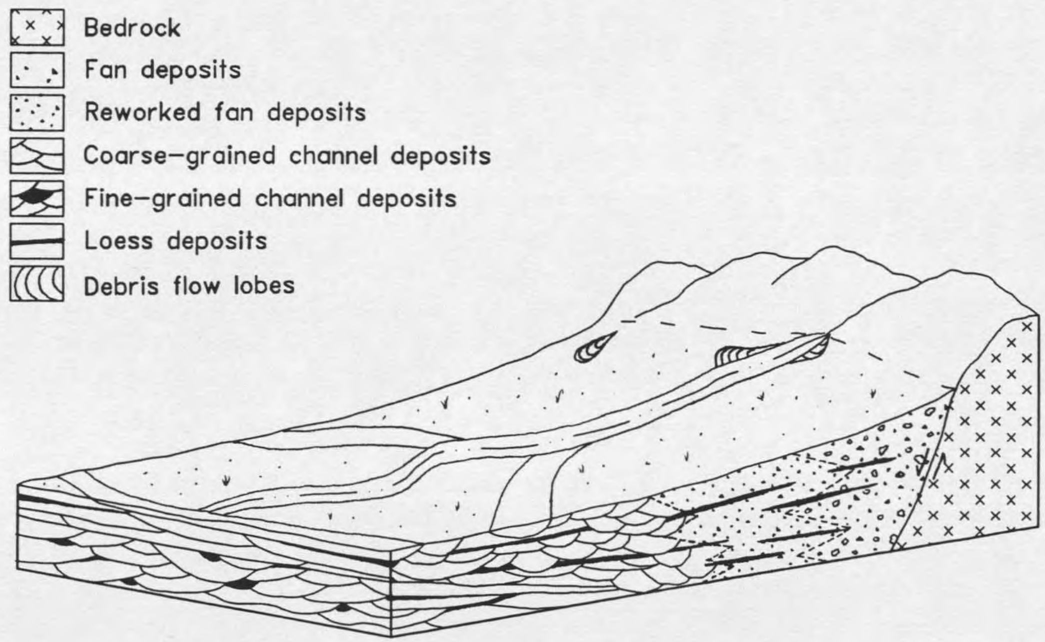


Figure 3. Conceptual diagram of aquifer architecture. No scale implied.

CHAPTER 2

THEORY

Physical water-budget and chloride mass-balance techniques can estimate the amount of ground water recharge occurring within a defined area. The following sections detail the theory upon which each method is based and the assumptions that are required to implement them.

Physical Water-budget

Water-budget analysis is based upon an equation which accounts for all the water entering and leaving a system. In a developed aquifer, these parameters may be written and arranged as follows:

$$R_{GW} = (P + I_{SW} + I_{GW}) - (ET + ET_D + E_R + O_{SW} + O_{GW} + U_{IRR}) \pm S_{SW} \qquad \text{Eq. 1}$$

where R_{GW} = ground water recharge (also equivalent to the change in ground water storage), P = precipitation, I_{SW} = surface water inflow, I_{GW} = ground-water inflow, ET = evapotranspiration, ET_D = evapotranspirative loss from septic discharge, E_R = evaporation from reservoirs, O_{SW} = surface water outflow, O_{GW} = ground-water outflow, U_{IRR} = lawn irrigation, and S_{SW} = the change in surface water storage.

The following assumptions are appropriate for this site, and are discussed below: 1) ground-water inflows (I_{GW}), reservoir evaporation (E_R), and surface storage (S_{SW}) are minimal; 2) all lawn irrigation water (U_{IRR}) is lost to evapotranspiration; 3) septic tank discharge is essentially equal to domestic water withdrawal.

Ground water inflow to the study area must come from the metamorphic rocks of the Bridger Range. Metamorphic rock has a primary porosity of less than one percent (Davis and Turk, 1964) and a hydraulic conductivity on the order of 10^{-7} cm/s or less (Gale, 1982; Stober, 1996). The small fractures observed in the field (<1mm wide) and the tendency for fracture widths to decrease with depth (Davis and Turk, 1964) suggest these flow rates are minimal, but the large area through which such flows may occur and the steep hydraulic gradients from the mountains make this component of the water budget difficult to quantify. For the purposes of the physical water-budget, ground-water inflows from the mountain front are considered minimal. This assumption will result in a slightly conservative estimate of ground water recharge.

Surface water storage change and evaporation are assumed negligible for several reasons. Aerial photographs and field reconnaissance revealed three small ponds within the study area which briefly detain excess spring runoff from Middle Cottonwood and Walton creeks. Infiltration and evapotranspiration rapidly diminish these ponds. No unobstructed views of the largest pond (in the Walton drainage) were available, and no access to the pond was permitted. Therefore, estimation of pond size, changes in storage, or evaporative loss was not possible. The small size of the ponds relative to the total study area and the ephemeral nature of these water bodies in general suggests that surface water storage (S_{SW}) and reservoir evaporation (E_R) are minimal.

Field reconnaissance and discussions with area residents indicate that lawn irrigation outside of the subdivisions is not widespread. A subjective determination of lawn irrigation patterns based on type of grass (native vs. introduced), "greenness" and vigor of lawn, and distinctness of irrigation boundaries (e.g., lush, green grass terminating at property boundaries), indicates that the majority of lawn irrigation occurs in the Wheatland Hills, Summer Ridge, Ranch, and Harvest Hills subdivisions. The remainder of lawns in the study area were apparently only sporadically irrigated. The distinct irrigation boundaries and lush lawns were almost always associated with exotic grass species (e.g., Kentucky Bluegrass) with shallow root systems and high water requirements (Steinegger and others, 1992). As sprinklers appear to be the dominant method of lawn irrigation, whatever water is not transpired by lawns is presumed to evaporate. As such, all lawn irrigation (U_{IRR}) is assumed to be lost to evapotranspiration.

The total ground water withdrawal that occurs in developed areas does not reflect the actual loss from the system. In rural areas, essentially all of the water withdrawn for domestic use (showers, washing machines, toilet flushing, drinking, hand and dishwashing, cleaning, etc.) is discharged through septic tank drain fields (Perkins, 1989, p. 231; Fetter, 1993, p. 16-18). Only a small portion of this water (ET_D) may be lost to evapotranspiration, the remainder gradually percolating back to the water table resulting in a net transfer of water from deeper flow systems to shallower ones.

The actual percentage of septic effluent water that is lost to evapotranspiration has been poorly characterized in the literature. Attempts were made in late summer and throughout the field season to locate unusually lush lawn areas that might indicate that water and nutrients were moving upwards from septic drainfields; however, no such locations were found. Discussions of septic tanks and the widespread problem of ground water contamination by septic tank effluent identified in Dunne and Leopold (1978, p. 183-87, 753), Freeze and Cherry (1979, p. 439), Miller (1980, p. 509), Todd (1980, p. 335), and Fetter (1993, p. 16-18; 1994, p. 473) suggest that the majority of effluent water from septic systems recharges the ground water system. Bauman (1985, p. 122), in a simplistic model of ground water pollution potential from septic systems in semi-arid Montana, assumed that 100% of septic tank effluent eventually reached the water table. In this study, bracketed estimates of the percentage of septic tank discharge that is lost to evapotranspiration are used to explore water loss from septic systems. Only the estimated evapotranspirative loss from septic discharge, ET_D, is considered an output from the system. The rest of the septic effluent water returns to the ground water system, negating the need to account for it specifically in the water-budget.

The net annual ground water recharge is calculated from the following equation:

$$R_{GW} = (P + I_{SW}) - (ET + O_{SW} + O_{GW} + U_{IRR}) \qquad \text{Eq. 2}$$

Figure 4 diagrammatically shows how each of these quantities relates to the natural system; the relative size of the arrow indicates the approximate magnitude of the each quantity.

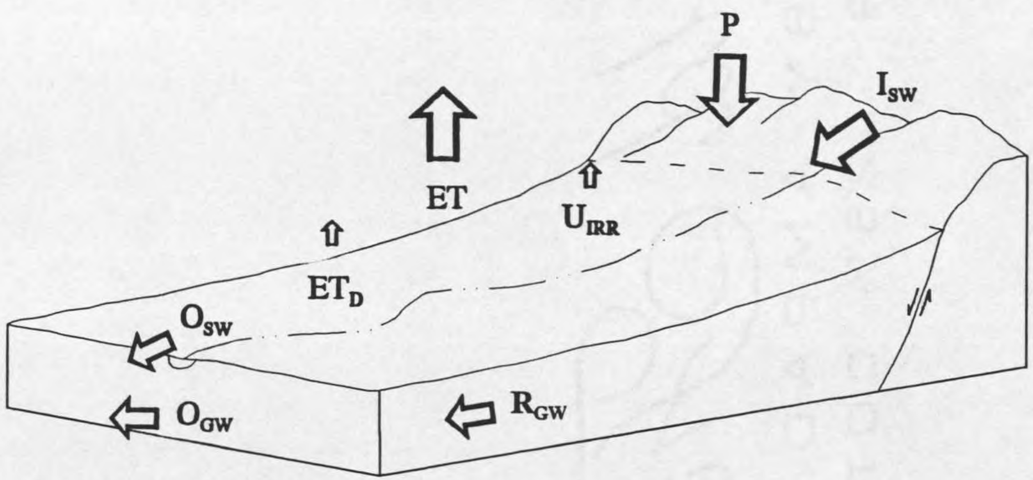


Figure 4. Schematic diagram of physical water–budget quantities. No scale implied.

Chloride Mass-balance

Another method of recharge estimation is based on the concentration of chloride in ground water as the result of evapotranspiration. To understand this procedure, several properties of the chloride ion and how it behaves in a natural system must be recognized.

> "Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few vital biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes." (Hem, 1985, p. 118)

Chloride enters the hydrologic cycle in coastal areas as sea spray, which is carried inland by atmospheric air masses and incorporated into precipitation. The chloride concentration in precipitation is greatest adjacent to these coastal sources, but decreases to a relatively constant level within 500 miles of the coast due to the vertical mixing of the air masses and, to a minor degree, washout by precipitation (Junge and Gustafson, 1957; Junge and Werby, 1958). Therefore, the average annual chloride input to the Gallatin Valley is expected to be essentially constant. Subsequent chloride enrichment in surface and shallow subsurface waters occurs as the result of evapotranspiration; since chloride does not leave with evaporated or transpired water, it becomes concentrated in the remaining water by these processes. This water either infiltrates towards the water table, is detained in surface reservoirs, or leaves the system as runoff. Thus, the ratio of the chloride concentration in precipitation relative to that in ground water reflects the proportion of precipitation that has successfully recharged the ground water system.

Dettinger (1989) suggests that the chloride input is equal to the product of the chloride concentration in precipitation (C_P) and the average yearly precipitation over the study area and contributing catchments (P). In a similar fashion, chloride output from the system is then either part of the water recharging the system ($C_R R$) or part of the runoff ($C_Q Q$)(Claassen and others, 1986; Dettinger, 1989). Setting the chloride input equal to output, the average annual recharge, R_{GW}, can be evaluated as:

$$R_{GW} = P\,(C_P / C_R) - Q\,(C_Q / C_R) \qquad \text{Eq. 3}$$

where P = average annual precipitation, C_P = [Cl^-] in precipitation, C_R = average [Cl^-] in recharge water, Q = average annual runoff, and C_Q = average [Cl^-] in runoff leaving the system.

The estimated amount of precipitation has a large influence on the recharge volume calculated from this method. Rather than depending upon estimates of the highly variable precipitation over the upper elevations of the contributing catchments, the measured stream inflow (S) and its chloride concentration (C_S) were used. Precipitation and streamflow together are presumed to provide all the chloride input to the ground water system, thus their contributing volumes are summed as indicated in the following equation:

$$R_{GW} = P\,(C_P / C_R) + S\,(C_S / C_R) - Q\,(C_Q / C_R) \qquad \text{Eq. 4}$$

Figure 5 diagrammatically shows how each of these water quantities and chloride concentrations relates to the natural system; the relative size of the arrow indicates the approximate magnitude of the each quantity.

USGS ground water chemistry analyses for the Gallatin Valley and the study area indicate an average chloride concentration of only 3.7 mg/L (USGS, 1992-1993). Feth (1981, p. 1) states that "where surface and ground waters contain less than 5 or 10 mg/L Cl, atmospheric sources may be the major contributors." As such, septic system effluent and maintenance chemicals, fertilizers, and livestock wastes are considered to be negligible sources of chloride. Some rock types, particularly marine shales with high anion-exchange capacities, can be sources of chloride contamination. However, these rock types are of minor extent within the study area and, as stated above, the low concentrations of chloride throughout the system reinforce the assumption of minimal rock-derived chloride.

Tritium Analysis

Tritium (^{3}H) is produced as a byproduct of thermonuclear testing and naturally as the result of cosmic neutrons impacting on nitrogen nuclei in the upper atmosphere according to the reaction:

$$^{14}N + 1 \text{ cosmic neutron} \rightarrow {}^{12}C + {}^{3}H$$

Tritium then enters the hydrologic cycle by colliding with oxygen (O_2) to form water ($^{3}H^{1}HO$)(Rosenstiel School of Marine and Atmospheric Science Tritium Laboratory, 1991; Environmental Isotope Laboratory, 1993). Thus, as long as water is exposed to the

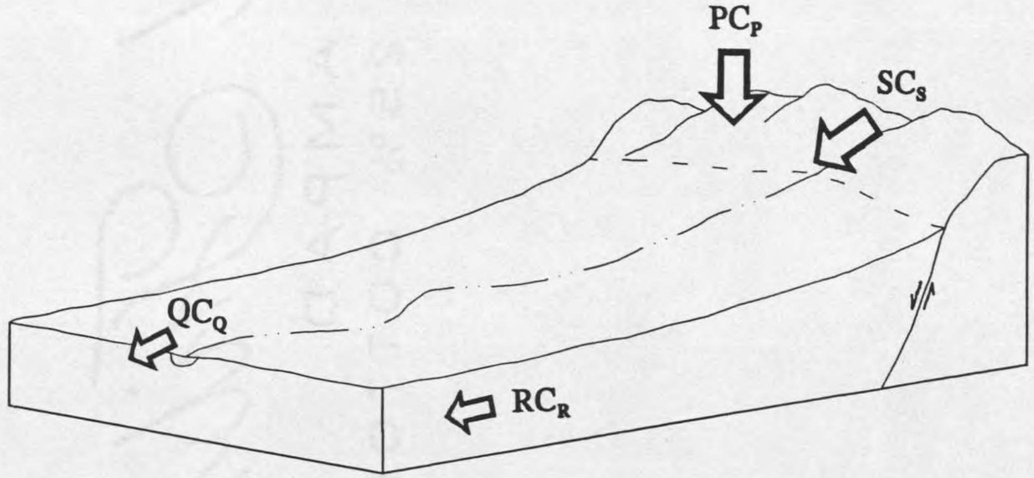


Figure 5. Schematic diagram of chloride mass-balance quantities. No scale implied.

atmosphere, it can incorporate tritium into the water molecule. After reaching the saturated zone, the soil shields the system from cosmic radiation and the amount of tritium in the water is fixed and it declines with a half-life of 12.34 years. The residual tritium levels provide qualitative estimates of ground water age that can be used to address the residence time of ground water within the alluvial bench.

Prior to the onset of above-ground nuclear testing in 1953, tritium levels in precipitation were less than 10 tritium units (TU) where one TU is equal to one tritium atom in 10^{18} hydrogen atoms (Fetter, 1994; Hendry, 1988). In the immediate post-bomb years, large amounts of tritium were injected into the atmosphere, incorporated into precipitation, and recharged to the ground water system. As a result of the variable amounts of tritium that were produced and the complexity of weather patterns that have distributed it, the resolution of this method has been reduced to separating pre-1953 water from post-1953 water as indicated in Table 1. The age determined by this method reflects how long it took for water entering the local ground water cycle to reach its present location (i.e., the sampling location and depth).

Table 1. Estimates of ground water age based on tritium concentrations (Hendry, 1988).

Concentration (TU)	Interpretation
> 100	Average ground water likely recharged during thermonuclear testing between 1960 and 1965.
10 - 100	Average ground water less than 35 years old.
2 - 10	Average ground water at least 20 years old.
< 2.0	Average ground water older than 30 years.
< 0.2	Average ground water older than 50 years.

CHAPTER 3

METHODS AND PROCEDURES

Location Numbering System

All wells and water meters are numbered according to the system as outlined by Slagle (1995)(Fig. 6). The first three characters indicate the township and its position north (N) or south (S) of the Montana Base Line; the second three characters indicate the relative position of the range east (E) or west (W) of the Montana Principal Meridian. The next two digits indicate the section number. The next four letters specify the quarter section (160-acre tract), quarter-quarter section (40-acre tract), quarter-quarter-quarter (10-acre tract) section, and the quarter-quarter-quarter-quarter section (2.5-acre tract), respectively. At each level of division, the tract of land is divided into four quadrants, labeled in a counterclockwise direction A, B, C, and D, starting with the northeast quadrant. Domestic and stock wells have an additional two digits that allow the distinction of wells in close proximity to each other; water meter location numbers terminate with the letter "m" to distinquish them from monitored wells.

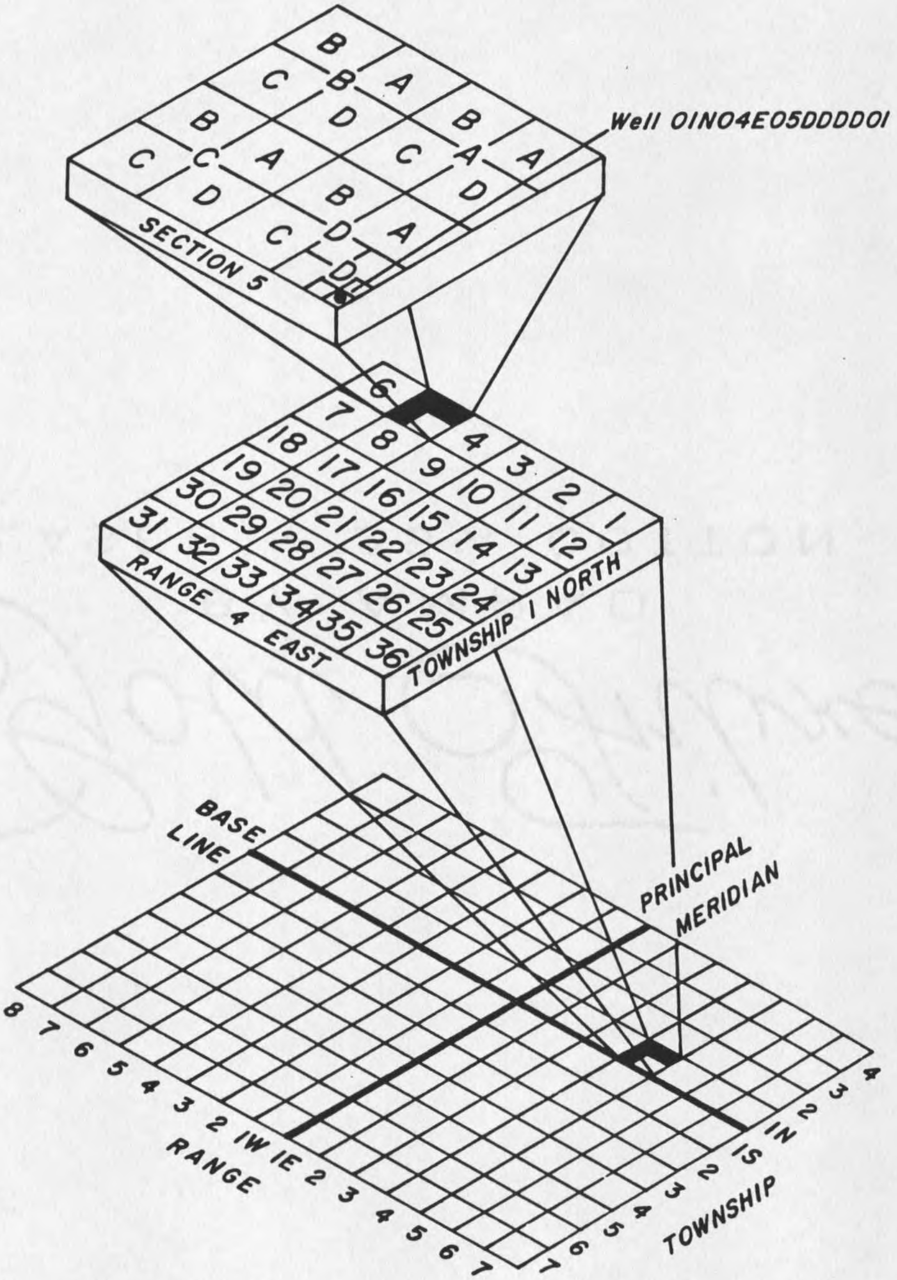


Figure 6. Location numbering system (from Slagle, 1995).

Physical Water-budget

Precipitation

No precipitation monitoring stations are present within the study area. Therefore, precipitation was estimated from a hand-contoured map of the thirty-year average precipitation (1961-90)(Custer and others, 1996). The precipitation isohyets were superimposed on the base map of the study area, then the areas between adjacent isohyets were calculated with a computer program and labeled A_1 through A_4 (Fig. 7).

The mean precipitation value between contours for each area was multiplied by the area to obtain an annual average precipitation volume. For example, the majority of the western boundary of the study area along Spring Hill Road lies approximately at the midpoint between the 16 inch and 18 inch isohyets and is presumed to receive 17 inches of precipitation. Thus, the lowermost area, A_1, essentially falls between the 17 and 18 inch isohyets and was multiplied by 17.5 inches of precipitation; A_2 was multiplied by 19 inches of precipitation; A_3 was multiplied by 25 inches of precipitation; A_4 was multiplied by 35 inches of precipitation. Each respective product of area and precipitation yields a volume of precipitation entering the system. The sum of all such areas *below* the elevation of stream gauges used to estimate surface water input was used in Equation 2; precipitation falling above the gauges was accounted for in the measurement of surface water inflow.

Surface Water Inflow and Outflow

Surface water inflow was measured with Stevens Type-F stage recorders installed above the range front fault on each of the four major streams flowing into the study area

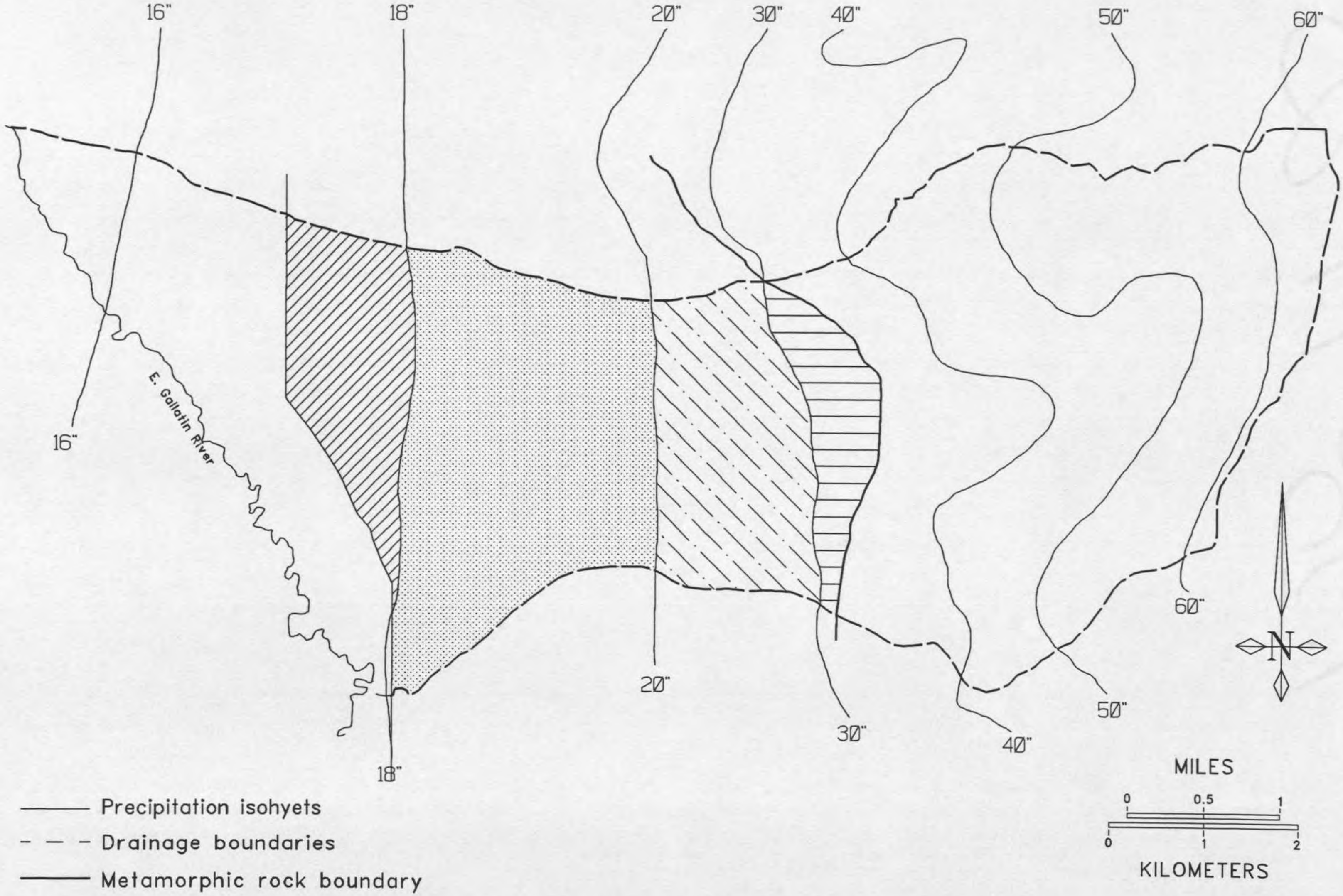


Figure 7. Precipitation isohyets and areas used to obtain annual precipitation volume.

(Fig. 8). Each stage recorder utilized a eight day clock and was mounted on top of an eight inch diameter PVC stilling well with a four inch diameter intake pipe (Fig. 9). Watt's Creek was independently gauged using a standard three-inch Parshall flume. A few, small irrigation ditches fed by and adjacent to Middle Cottonwood Creek are present below the range-front fault; their contribution to surface water inflow is incorporated with that of Middle Cottonwood Creek as Middle Cottonwood Creek is gauged above all diversions.

Weekly discharge measurements were made at each stream from March 15, 1995 to March 15, 1996 using a Marsh-McBirney electronic flowmeter. Stage-discharge relationships were estimated by regressing stream stage against discharge using low-order polynomial regression (Appendix A). A poor correlation between stage and discharge was achieved when all recorded measurements were used together. Separating the stage-discharge data pairs from the rising and falling limbs of the stream hydrographs improved correlations significantly for Middle Cottonwood, Schafer, and Sypes creeks. Modifications of the stream channel (i.e., width, depth, roughness, etc.) related to the seasonal high discharge of spring runoff necessitated this separation of data. However, frequent modification of the Walton Creek channel, both natural and man-made, throughout the period of record required more extensive analysis. Stage recorder graphs and arithmetic plots of stage versus discharge were used to identify four intervals of constant stage-discharge relationship separated by three intervals of rapid change. A stage correction factor was estimated by correlating discharges of equal magnitude (as measured during weekly visits) and taking the difference in stage indicated by the staff gauge. This

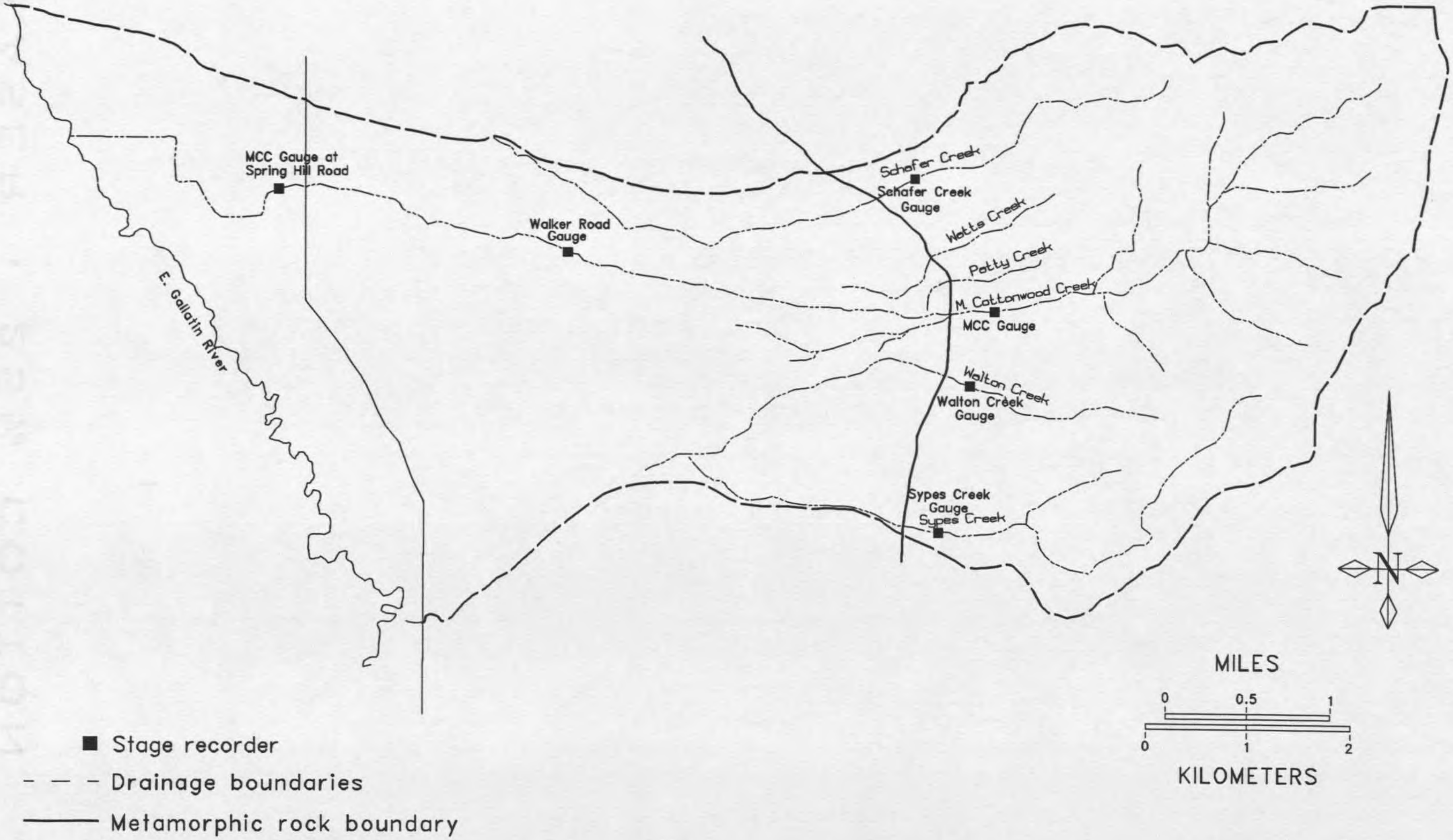


Figure 8. Locations of stage recorders used to measure streamflow.

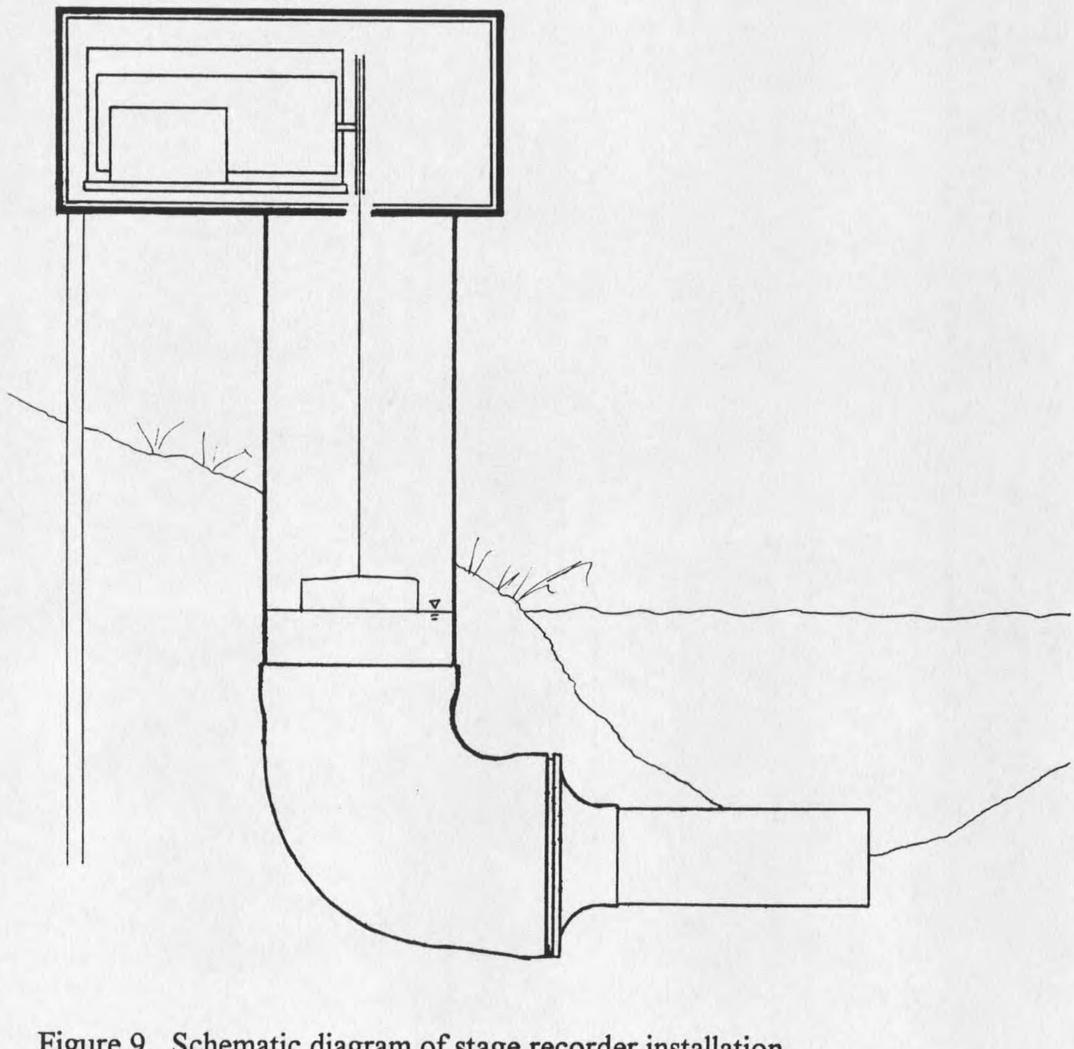


Figure 9. Schematic diagram of stage recorder installation.

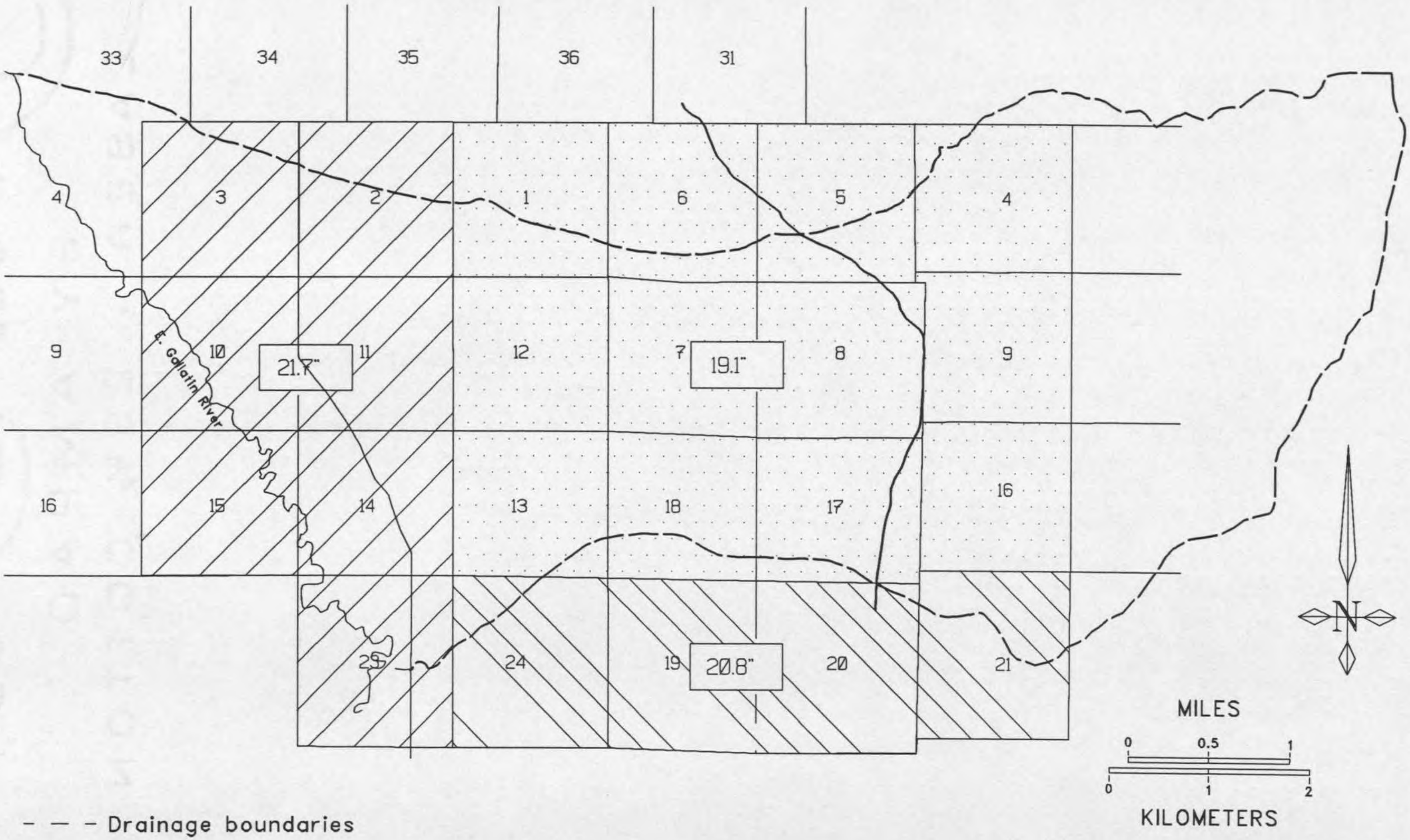
difference was then divided evenly over the period of change. At the point at which the channel appeared to stabilize again, the difference was added as constant. For example, the correction factor from each erosional event was added to the stage of each subsequent stable period. All stage-discharge data pairs from Walton Creek were then used together to develop a single predictive equation for discharge. In this manner, the effects of changes in the stage-discharge relationship on discharge estimates for Walton Creek were minimized over the period of record. As Watt's Creek was monitored with a flume of known dimensions, only stage measurements were required to determine discharge. Recorder graphs of stream stage were then digitized at 0.05 day increments. The discharge for each increment was obtained by substituting the stage values into the stage-discharge regression equations.

Missing discharge data were estimated by regressing available discharge data against the available discharge data of the other streams. Visual examination of hydrographs for each of the streams allowed the identification of those discharges dominated by snowmelt and spring precipitation and those dominated by ground water baseflow contributions. Stream discharges for day 74.5 (March 15, 1995) through day 199.95 (July 18, 1995) were dominated by snowmelt and spring precipitation; missing discharge data were determined by regressing each stream's discharge for this period against the discharge of the other streams for the same period (Appendix B). Discharges for day 200.0 (July 19, 1995) through day 440.5 (March 15, 1996) were dominated by baseflow contributions; missing discharge data for this period was estimated, as above, by regressing stream discharges for this period against each other. For those periods from day 341.8 (December 7, 1995) through day 434.8 (March 9, 1996) for which no stream measurement data were available, stream discharge was approximated by a straight line segment drawn between existing data points.

The only surface water outflow from the study area occurred on Middle Cottonwood Creek and was measured using a Stevens Type-F stage recorder just across the western edge of the study site where the stream crosses Spring Hill Road. This outflow occurred within the time period dominated by snowmelt and spring precipitation. Discharge was measured daily during the initial spring runoff, and weekly after the peak discharge. The procedures outlined above for the regression of the stage-discharge relationship, digitization of stream stage values, and discharge estimation were used.

Evapotranspiration

Actual evapotranspiration (AET) is typically very difficult to measure and most of the methods used to estimate this quantity require intensive data on humidity, wind speed, and dew point temperature (Dingman, 1994, p. 294 -301) which are not available for the area. However, the potential evapotranspiration (PET), which is much simpler to calculate, is often used to approximate AET (Todd, 1980, p. 362). A PET estimate is available from the Montana Agricultural Potential System (MAPS)(Caprio and others, 1994), and is used as a maximum value of ET. This GIS-based program mapped the Thornthwaite PET rates in Montana with a cell resolution of approximately 3 X 3 minutes (approximately 2 X 3 miles) in size. Each township, range, and section was given an annual PET value, and grouped with other sections with the same value (Fig. 10). The



— — — Drainage boundaries

——— Metamorphic rock boundary

Figure 10. Evapotranspiration estimates and areas used to obtain annual evapotranspiration volume.

product of the PET value and the corresponding area yielded a potential ET volume for that portion of the study area. The sum of these areas was used in Equation 2.

How closely PET estimates approximate AET water losses is governed by the time of year, the amount of water available, and length of time that water is at or near the ground surface and subject to evapotranspirative losses. To estimate the sensitivity of recharge estimates to the possible overestimation of evaporation losses provided by the MAPS estimate, arbitrary minimum and intermediate estimates of AET (50% and 75% of the PET estimate, respectively) were explored.

Ground Water Outflow

Ground water outflow was estimated from Darcy's law according to the equation:

$$Q = TIw$$

where Q is ground water outflow (m^3/year), T is the transmissivity of the aquifer (m^2/year), I is the hydraulic gradient (dimensionless), and w is the width of the aquifer (m).

No recovery or pump tests were performed as part of this study. However, previous recovery and pump tests from area consultants (Gaston Engineering, 1995; Morrison-Maierle, 1993a, 1993b) were re-interpreted to evaluate the transmissivity values obtained. Pump test data, interpretations, and transmissivity estimates are discussed in Appendix C. Rather than use hydraulic conductivity estimates, transmissivity estimates from these pump tests, which incorporate the thickness of water-bearing units, have been used in ground water flow calculations.

Hydraulic gradients were obtained or calculated from potentiometric maps by Morrison-Maierle (1993b), Erickson (1994), and Slagle (1995). An additional estimate of the hydraulic gradient was approximated from topography on the 1:24000 Miser Creek Quadrangle. These estimates showed little deviation, and the average of these estimates was used. Width of the aquifer was measured along a straight line connecting the intersections of Spring Hill Road and the northern and southern study boundaries.

Domestic and Irrigation Water Use

Sensus SR II well flowmeters were installed on two households within the study area to evaluate the role of domestic withdrawal and irrigation as a source of water loss from the ground water system (Fig. 11). A primary flowmeter was installed in-line with the well intake pipe to measure total water withdrawn from the well for domestic, in-home and external use. Additional meters were placed on all outdoor spigots and hydrants to measure external water use. Domestic (non-irrigation) water use was obtained from the difference between these measurements.

Meters already installed in five Summer Ridge households as part of the subdivision covenants were also monitored. These meters, as above, were installed in-line with the well intake pipe to monitor total water withdrawn from the well. As no measurement of external water use was made at these sites, average water use for each household for the months of November and December 1995 and January and February 1996, when no irrigation occurred, was used to determine domestic water use (e.g., showers, shaving, dish and clothes washing, etc.). The monthly domestic water use for

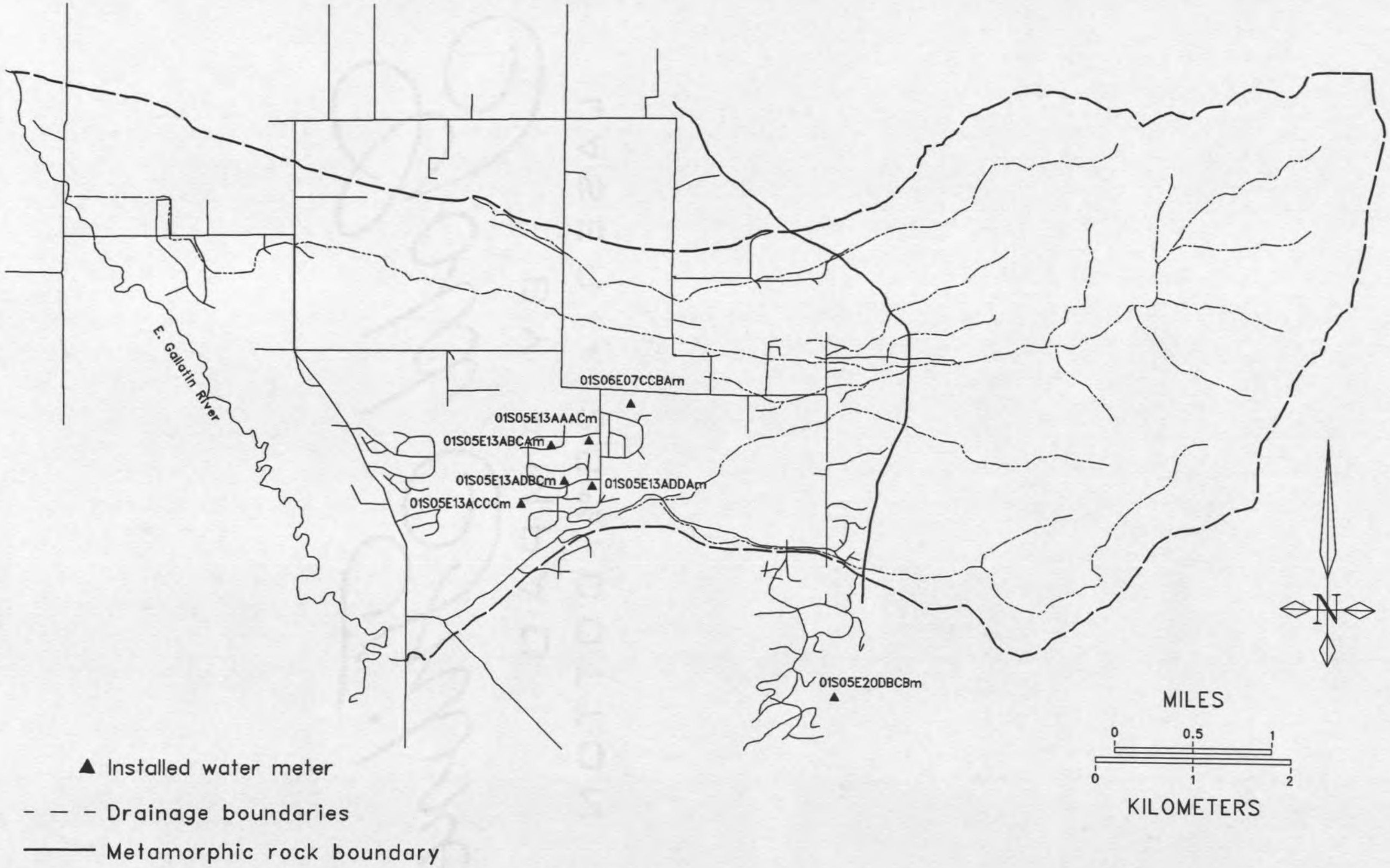


Figure 11. Location of installed water meters used to determine domestic water use.

each household was divided by the number of days per month and number of residents. These values were averaged to obtain the daily per capita domestic water use. This value was multiplied by the number of occupied houses in the study area and the average number of people living in rural housing units in Montana and Gallatin County (U.S. Department of Census, 1990a, 1990b) to obtain the total average annual domestic water use.

An estimate of external water use (e.g., lawn and garden irrigation, car washing, etc.) was made by subtracting a household's average domestic water use from the total water used during the irrigation months, May through October. The monthly household external water use, hereafter referred to as lawn and garden irrigation, was averaged for all the irrigation months and subsequently averaged for all meter sites to obtain the average monthly lawn and garden irrigation. This value was multiplied by the number of houses that irrigated during the study period, as determined by field reconnaissance, and the number of irrigation months to obtain the total annual lawn and garden irrigation volume.

Septic Tank Evapotranspiration Loss

The amount of septic tank discharge lost to evapotranspiration was obtained as a percentage of domestic water use. As the previously cited studies suggest that water is not actually lost by this process, the septic tank ET loss was estimated as 0% of domestic water use. To explore the sensitivity of recharge estimates to this parameter, the quantity of septic tank ET was arbitrarily bracketed as 0%, 10%, and 20% of domestic water use.

Chloride Mass-balance

Chloride Concentrations in Precipitation

Chloride concentrations in precipitation for the joint National Oceanographic and Atmospheric Administration (NOAA) and National Weather Service (NWS) weather station at Clancy, Montana (the closest site to the study area) were obtained from the National Atmospheric Deposition Program/National Trends Network for calender years 1984 through 1994 (NADP/NTN, 1984-1994; Appendix D). Annual mean chloride concentration was averaged over the years indicated to obtain the value used in the mass-balance.

Chloride Concentrations in Streams

Each of the primary streams in the study area (Middle Cottonwood, Schafer, Sypes, Walton, and Watts creeks) was sampled for chloride on July 29 and 30, 1995 (Fig. 12). Factory-fresh, one liter, high density polyethylene bottles were rinsed three times with stream water, filled to within a centimeter of the lip with raw water, and tightly sealed without preservative. Samples were refrigerated and shipped to the State of Montana Department of Environmental Quality Laboratory for major ion analysis (Appendix E).

Chloride Concentrations in Recharging Water

Six wells, selected to represent different depths and locations within the study area, were sampled for chloride on October 2, 3, and 4, 1995 (Fig. 12). Wells were sampled via

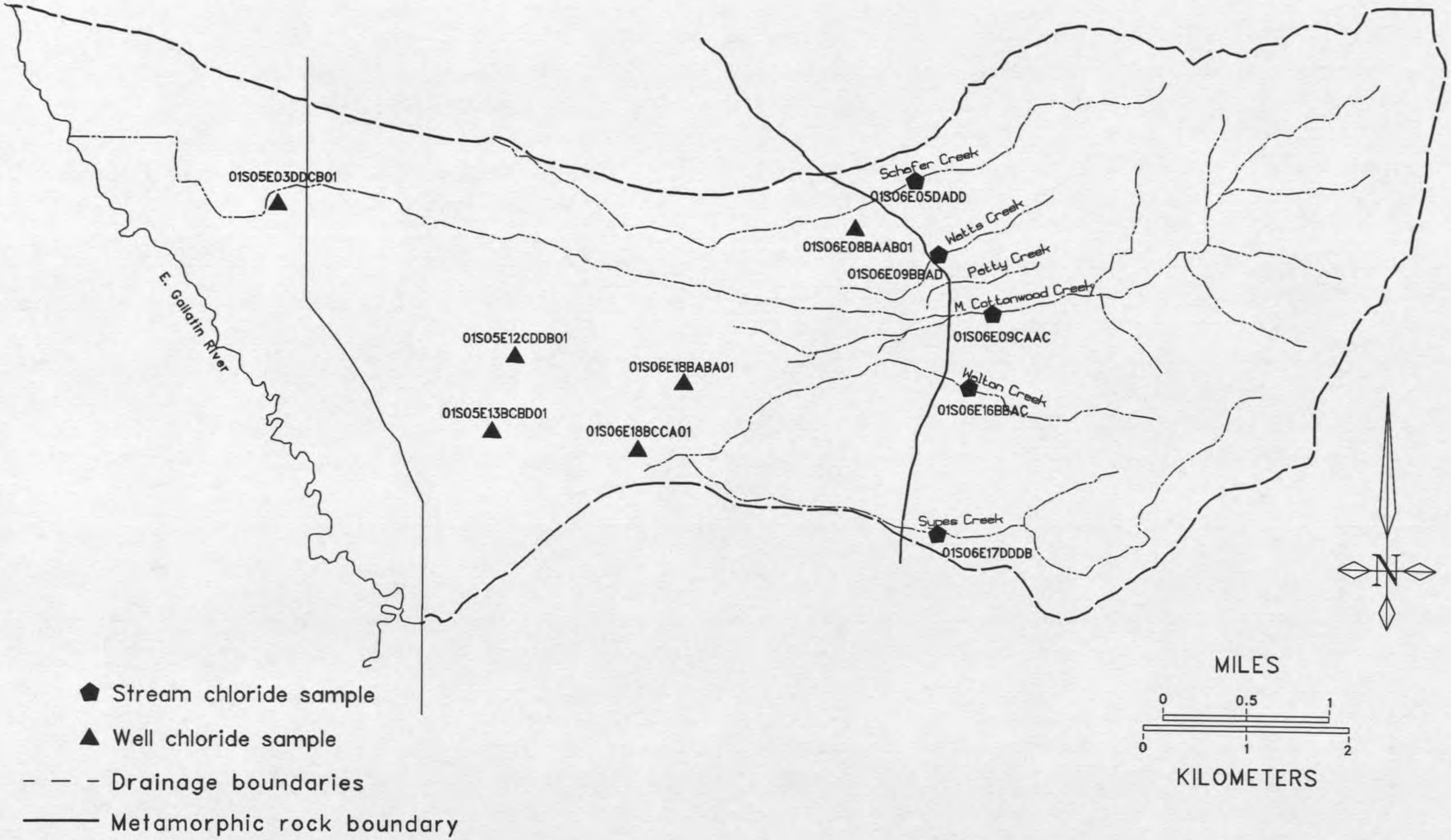


Figure 12. Location of stream and well samples analyzed for chloride.

hydrants adjacent to the well, where available, or from external house spigots. Wells were pumped at approximately 10 gpm (gallons per minute) for a minimum of five minutes or until water temperature had stabilized, and then sampled. As with surface water samples, new polyethylene bottles were rinsed three times with well water and filled to within a centimeter of the lip with raw water, without preservative. The same laboratory and analytic procedures used for stream water samples were utilized (Appendix E).

Tritium Analysis

Sample Collection

Four water samples were analyzed for tritium, three from wells and one from Middle Cottonwood Creek (Fig. 13). The wells were chosen to test whether deep aquifers identified in consultant's reports ("aquifers #3 and #4"; Morrison-Maierle, 1993a, 1993b; Gaston Engineering, 1995) are receiving modern (younger than 50 years) recharge. The deepest well tested was completed at a depth of 366 feet, but perforated at various intervals from 230 to 366 feet. The perforations necessitated the use of a packer during sampling in order to obtain a sample from the 350-366 foot interval. For comparison, two shallower unscreened, open-end wells completed at 139 and 143 feet were also chosen to assess recharge to what has been interpreted by area consultants as an overlying aquifer. The stream sample was taken to determine the current tritium concentration of recharging water.

One liter water samples were required for the tritium analysis. The intermediate depth wells were sampled on February 8, 1996 via hydrant after 5 well volumes had been

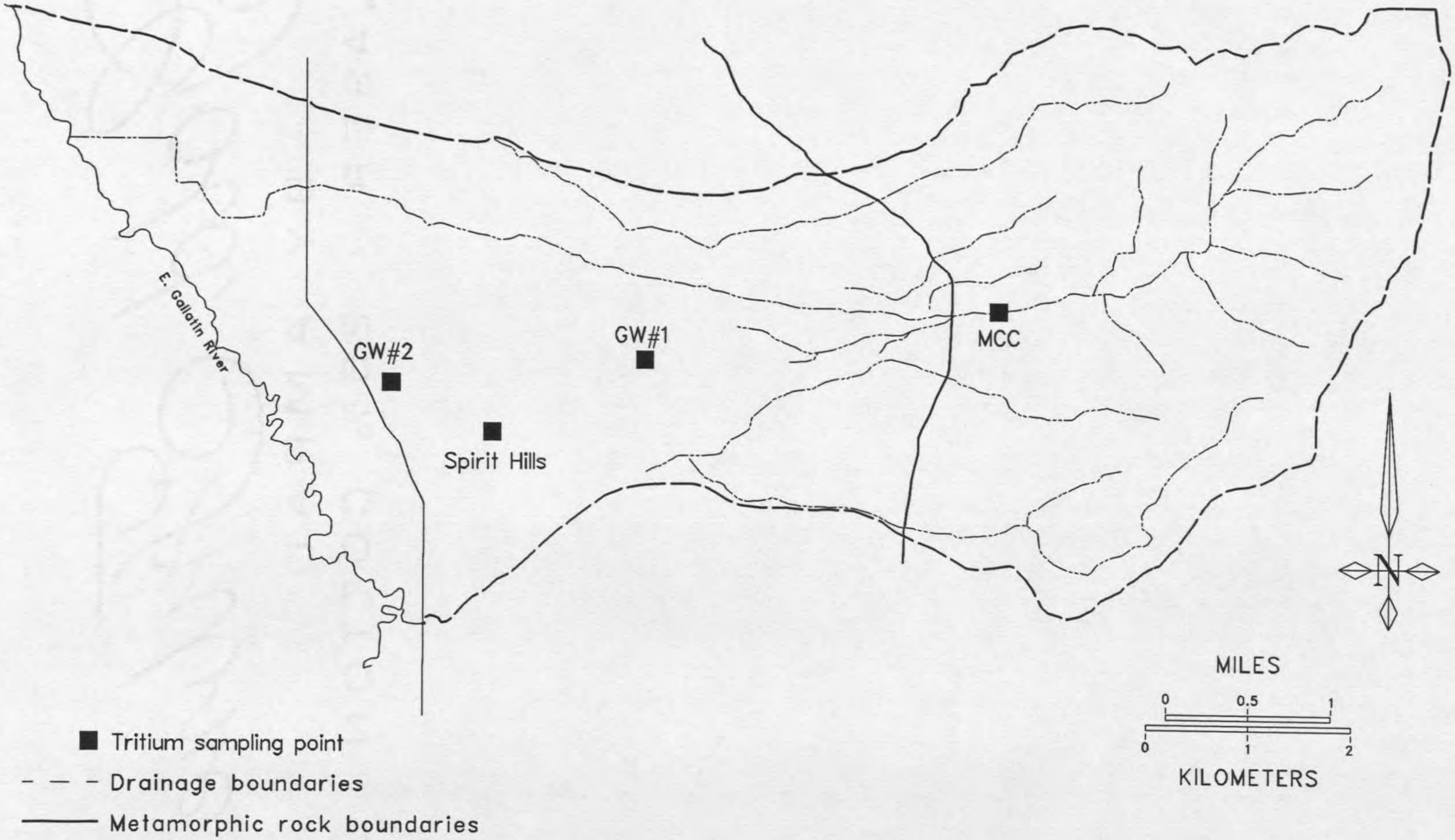


Figure 13. Location of stream and well samples analyzed for tritium.

evacuated. The well completed at 139 feet (GW#1) was pumped at 9 gpm; the well completed at 143 feet (GW#2) was pumped at 11 gpm. On March 6, 1996, the deepest well (Spirit Hills) was pumped for 88 minutes at between 15 and 35 gpm with a packer in place at 341 feet. 2170 gallons, approximately 6.5 well volumes, were evacuated prior to sampling to ensure the aquifer water was properly represented.

The stream sample, also taken on February 8, 1996, was taken in mid-stream to avoid excessive sediment. The sample was dipped from the stream at a location where the stream was less than 16 centimeters deep. Depth integrated sampling was not possible.

Factory fresh, high density polyethylene bottles were rinsed three times with the water to be sampled, filled to within a centimeter of the lip with raw water, sealed tightly, and refrigerated. No special preservation techniques (e.g., acidification, filtration) were required. The samples were shipped on March 7, 1996 to the Rosenstiel School of Marine and Atmospheric Science Tritium Laboratory at the University of Miami for analysis.

Well Monitoring

Water levels in thirty domestic and stock wells across the study area were monitored on a monthly basis from August 1995 to March 1996 (Fig. 14). Measurements were made between 10 a.m. and 4 p.m. when the homes were unlikely to be occupied. If the well pump was running upon arrival or during measurement, at least one hour was allowed for water levels to recover prior to further measurement attempts. A measuring tape was used to determine the casing height of each well above the average ground surface. A rusted, steel surveyor's tape was lowered into each well to a recorded depth

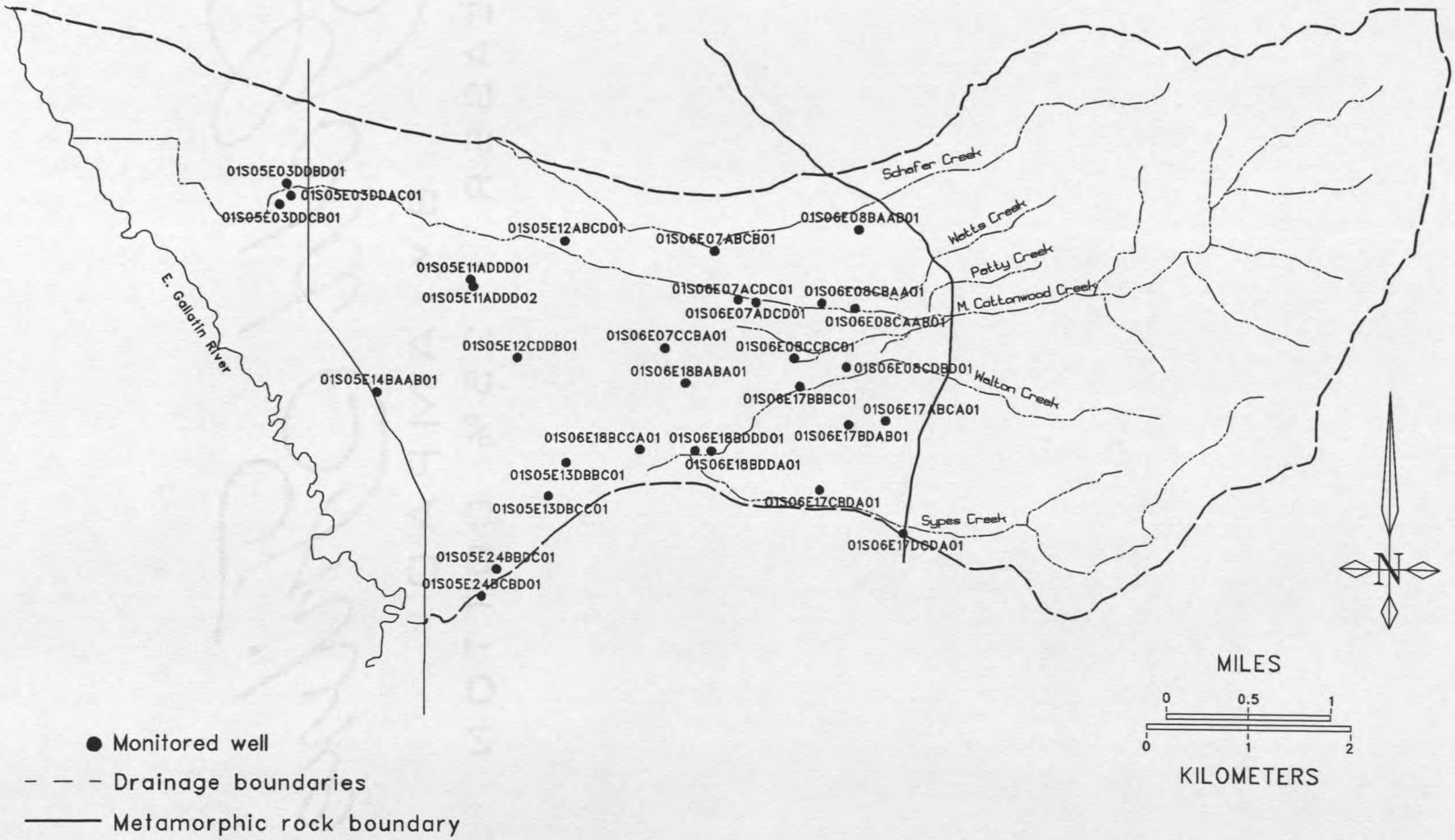


Figure 14. Location of monitored wells.

considered to be slightly greater than the actual depth to water. When the steel tape was withdrawn from the well, the depth at which the highly visible horizontal water line cut the tape was recorded. The difference between the total depth and the depth of the water line, minus the casing height, is equal to the depth to water below ground level. Bleach was used to decontaminate the tape between successive measurements.

The elevation of the top of each well casing was determined by a global positioning satellite (GPS) survey using a Trimble GeoExplorer GPS unit. To increase the accuracy of the survey, over 180 satellite fixes were collected for each well and differential correction was applied using a GPS base station at MSU. Elevation data from the GPS survey has an error estimate of two to five meters. Casing height was subtracted from all elevation data to obtain ground surface elevations from which water level elevations were ultimately determined.

CHAPTER 4

RESULTS

In the following sections, measured volumes are reported to the appropriate number of significant figures to avoid excessive and erroneous precision not warranted by the measurement techniques. Contributing quantities (e.g., area, length) are listed as used in the calculations.

Physical Water-budget

Precipitation

The 30-year average precipitation volume for the study area is 10,300,000 m^3 (8,340 ac.ft.)(Table 2; Fig. 7). This 30-year average precipitation value is used in the water-budget ground water recharge calculation.

Surface Water Inflow and Outflow

Summary hydrographs for Middle Cottonwood, Schafer, Walton, Sypes, and Watts creeks are plotted to the same scale in Figure 15 and summarized in Table 3. Actual dates corresponding to the numbers on the x-axis are given in Appendix F. Note that the Middle Cottonwood drainage is the largest of those studied and that the Middle Cottonwood Creek discharge dominates the total stream inflow for this area. Drainage area is not the only factor which determines discharge. For example, the Sypes drainage is approximately 1.3 times larger than the Schafer drainage, and yet it yields only a third of the streamflow. Future work is needed to determine whether complex structural features within the upper basin areas of the Sypes drainage control significant inter-basin or subsurface flows. Discharge measurements were made at several points along Middle Cottonwood Creek during spring runoff. Minimal stream loss was detected as the stream crosses the inferred location of the range front fault (Table 4) suggesting the fault may not be a primary conduit for ground water recharge. A comparison of observed runoff and peak discharges with regression estimates developed by Parrett, Omang, and Hull (1983) indicates that the measured flows in the 1995-96 water year were only slightly higher than the annual flow calculated from estimated average daily stream flow (Appendix G).

Table 2. Average annual precipitation volumes for study site subareas.

Subarea	**Area**	**Mean precipitation**	**Precipitation volume**
A_1	3.40 km^2 (1.31 mi^2)	44.5 cm (17.5 in)	1,510,000 m^3 53,400,000 ft^3 1,220 ac. ft.
A_2	9.01 km^2 (3.48 mi^2)	48.3 cm (19 in)	4,350,000 m^3 154,000,000 ft^3 3,530 ac. ft.
A_3	4.66 km^2 (1.80 mi^2)	63.5 cm (25 in)	2,960,000 m^3 104,000,000 ft^3 2,400 ac. ft.
A_4	1.80 km^2 (0.696 mi^2)	81.3 cm (32 in)	1,470,000 m^3 51,800,000 ft^3 1,190 ac. ft.
Total area	18.88 km^2 (7.29 mi^2)	-----	10,300,000 m^3 363,000,000 ft^3 8,340 ac. ft.

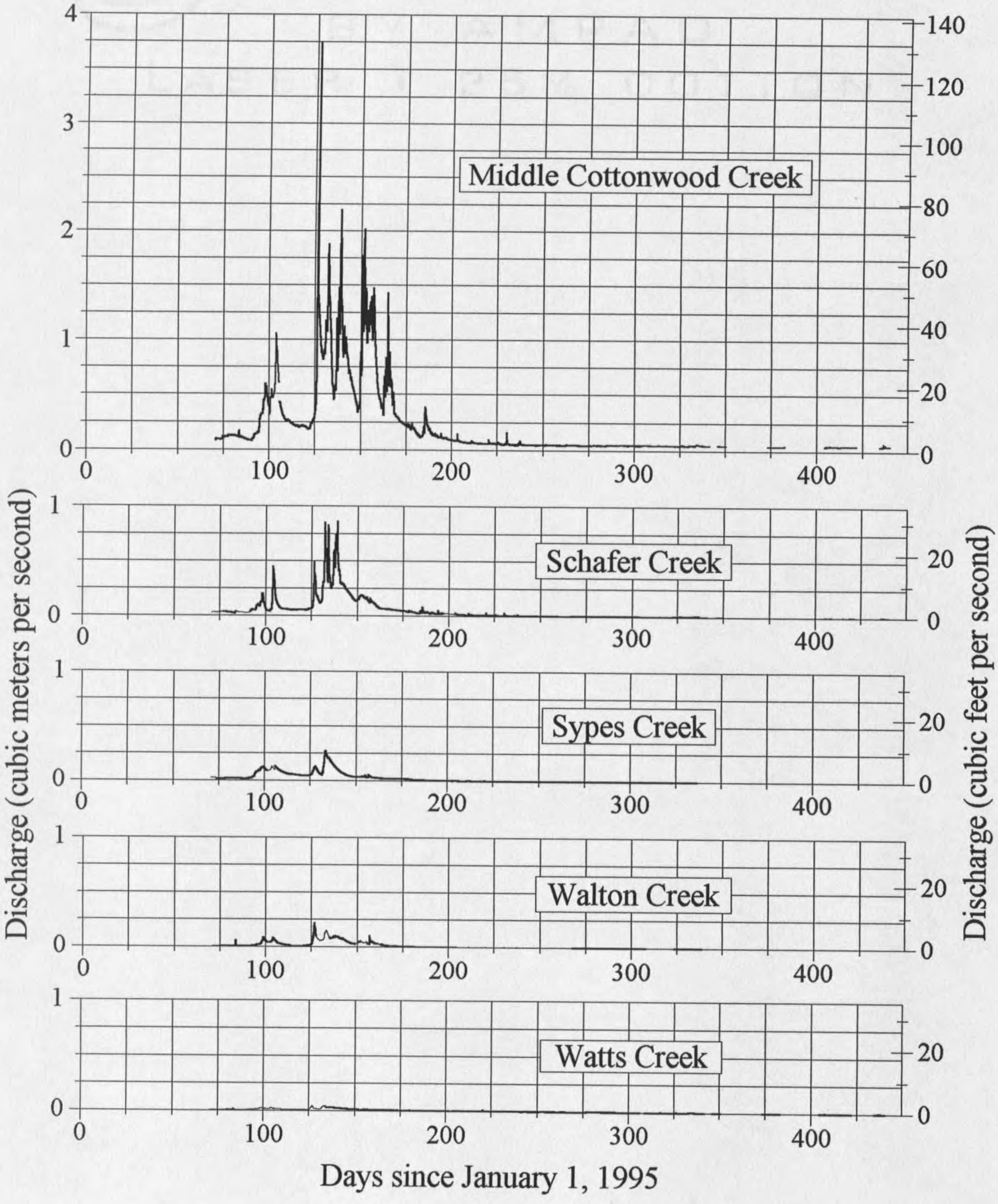


Figure 15. Summary hydrographs for Middle Cottonwood, Schafer, Sypes, Walton, and Watts Creeks for March 15, 1995 - March 15, 1996.

Table 3. Cumulative surface water inflow, March 15, 1995 - March 15, 1996.

Source	Discharge
Middle Cottonwood Creek	5,890,000 m^3 208,000,000 ft^3 4,780 ac. ft.
Schafer Creek	1,330,000 m^3 46,800,000 ft^3 1,080 ac. ft.
Sypes Creek	558,000 m^3 19,700,000 ft^3 452 ac. ft.
Walton Creek	343,000 m^3 12,100,000 ft^3 278 ac. ft.
Watts Creek	186,000 m^3 6,570,000 ft^3 151 ac. ft.
Total surface water input	8,310,000 m^3 293,000,000 ft^3 6,730 ac. ft.

Surface water outflow occurred on Middle Cottonwood Creek at the western margin of the study area from approximately May 5 to June 17, 1995 (Table 5; Fig. 16). Figure 16 is a summary hydrograph for the Middle Cottonwood Creek gauge at Spring Hill Road. Data is plotted at the same scale as Figure 15. Although a crest gauge was present, no stage recorder was installed at this site for the first six days of flow, and as a result this portion of the hydrograph has been reconstructed from information gathered from the crest gauge and discussions with landowners. According to conversations with two landowners, the flow at this site was initiated at approximately four o'clock in the morning on May 15, 1996. The crest gauge indicated the highest stage the water reached

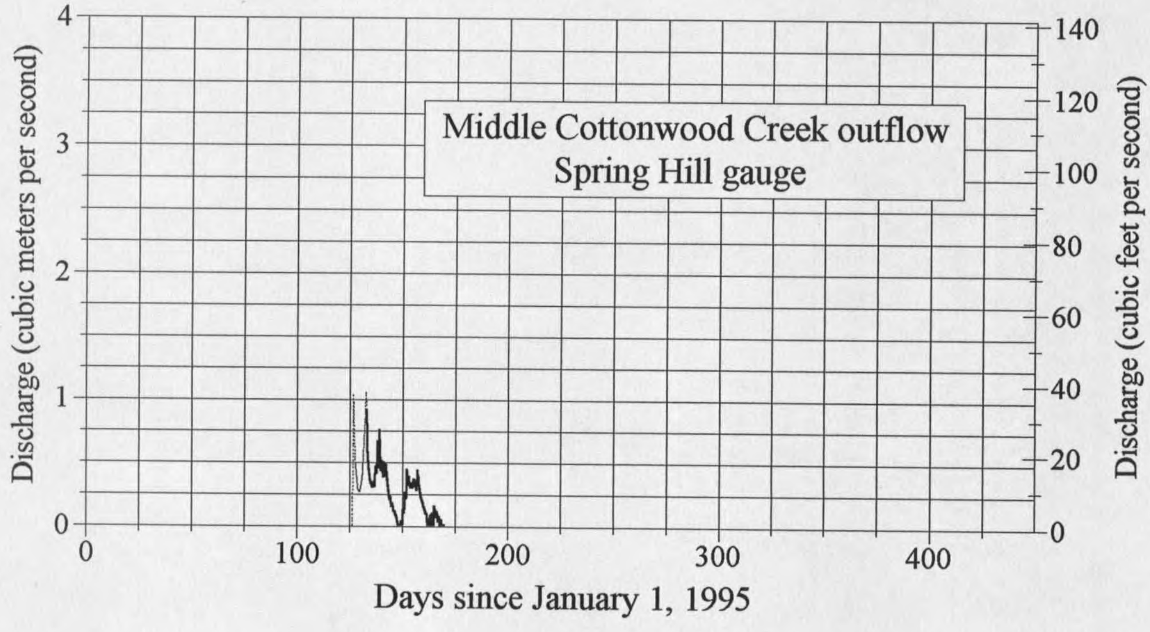


Figure 16. Summary hydrograph of outflow for Middle Cottonwood Creek for March 15, 1995 - March 15, 1996.

prior to and between measurements of discharge which were performed twice daily for the duration of flow. None of the other streams discharged past the western study boundary.

Table 4. Middle Cottonwood Creek stream loss across the range-front fault.

Date measured	Measured discharge (ft^3/sec)		Discharge loss per unit length of stream (ft^3/ft)
	MCC gauge	Saddle Mtn. Road	
4/15/95	13.87	12.18	0.0004
4/22/95	9.37	7.51	0.0004
4/29/95	9.74	7.30	0.0005
5/6/95	54.23	42.66	0.0025
5/13/95	41.50	43.60	-0.0005
5/20/95	35.09	37.53	-0.0005
5/27/95	14.96	15.93	-0.0002
6/3/95	32.22	28.94	0.0007
6/10/95	13.01	14.06	-0.0002
6/17/95	12.40	11.61	0.0002
6/24/95	7.78	5.11	0.0006
7/1/95	6.12	2.96	0.0007
7/8/95	5.69	1.89	0.0008
7/15/95	4.58	0.89	0.0008
7/22/95	3.57	0.70	0.0006

Table 5. Cumulative surface water outflow, March 15, 1995 - March 15, 1996.

Source	**Discharge**
Middle Cottonwood Creek	1,060,000 m^3 37,600,000 ft^3 862 ac. ft.

<u>Evapotranspiration</u>

The bounds of the township, range, and sections for which evapotranspiration data are available, grouped by common value, are shown in Figure 10. The study site subareas, ET estimates, and ET volumes are summarized in Table 6. As with the precipitation, ET is only estimated for those areas *below the general elevation of the stream gauges* as ET losses above this elevation are accounted for in the surface water inflow measurement. The majority of the study area is located in the zone of the lowest estimated ET rate but, due to its size, it accounts for the greatest amount of ET loss from the system. The western third of the study area is in the zone of the highest estimated ET rate.

Table 6. Average annual ET volumes by area.

PET estimate	Area	ET volume (area X PET estimate)
21.7"	4.74 km^2 (1.83 mi^2)	2,610,000 m^3 92,300,000 ft^3 2,120 ac. ft.
20.8"	0.345 km^2 (0.133 mi^2)	183,000 m^3 6,450,000 ft^3 148 ac. ft.
19.1"	13.85 km^2 (5.35 mi^2)	6,720,000 m^3 237,000,000 ft^3 5,450 ac. ft.
Total area	18.94 km^2 (7.28 mi^2)	9,520,000 m^3 336,000,000 ft^3 7,720 ac. ft.

Ground Water Outflow

Table 7 shows the estimate of ground water outflow across the western boundary of the study site, utilizing the average transmissivity estimate from Appendix C.

Table 7. Ground water outflow, March 15, 1995 - March 15, 1996.

Transmissivity	Average hydraulic gradient	Width of study area	Annual ground water discharge
53.42 m^2/day (4301 gpd/ft)	0.0163	5070 m (16600 ft)	1,600,000 m^3 57,000,000 ft^3 1,300 ac. ft.

Domestic and Irrigation Water Use

Table 8 shows the average daily per capita water use by household and for the area as a whole. Note that the average daily per capita water use, 45 gallons, calculated from water meters installed on houses within and adjacent to the Summer Ridge Subdivision, is substantially lower than the 100 gallons per capita per day specified by the Department of Environmental Quality standards for small water systems (Montana Department of Health and Environmental Quality [MDHEQ], 1992).

Table 9 shows the total annual average domestic water use for the entire study area for the period of March 15, 1995 to March 15, 1996 based upon the number of completed/occupied houses, the average number of people per household for rural Gallatin County, and the average daily per capita water use presented above (Table 8). Note that the figure of 2.7 people per household, according to the U.S. Department of Census (1990a, 1990b), is lower than the 3.5 people per household suggested by the Montana Department of Health and Environmental Quality for such estimates.

Table 8. Average daily domestic water use per capita.

Meter location	Water use (gallons) divided by number of days and residents				
	1995		1996		
	Nov.	Dec.	Jan.	Feb.	Average
01S05E13ABCAm	45	40	33	34	38
01S05E13ACCCm	63	65	41	43	53
01S05E13ADDAm	44	45	41	51	45
01S05E13AAACm	45	51	46	46	47
01S05E13ADBCm	54	56	56	51	54
01S06E07CCBAm	39	44	27	37	37
01S05E20DBCBm	39	44	45	44	43
Avg. of all sites	-----	-----	-----	-----	**45 ± 6.2**

Table 9. Total average annual domestic water use.

Number of houses	Avg. number of people per household	Avg. daily per capita water use	Total avg. annual domestic water use
315	2.7	45 gallons	53,000 m^3 1,900,000 ft^3 43 ac. ft.

Table 10 shows the average monthly lawn and garden irrigation water use for May to October, 1995. Note that the average irrigation value, 9403 gallons, calculated as the amount of water used above a household's average domestic water use, is much lower than the 72400 gallons per month used by Morrison-Maierle (1993b).

Table 11 shows the total volume of lawn and garden irrigation for the area which is presumed to be lost to evapotranspiration. The number of houses irrigating was determined from observations of which households had "lawns"--lush, green, exotic or native grasses with relatively abrupt boundaries--versus those households with bare soil or native grass areas that are not irrigated.

Table 10. Average monthly household lawn and garden irrigation.

Meter location	Water use (in gallons) above average household domestic use						
	1995						
	May	June	July	Aug.	Sept.	Oct.	Average
01S05E13ABCAm	N/A	12525	16025	22525	15525	6325	14585
01S05E13ACCCm	1897	5510	6875	10575	3675	975	4918
01S05E13ADDAm	1400	6400	14600	29900	31200	16800	16717
01S05E13AAACm	3450	3550	2050	31750	16550	1450	9800
01S05E13ADBCm	1930	1500	1190	0	350	0	994
Avg. of all sites	-----	-----	-----	-----	-----	-----	**9403 ± 5900**

Table 11. Total average annual lawn and garden irrigation lost to ET.

Number of houses irrigating	Avg. monthly irrigation per household	Irrigation season (May - October)	Total irrigation water lost to ET
275	9403 gallons	6 months	59,000 m^3 2,100,000 ft^3 48 ac. ft.

Septic Tank Evapotranspiration Loss

The lack of green lawns associated with known locations of septic systems supports the theoretical assumption that septic tank effluent is not subject to significant evapotranspiration loss. Table 12 shows the annual volume of septic effluent water lost to ET, calculated as 0% of annual domestic water use.

Table 12. Total annual volume of septic effluent water lost to ET.

Domestic water use	% septic water lost to ET	Volume of water lost to ET
53,000 m^3 1,900,000 ft^3 43 ac. ft.	0	0 m^3 0 ft^3 0 ac. ft.

Quantities Used in the Physical Water-budget

Tables 13 and 14 indicate the water quantities used in Equation 2 to estimate ground water recharge for the period March 15, 1995 to March 15, 1996. Table 13 summarizes the system inputs used in the physical water-budget; Table 14 summarizes the system outputs. An extensive listing of all system output combinations explored is given in Appendix H. Figure 17 shows both the input and output quantities and illustrates where each process occurs.

Table 13. Summary of physical water-budget inputs.

Source	Volume
Precipitation	10,300,000 m^3 363,000,000 ft^3 8,340 ac. ft.
Surface water inflow	8,310,000 m^3 293,000,000 ft^3 6,730 ac. ft.
Total annual system input	18,600,000 m^3 657,000,000 ft^3 15,100 ac. ft.

Table 15 reflects the physical water-budget estimate of ground water recharge calculated from Equation 2, based on the values given in Tables 13 and 14.

$P = 8{,}340 \pm 1{,}700$ ac. ft.
$I_{SW} = 6{,}730 \pm 340$ ac. ft.

$ET = 7{,}720 \pm 3{,}100$ ac. ft.
$O_{GW} = 1{,}300 \pm 1{,}300$ ac. ft.
$O_{SW} = 832 \pm 43$ ac. ft.
$U_{IRR} = 48 \pm 24$ ac. ft.
$ET_D = 0$

$R_{GW} = 5{,}100 \pm 3{,}800$ ac. ft.

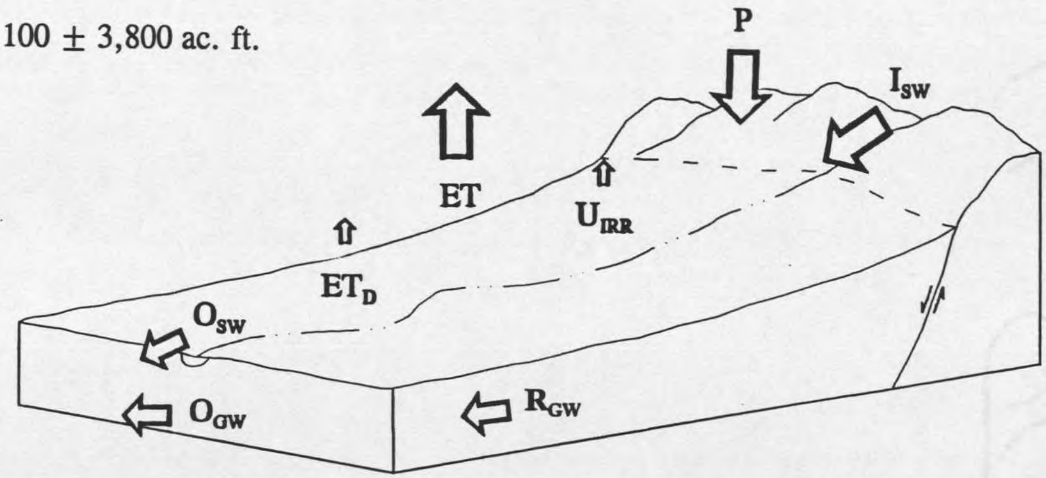


Figure 17. Actual physical water-budget quantities. No scale implied.

Table 14. Summary of physical water-budget outputs.

Source	**Volume**
Evapotranspiration	9,520,000 m^3 336,000,000 ft^3 7,720 ac. ft.
Ground water outflow	1,600,000 m^3 57,000,000 ft^3 1,300 ac. ft.
Surface water outflow	1,060,000 m^3 37,600,000 ft^3 862 ac. ft.
Irrigation water use	59,000 m^3 2,100,000 ft^3 48 ac. ft.
Total annual system output	12,300,000 m^3 433,000,000 ft^3 10,000 ac. ft.

Table 15. Physical water-budget estimate of ground water recharge.

Calculated ground water recharge	6,300,000 m^3 220,000,000 ft^3 5,100 ac. ft.

Chloride Mass-balance

Chloride Concentrations in Precipitation

Table 16 shows the annual weighted mean chloride concentration in precipitation for the calendar years 1984 to 1994. Note that the detection limit is 0.01 mg/l. Each annual chloride concentration value represents the mean value of 52 weekly measurements of the chloride concentration in precipitation. The average of these values for the 11-year period is given in Table 16.

Table 16. Annual weighted mean chloride concentration in precipitation at Clancy Station, Jefferson County, MT.

Year	**Chloride concentration**
1984	0.13 mg/l
1985	0.09 mg/l
1986	0.05 mg/l
1987	0.09 mg/l
1988	0.05 mg/l
1989	0.09 mg/l
1990	0.11 mg/l
1991	0.06 mg/l
1992	0.05 mg/l
1993	0.05 mg/l
1994	0.06 mg/l
11-year average	**0.08 ± 0.027 mg/l**

Chloride Concentrations in Streams

Table 17 shows the sampling date, location, and chloride concentration of streams within the study area measured during this study. Note that the detection limit is 1.0 mg/l.

Chloride Concentrations in Recharging Water

Table 18 shows ground water chloride concentrations obtained as part of this study. Also indicated are the sampling interval and well completion depth. Sampling interval and well completion depth are not known for well 01S05E18BABA01; the well log originally identified for this well was found to refer to the owner's previous well.

Table 17. Chloride concentrations in streams.

Sampling date	Source and location	Chloride concentration
7/29/95	Schafer Creek 01S06E05DADD	1.0 mg/l
7/29/95	Sypes Creek 01S06E17DDDB	1.1 mg/l
7/30/95	Walton Creek 01S06E16BBAC	1.0 mg/l
7/30/95	Watts Creek 01S06E09BBAD	1.1 mg/l
Avg. of all samples	-----	**1.1 ± 0.05 mg/l**

Table 18. Chloride concentrations in ground water.

Sampling date	Well location	Sampling interval/ completion depth	Chloride concentration
10/2/95	01S06E08BAAB01	180' / 180'	1.5 mg/l
10/2/95	01S05E18BABA01	N/A / N/A (>90' swl)	1.3 mg/l
10/3/95	01S06E18BCCA01	280 - 300' / 313'	2.1 mg/l
10/3/95	01S05E24BBDC01	160 - 262' / 262'	2.6 mg/l
10/3/95	01S05E03DDCB01	78' / 78'	3.2 mg/l
3/6/96	01S05E13BCBD01	341 - 366' / 366'	3.3 mg/l
Avg. of all samples	-----	-----	**2.3 ± 0.77 mg/l**

swl = static water level

Quantities Used in the Chloride Mass-balance

Figure 18 summarizes the water quantities and chloride concentrations used in the chloride mass-balance. Table 19 shows the chloride mass-balance estimate of ground water recharge calculated from Equation 4, based on the values given in Tables 16 - 18.

$P = 8{,}340 \pm 1{,}700$ ac. ft.
$C_P = 0.08$ mg/l
$S = 6{,}730 \pm 340$ ac. ft.
$C_S = 1.1$ mg/l
$Q = 832 \pm 43$ ac. ft.
$C_Q = 1.1$ mg/l
$C_R = 2.3$ mg/l

$R = 3{,}000 \pm 1{,}700$ ac. ft.

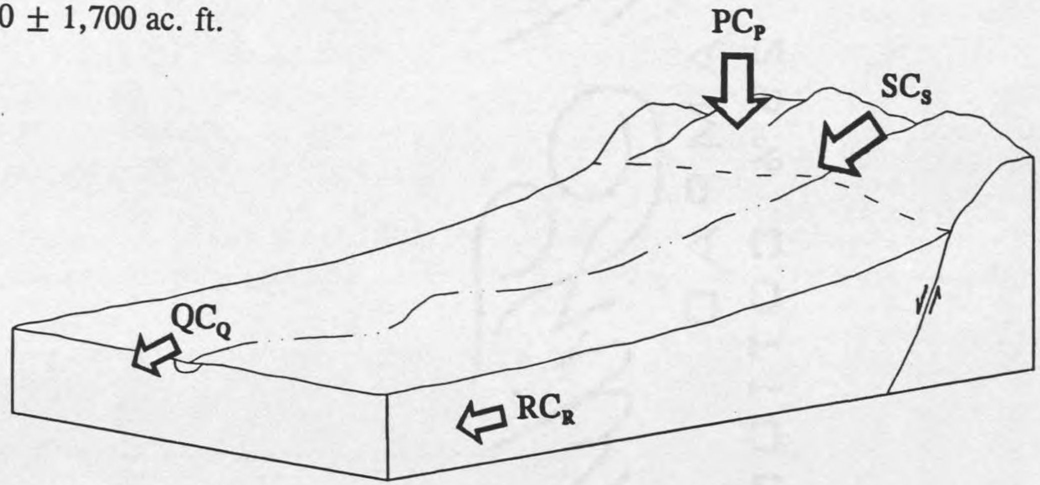


Figure 18. Actual chloride mass-balance quantities. No scale implied.

Table 19. Chloride mass-balance estimate of ground water recharge.

Calculated ground water recharge	3,700,000 m^3 130,000,000 ft^3 3,000 ac. ft.

Tritium Analysis

Table 20 gives the location, sampling depth, sampling elevation, and tritium concentration as reported from analyses by the Tritium Laboratory at the Rosenstiel School of Marine and Atmospheric Science at the University of Miami. Note the low level of tritium in the Spirit Hills sample relative to the other samples, and the high value at GW#2. Figure 19 shows the relative location of each of the tritium samples as well as pertinent well construction information.

Table 20. Tritium sample locations, depth, elevation, and concentration (TU).

Sample	Location	Sampling depth (elevation)	TU
MCC	01S06E09CAAC	Surface (5385')	22.5 (±0.7)
GW #1	01S06E07CCCB01	139' (4737')	24.1 (±0.8)
Spirit Hills	01S05E13BCBD01	341 - 366' (4353 - 4328')	0.43 (±0.09)
GW #2	01S05E14ABBB01	143' (4465')	40.4 (±1.3)

Well Monitoring

Table 21 shows the location number, ground surface elevation (feet), and depth to water measurements (feet) for monitored domestic and stock wells for the period August 1995 through March 1996. This dataset was used to construct potentiometric maps for the eight months of monitoring in 1995 and 1996. Potentiometric maps for August 1995