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Evaluation of the Ground-water Contribution to Muddy Creek from the Greenfields Irrigation District

to

Cascade County Conservation District
Great Falls, Montana

by

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ABSTRACT

A hydrologic investigation of the Greenfields Irrigation District, 30 miles northwest of Great Falls, Montana, was undertaken to determine the sources and quantities of runoff to the Muddy Creek drainage of the Sun River. The Greenfields Bench comprises three gravel terraces and most of the Greenfields Irrigation District, a portion of the U.S. Bureau of Reclamation's Sun River Project. The 52,000 irrigated acres are served by an average of 166,000 acre-feet (af) of irrigation water per year. Average annual precipitation is 12-13 inches (in.).

The mix of crops on the Bench was found to be 69% small grains and 31% forage, with a 1981-1983 average consumptive water demand of 1.29 ft. and 1.94 ft. respectively, as determined with evaporation pans. The average crop-water demand on the Bench was 77,560 af.

The 52-year precipitation record from 1931-82 at Fairfield showed that an average of 2.22 in. of precipitation with a standard deviation (sd) of 1.59 occurred in May and an average of 2.86 in. (sd = 1.75) occurred in June. Precipitation in July and in August averaged about 1.2 in., with one negative standard deviation nearly zero. Irrigation diversions onto the Bench in May and June were shown to exceed three times the crop water demand. Higher monthly diversion rates and high natural precipitation correllated with high average monthly runoff in Muddy Creek.

The gravel aquifer of the Bench is generally capable of high water yields, but the saturated thickness is usually less than 20 feet (ft.) Transmissivities ranged from 192 to 22,600 ft^2/day and specific yield

ranged from 0.11 to 0.13. The western one-third of the Bench had consistently greater permeability whereas the remainder was more heterogeneous.

Thirteen canal ponding tests were run, giving seepage rates of 0.45 to 4.7 ft^3/sec/mile. The total canal seepage in 1982 was calculated to equal 37,136 af. The discharge of canal waste water to Muddy Creek was estimated to equal 20,930 af as determined by hydrograph separation techniques. The distribution system loss was equal to 40% of the total annual irrigation water diversion onto the bench.

Eight on-farm irrigation water budgets were calculated from field studies. The average, single irrigation application was 0.85 ft. Surface runoff from the fields averaged 15% of the total application, and ground-water loss averaged 52%. The average on-farm irrigation efficiency, taken as the unsaturated zone recharge plus evaporation during irrigation, was 33%.

A hydrologic budget for the Greenfields Bench during water year 1982 was prepared. Total water input was 206,600 af (precipitation = 62,600 af; irrigation water = 144,000 af). Surface and ground-water runoff was 102,350 af (50%). Crop water use was 67,880 af (33%); non-growing season evapotranspiration was 22,920 af (11%) and soil and ground-water storage increased by 13,450 af (6%).

Hydrograph separation analyses indicated that 65% of total runoff in Muddy Creek was baseflow and 35% was derived directly from surface water. Analysis of ground-water recharge and surface-water runoff events showed that 11% of the total runoff was attributable to precipitation, 45% from delivery system losses and 44% from on-farm water losses.

The water budgets indicate that 42% of the total crop water needs were met by direct irrigation. Of the remaining 58%, 21% was met by precipitation or stored soil moisture, and 37% by sub-irrigation.

Runoff and erosion control alternatives for Muddy Creek include widespread delivery system and on-farm irrigation efficiency improvements, knowledge and use of irrigation scheduling, a dam and reservoir on Muddy Creek, and a ground-water recharge and reuse system.

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1. INTRODUCTION

This report presents results of a project conducted by the Montana Bureau of Mines and Geology (MBMG) for the Cascade County Conservation District entitled, "Evaluation of the Ground-Water Contribution to Muddy Creek from the Greenfields Bench Irrigation District". The original contract period began July 1, 1981 and ended July 1, 1983, but was extended through December 31, 1983. The study area comprises the Greenfields Bench (also known as the Fairfield Bench), containing about 58,000 acres in the vicinity of Fairfield, Montana which is about 30 miles northwest of Great Falls, Montana (see Figure 1).

1.1 Problem Description

Excess irrigation water and return flows from the Greenfields Bench discharge to Muddy Creek, causing its average annual flow to be increased 10 to 20 times over pre-irrigation conditions. The increased flow and energy of Muddy Creek has caused extensive erosion of the fine-grained alluvial bank and bed materials in the lower Muddy Creek Valley since the 1930's. The average annual sediment load of Muddy Creek at Vaughn is about 213,000 tons per year and average annual flow for the period 1971-77 was 107,000 acre-feet (af). The estimated virgin annual discharge of Muddy Creek is 2,000 to 7,000 af.

The high sediment load limits downstream beneficial water use and causes problems for irrigators using Muddy Creek or Sun River water below Muddy Creek. It also presents a major water-quality and environmental degradation problem in Muddy Creek and the lower Sun River. The sediment load contributes a visible plume and major suspended load input to the

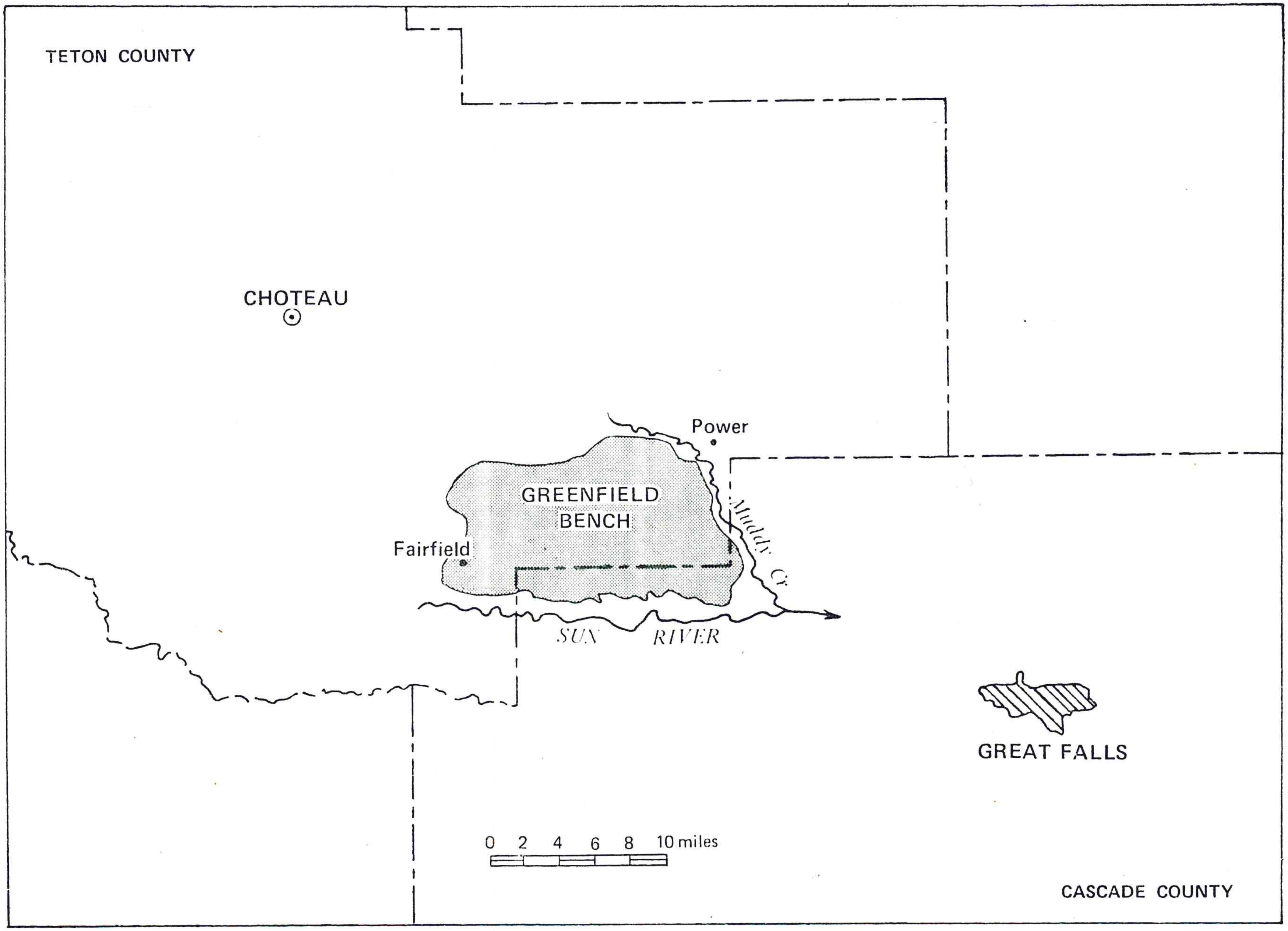


Figure 1 – Greenfield Bench location map.

Missouri River at Great Falls, Montana. Major channel changes have occurred in the lower Muddy Creek Valley, and approximately eight acres of farm or pasture land are lost to erosion each year.

The irrigation water delivery system for the Greenfields Bench consists of approximately 295 miles of canals and laterals. A rehabilitation and betterment program from 1978-1983 has resulted in concrete lining or buried pipe replacement of 95 miles of canal, however, most canals remain unlined. The U.S. Bureau of Reclamation (1976) indicated that canal seepage losses result in a continual loss of productive irrigable land because of high water tables, a decrease in thf systems' water delivery capacity available for crop production, and requirements for additional drainage construction.

Approximately 85% of the farmland on the Bench is flood irrigated. Substantial on-farm irrigation water losses to surface water and groundwater runoff occur, resulting in a high water table over most of the Bench. An average of 55% of the annual precipitation falls during the growing season, and at times aggravates the runoff problem. Crop water needs are supplied by a combination of surface irrigation, precipitation and sub-irrigation.

1.2 Study Rationale

Most of the irrigation return flows drain to Muddy Creek via a network of surface ditches and drainages which collect ground water from the shallow gravel aquifer throughout the interior of the Bench. The groundwater system is fed by recharge from canals and on-farm irrigation. Surface water runoff results from canal wasteage, direct storm runoff and on-farm tailwater runoff. About 65% of the runoff from the Bench occurs as ground-water discharge to drains. The shallow gravel aquifer is the common medium through which most irrigation runoff occurs. The rationale for this investigation was to study the characteristics of the ground-water system so that excess irrigation runoff could be controlled directly on the Bench. Potential control techniques would include identifying and limiting infiltration and leakage into the ground-water system, reducing peak glows in Muddy Creek or making conjunctive use of both surface water and ground water for irrigation use on the Greenfields Bench.

1.3 Project Objectives

Project objectives as outlined in the contract included:

a. measuring the flow of drainways from the Bench to Muddy Creek;

b. determining ground-water levels and hydrogeologic characteristics of the gravel aquifer;

c. calculating ground-water discharge rates and the overall hydrologic budget of the Greenfields Bench.

Secondary objectives developed during the course of the project included:

d. sampling of ground water for chemical analyses and interpreting ground-water quality data for the Bench;

e. evaluating the potential for ground-water reuse or conjunctive use applications.

1.4 Previous Work

Previous work concerned directly with the Greenfields Irrigation District or Muddy Creek includes several studies by the U.S. Bureau of Reclamation:

a. The Muddy Creek Study, 1967, a water quality study of the effects of irrigation on salt loading in Muddy Creek.

b. Information on Muddy Creek Erosion Problem, 1974. This report appraised possible solutions to the Muddy Creek erosion problem, including a dam near Power.

c. Report on Proposed Rehabilitation and Betterment Program Greenfields Irrigation District, 1976.

d. Muddy Creek Erosion Problem, A Coordinated Strategy for Federal Action, 1981.

e. Muddy Creek Study Plan Formulation Review Document, 1982.

f. Draft Special Report on Muddy Creek Study Montana, 1983. This was a brief technical and economic review of structural erosion control alternatives. A dam and reservoir near Power with an estimated construction cost of $23 million was recommended.

The U.S. Army Corps of Engineers (1979) prepared an evaluation of channel erosion control structures for Muddy Creek using stone revetments, stone-filled soil moisture interceptor trenches and reopening old meanders to reduce channel slope. Construction costs for revetment of 45 stream miles was estimated at $14.4 million in 1979. The other alternatives were not considered to be effective.

The Greenfields Irrigation District (GID) was organized in 1931 and has provided annual summary reports to the U.S. Bureau of Reclamation regarding water supply and distribution on the Greenfields Bench. The GID also keeps records of water delivered to farmers and flows in main canals and some wasteways.

The first report which attempted to examine the overall irrigation-runoff relationship on the Bench was prepared by Systems Technology, 1979, "Muddy Creek Special Water Quality Project". It attempted to combine previous studies and data, and suggested a number of recommended courses of action for erosion control including: on-farm water management, supply canal relief, an interceptor canal and stabilization of the Muddy Creek channel.

The Montana Water Quality Bureau conducted two studies of nutrient occurrence on the Greenfields Bench. One study (Walther, 1981) presented results of nitrate sampling and ground-water levels from domestic wells. Nitrate levels were frequently elevated, occasionally above recommended state drinking water standards, but difficult to predict. A second study (Walther, 1982) presented nutrient data for Muddy Creek and wastewater drains.

The Montana Cooperative Extension Service conducted irrigation scheduling, spring grain crop quality, and nitrogen application and translocation studies on the Bench in 1980-83. Results were presented in several short bulletins published by the Cooperative Extension Service, Bozeman, Montana. The irrigation scheduling project was viewed as being potentially successful in reducing over-irrigation, however, its long-term adoption by area farmers is uncertain.

None of the previous investigations collected extensive field data or sought to examine the overall hydrologic system of the Greenfields Bench and quantify sources of the irrigation return flows.

2. STUDY DESIGN

Project objectives were accomplished primarily through detailed field investigations over three irrigation seasons and two winter periods. Analyses of the field data collected by the MBMG and other agencies resulted in hydrologic budgets for the Greenfields Bench.

Irrigation return flow and ground-water discharge from the Greenfields Bench was monitored with flumes, weirs, other channel controls and continuous recorders during the period June 1981 through September 1983 (see Figure 2). Flumes were 9 to 36-in. Parshall type; weirs were five foot Cipolletti type. Additionally, there was one pipe culvert control station, one cement-box-culvert station, and one open-channel station. Three new streamflow stations were contracted to the U.S. Geological Survey (USGS). One was established on Muddy Creek near Power, and accounted for all discharge accruing from the northern end of the Bench, a second was placed on Tank Coulee and the third on Spring Coulee where these coulees leave the Bench. All stations except flumes were rated with current meter measurements.

The MBMG drilled and installed 21 wells for observation or pumping purposes on six study fields. These wells provided geological information regarding the lithology of the unconsolidated deposits, depth to weathered shale bedrock, water-bearing zones, gravel size, thickness and the occurrence of clay and caliche beds.

Ground-water recharge and water-level trends were monitored through a network of 3-in. diameter observation wells with continuous recorders installed in six study fields across the Bench (Figure 2). Additional ground-water level data were collected on a periodic basis from private domestic wells across the Bench.

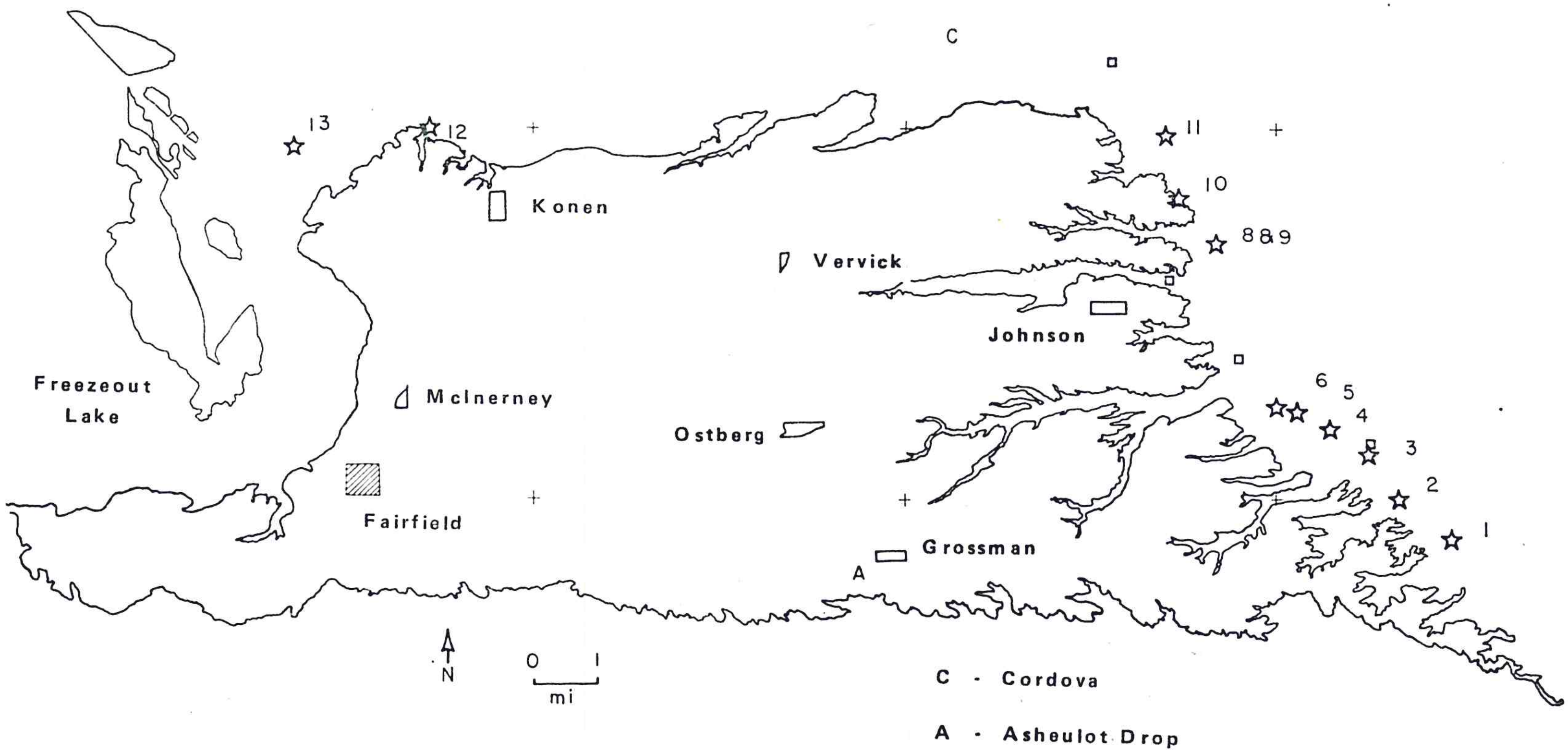


Figure 2 — Monitoring site location map.

The hydraulic properties of the shallow aquifer on the Bench were determined primarily from pumping tests of 3 to 42 hours duration, with drawdown measured in observation wells except for the Ostberg field. Additional spatial permeability data were obtained from 10-15 minute (min.) specific-capacity tests of private wells conducted across the Bench for this investigation.

Water supply data obtained from the GID included all irrigation water inflow at the A-drop canal structure near Fairfield and diversion rates to the six study fields for most irrigation periods. In cooperation with the GID, a series of 13 canal seepage tests were made to measure water loss rates directly from large canals and laterals.

Information on precipitation, evaporation, soil moisture and crop water use was obtained from the Montana Cooperative Extension Service. They conducted irrigation scheduling training with farm cooperators which included the six MBMG study fields. Ground-water runoff from on-farm irrigation was determined by inflow, outflow and ground-water level measurements during irrigation water applications on the six study fields. Current meter measurements by MBMG and GID determined inflow, Parshall flumes measured outflow, and continuous recorders on wells measured changes in ground-water levels.

Hydrologic balance calculations for on-farm irrigations were done by summation of the water inputs and outputs during an irrigation event assuming steady state ground-water conditions. The effect of transient changes in water table elevation on ground-water outflow during irrigation events was simulated with a two-dimensional finite difference computer model.

The hydrologic balance for the entire Greenfields Bench was developed by extrapolation of the on-farm water balances and canal seepage tests, along with direct measurements of surface water runoff in the drains. The calculated balance was compared to independently measured inflows or outputs such as the flow in Muddy Creek.

Water quality data provided qualitative information regarding ground-water flow paths, low permeability areas and effects of bedrock on hydrochemistry.

3. GEOLOGY

3.1 Bedrock Geology

The bedrock surrounding and underlying the Greenfields Bench is the Cretaceous Colorado Group, composed of the Lower Cretaceous Blackleaf Formation and Upper Cretaceous Marias River Formation. Both formations consist primarily of dark gray marine shale with numerous, thin sandstone beds and some bentonite beds. The combined thickness of both formations is approximately 1,500 ft.

A structure contour map of the top of the Colorado Group beneath the gravel terraces is shown in Figure 3. Elevation data were obtained from domestic well logs and MBMG drill holes. The younger Cretaceous and Tertiary age rocks overlying the Colorado Group were removed by pre-Pleistocene erosion leaving a gently eastward sloping plain. The gravel teraces were deposited directly on the weathered shale surface and, as a result, surface topography generally mirrors the underlying bedrock contours. The weathered shale zone averages about 7 ft. thick and consists of dark gray clay with scattered pebbles.

3.2 Quaternary Geology

Three gravel terraces collectively comprise the Greenfields Bench and are shown on Figure 4. All are believed to be Quaternary in age (Maughn, 1961) and deposited by an ancestral Sun River, flowing in a more northeasterly course. The oldest and highest terrace, mapped as Qts5, is locally called the First Bench and has an average gradient of 24 ft/mile. The second Bench, mapped as Qts4, lies 120 ft below the First Bench and has an average gradient of about 19 ft/mile. The Third Bench, mapped as

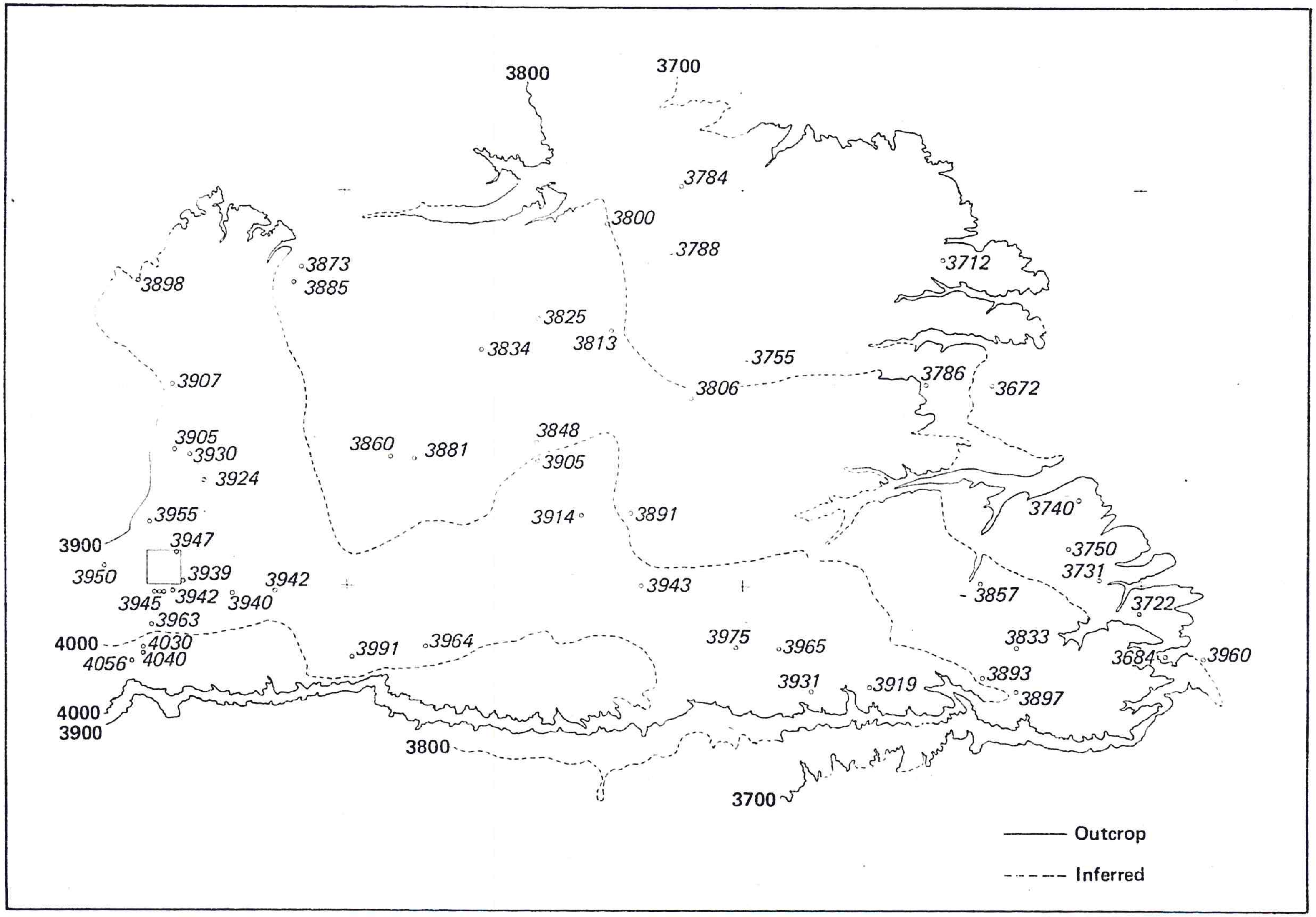


Figure 3 — Structure contours on top of the Colorado Shale.

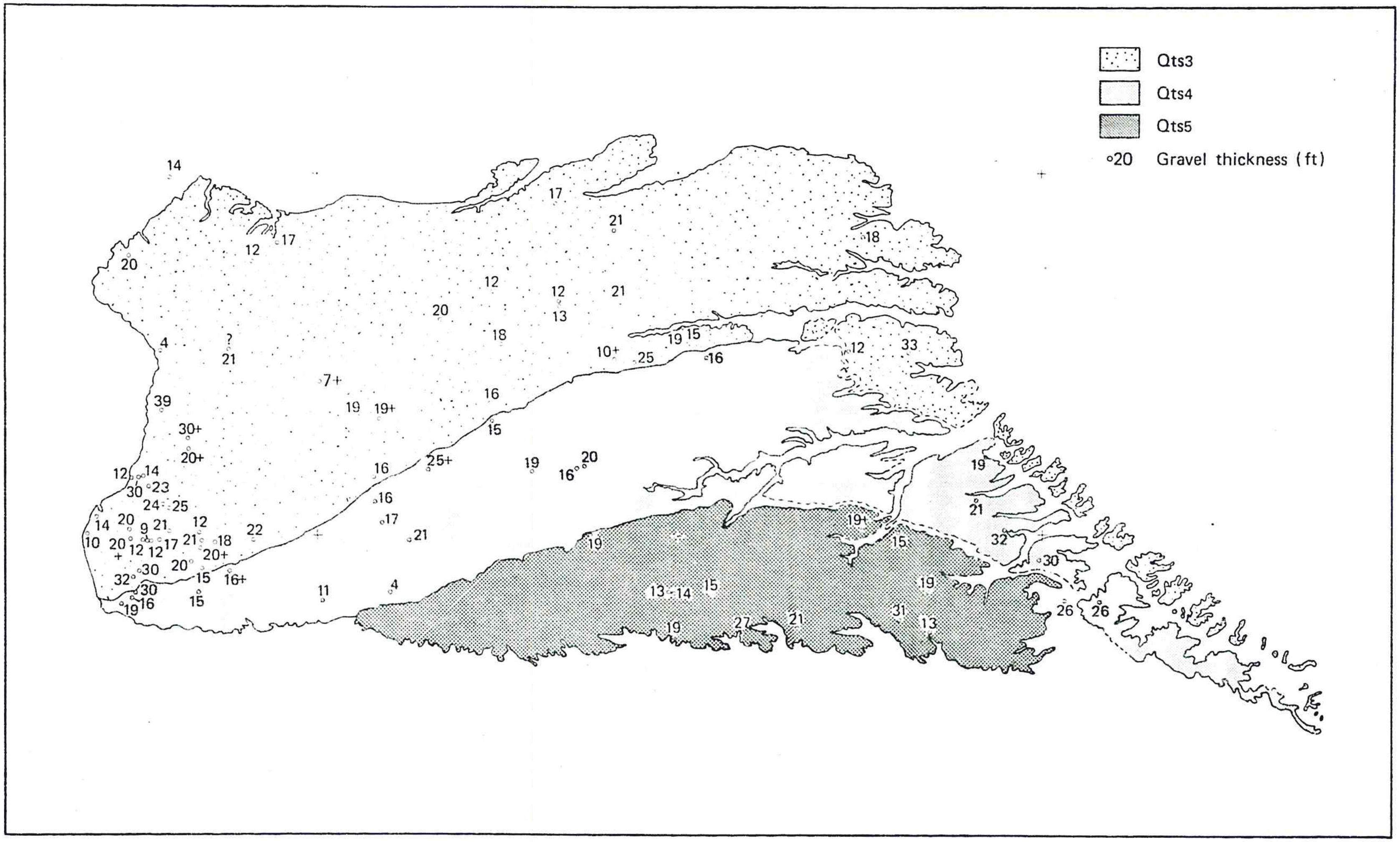


Figure 4 — Gravel terraces of the Greenfield Bench.

Qts3, lies about 75 ft. beneath the Second Bench and also has an average gradient of about 19 ft/mile. Two younger gravel terraces lie closer to the present Sun River channel and are identified by Maughn as the Asheulot Bench (Qts2) and Sun River Terrace (Qts1).

A north-south cross-sectional diagram through the eastern end of the Greenfields Bench is shown in Figure 5. The relatively thin terrace deposits are perched well above the Sun River and Muddy Creek and are effectively isolated as a hydrogeologic unit by the Coloraeo Shale. This simplifies the hydrogeologic framework by eliminating significant leakage to or from adjacent or underlying aquifers and surface-water bodies.

The gravel deposits are poorly to moderately well-sorted and are composed chiefly of oblate, well-rounded cobbles and pebbles of quartzite and argillite. Pebble sizes range primarily from 0.5 to 3 in. in diameter and are usually well imbricated. Cobbles exceeding one foot in diameter are often present on the western end of the Bench.

The gravel may occur in relatively clean beds, sometimes intercalated with medium-coarse sand, or it may occur in a heavy clay matrix. Locally, 1-2 ft. gravel beds have been cemented by caliche into a conglomerate. Caliche rinds almost universally coat the undersides of pebbles in the near-surface 10 ft. The unsorted gravel-clay material is very dense and extensive and, in places, acts as an aquitard, confining lower ground-water bearing zones and perching a very shallow ground-water zone.

A drill hole at the Konen study field in the northwestern end of the Bench encountered glacial till at a depth of 20 to 25 ft. The present till suggests the possibility that glacial or glacio-lacustrine deposits

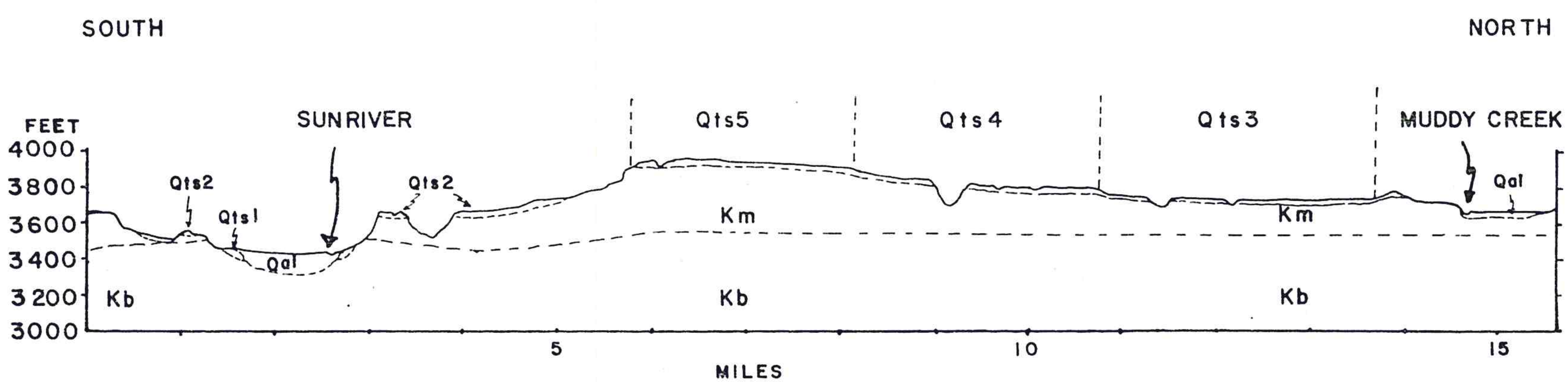


Figure 5 — Geologic cross-sections through the Greenfield Bench.

may overlay or be inter-tongued witi one or more fluvial gravel beds. Such conditions are known to exist north of the Choteau, Montana area. Multiple glacial and inter-glacial periods in the Quaternary, as well as the effects of glacial Lake Great Falls, could have been involved in contributing to the deposits on the Bench. The few published works on the extent of glaciation usually indicate that the Greenfields Bench lies just outside of the southern and western terminus of the continental ice sheets. More detailed drilling and mapping would be required to confirm the type and extent of any glacial or glacio-lacusterine deposits.

The thickness of the gravel and other unconsolidated deposits on the Bench is shown in Figure 6. Data were obtained from domestic wells and MBMG drill holes, but are relatively sparse in the interior of the Bench. Terrace deposits appear to be uniformly thicker on the west end of the Bench, especially just north of Fairfield where over 50 ft. of unconsolidated deposits were encountered. Several areas, when unconsolidated deposits are greater than 30 ft. thick, occur on the eastern fringe of the Bench. Generally, gravel thickness on the Bench averages about 19 ft based on data from 76 domestic wells. The average depth to the top of the gravel from the ground surface was found to be about 4.5 ft.

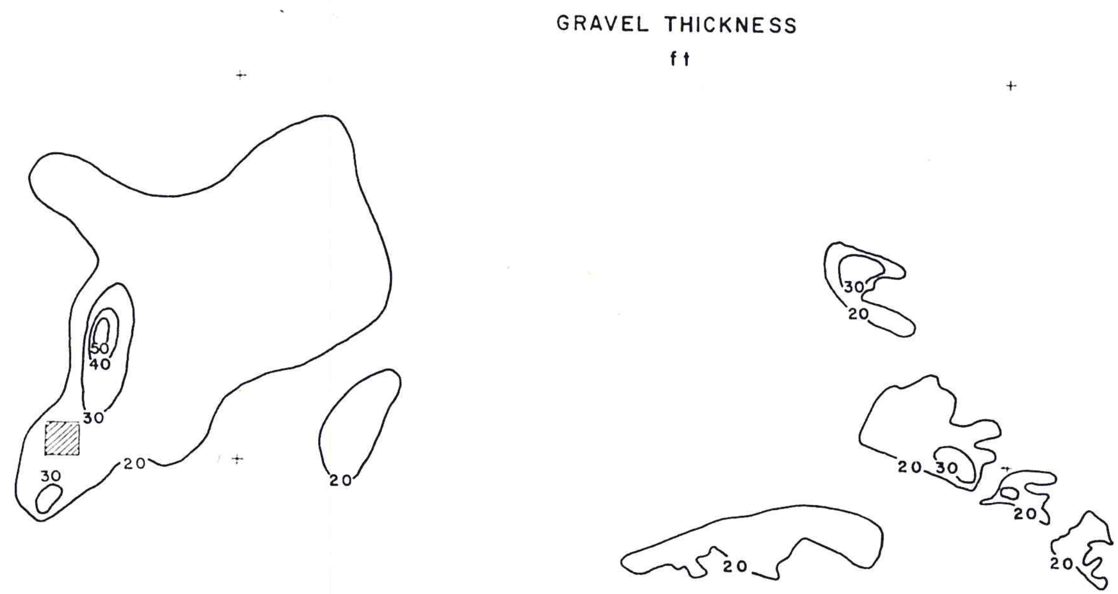


Figure 6 — Gravel thickness map.

4. AGRICULTURAL WATER DEMAND

4.1 Irrigated Area

The Greenfields Bench (also called the Fairfield Bench, locally) consists of a total of approximately 58,000 acres of irrigated cropland including minor amounts of land in residential or other non-agricultural uses. This area was determined by planimetering with a Calcomp 9,000 digitizer using 1:62500 scale maps and aerial photos. Detailed plat maps of 1:6336 scale indicate that about 10% of the land area within the Bench is not irrigated because of roads, spoil banks, dwellings, etc. Therefore, approximately 52,000 acres were considered actually irrigated on the Greenfields Bench. Approximately 2,090 acres on the extreme western end of the Bench drain to Freezeout Lake; the remainder drains to Muddy Creek.

The Asheulot Bench is also served by water from the Greenfields Bench, and some subsequent average water-use factors were calculated using the combined irrigated area of both benches. This bench consists of about 6,375 acres total, of which about 5,740 acres are actually irrigated.

Greenfields Irrigation District reports indicate that more irrigated land has come into production between 1968 and 1982. Of the total 80,000 acres in the Greenfields Division, 11% were classified as fallow or idle in 1968, whereas less than 1% were so classified in 1982. This indicates that over 8000 acres of new cropland were added during the period. If only the Greenfields Bench is considered within the Division, a proportionate increase would be equivalent to about 6,000 irrigated acres added over the period.

4.2 Potential Evaporation

The process of the change in state of water molecules from the liquid to the gaseous phase and transfer of the water vapor into the atmosphere is called evaporation. It is caused primarily by the input of heat energy into a body of water or surrounding medium and thus reaches its maximum in the summer. If evaporation occurs from a free water body in which the supply of water is not limited, it is said to occur at the maximum potential rate, given the ambient environmental conditions at the site. Such would be the case from a permanent lake or maintained container of water. In practice it is almost impossible to distinguish between evaporation and the transpiration of vegetation on the land surface, and so they are usually considered together. Estimates of average potential evapotranspiration (PET) are published on small-scale maps of the United States and indicate the Greenfields Bench area experiences about 35 in. per year (Dunne and Leopold, 1979). Average PET during the growing season was estimated to be 26 in. from a map prepared by Caprio (1973).

4.3 Actual Evapotranspiration

On bare ground, evaporation usually occurs at rates less than the potential rate. This is because free water is only infrequently available at the land surface, and the suction forces of evaporation must work against the sorptive and capillary forces holding water in the soil. Where soil moisture content increases with depth, as on irrigated lands with a shallow water table, plants short-circuit the flow path for soil water and readily move it to the surface through roots, stems and leaves in the transpiration process. The rate of transpiration is dependent on the crop type and growth stage as well as the same meteorological factors causing direct evaporation.

Research by Montana State University and the Extension Service has found that estimates of crop water use can be made by measuring evaporation from a galvanized wash tub. Once evaporation has been measured and corrected for rainfall from the same period, crop coefficients can be multiplied by the evaporation rates to obtain an estimate of actual crop water transpiration for intervals of several days to one week (Bauder, and others, 1982). The crop coefficient for spring wheat, for example, ranges from 0.2 at 5 days post-emergence to about 1.03 at 50 days post-emergence. Crop water use over the growing season generally is less than the potential evapotranspiration rate due to the limited root and leaf development early in the season for small grains, and the one to three harvestings per season in the case of alfalfa.

Crop water use data were collected by CES field staff in the 1981, '82 and '83 growing seasons on the Greenfields Bench (Bauder and Cullen, 1981; Bauder and Jones, 1982; Hertzog and Bauder, 1983). The number and location of collection sites and periods of data collection varied considerably in the three years, but are summarized in Table 1. Data were estimated by CES and MBMG to cover portions of the growing season not actually monitored.

TABLE 1

Average Growing Season Crop Water Use on the Greenfields Bench[1]

YEAR	PERIOD OF DATA	CROP	NO. OF SITES	WATER USE IN.	WATER USE FT.	ESTIMATED[2] CROP-WEIGHTED AVERAGES FOR SEASON FT.
1981	Mid-June	Alfalfa	3	27.3	2.27	2.27
	thru	Spring Wheat	5	18.4	1.53	
	August	Barley	4	20.8	1.73	
		Winter Wheat	1	18.0	1.50	1.61
	Average of all Grains					
1982	Mid-May	Alfalfa	2	14.6	1.22	1.74
	thru	Spring Wheat	5	13.3	1.11	
	August	Barley	6	13.4	1.12	
	Average of all Grains					1.11
1983	Late-May	Alfalfa	0			1.80(est)
	thru	Spring Wheat	7	10.0	0.83	
	July	Barley	13	10.1	0.84	
	Average of all Grains					1.16(est)

1 Data from Cooperative Extension Service, Montana State University, Bozeman, MT.

2 Data estimated for some early and late portions of growing season.

Crop water use was found to vary significantly, particularly between 1981 and the two following years. Weather records from Fairfield in 1981 indicate that April through September temperatures averaged 5.9 degrees above normal. Temperatures in 1982 were slightly cooler than normal with near-normal precipitation.

Based on CES data, it was estimated that actual average water use by small grain crops averaged 70-80% of PET during the May-August growing season. Water use by alfalfa averages about 90% of PET during its May-September growing season. The total average crop water use on the Bench is dependent on the proportion of small grain to alfalfa cropland, given the PET rate.

4.4 Trends in crop areas and average crop water use

Crop distribution records indicate a significant shift in the types of crops irrigated on the Bench (GID, n.d.). In 1968, fallow land, grain crop and forage area comprised 11, 42 and 47%, respectively. In 1982 the distribution changed to less than 1% fallow, 69% grain crop, and 31% forage. The major change was caused by a 12-fold increase in the acreage devoted to barley.

Based on the data from 1981, 1982 and 1983 in Table 1, the estimated annual grain crop water use was 1.29 ft., whereas alfalfa crop water use was 1.94 ft. The historic irrigated acreage data (section 4.1) and average crop water use rates can be examined for trends in irrigation water requirements. In 1968, the total irrigated acreage on the Greenfields Bench was about 46,000 acres, and increased to about 52,000 in 1982. The average total crop water demand change between 1968 and 1982 is presented in Table 2.

Table 2
Change in Average Crop Water Demand Due to Change in Crop Types, Greenfields Bench, 1968 and 1982

YEAR	IRRIGATED BASE ACRES (ac)	% GRAIN	GRAIN DEMAND (ft/yr)	% FORAGE	FORAGE DEMAND (ft/yr)	WEIGHTED DEMAND (ft/yr)	AVERAGE CROP DEMAND (af/yr)
1968	46,000	47	1.29	53	1.94	1.63	74,980
1982	52,000	69	1.29	31	1.94	1.49	77,480
Change	+6,000	22		22		0.14	2,500

The results indicate that the shift to barley, which uses less water than forage crops, was offset by the increase of irrigated cropland. The small increase in total crop water demand is about 3% and is probably not significant due to the uncertainties and assumptions in the data.

The actual crop water use in 1982, using demand factors of 1.11 ft. for small grains and 1.74 ft. for alfalfa, and area factors of 69% and 31%, respectively, amounts to 1.31 ft/ac or 67,880 af over the total irrigated area.

5. HYDROLOGIC INPUTS TO THE GREENFIELDS BENCH

5.1 Precipitation

The Greenfields Bench is located on the semi-arid high plains of Montana, typified by a dry continental climate. Yearly precipitation averages about 12 in., but exhibits wide annual fluctuations and spatial variability. Table 3 gives precipitation normals for four National Oceanic and Atmospheric Administration (NOAA) stations surrounding the Bench. Although annual precipitation is relatively low, approximately 55% of it falls during the early growing season in May, June and July. This precipitation pattern is relied upon by surrounding dryland farmers for successful small grain production.

5.1.1 Precipitation Probability

Based on Table 3, it can be expected that Fairfield will receive about 2.2 in. of rain in May, and 3 in. in June, etc., in an average year. However, the wide fluctuations in annual precipitation require that the probability of receiving a certain amount of rain be assessed. Irrigation systems are constructed primarily to alleviate the uncertainty of natural precipitation fluctuations and to provide a dependable supply of water to the crops.

The distribution of monthly rainfall during the growing season at Fairfield, Montana during the period 1931-82 is shown in Figure 7. May has a non-normal distribution, as indicated by a Chi-squared test which gave a chi-square value exceeding the 99% level of probability for normal distributions. The same test indicated that June precipitation is normally distributed. The arithmetic mean and one standard deviation either side of the mean are also shown. May has a mean of 2.22 in. and a

Table 3. PRECIPITATION NORMALS, 1941--1970

inches

					MONTH OF YEAR							
STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Fairfield	0.43	0.39	0.58	0.88	2.22	3.32	1.32	1.01	1.10	0.52	0.43	0.31	12.51
Sun River	0.48	0.40	0.67	1.03	2.34	3.09	1.36	0.97	1.05	0.57	0.49	0.39	12.84
Great Falls	0.88	0.75	0.97	1.18	2.37	3.11	1.27	1.09	1.17	0.68	0.81	0.71	14.99
Brady	0.30	0.29	0.49	0.86	2.17	3.08	1.33	1.09	0.91	0.50	0.39	0.33	11.74

Source: National Oceanic and Atmospheric Administration, 1981.

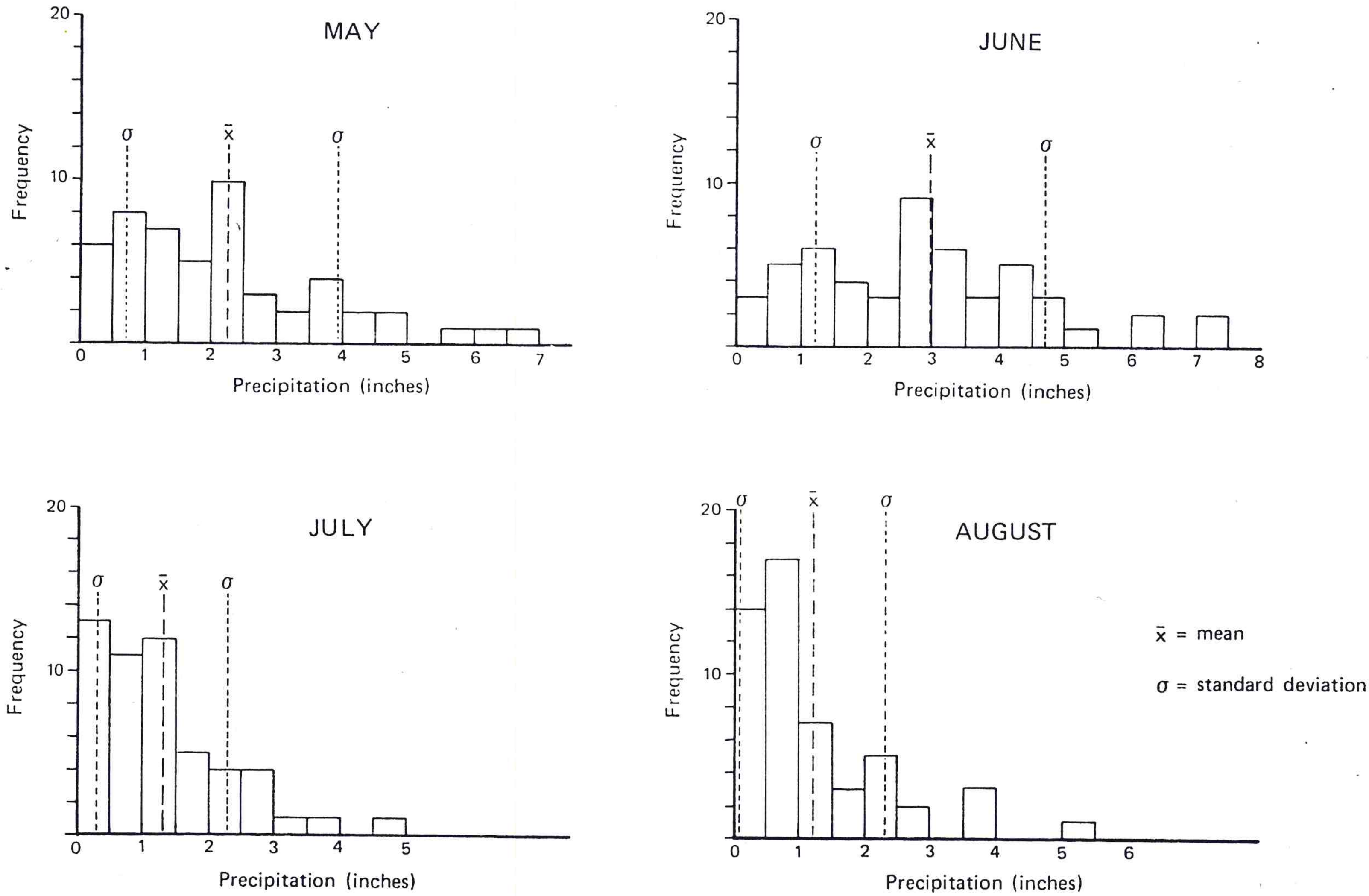


Figure 7 — Distribution of growing season rainfall at Fairfield, Montana.

standard deviation of 1.59 in. June has a mean of 2.86 in. and a standard deviation of 1.75 in. The standard deviation is a measure of the dispersion of the data points about the mean. The greater the standard deviation, the greater the dispersion. May and June have rather large standard deviations relative to the critical nature of crop water requirements. In June, for example, Fairfield can expect to receive from 1.11 to 4.61 in. of rain, in 68% of all years, and more or less than this range the other 32% of the time.

The rainfall distribution is quite different for July and August. The means for both months are smaller; near 1.2 in. The standard deviations are also smaller; however, the lower limit in both months is only slightly above zero. Log-normal data plots gave straight lines for the probability curves, and were judged as a suitable distribution.

The probability of receiving any particular amount of precipitation in a month can be shown in cumulative percent-frequency graphs, as in Figure 8. The log-normal curves for each of the four months were fitted by eye. There is a break in slope of each curve that may represent the effects of different storm patterns which predominate during wet and dry periods.

With these curves, it can be said, for example, that for Fairfield in June, 2.7 in. of precipitation could be expected 50% of all years; at least 1.1 in. could be expected 80% of the time, or that conversely, 1.1 in. or less will be received 20% of the time.

For agricultural purposes it is common to select a fairly safe probability level, say the 70% level of exceedance, as a reliable precipitation amount to plan on. In May, the 70% level is 1.2 in. and in June

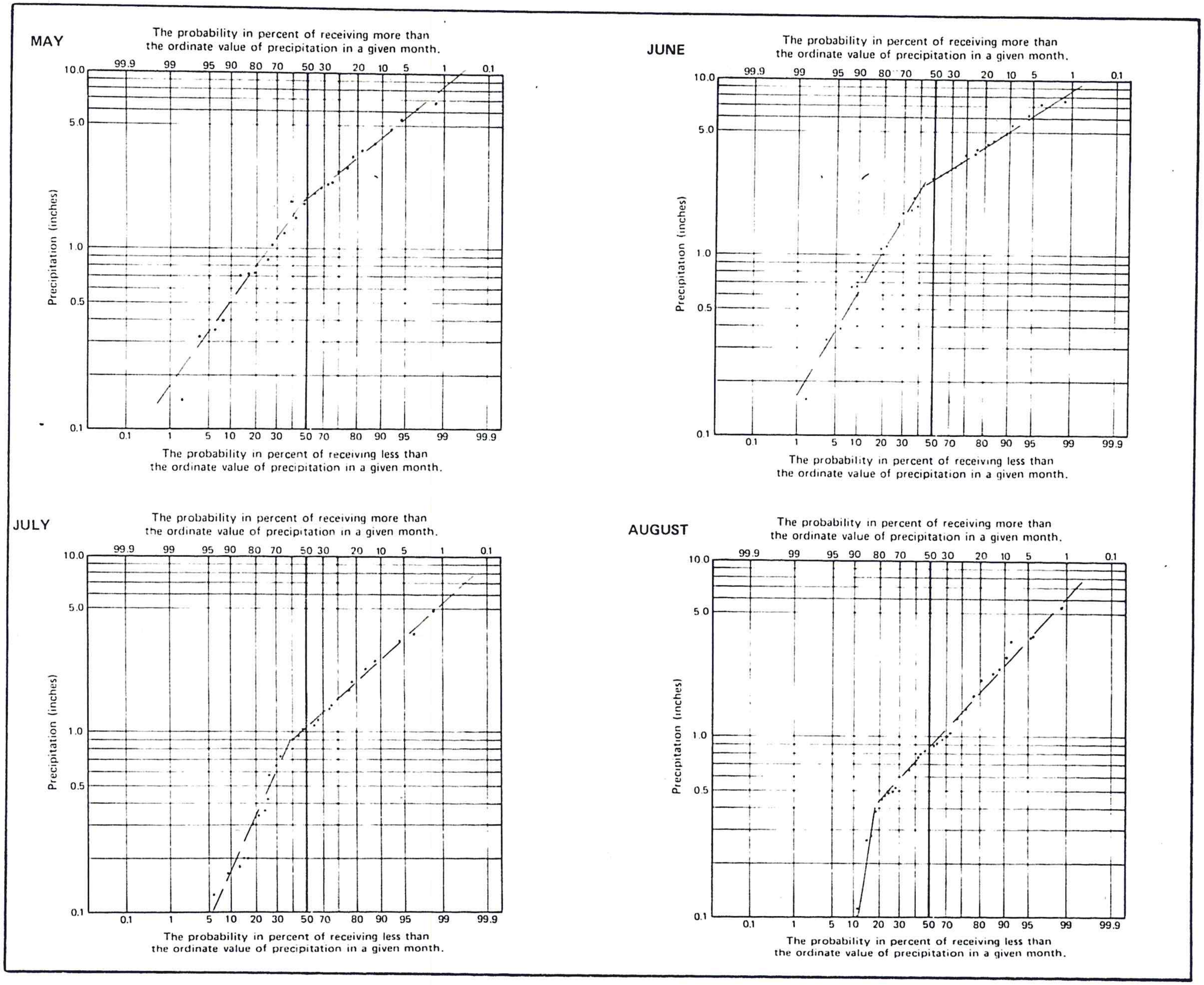


Figure 8 — Precipitation probability curves for the growing season at Fairfield.

it is about 1.7 in. The 70% level in July and August is about 0.6 in., but high evapotranspiration rates can render this small amount ineffective and so cannot be depended on.

Montana Cooperative Extension Service studies on the Bench in 1980-82 provided average daily crop water use rates for most of the growing season (Bauder and Jones, 1982 and Bauder and Cullen, 1981). In May 1982, for example, the average crop coefficient was 0.07 in./day, which gives a monthly water use demand of 2.17 in. The effective portion (that which infiltrates, typically about three-fourths) of the 70% precipitation level of 1.2 in. could be subtracted, leaving roughly 1.3 in. of water to be supplied through irrigation or stored soil moisture in a typical year. These values will vary from year to year depending on local weather conditions and could be adjusted based on experience or on continual monitoring of evapotranspiration and precipitation.

5.1.2 Precipitation and Irrigation Water Supply

Figure 9 is a series of graphs for each of the four main growing season months, plotting the monthly precipitation versus the average flow at A-Drop near Fairfield during the period 1969-82. A-Drop is the discharge-rated canal structure which conveys all the irrigation water to the Greenfields Bench. Each data point is labeled with a number which is the rank order (largest = 1) of mean monthly flows of Muddy Creek (measured at the USGS station) near Vaughn (Gordon) for the 14-year period. The lower stippled region is an estimate of monthly crop water use demand for 50,000 irrigated acres, expressed as a function of the amount of total monthly precipitation. It is based on the three years of crop water use data from CES irrigation scheduling work on the Bench. Of

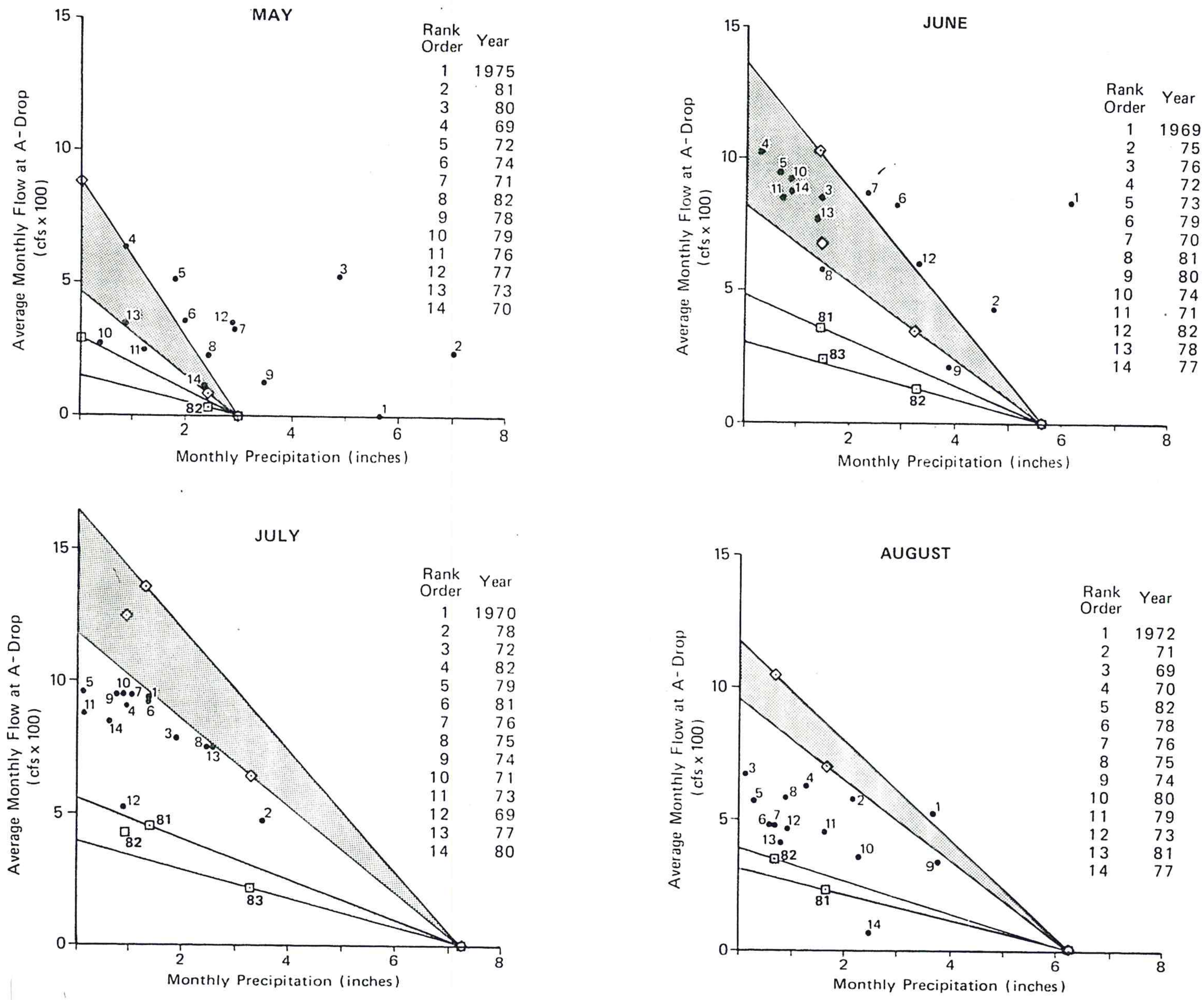


Figure 9 — Monthly precipitation versus flow at A-drop and rank order of flows in Muddy Creek.

the total monthly precipitation, 75% was considered effective and was subtracted from the total crop water requirement to give the rate of irrigation water required at A-Drop. The potential contribution of stored soil moisture was neglected in all graphs; it would have the effect of lowering the position of the curves.

The upper stippled region is equal to three times the lower region (3 x vertical axis value of lower region), and represents the approximate annual average excess of irrigation water inflow over annual irrigation requirements. That is to say, the upper region includes a factor for all the water losses in the system. The trend of both stippled regions indicates that as precipitation increases, the amount of irrigation water required by the crops decreases up to a point beyond which precipitation would supply the entire consumptive crop needs.

The graphs indicate that high runoff in Muddy Creek was often directly caused by a supply of irrigation water far in excess of crop water requirements. It is difficult to express the crop water use demand since it varies with local micro-climatic and day-to-day weather conditions. Crop water use data collected by CES on the Bench over a three-year period were utilized to develop the empirical relationships between total monthly precipitation and monthly crop water use. The procedure used to develop the crop water use lines is outlined in Figure 10. The stippled regions simply envelope the two to three data points available per month, and are a simplification of many interactive factors. If more years of data were available, a predictive crop water use model could be constructed along with statistically determined confidence limits. The mean monthly discharges and rank!order of Muddy Creek streamflow measured near Vaughn are given in Table 4.

The use of monthly averages forces a steady state condition (i.e., no change in rates during the month) on the often very transient nature of crop demands, precipitation and irrigation water diversions. Segregating continuous data by month sometimes resulted in obscurring the effect of major changes near the monthly borderlines. The runoff in

Figure 10

Crop Water Demand Curve Calculations For Figure 9

1. The average monthly crop water demand (CD) for barley, spring wheat and alfalfa was obtained from Montana Cooperative Extension Service reports for 1981, 82 and 83 (the high CD line of the crop water use envelope for May was estimated).

2. The lower right hand point ( ) of the crop demand envelopes was found by dividing the lowest monthly average crop water use rate (from 1981, 1982 or 1983 data) by 0.75. This value is the amount of precipitation required to satisfy the total monthly crop water demand if only 75% of the precipitation is considered effective. No irrigation water is theoretically required, and so the ordinate value (Flow at A-Drop) is zero.

The other crop water demand points ( ) defining the envelope were determined as follows:

3. The average monthly precipitation (P) from the Fairfield NOAA station and/or CES "fencepost" rain gages in study fields was determined.

4. The irrigation water (IW) required to just meet monthly crop demands in excess of effective precipitation (EP) was determined by:
   EP = P x 0.75 (except as given by Hertzog and Bauder for 1983)
   IW(ft/mo) = CD - EP

5. The average monthly irrigation water flow at A-Drop (AD) required to satisfy IW over the entire Greenfields Bench was determined by:
   $AD(ft^3/s) = IW(ft/mo) \times 50{,}000(ac) / 1.98(ac.ft/ft^3/s)$ / No. days/mo

6. Data points were plotted as P (horizontal axis) vs. AD (vertical axis). Lower right-hand data points where AD = 0 were determined from the lowest monthly CD, - 0.75, to allow for effective precipitation.

7. The upper stippled region was defined as the area enveloped after the AD values of the lower data points were multiplied by 3, using the same P values.

Muddy Creek necessarily lags behind precipitation and irrigation water return flows since most of it returns at least partially via the groundwater system. Therefore, in some cases, the cause-effect relationship can be seen better if the rank order of the following month is also checked. Even with these limitations, the graphs offer some insight into the system-wide relationships among crop water demand, total water input to the Bench and irrigation return flows to Muddy Creek.

Table 4. Mean monthly flows and rank order for Muddy Creek near Vaughn

	Mean Monthly Flow in ft^3/s, Rank Order by Month					
YEAR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1982	55.3, 3	118, 8	166, 12	316, 4	291, 7	180, 5
1981	49.4, 4	225, 2	200, 8	279, 6	268, 11	79.5, 13
1980	32.4, 10	175, 3	173, 9	137, 14	210, 12	130, 10
1979	72.5, 2	104, 10	225, 6	288, 5	294, 6	112, 11
1978	42.4, 7	111, 9	147, 13	347, 2	280, 8	169, 6
1977	44.6, 6	91.7, 12	129, 14	231, 13	138, 14	70.5, 14
1976	39.2, 8	92.1, 11	253, 3	272, 7	275, 10	167, 7
1975	162, 1	264, 1	268, 2	270, 8	402, 1	155, 8
1974	27.6, 14	127, 6	173, 10	253, 9	277, 9	131, 9
1973	32.5, 9	78.1, 13	237, 5	235, 11	198, 13	94.1, 12
1972	30.8, 13	129, 5	243, 4	323, 3	363, 2	218, 1
1971	31.5, 11	126, 7	170, 11	253, 10	341, 4	205, 2
1970	31.1, 12	75.1, 14	216, 7	367, 1	315, 5	192, 4
1969	48.5, 5	142, 4	455, 1	233, 12	344, 3	202, 3

Source: U.S. Geological Survey, Water Resources Data for Montana, Water Years 1969-1982.

Figure 9 indicates that in May of most years, much more water than even three times the crop demand was diverted onto the Bench. The largest monthly flows in Muddy Creek occurred in 1975 and 1981, years of heavy precipitation. In May 1975, no irrigation water was supplied to the Bench. May 1980 ranked third in Muddy Creek runoff for that month, illustrating the multiplicative effects of high precipitation and high irrigation water input. The years 1969 and 1972 ranked 4 and 5, respectively, indicating that even in years of below-normal precipitation, high water delivery rates onto the Bench resulted in greater than average monthly flows on Muddy Creek. This suggests that although irrigation water is available, many farmers or their crops are not ready for or do not need irrigation in May. Most irrigation in May is of alfalfa and pasture and very little of grain crops. Stored soil moisture from early spring recharge may be sufficient for much of the crop water needs in May. The large excess of irrigation water input over irrigation requirements indicates that May is a period of large seepage losses to the soil and the ground-water system. The relatively large seepage rate which occurs when irrigation water is first turned into the canal system is commonly referred to as "watering-up" the system.

In June of most years, the average water delivery rate is within or above the upper crop-water demand envelope. The year having the greatest runoff in June was 1969; it also had the largest precipitation amount and an average diversion rate. In general, greater than average monthly flows in Muddy Creek occurred in years when the water supply to the Bench was near or above the midpoint of the upper crop-water demand envelope. As in May, the large excess of irrigation water input over irrigation requirements indicates that June is also a period of large seepage losses to the ground-water system.

In July the locus of the points drops below the upper crop-water demand envelope. By this time of year the relation among precipitation, irrigation water supply and runoff becomes more complicated because of the effects of previous irrigation and the time delay for the return flows to reach Muddy Creek. High precipitation such as in July 1978 can result in high runoff, even with less than average irrigation water input. A combination of near normal precipitation and a greater than average irrigation water input apparently resulted in the large runoff of July 1970. The number three rank of July 1972 may have resulted from the water supply rate of June 1972, which was the greatest of any monthly rate in the 14-year period.

August data demonstrate a strong positive correlation between the water supply rate and runoff in Muddy Creek. The largest four August runoff years had relatively high water supply rates, with the two highest years also experiencing greater than normal precipitation. Although August 1974 experienced the greatest amount of precipitation, runoff was less than normal in Muddy Creek, possibly because of much drier than normal conditions in June and July. The August data suggest that although the water supply rate to the Bench is generally reduced when precipitation increases, it is not reduced enough to prevent excessive runoff. The irrigation district is limited in this respect because of the long travel time of water in the canal system, much of which is eventually wasted to Muddy Creek under the existing operating system.

The locus of August points is again lower with respect to the crop water demand envelopes indicating that in late summer, crops are utilizing more water from sub-irrigation and stored soil moisture. The crops are utilizing some of the ground-water recharge from May and June which was stored in the shallow ground-water system, thereby lessening late season irrigation requirements.

The graphs of Figure 9 are an attempt to simplify some very complex and dynamic interrelationships with a steady-state depiction. An irrigation district does not always have sufficient information or time to adjust water supply rates to changing climatic conditions. However, some important characteristics of the irrigation system are indicated:

1) In May of most years irrigation water supply far exceeds crop irrigation requirements even allowing for measured canal and farm seepage losses. A substantial volume of water is wasted to Muddy Creek during initial "watering-up" of the canal network and in deliveries to a small number of irrigators.
2) Irrigation water supply is generally decreased with increasing precipitation, but not rapidly enough to prevent excessive runoff. A limitation of the existing system is the 48 hours of water travel time between Pishkun reservoir and the Bench.
3) If authorized, the GID could deliver irrigation water to the Bench based on a combination of real-time meteorological monitoring and experience, or precipitation-transpiration probability functions.
4) A real-time or average monthly charting system such as illustrated by these graphs could serve as a goal for irrigation district managers to follow in reducing over-supply or avoiding

water shortages. Conversion to a computer-based information management system would be helpful. The GID could provide crop irrigation requirement information to farmers when water orders are placed.

5.1.3 Spatial Variability of Precipitation

Little can be said of the spatial variation of precipitation across the Bench except that large variations occur within any short measurement interval, as indicated by the Cooperative Exension Service data for 1981 and 1982 given in Figure 11. The random nature of precipitation, along with differences of measurement devices, siting and reading probably account for the variations.

The precipitation normals for Fairfield, Sun River, Great Falls and Brady show only minor long-term differences during the growing season. More recent data including the NOAA station at Power suggest a south to north or southwest to northeast decrease in average precipitation. The approximately 300 ft. elevation difference across the Bench and closer proximity of the mountain foothills to the south may be responsible for this trend.

The large local variations which occur from individual storms indicate that farmers should measure precipitation at their fields to obtain their own reliable irrigation planning information. If farmers preferred a centralized information source, the irrigation district manager could use one to three well planned meteorological stations to estimate irrigation water requirements for individuals and the entire Bench. Since average precipitation tends to vary inversely with the area covered by

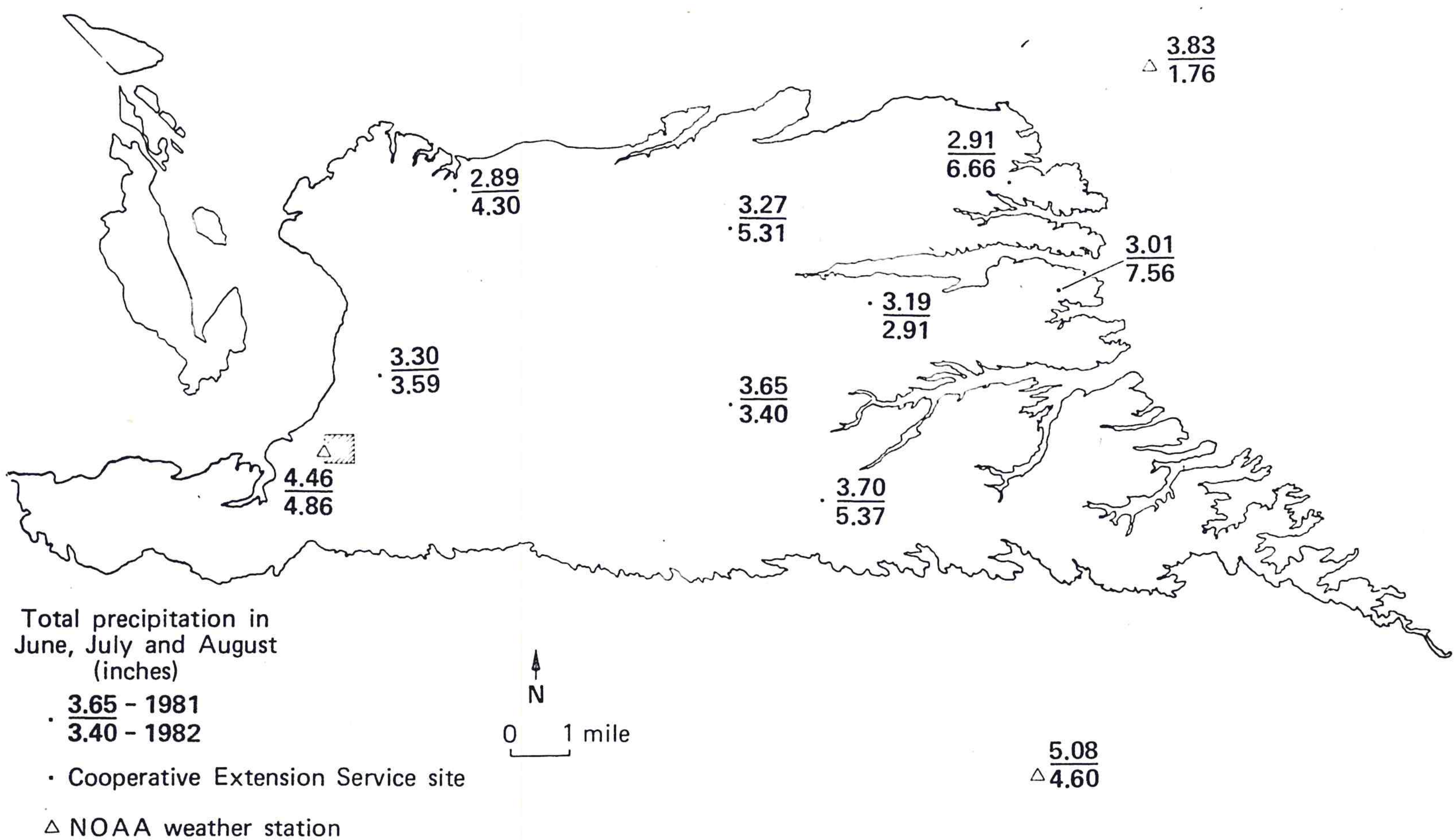


Figure 11 — Precipitation variability in June, July and August of 1981 and 1982.

the gage, the crop-water demand thus calculated should usually be adequate.

5.2 Irrigation Water Supply

5.2.1 Historical Trends

All irrigation water delivered to the Greenfields and Asheulot Benches is supplied through one large canal, the Sun River Slope Canal, and passes through a discharge-rated section just above a large drop structure called A-Drop. Total annual inflows over the past 15 years, along with May through August precipitation totals, are given in Table 5. The average annual delivery rate for the 15-year period was 166,000 acre-feet (af) with a standard deviation of almost 28,000 af.

Irrigation water is delivered to the Bench by the GID in response to water orders from irrigators. The sum of all water orders plus a loss factor estimated by the GID determines inflows at A-Drop. Inflow rates are quite variable from year to year, being dependent on factors including decisions by farmers, growing season rainfall, mountain snowmelt supplying Gibson reservoir, the cropping pattern on the Bench, canal lining, and management practices by the GID.

Comparisons of the five-year moving averages of inflow and precipitation may indicate some degree of inverse correlation with growing season precipitation. The other factors combine in most years to obscure the relationship. A rehabilitation and betterment program sponsored by the U.S. Bureau of Reclamation and carried out by the GID has resulted in the replacement of unlined distribution canals with 65 mi. of concrete lined canals and 30 mi. of buried pipeline since 1978. The GID estimates

Table 5. Annual Irrigation Water Inflow to the Greenfields Bench.

YEAR	INFLOWS Total af	INFLOWS 5-Year Average af	PRECIPITATION[1] Total May-Aug in	PRECIPITATION[1] 5-Year Average in
1969	203,705		7.88	
1970	186,413		6.43	
1971	195,770		5.59	
1972	206,743		6.14	
1973	175,769	193,680	2.42	5.69
1974	178,253		7.37	
1975	123,241		16.42	
1976	181,191		6.10	
1977	114,946		8.67	
1978	143,069	148,145	9.21	9.55
1979	175,750		4.01	
1980	149,800		10.25	
1981	148,597		11.43	
1982	160,744		7.28	
1983	146,040	156,186	6. [2]	7.79
n = 15				
Mean	166,002		7.68	
Standard Deviation	27,913		3.33	

[1] Based on Fairfield, Montana NOAA Station.

[2] Precipitation for June, 1983 was estimated.

that this work has resulted in saving 30,000 af of water per year in seepage losses (Nypen, 1983). This should result in a similar reduction in annual inflows although more time is needed to observe the long-term trend.

5.2.2 Average Delivery Factors

Relationships between the previously cited quantities offer some useful rules-of-thumb for irrigation water delivery to the Bench. The average 1969-83 water delivery rate to the Greenfields and Asheulot Benches was 3.07 af per irrigated acre.

Montana Cooperative Extension Service studies of crop water use on the Bench in 1981-83 allow an estimate of the average crop water use to be made. Weighting the alfalfa crop water demand by 30% of the area and the small grain demand by 70%, the weighted average crop water demand was 1.81 ft., 1.30 ft., and 1.35 ft. for 1981, 1982 and 1983, respectively. The three year average is 1.49 ft. The total average demand for the 52,000 irrigated acres on the Greenfields Bench is then about 77,480 af/yr.

The Gross Delivery-Demand Factor, obtained by dividing the 166,000 af/yr average delivery rate by the 77,480 af/yr average demand, equals 2.14. That is, without considering the water supplied by natural rainfall during the growing season and stored soil moisture at the start of the growing season, approximately 2.14 times the water required by the crops is typically delivered onto the Bench.

The Net Delivery-Demand Factor takes into account the average amount of water supplied by natural precipitation during the growing season, which for the 1969-83 period is about 7.7 in. for May through August. If 75% of this is considered to be effective, an average of about 25,025 af of rainfall is available to satisfy growing season crop demands. The Net Delivery Demand Factor found by dividing the 166,000 af average delivery rate by the remaining 52,455 af crop demand, is about 3.16. That is, approximately 3.17 times the average crop water demand is delivered as irrigation water to the Bench if 75% of total averge growing season precipitation is considered to be effective in reducing the net crop demand. If soil moisture is at field capacity at the beginning of the growing season, this ratio would be about 4.2, assuming 50% of the average available water holding capacity (six inches) was supplied to the crop.

The delivery-demand factors should be considered tentative since the average crop water demand is based on only three years of data. These factors include irrigation water used to flush the canal network in the spring and the extra delivery water required to provide the necessary diversion heads on the eastern end of the Bench.

5.2.3 Timing and Duration

The irrigation water inflows at A-Drop generally begin in early May and continue through mid-September. In the 1969-83 period, the average date of first flow at A-Drop was May 11, with a standard deviation of 8 days. The average date of last flow was September 19 with a standard deviation of 16 days. The average duration of irrigation inflows for the 15-year period is 130.3 days.

The average inflow rate to the Bench, given the average annual inflow volume of 166,000 af over 130.3 days, is about 643 ft^3/s.

The shortest duration of inflows was in 1977, a year of low snowpack and runoff into Gibson Reservoir. The longest duration was in 1971, when abundant storage in Gibson Reservoir was available and spillway gates were utilized in June to discharge excess water to the Sun River.

5.2.4 Irrigation Water Quality

Several samples of irrigation water were analyzed, indicating that it is of very good chemical quality for irrigation purposes.

A sample of inflow at A-Drop collected June 23, 1981, had a specific conductance of 227.9 micro-mhos per centimeter at $25^{\circ}C$ (umhos @ $25^{\circ}C$), total dissolved solids (sum) of 183 milligrams per liter (mg/l), and a sodium adsorption ratio (SAR) of 0.05. These values give an irrigation water rating of both low salinity and low sodium hazard according to the U.S. Department of Agriculture classification system. The high quality reflects the purity of the source water of the Sun River and Gibson Reservoir as it leaves the mountains west of Fairfield.

A water sample was taken at the Greenfields Main Canal on June 26, 1981 at the extreme eastern end of the distribution system near J-wasteway. The chemical quality remained very good with specific conductance equal to 230.2 umhos @ $25^{\circ}C$, dissolved solids of 181 mg/l and a SAR of 0.06. This sample indicates that very little change in chemical quality occurs within the canal system on the Bench.

A second sample was collected at A-Drop on May 4, 1982, giving a specific conductance of 332.1 umhos @ $25^{\circ}C$, dissolved solids of 288 mg/l and a SAR of 0.07. Some seasonal variation in irrigation water quality occurs, but the quality probably remains good for irrigation purposes.

6. RUNOFF FROM THE GREENFIELDS BENCH

Irrigation water and precipitation which is not evaporated or transpired, results in surface water or ground-water runoff. A diagrammatic sketch of the recharge and runoff components from the Greenfields Bench is shown in Figure 12. The principal sources of runoff and ground-water recharge are 1) canal seepage, 2) canal waste-water, 3) on-farm tailwater 4) on-farm deep percolation of irrigation water and 5) heavy precipitation. The Bench is laced with two networks of open channels; the canals, laterals and farm ditches which convey irrigation water to the crops; and the drains which prevent water-logging of the root zone by removing excess ground water from the interior of the Bench.

The rate of flow of ground water is much slower than that of surface water. Typical average seepage velocities of ground water on the Bench are about 5 to 20 feet per day (ft/d). Typical average velocities in irrigation canals and drains are about 0.5 to 2 ft/s or 43,000 to 173,000 ft/d. The three to four orders of magnitude difference in velocity imparts fundamental differences in the time-rate of runoff for surface water and ground water. Surface water runoff is characterized by relatively rapid water transport across the Bench (hours to days), and very little storage in channels; whereas ground water is characterized by slow transport (days-months) and a large storage component within the aquifer.

The network of about 265 miles of open drains and 20 miles of closed drains creates a dynamic and local ground-water zone down to the depth of the drains. The ground-water zone below drain depth constitutes the more stable regional flow system. The drains function to expedite the discharge of shallow ground water from the upper portion of the gravel aquifer and to lower the water table beneath the fields.

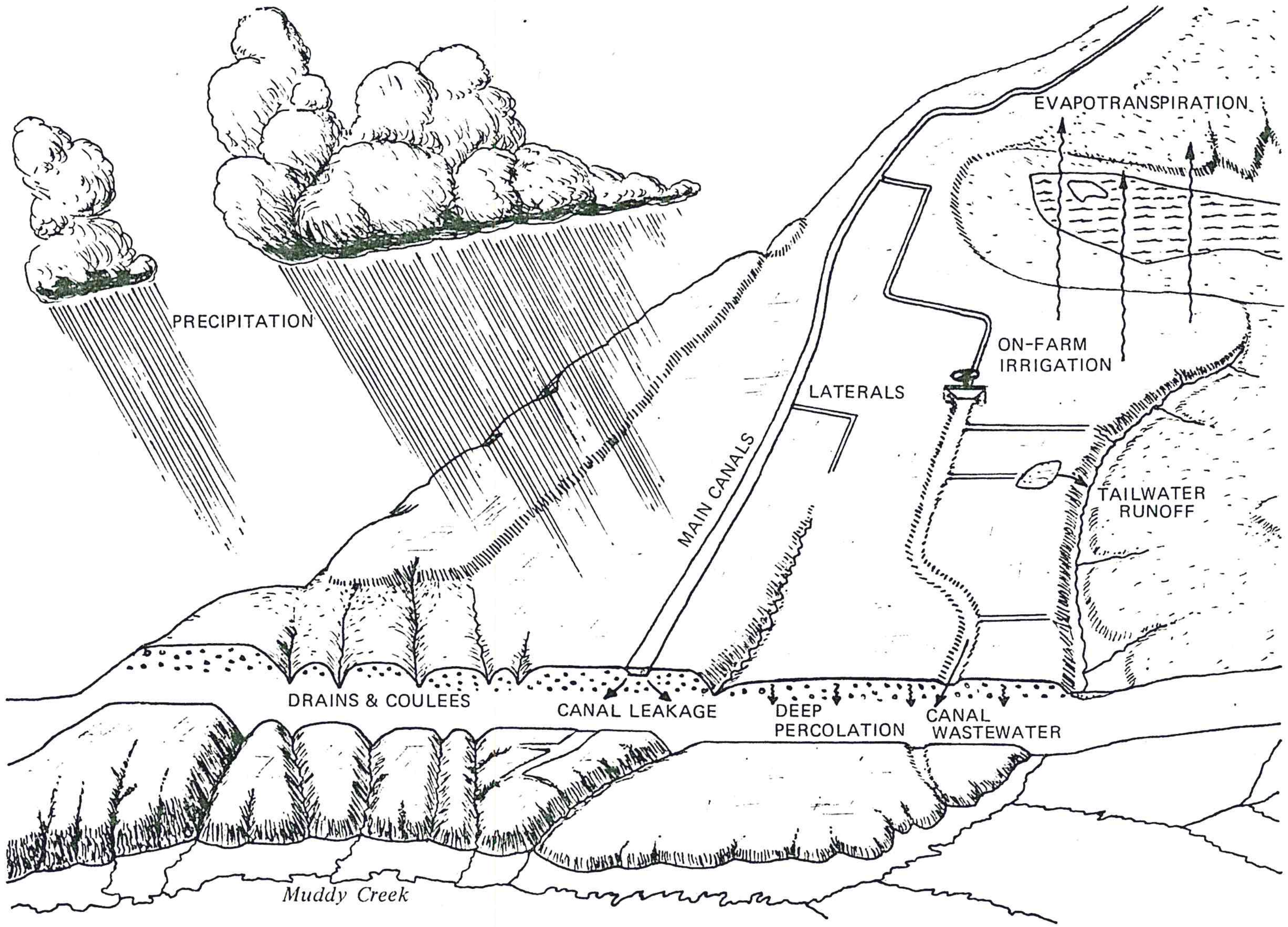


FIGURE 12   DIAGRAMMATIC VIEW OF RUNOFF FROM THE GREENFIELDS BENCH

The depth of the drains penetrates one-fourth to one-half of the total aquifer thickness throughout the interior of the Bench. However, at the edges of the Bench where the drains and coulees discharge to Muddy Creek, the drains are cut through the entire aquifer thickness and have drained most of the ground water and surface water from the Bench. The relatively impermeable Colorado Shale bedrock beneath the gravel aquifer prevents significant downward leakage. In its simplest concept, the Bench drains like a sediment-filled bathtub, with almost all water discharging from the lower eastern and northern ends. This feature allowed the total ground-water and surface-water runoff from the Bench to be measured directly in the drains and coulees on the margin of the Bench. Section 6 presents the characteristics and occurrance of ground water and surface water on the Bench and in Muddy Creek. Section 7 discusses the sources of ground-water recharge and surface water runoff.

6.1 Ground Water

6.1.1 General Background

The gravel deposits of the Greenfields Bench probably always contained limited ground-water resources even before irrigation began. Cleiv Springs, in the northeast corner of the Bench, was reported to supply water to Indian users. Early settlers reportedly dug shallow wells which although yielded some water, periodically went dry. Even today, on the First Bench above the level of the highest irrigation, ground water occurs although it is slightly more mineralized since these deposits have not been leached by irrigation water.

Irrigation in the early years of the Greenfields Project resulted in leakage of water into the terrace deposits where it caused the buildup of a shallow water-table aquifer underlain by the relatively impermeable Colorado Shale. Ground-water flow occurred in response to the elevation change across the Bench and the local differences in the head (elevation of the water table above a fixed datum) caused by the various recharge sources. Drains were dug to alleviate soil water-logging problems, and connected to the coulees cutting into the Bench.

Ground water moves from the higher portions of the bench to drains and coulees where it discharges and becomes part of the surface-water flow, draining primarily to Muddy Creek. Since irrigation and precipitation occurs in an annual cycle, so the ground water system fluctuates in a generally annual cycle of recharge, storage and discharge to streams. If the annual change in the overall water storage of the ground-water system is minimal, it is said to be at steady state. In a shallow ground-water system of limited extent, such as the Greenfields Bench, a quasi-steady state condition is approached over a one-year period. With this premise it is reasonable to examine the hydrologic outputs and run-off from the Greenfields Bench in terms of the annual flux of the components in the ground-water and surface-water systems.

6.1.2 Ground-water Heads

The direction of ground-water flow can be seen from a water table map. Figure 13 is a contour map of water-table elevations in the gravel aquifer measured in July and August, 1981. It can be said that, in general, ground-water elevations closely mirror the surface topography

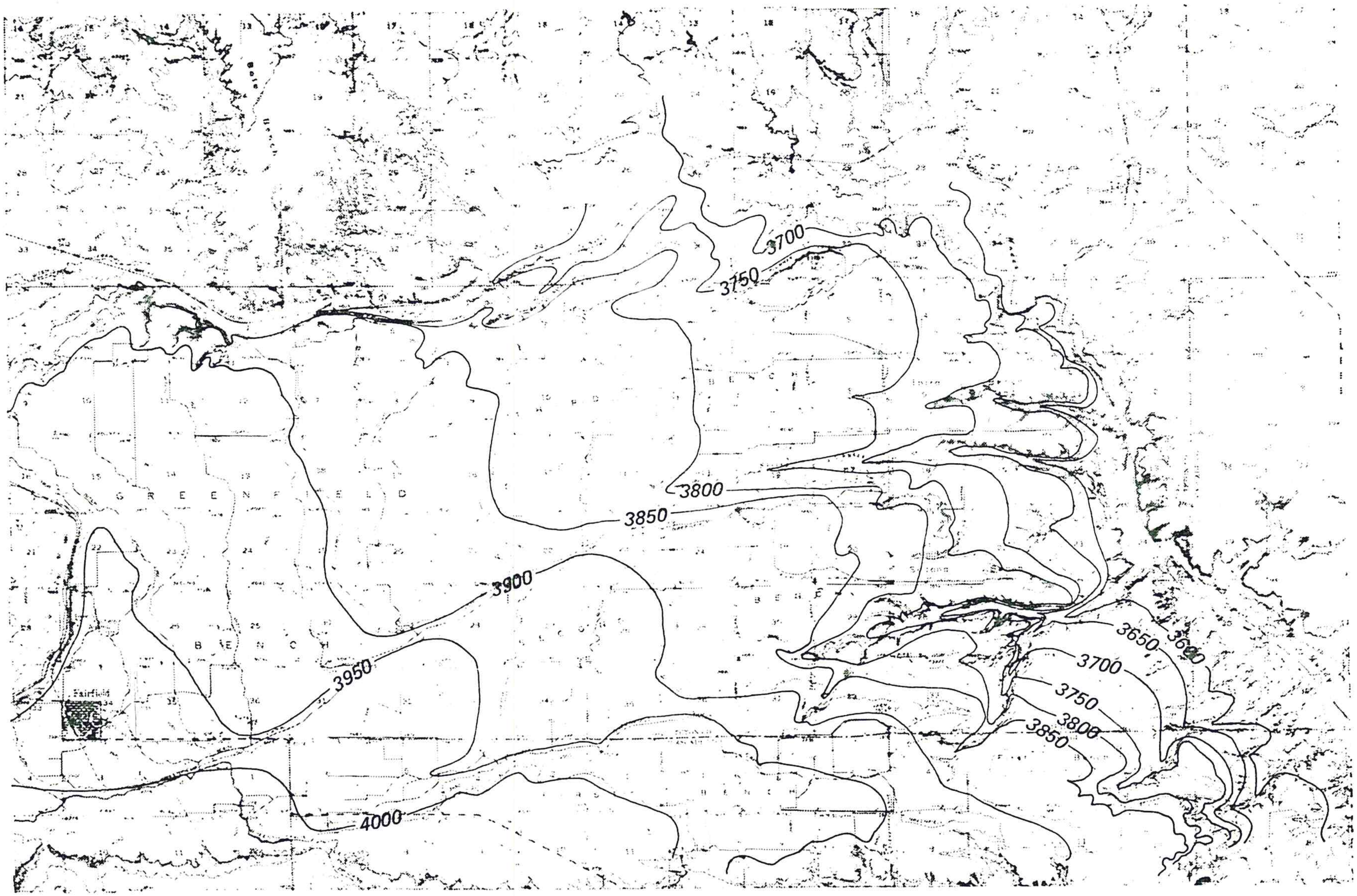


Figure 13 — Water table elevation of gravel aquifer from domestic well data collected June-August,1981. (feet-msl)

and bedrock configuration. Ground-water flows from the higher western end of the terraces to Muddy Creek, and successively from the First and Second Benches to the Third Bench. Near the edges of the Bench, ground-water flow diverges towards the numerous coulees and drains which dissect the gravel aquifer and convey the runoff to Muddy Creek.

Water-table elevations in Figure 13 represent a period of high ground-water levels during the peak of the irrigation season. Domestic well inventories were made occasionally throughout this investigation in an attempt to bracket the overall range of water level fluctuations. Figure 14 presents results of two of the most differing inventories with respect to ground-water levels. The generally lower water levels were measured on May 12-13, 1982[1], while the higher levels were measured during July 7-13, 1983. The May measurements were made just prior to the beginning of the irrigation season.

The largest water-table fluctuations were observed on the western end of the Third Bench, from 5 to 33 ft. The well with the 33 ft. change was an MBMG observation well drilled in early 1983. Previous attempts to measure water levels in this area were hampered by the lack of wells which penetrated the entire thickness of gravel and cobble deposits. Fluctuations of about 10 ft. were observed on the First Bench. The middle and eastern portions of the Second and Third Benches experienced smaller fluctuations; about 2 to 8 ft. One well in the extreme northeast corner of the Bench actually had a higher static water level in May 1982 than in July 1983.

[1]The McInerney well one mile north of Fairfield was measured in April 1983.

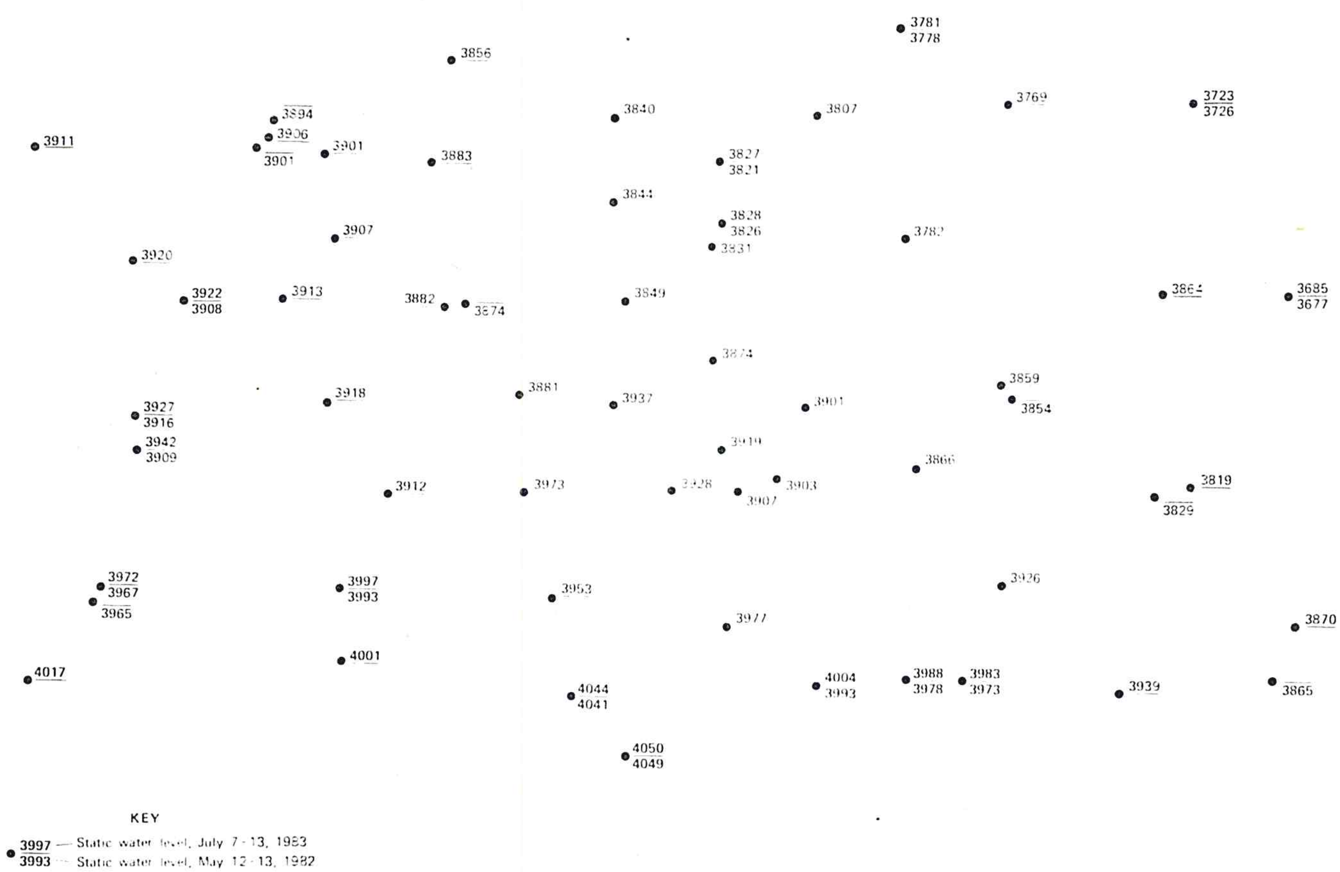


FIGURE 14 RANGE OF WATER TABLE ELEVATIONS MEASURED ON THE GREENFIELD BENCH, 1981-1983.

The data indicate that the water level fluctuates an average of 8 ft. per year (standard deviation = 7.6 ft., n = 17) on the irrigated area of the Bench. Water level declines are greater on the western end of the Bench. Ground-water flow from the western end of the bench helps minimize the declines on the eastern end. Generally, thicker unconsolidated deposits on the western end of the Bench allow for more ground-water storage and has reduced the need for shallow drains. As a result, more ground water moves through the regional flow system without being intercepted by drains. Smaller water-table fluctuations in the middle and eastern end of the Bench are caused by a combination of a thinner aquifer, more drains, and the flow of ground water from the upgradient west end.

Ground-water levels were monitored continuously with recorders at six study fields on the Bench. Ground-water hydrographs of three observation wells for the 1982 water year are shown in Figure 15. Ground-water levels decline throughout the fall, winter and early spring as ground water is released from storage to discharge to drains and coulees. Levels begin to rise in early May in response to the initial turnout of irrigation water into canals and increased precipitation. The sharp peaks are caused primarily by irrigation of the study fields, occasionally augmented by precipitation recharge. The Grossman hydrograph illustrates the effect of early season canal leakage on ground-water levels. The increase of several feet in the water table during May and early June probably results from leakage of the MC-21 canal located about 300 ft. south of the observation well.

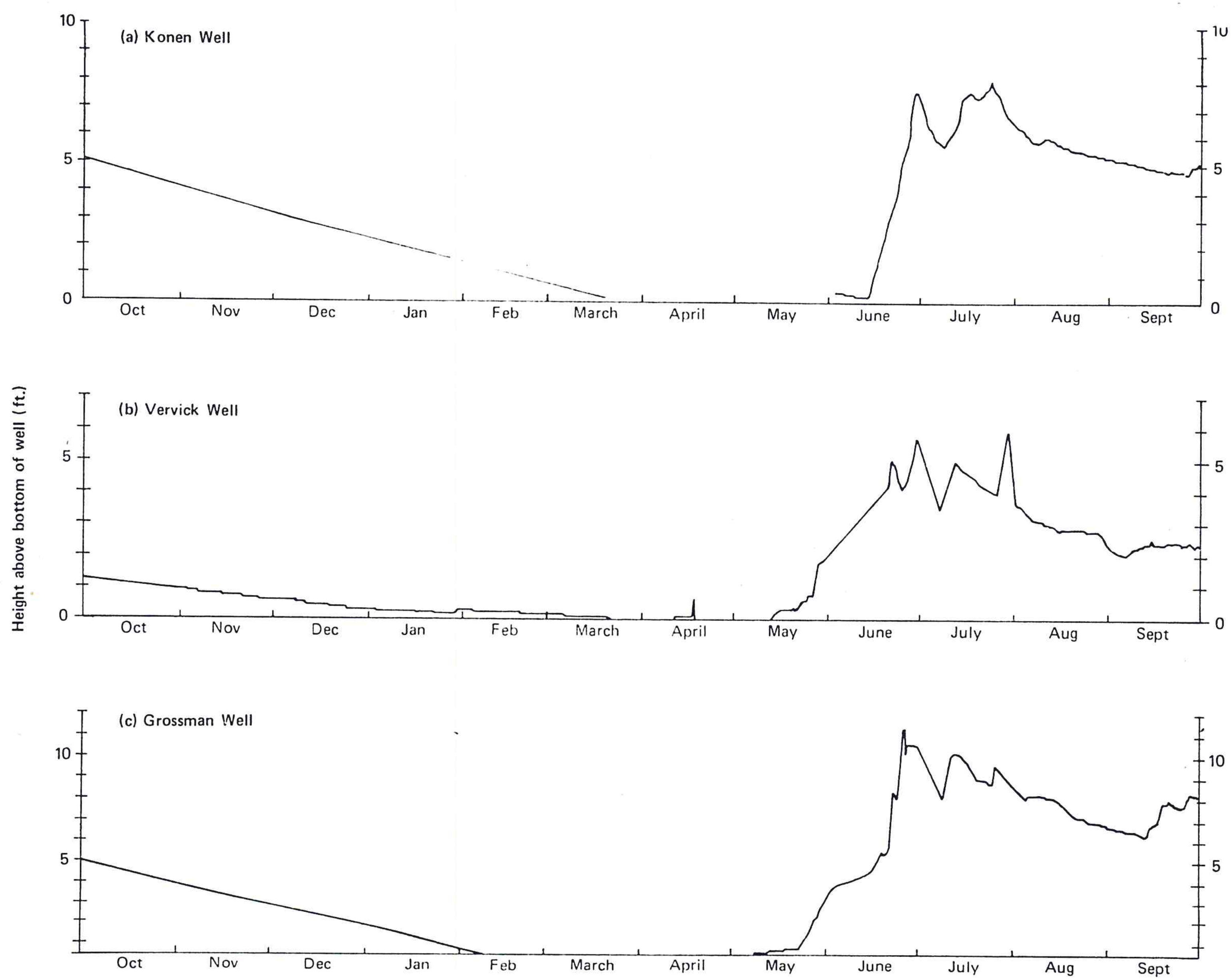


Figure 15 — Ground water hydrographs of three observation wells for water year 1982.

6.1.3 Aquifer Characteristics

Each ground-water aquifer has unique properties relating to the transmission and storage of water within the pore spaces of the aquifer material. Measurement of these properties, principally the transmissivity and storage coefficient or specific yield, allow for quantitative evaluation of ground-water yield and water-level changes. A more general parameter, the hydraulic conductivity, is obtained by dividing the transmissivity by the saturated thickness of the aquifer. The hydraulic conductivity is dependent on the properties of the aquifer and the water within it.

The aquifer properties of the Greenfields Bench gravel deposits were determined with five pumping tests. The pumping test is a standard hydrogeological method of stressing the aquifer through pumping a production well, while simultaneously measuring the decline of water levels in one or more nearby observation wells or in the pumped well. A graph of drawdown versus duration of the pumping test is made and matched with known solution curves from which transmissivity and the storage coefficient can be calculated. A composite plot of the five aquifer tests is shown in Figure 16. A summary of the test results and well locations are given in Table 6.

6.1.3.1 Transmissivities

Large variations in transmissivity and hydraulic conductivity occur on the Bench, exceeding two orders of magnitude (100 times). This indicates that the deposits comprising the aquifer possess a large range in characteristies such as grain size distribution, degree of caliche cementation and clay content.

AQUIFER TEST RESULTS

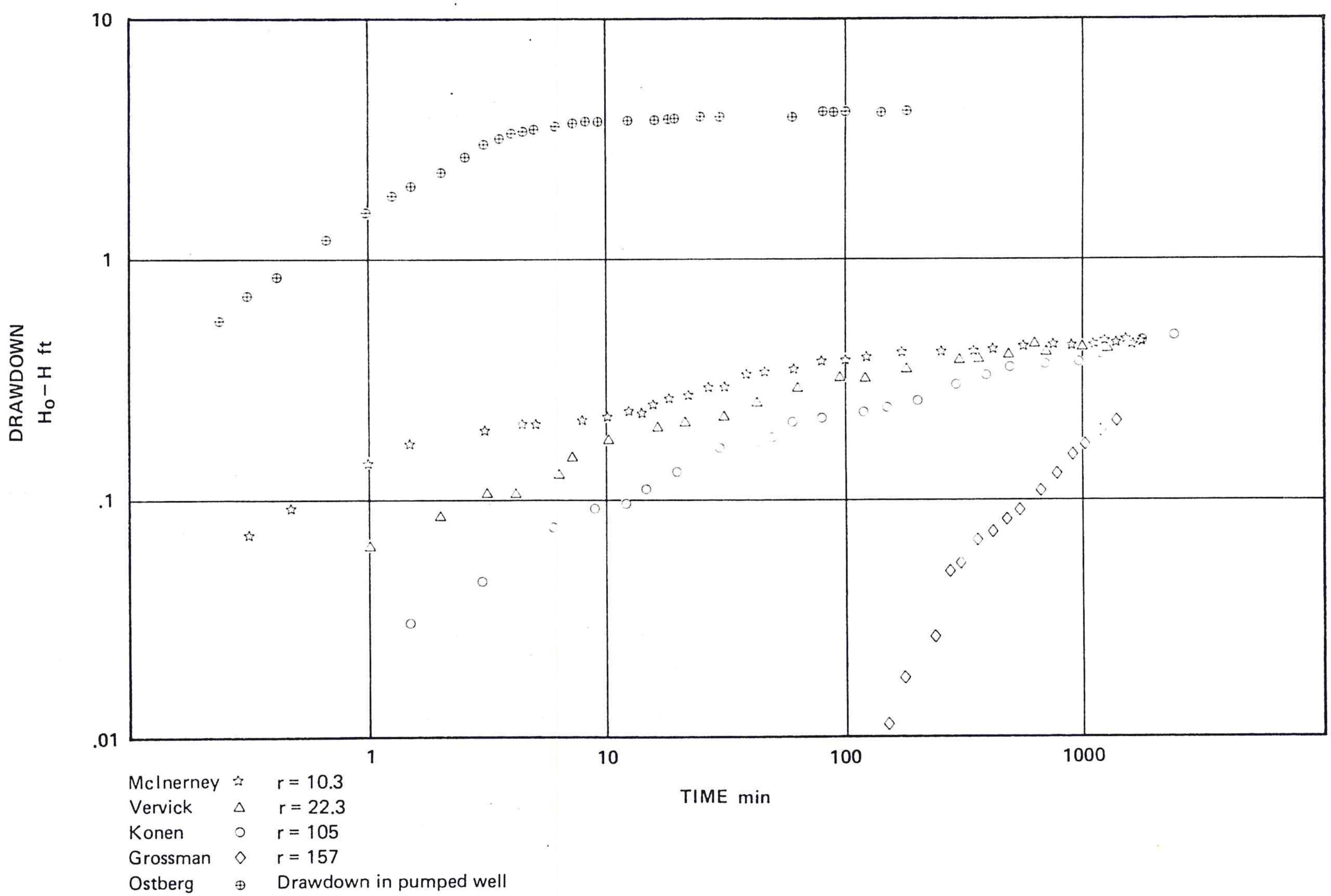


Figure 16 — Time-drawdown curves for aquifer tests.

Table 6. Aquifer test results for the Greenfields Bench.

Site	Location	Date Day Mo Yr	Total t min	Q gpm	r ft	b ft	T ft^2/d	Sy	S	Kr ft/d	Kz/Kr
McInerney	22N3W27ADDD	7/27/83	1700	63.8	10.3	22.0	16,000	0.13	0.03	727	0.048
Konen	22N3W12BDCB	10/19/82	2400	107	105	17.2	22,600	--	.012	1,327	.013
Vervick	22N2W14BBBC	10/27/82	1215	30	22.3	12.2	8,100	--	.017	643	0.11
Grossman	21N2W01DDDB	10/15/82	1295	42.5	157.	15.5	3670	0.11	--	236	0.42
Ostberg	22N2W26CCDB	10/6/82	180	6.	-[2]	10.0	192	--	--	19.	--

1. t = duration of test
   Q = Average pumping rate
   r = Distance between pumped well and observation well
   b = Initial saturated aquifer thickness
   T = Transmissivity
   Sy = Specific yield
   S = Elastic storage coefficient
   Kr = Horizontal hydraulic conductivity
   Kz = Vertical hydraulic conductivity

2. No drawdown occurred in observation well 40 ft. away; drawdown measured in pumped well.

Lithologic logs from the test wells indicate that the uniformity of grain size and thickness of the gravel deposits may be the primary factors giving the highest transmissivity values. The Konen production well produces water from a relatively clean pea-sized gravel bed at 20 to 22 ft. Piezometers were completed in this zone and two higher zones composed of a gravel-clay matrix. Water injections into the piezometers indicated that the 20-22 ft. zone was responsible for most all of the ground-water transmission. This zone was found to be confined by the overlying clay-rich material, and had about 16 ft. of pressure head. The Ostberg location study field profile was dominated by an abundance of caliche and gravels within a clay matrix. The saturated thickness was 10 ft--somewhat less than the other sites. The transmissivity from the pumping test was very low in comparison to the other sites--only 192 ft^2/d. Slug injection tests were attempted on all eight observation wells in the field and indicated similar low permeability.

The McInerney, Vervick and Grossman fields have intermediate transmissivities of 16,000, 8,100 and 3,670 ft^2/d, respectively. The McInerney site had a relatively large saturated thickness and large percentage of coarse gravels and cobbles in the profile. Lithologic profiles of the Vervick and Grossman sites indicate that most of the gravel zones were contained within a sandy-clay matrix or intercolated with clay beds.

6.1.3.2 Storage coefficients

For an unconfined aquifer, as is the case over most of the Greenfields Bench, the ground-water storage term is known as the specific yield. This value is the volume of water released from storage per unit surface area of aquifer per unit decline in the water table.

Storage coefficients for the gravel aquifer were difficult to determine because of the heterogeneity of the deposits, observation well completions and the limitations of the aquifer tests. Two tests, McInerney and Grossman, gave specific yield values in the expected range for unconfined gravel aquifers, 0.13 and 0.11, respectively. The Konen and Vervick tests gave values intermediate between that expected for confined and unconfined aquifers. No storage value could be determined at the Ostberg site since no observation well drawdown occurred. The clay-rich soil and subsoil zone in the upper profile can create confined aquifer conditions in the lower gravel zones. There may be an additional perched un-confined aquifer, such as at the Konen site. The response of an observation well open to the entire saturated profile under these conditions gives a storage coefficient intermediate in value between the specific yield of the unconfined aquifer and the storge coefficient of the confined aquifer (Rushton and Howard, 1982).

The vertical to horizontal conductivity ratio (Kz/Kr) values calculated from the pumping test data suggest that anisotropic conditions (conductivity varies with direction) predominate in the Greenfields Bench aquifer. Three of the four values in Table 6 indicate that vertical hydraulic conductivity is 10 to 100 times less than the horizontal hydraulic conductivity. The relative flatness of the aquifer test curves

(Figure 16) suggests that water derived from gravity drainage of the aquifer affected the water level in the observation wells throughout most of the test periods. In aquifers which are more isotropic, the effects of vertical drainage are completed during the middle stage of an aquifer test.

In an independent analysis of the water balance of the Greenfields Bench, Zaluski and others (1984) calculated an average specific yield of the gravel aquifer within the zone of water-table fluctuation. The reported average specific yield of 0.07 appears reasonable for the type of deposits on the Bench.

The heterogeneity of the unconsolidated deposits on the Bench created complexities in the interpretation of aquifer test results. These could be partially overcome by the installation of piezometers at various depths in place of a single observation well, and re-running aquifer tests. Additional geologic sampling and geophysical logs could also aid in interpretation. The results to date point out the need for site-specific and detailed aquifer testing prior to major ground-water development. Generally, the Greenfields Bench aquifer was found to be a productive ground-water source with an average permeability equivalent to the better sand and gravel aquifers reported in ground-water literature (Todd, 1970).

6.1.4 Ground-water Quality

A water-quality investigation was conducted to make preliminary hydrochemical interpretations and to assist in ground-water flow system analysis. It was a minor portion of the Greenfields Bench study, and further work is required to understand the hydrochemical system in detail.

6.1.4.1 Observed chemical characteristics

A network of domestic and test wells geographically dispersed across the Bench were sampled on three separate occasions to evaluate spatial and seasonal changes of water chemistry within the gravel aquifer. Samples were collected on or about April 28, 1981, September 2, 1981 and May 10, 1982. All samples were analyzed for common dissolved anions and cations. In addition, the April 28, 1981 samples were analyzed for a suite of trace elements. Summary tabulations of the results are listed in Table 7, and Appendix B contains the results of each analysis. Figure 17 shows the location and reference numbers of the sample sites. Results of the analyses were assessed for their chemical equilibrium with various mineral phases by using the computer program WATEQF, of the U.S. Geological Survey (Plummer and others, 1976).

Specific conductance (SC) measurements were taken of 170 ground-water samples during the domestic well inventory of July-August, 1981.

A summary of the water quality data indicates:

1) Ground water on the Bench is primarily a magnesium-bicarbonate type;

2) Ground water usually contains less than 750 mg/l total dissolved solids (TDS);

3) There was little change in chemical composition of ground water between the pre-irrigation sample set in April, 1981 and the post-irrigation samples in September, 1981.

Table 7. Summary of Ground-water Quality Sampling and WATEF Results.

Site No.[a]	Sampling Date Mo Day Yr	Calc. Diss. Solids mg/1	Lab SC umhos/cm 25°C	Ca/Mg[b]	SO_4/Tot.Anions X 10^2	pH	PCO_2[c] bars x10^{-2}	Log IAP/KT[d] calcite	Log IAP/KT[d] dolomite	NO3 (N) mg/1
1	4-1-81	287	550	.45	5.1	7.33	1.16	-.38	-.56	1.2
	9-2-81	329	575	.45	4.3	7.20	1.84	0.35	0.43	2.9
2	4-1-81	509	896	.40	19.9	7.36	1.18	-.28	-.31	3.8
	9-3-81	485	777	.43	12.2	6.95	3.64	-.53	-.77	4.9
3	4-1-81	457	855	.30	9.0	6.94	3.40	-.72	-1.05	6.3
	9-3-81	482	820	.32	7.5	7.18	2.28	-.31	-.22	12.2
4	4-1-81	263	464	1.23	6.1	7.57	.59	.04	-.13	.5
	9-2-81	274	464	1.43	4.2	8.05	.21	.66	1.12	1.0
5	4-2-81	612	1,154	.32	8.1	7.46	1.34	.02	.39	16.0
	9-3-81	365	610	.31	6.8	7.29	1.44	-.42	-.46	4.4
6	4-2-81	2,789	3,963	.22	44.5	7.26	2.18	-.07	.43	17.1
	9-3-81	2,480	3,232	.23	34.2	7.30	2.48	.13	.86	30.6
7	4-2-81	296	565	.26	3.8	7.41	1.02	-.43	-.46	2.6
	9-2-81	285	503	.27	3.7	7.82	3.93	.04	.57	3.6
8	4-2-81	313	593	1.22	9.4	7.03	2.15	-.50	-1.29	.1
	9-2-81	395	674	1.17	10.6	6.88	3.90	-.42	-.99	.12
9	4-2-81	282	548	2.45	4.9	7.22	1.29	-.21	-.98	6.9
	9-2-81	160	296	2.73	9.0	7.05	1.21	-.69	-1.83	.4
10	4-2-81	702	1,170	.36	22.2	7.56	.97	.08	.47	3.6
	9-3-81	812	1,306	.32	21.4	6.75	7.76	-.59	-.76	3.5
11	4-2-81	556	973	.54	7.8	7.13	2.95	-.18	-.27	.9
	9-3-81	534	897	.37	15.5	7.00	3.41	-.47	-.58	1.3

Table 7. (Continued)

Site No.[1]	Sampling Date Mo Day Yr	Calc. Diss. Solids mg/1	Lab SC umhos/cm 25^oC	Ca/Mg[b]	SO_4/Tot.[b] Anions X 10^2	pH	PCO_2[c] bars $x10^{-2}$	Log IAP/KT[d] calcite	Log IAP/KT[d] dolomite	NO3 (N) mg/1
12	4-3-81	433	781	.20	9.6	7.66	.69	-.10	.36	3.3
	9-3-81	413	736	.20	9.2	7.15	2.25	-.64	-.69	4.1
13	4-3-81	735	1,241	.20	14.1	7.52	1.28	-.07	.39	5.7
	9-3-81	602	1,038	.20	11.7	7.35	1.83	-.25	.13	5.6
14	4-3-81	412	778	.27	7.0	7.88	.42	.15	.72	3.4
	9-3-81	430	774	.27	8.1	7.14	2.39	-.52	-.59	5.1
15	4-3-81	365	662	.29	7.1	7.90	.36	.16	.75	3.8
	9-3-81	389	736	.27	6.4	7.85	.41	.12	.68	11.3
16	6-23-81	119	228	2.57	4.6	8.25	.06	-4.52	.06	.03
17	6-24-81	653	1,210	.30	10.1	8.00	.38	.30	.99	23.7
	9-4-81	651	1,171	.30	10.1	7.39	1.63	-.27	-.11	24.9
18	6-24-81	625	1,157	.28	15.0	7.03	2.88	-.65	-.88	21.5
	9-4-81	721	1,222	.26	19.9	7.78	.52	.12	.72	16.0
19	6-23-81	121	230	2.41	5.5	7.90	.07	.24	.12	.05

a. See Figure 17.

b. Mole ratios from analytical molality.

c. Computed partial pressure of carbon dioxide in the ground water.

d. Log of ion activity product divided by the solubility product of the solid species. Positive values indicate supersaturation; negative values indicate undersaturation; zero corresponds to the equilibrium condition.

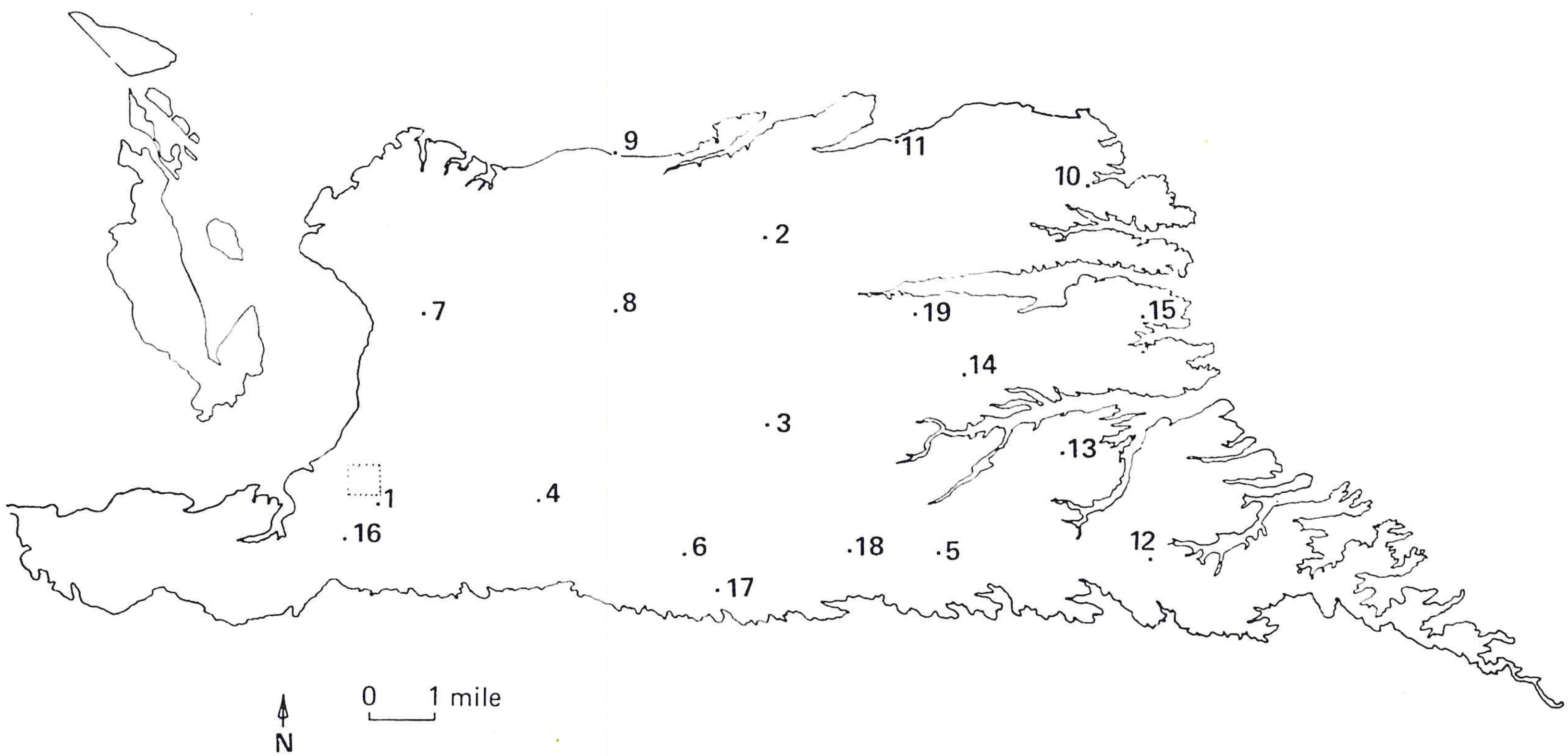


Figure 17 – Water quality sampling sites.

4) Total dissolved solids does not increase in a consistent manner with increasing path length along the ground-water flow system, although the four lowest TDS samples all were taken from the western one-third of the Bench;

5) Areas of high specific conductance occur within the Bench, and the western one-third of the Bench usually had SC values less than 600 umhos @ 25^{o}C;

6) In irrigation water, dissolved calcium concentrations are dominant over magnesium whereas in ground water the opposite is usually true;

7) The sulfate ion increases in concentration along the ground-water flow path, and had the largest molal percent of total anions in a sample collected at the gravel-shale contact;

8) Ground water was slightly under-saturated with respect to calcite, and was less-saturated in the September 1981 sample set;

9) Ground water was under-saturated with respect to dolomite in 60% of the samples, and over-saturated in 40%;

10) A moderately oxidizing environment occurred in October 1981, when a single redox measurement on the Grossman well gave an Eh value of +217 millivolts;

11) Ground water on the un-irrigated portion of the First Bench contained elevated concentrations of sodium, nitrate, selenium and total dissolved solids.

6.1.4.2 Water quality interpretations

The chemical quality of ground water on the irrigated portion of the Bench is generally good, suitable for domestic, stock and irrigation uses. Nitrate, however, was occassionally elevated, with 3 samples on the irrigated area and all samples on the unirrigated area having concentrations greater than 10 mg/l as nitrogen. For irrigation, the ground water ranks as medium to high salinity and low sodium hazard according to the U.S. Department of Agriculture classification.

The chemical composition of ground water was similar among the three sampling periods, and differed to a minor extent geographically over the bench. This suggests that the hydrochemistry is controlled primarily by processes occurring in a similar fashion all over the bench; those being irrigation recharge and reactions in the unsaturated zone. The chemical variations which are evident over the Bench are most likely attributable to variations in the characteristics of the soils and unconsolidated deposits, and differences in well depth and construction.

The western one-third of the Bench had consistently lower SC and TDS values. This area coincides with the upper-most recharge area of the flow system and may reflect the greater aquifer permeability also found here. Three samples in this region, Freeman, Schrock and Cleiv Springs, all had high calcium to magnesium mole ratios compared to other samples. This ratio was also characteristic of the irrigation water sampled from the main canals, and suggests that water quality at these sites is largely influenced by canal leakage water.

The specific conductance measurements made in the domestic well inventory during July and August 1981, indicate that local hydrologic and soils conditions dominate ground-water quality. Thirty-six measurements on the First Bench averaged 603 umhos @ $25^{o}C$ with a standard deviation of 231 umhos. The 50 measurements on the Second Bench averaged 929 umhos @ $25^{o}C$ with a standard deviation of 633 umhos. There were 84 measurements on the Third Bench which averaged 825 umhos @ $25^{o}C$ with a standard deviation of 847 umhos. The data suggest that the Second Bench may have an overall higher clay content, resulting in higher SC values and lower permeability.

Wells on the Second Bench consistently had higher ground-water SC values than the other benches. The Third Bench had both the lowest SC's (on the western end) and the highest (in the central area). Several high

SC areas correspond to areas with high clay content soils as given by soil survey maps (USDA, 1982; and Geiseker, 1937).

An indication of a minor water-quality trend relative to the regional ground-water flow system was provided by sulfate ion concentrations. The percentage of sulfate to total anions expressed in molality was consistently greater progressively down the regional ground-water flow system. It ranged from 5% near Fairfield to 22% on the eastern end of the Third Bench, in the April 1981 sample set. The unirrigated area of the First Bench had consistantly higher sulfate, ranging from 10 to 44%.

Sulfate concentrations were very low in the irrigation water and ranged from 5 to 6% of total anions as molality. The sources of sulfate are believed to be primarily in the Colorado Shale bedrock and weathered shale zone near the gravel deposits. A water sample taken at the gravel-shale contact while drilling the Vervick production well gave 29% sulfate. Dissolution of gypsum and oxidation of pyrite contained in the shale are the two most likely mechanisms for the introduction of dissolved sulfate into the regional ground-water system. In general, however, sulfate concentrations were at or below the recommended drinking water standard of 250 mg/L, and pose no problem for irrigation.

6.1.4.3 Ground-water quality evolution

The water quality samples and WATEQF program results allow some tentative ground-water quality evolution paths to be suggested. The irrigation and canal recharge over the bench introduce oxygen to the soil water and ground-water zones, and the enhanced biological activity in the root zone creates acidic conditions because of CO_2 production by root respiration and organic matter decay. The reaction of CO_2 with water causes decreases in aqueous pH.

The acidic environment during the growing season promotes dissolution of solid phase minerals in the soil and sub-soil, with calcite and dolomite being important minerals on the Bench. Recharge water infiltrating soils containing calcite and dolomite tends to dissolve these minerals until they reach the limit of solubility under the field conditions that exist. The water is then said to be saturated with respect to these minerals. The dissolution of calcite produces Ca^{2+} and CO_3^{2-} ions, and the dissolution of dolomite produces Ca^{2+}, Mg^{2+} and CO_3^{2-} ions.

The WATEQF program computed saturation indicies for calcite and dolomite. Most of the samples indicated that the ground water was slightly under-saturated with respect to calcite. Nine of fifteen samples were less saturated in September, probably because of the generally higher P_{CO2} conditions which allow greater solubility. The canal irrigation water was found to be super-saturated with calcite, because of the low P_{CO2} conditions of surface waters at equilibrium with the atmospheric CO_2. The ground water was supersaturated with dolomite in 7 of the 15 April samples and in 5 of the 15 September samples. In general, the ground water is close to saturation with respect to calcite and dolomite, although seasonal variations exist.

Firm conclusions cannot be made without more data, however, several ground-water evolution pathways may be hypothesized. If it is assumed that calcite and dolomite are well mixed in the terrace deposits, relatively large quantities of both calcite and dolomite may be dissolved in the upper soil zone where high P_{CO2} levels and low pH occur. As the water table declines following recharge events, ambient P_{CO2} decreases, pH rises and CO_2 degasses from the water. The water becomes supersaturated with calcite and dolomite. Calcite precipitates in the subsoil while dolomite does not because of its much slower precipitation rate. The ground water then conuains more dissolved magnesium than calcium.

Other factors could cause a similar outcome, however. Cation exchange of calcium for sodium on clay particles should occur to a greater extent than the exchange of magnesium for sodium, thus disproportionately reducing dissolved calcium concentrations. In addition, marine clays from the Colorado Shale will release Mg and absorb Ca until the water achieves a Ca/Mg ratio of 0.45 or the clay supply is exhausted (Berner, 1971). Most of the water samples approach this ratio as illustrated in Figure 18. The samples with high Ca/Mg ratios indicate ground water dominated by irrigation recharge.

The widespread occurrence of caliche deposits ($CaCO_3$) confirms that calcite precipitation has occurred since the terraces were deposited. Caliche deposits are common in semi-arid environments where soil water saturated with calcite infiltrates a short distance into the soil and then evaporates, leaving behind the mineral deposits. The caliche deposits on the Bench probably formed in this manner. However, it is not known how caliche deposits have been affected by the period since irrigation began. The change to a more humid and acidic environment through irrigated farming would imply that the caliche may tend to be dissolved in the shallow soils, possibly translocated through the ground-water system or re-deposited at a greater depth. Observations during drilling operations confirmed the presence of $CaCO_3$ rich zones at depths greater

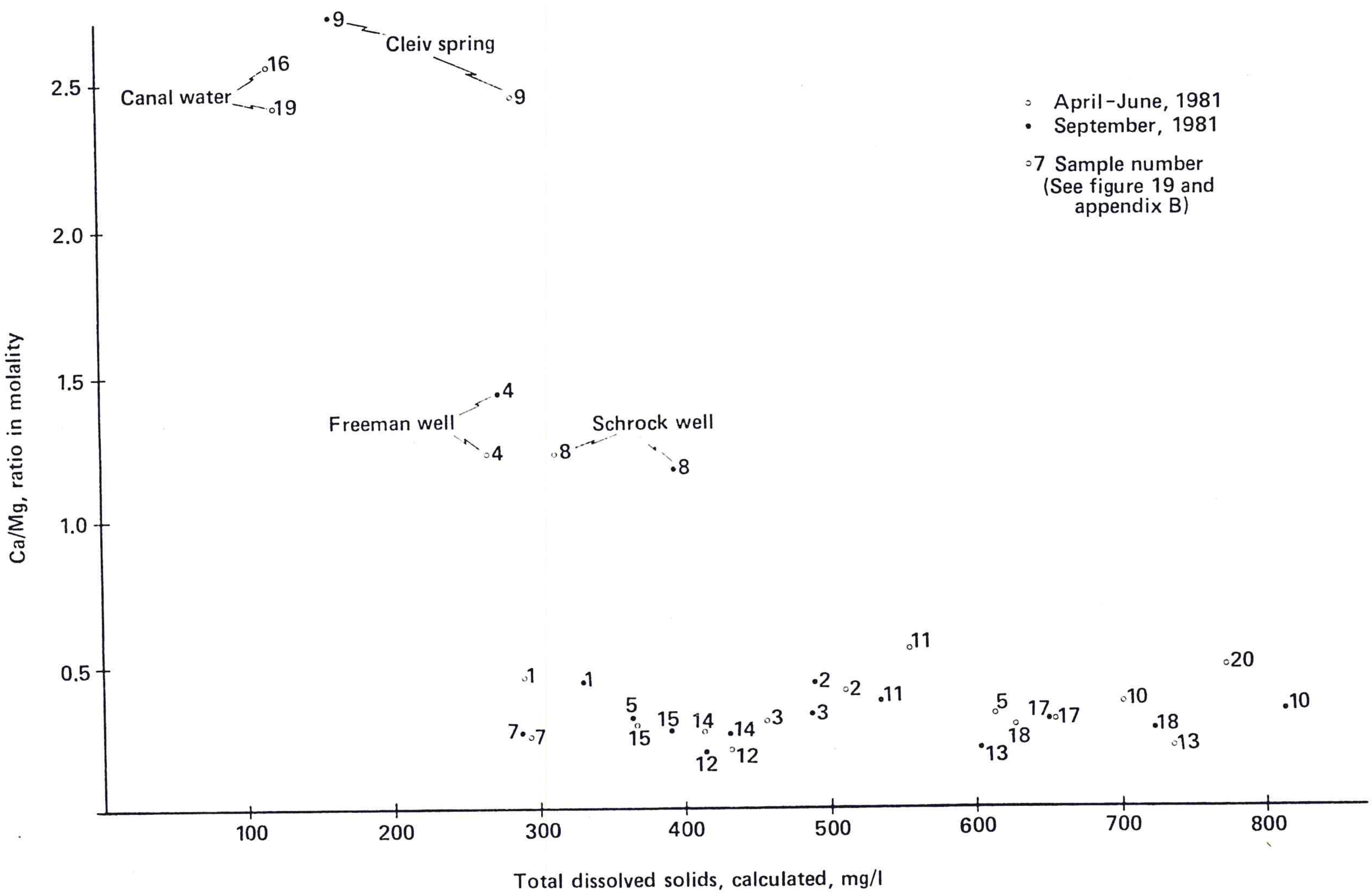


Figure 18 — The Ca/Mg ratio as an indicator of ground water quality evolution.

than that reported for typical caliche deposits.

A rough mass balance of calcium was performed using water quality data from canal samples and Muddy Creek. The input of calcium in irrigation water was calculated using 41 mg/l in a volume of 144,000 af/yr, and the output of calcium in Muddy Creek was taken from a USGS report as 7134 tons per year (USGS, 1982). The calculated outflow was about 12% less than calculated inflow, which is equivalent to an input difference of 4.6 mg/l. The absence of a major difference indicates that a significant flux of Ca out of the system is not occurring now. This further suggests that most calcareous material is being translocated and redeposited. More specific water quality and mineralogical sampling would be required to develop a thorough understanding of ground-water quality evolution on the Bench.

6.2 Surface Water

Surface water runoff from the Greenfields Bench occurs in drainways and coulees that eventually discharge to Muddy Creek or Freezeout Lake. The Asheulot Drop structure conveys irrigation water as an output from the Greenfields Bench although it is not actually runoff.

The measurement of the discharge in drains was undertaken as a way to quantify the total water runoff from the Bench. The flow of the drains and of Muddy Creek is composed of groundwater discharge to the drains plus direct surface water runoff from canal wasteage, surface irrigation runoff and precipitation-induced surface runoff. This section (section 6) presents the total runoff in drains and in Muddy Creek. Section 7, on runoff and recharge sources, delineates the amount of runoff due to surface water and ground-water sources.

6.2.1 Drain Discharge

Discharge in 11 small drains was measured continuously by the MBMG at locations (see Figure 2) from May 1981 through September, 1983. The USGS measured the flow of Tank Coulee and Spring Coulee from October 1981 through September 1983. The Greenfields Irrigation District has measured the discharge in Spring Coulee at J-Wasteway approximately 6 mi. above its mouth for many years, although the station was inoperable in 1982. Montana DPARTMENT OF Fish, Wildlife and Parks, and Water Quality Bureau personnel measured drain discharge into Freezeout Lake from the western end of the Bench on an intermittent basis.

Individual drains along the northern edge of the Bench were not monitored. The collective runoff from the northern edge was measured by the USGS at a new gaging station on Muddy Creek near Power (MCP). There were no significant drains discharging from the southern edge of the Bench, although numerous springs and seeps are evident. The discharge occurs primarily as seepage to the lower terrain around the Bench and as evapotranspiration. This runoff was not quantified, and although it may collectively amount to a significant discharge, it was judged to be within the measurement error of the other data.

Drain discharge values are shown in Appendix A as daily and monthly averages. A composite semi-logarithmic graph of mean monthly drain discharges for water year 1982 is shown in Figure 19. The annual low flow is generally in February-March, with a number of the small drains having no flow for one or more months. Early spring snowmelt causes some

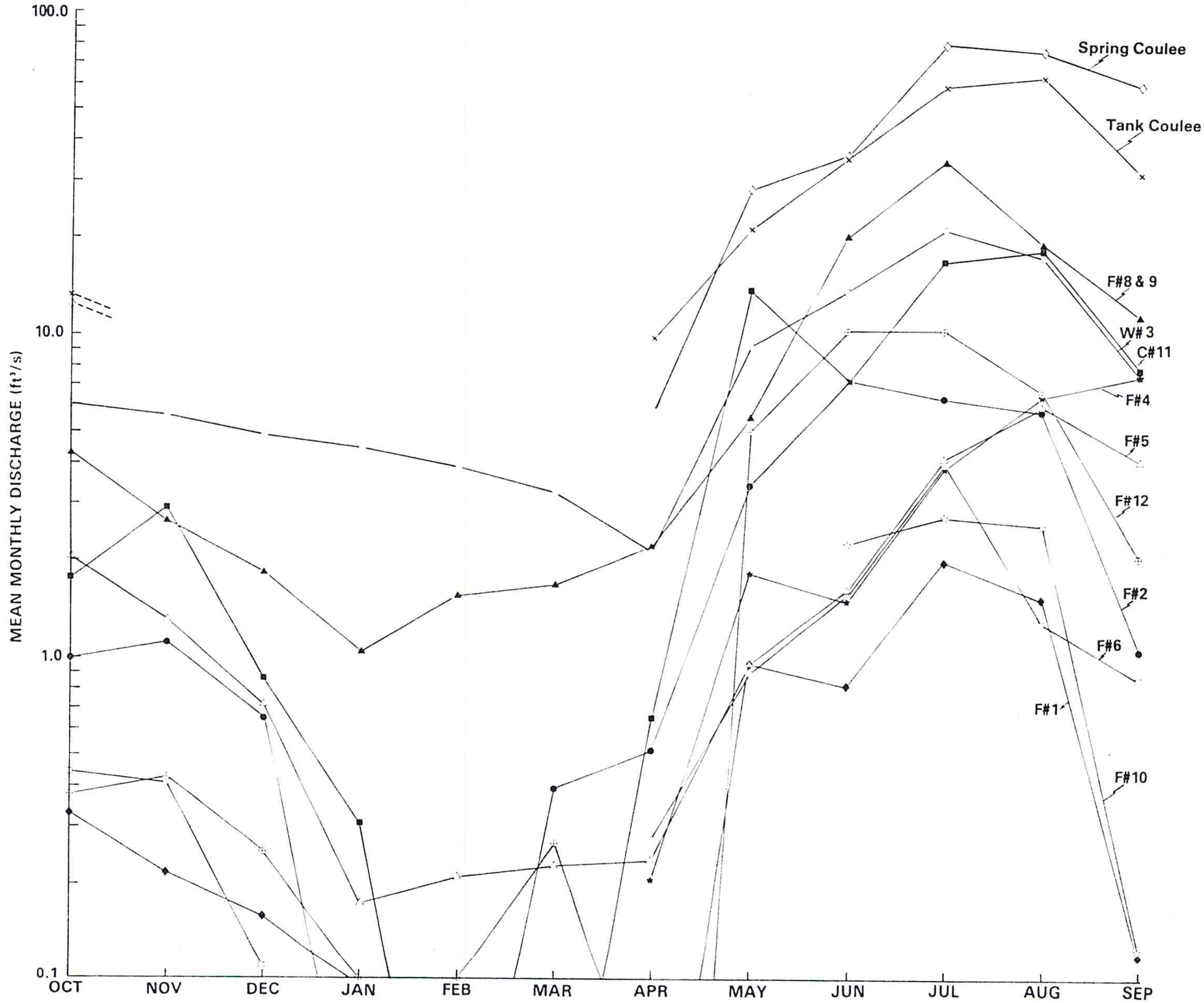


Figure 19 — Mean monthly discharge of drains on the Greenfield Bench in water year 1982.

sporadic flow increases, but the large jump in discharge occurs in mid-May when irrigation water is turned onto the Bench. The average monthly peak flow was reached by 2 drains in June, by 6 drains in July, by 3 drains in August and by 1 in September. August flows in the larger drains tended to be greater than June flows, which reflects the increased ground-water storage and lag time associated with the bigger drain area. Flow patterns of the smaller drains were more erratic for a number of reasons. Some small drains provide irrigation water for farmers on the edge of the Bench, and were diverted above the gaging station. Small drains are affected to a greater relative extent by the specific irrigation water deliveries to a small number of farms in the drainage area.

From September through mid-winter the discharge of most drains declines steadily and is composed primarily of ground-water baseflow. The slope of the baseflow period line indicates the ground-water storage capacity of the drain area. The graph of the small drains decline steeply whereas the graph of the larger drains have a gentler slope.

There are three main drains and at least three other small drains discharging to Freezeout Lake from the Greenfields Bench. MBMG stations #12 and #13 monitored two of these. Others were monitored on an intermittent basis by the Montana Water Quality Bureau (Brown, 1983). Total annual flows were estimated for each drain; the sum of which was 6,700 af.

6.2.2 Discharge in Muddy Creek

The three USGS gaging stations on Muddy Creek which operated during the 1982 and 1983 water years give an excellent profile of the cummulative runoff from the Bench. Table 8 gives the total discharge in acre-feet of all drains monitored by MBMG and USGS in water year 1982 in comparison to the stations on Muddy Creek.

The sum of the discharge of all stations above the USGS gage near Vaughn (MCV at Gordon) come to 5.3% less than the total discharge independently measured at the Gordon gage on Muddy Creek. The difference is due partially to small unmeasured drains from the Bench, partially to ungaged storm runoff from the dry-land area and partially due to measurement errors and winter period estimation techniques for the Spring Coulee, Tank Coulee and Muddy Creek at Power sites. The 14.2% difference between the additional drains south of Gordon and the Muddy Creek at Vaughn station is primarily the result of irrigation canal inflows from the Sun River Valley Ditch.

The individual station discharges and the cummulative discharge of Muddy Creek for water year 1982 is shown graphically in Figure 20.

The runoff from a portion of the dryland area contributing to Muddy Creek was gaged at the Cordova railroad grade crossing. Current meter measurements and a continuous recorder were employed to obtain the rating curve and annual discharge. In water year 1982, the total discharge was 1004 af. The drainage area at the gage is about 48.1 mi^2 or 30,770 ac. Runoff yield from the basin was 0.0326 ft/yr, or about 0.392 in/yr. This represents 3.7% of the total precipitation at Power in water year 1982. In water year 1983, the total discharge of Muddy Creek at Cordova was about 400 af, giving a runoff yield of about 0.013 ft/yr, or 0.16 in/yr.

A large additional dryland area is tributary to Muddy Creek between Cordova and the USGS gaging station near Vaughn (Gordon). The total

Table 8. Discharge at Drains and Muddy Creek in Downstream Order, Water Year 1982

MBMG STATION	USGS STATION[1]	TOTAL DISCHARGE Af	SUBTOTAL Af	% DIFFERENCE
	MCP	31,534[2]		
11		4,116		
10		225		
8 & 9		5,792		
	SC	20,278[2]		
	TC	16,572[2]		
6		606		
5		1,334		
4		1,328		
			81,785	
	MCnV	86,340		5.3
3		6,158		
2		1,758		
1		392		
			90,063	
	MC@V	110,300		14.2

[1] MCP = Muddy Creek near Power

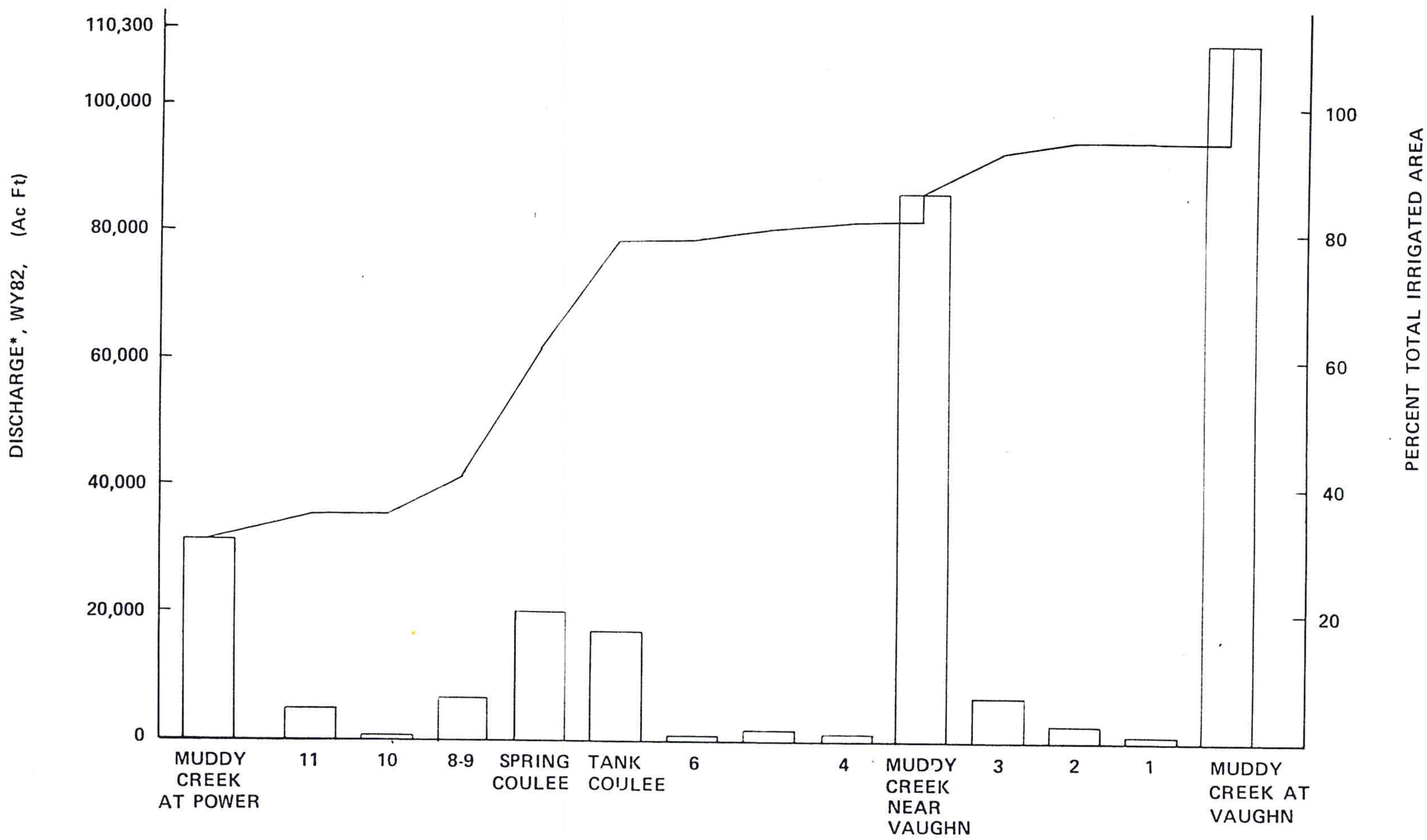
SC = Spring Coulee

TC = Tank Coulee

MCnV = Muddy Creek near Vaughn (Gordon)

MC@V = Muddy Creek at Vaughn

[2] Flows were estimated for Nov-Mar period.



* Discharge estimated for some stations in some months.

Figure 20 — Individual and cumulative drain discharge to Muddy Creek, water year 1982.

dryland drainage area is about 96 mi^2 or 61540 ac. The total estimated dryland runoff at the Gordon station in water year 1982 was about 2006 af based on extrapolation of the Cordova station data. In water year 1983 the total estimated dryland runoff would be 800 af.

At the USGS gaging station at Vaughn, another 20.8 mi^2 or 13,307 ac of dryland area is tributary to Muddy Creek, bringing the total dryland drainage area to about 74,850 ac. The estimated 1982 and 1983 water year dryland runoff is 2440 af and 970 af respectively.

A second estimate of the mean annual runoff at the Cordova station was made with a channel geometry method presented by Omang and others (1983). The multiple regression equation was developed for ephemeral streams in southeastern Montana and is not strictly applicable to Muddy Creek. However, the geology and climate of the report area north of the Yellowstone River is similar to that of Muddy Creek. The method requires only field measurements of the bankfull channel width. The average bankfull width of Muddy Creek near Cordova was found to be about 24 ft. The corresponding regression equation from Omang and others, gives a mean annual flow of 3,060 af. Extrapolation of this yield over the entire dryland drainage area of Muddy Creek gives an annual dryland runoff contribution of about 7,440 af. This is equivalent to 6.7% of the total flow at Muddy Creek at Vaughn in water year 1982.

Based on the above determination, it is estimated that the dryland drainage area of Muddy Creek contributes between 2,000 to 7,500 af per year. Although this runoff amounts to only 2 to 9% of the total annual flow of Muddy Creek, it is concentrated in a brief peak and often coincides with the peak irrigation season.

For example, the June 29, 1982 storm event produced peak average daily discharge values of 307 ft^3/s at Cordova, 372 ft^3/s at Power, 679 ft^3/s at Gordon and 839 ft^3/s at Vaughn. The dryland runoff might constitute from 10 to 50% of peak runoff flows in Muddy Creek due to these regional storms. The dryland runoff undoubtably aggravates the erosion problem in the Muddy Creek channel. The Muddy Creek channel above Cordova and those of other larger dryland tributaries, however, appear quite stable, well vegetated and are not undergoing accelerated erosion. The initiation and primary continuing cause of erosion in the Muddy Creek channel is the large volume of irrigation return flows from the Greenfields Bench.

6.2.3 Drainage Area vs. Discharge

Comparisons of the discharge versus the drainage area are often useful in determining locations which contribute excessive runoff. On the Bench, such area could be targeted for further investigation and irrigation improvements. However, the interactions of surface watfr and ground-water during the irrigation season present complications. The drains function to rapidly de-water only the upper portion of the aquifer throughout the interior of the Bench. As the drains and coulees approach the edges of the Bench, they intersect the entire aquifer thickness and drain the regional flow system as well. Hence, portions of a given ground-water recharge volume may eventually discharge to different drains depending upon the water-table elevation in relation to the local drains. In addition, surface water runoff from canal or farm wasteage may discharge to a drain other than the local one because of the network of canals available to re-route the water.

Despite this, the topographic drainage area which is irrigated is probably the most useful boundary to assign to the drains because of the general conformity among the bedrock, topographic and water table configurations. The construction of the topographic divides is somewhat arbitrary in the interior and western end of the Bench because of the lack of definitive relief.

Drainage areas were calculated using a Calcomp 9000 digitizer on a 1:62500 scale map. The gross irrigated area of the Greenfields Bench was 58,165 ac. Approximately 2,090 ac drain to Freezeout Lake and 1,751 ac drain off the south end of the Bench, leaving 54,324 ac as the gross irrigated area draining to Muddy Creek. About 10% of this is not actually irrigated because of use for roads, spoil banks, farm yards and buildings. The USGS gaging station at Muddy Creek near Vaughn (Gordon) receives the discharge from all but Flume #1 and Weirs #2 and #3, a total of 2,312 ac. With this addition, the gross irrigated drainage area of the Muddy Creek near Vaughn station is 52,012 ac.

The irrigated area and runoff volumes for the Muddy Creek station are compared with those of each individually monitored drain in Table 9. Four different time periods are shown to compare the high runoff periods (June-August 1981 and June-August 1982), the baseflow period (September 1981-April 1982), and the total annual runoff for water year 1982.

The MCV station integrates the runoff from most of the Bench, and for water year 1982, 1.66 af/ac or 0.14 af/ac/mo was the average runoff. The MCV and MCP stations include runoff from the large range and dryland farm area north and east of the Greenfields Bench and a very small amount of un-gaged irrigation runoff. The percent differences shown at the bottom of Table 9 indicate the resultant magnitude of these components, plus measurement error.

It can be seen that the smaller drains have a large rate of runoff in the growing season. This is primarily attributable to the wasteage of surface canal water into these drains at the ends of the Bench.

Irrigation season runoff is 2 to 10 times greater per unit area than during the baseflow period indicating that surface water runoff and transient ground-water runoff occur rapidly and are a major component of the total runoff. Spring Coulee has a substantially greater runoff rate than Tank Coulee, because it is a major waste water drain for the Greenfields main canal.

Table 9. Drain Runoff and Irrigated Areas on the Greenfields Bench

Station[1] (Fig. 2)	Irrigated Area (Ac)	Jun-Aug, 1981 Af	Jun-Aug, 1981 Af/Ac	Sept 81 - Apr 82 Af	Sept 81 - Apr 82 Af/Ac	Jun-Aug, 1982 Af	Jun-Aug, 1982 Af/Ac	Water Year 1982 Af	Water Year 1982 Af/Ac
1	85	251	2.95	131	1.54	268	3.15	392	4.61
2	343	2,796	8.15	600	1.75	1,254	3.66	1,758	5.13
3	1,884	3,250	1.72	2,458	1.30	3,277	1.74	6,158	3.27
4	437	750	1.72	70	.16	733	1.68	1,328	3.04
5	280	913	3.26	511	1.82	730	2.61	1,334	4.76
6	191	472	2.47	138	.72	421	2.20	606[2]	3.17
TC	15,228	--	--	--	--	9,830	0.64	16,572[2]	1.09
SC	11,773	--	--	--	--	11,910[2]	1.01	20,248[2]	1.72
8 & 9	3,980	6,577	1.65	1,466	.37	3,917[2]	.98	5,792[2]	1.46
10	91	465	5.1	24	.26	199	2.19	225	2.47
11	1,085	1,395	1.29	945	.87	2,286	2.11	4,116[2]	3.79
MCP	18,837	--	--	--	--	16,140	.86	31,534[2]	1.67
DIV[3]						1,000		3,000	
MCV	52,012	45,570	.88	25,840	.50	47,210	.91	86,340	1.66
stations: 4, 5, 6, TC, SC, 8 & 9, 10, 11 and MCP						47,166		81,755	
% difference:						<1		5.3	

1 TC = Tank Coulee, SC = Spring Coulee, MCP = Muddy Creek at Power, MCV = Muddy Creek near Vaughn.
2 Extended periods of records were interpolated due to lack of continuous data.
3 DIV = Diversions by U.S. Fish and Wildlife Service between Power and Gordon, 1000af in August, 2000af in September.

The 1981 and 1982 irrigation seasons produced quite similar runoff despite the fact that they were dissimilar in terms of weather conditions. 1981 was hotter, and about 10,000 af less was diverted onto the Bench than in 1982. However, there was 4.15 in. more precipitation at Fairfield during May-August of 1981 than in 1982.

The drains on the west end of the Bench discharging to Freezeout Lake were estimated to yield a total of 6700 af/yr (Brown, 1983). A combination of periodic drainflow measurements and crest-stage gages was utilized to obtain the estimate. This discharge amounts to 3.2 af/ac, over the estimated 2,090 ac drainage area.

The characteristic of some drain areas to produce excessive runoff is illustrated in Figure 21, which compares the cumulative percent irrigated area and the cumulative percent of total drain discharge from the Greenfields Bench. Generally, discharge volume correllates with irrigated drainage area. However, drains for which the graph of the percent-discharge line has a greater slope than the corresponding percent-area line are ones with above average discharge per unit area. Accordingly, drain areas #11, Spring Coulee, #5 and #3, #2 and #1 are ones which could be prioritized for irrigation water management control.

6.2.4 Drain Discharge Response to Precipitation

The response of 3 drains to precipitation as recorded at Fairfield during summer, 1982 is shown in Figure 22. Three rainfall events of a regional nature can be contrasted. Average rainfall values were obtained from the Fairfield, Sun River and Power NOAA stations. The May storms resulted in an average of 2.23 in of rain over the Bench. The drains

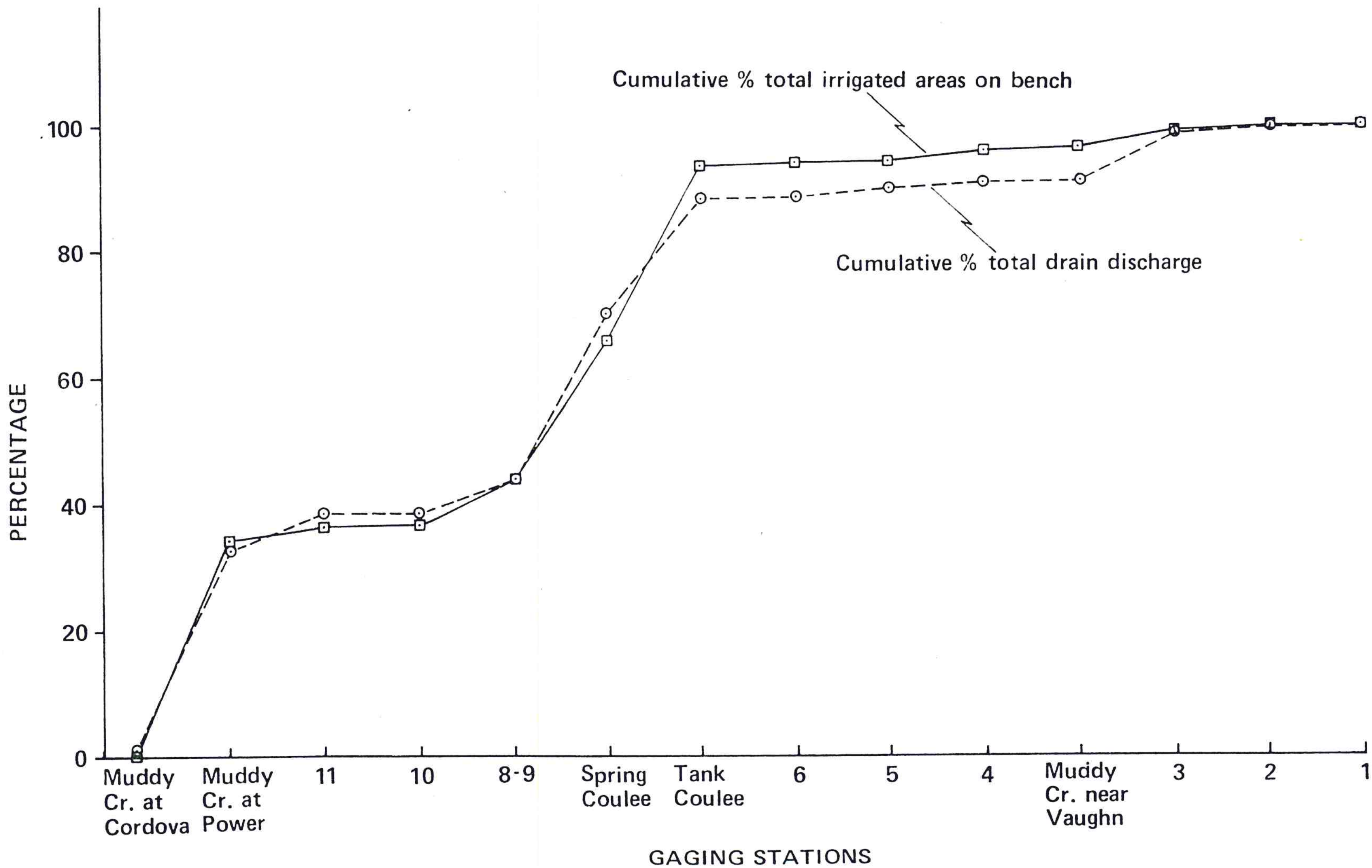


Figure 21 — Cumulative irrigated area versus cumulative drain discharge in percentages for water year 1982.

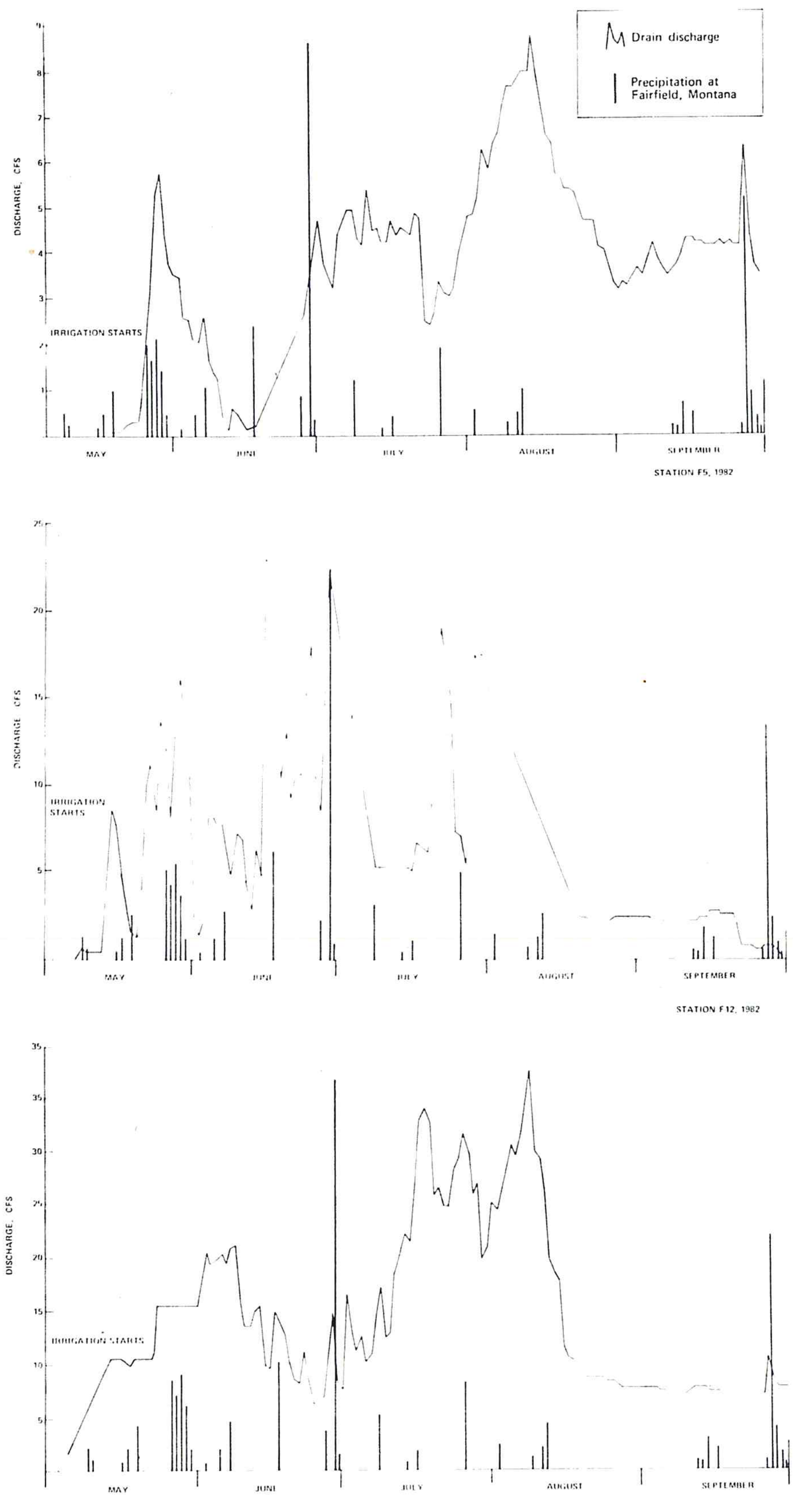


Figure 22. — Drain discharge response to precipitation.

show large runoff peaks associated with the storm. The storm of June 28-30 gave an average of 1.4 in. of rain over the Bench, resulting in sharp, but brief, runoff peaks. The storm of September 26-28 occurred after the irrigation season and produced an average of 1.8 in. of rain, but gave only very small runoff peaks in the drains.

The smaller drain response to the September event is the result of the lack of excess irrigation water on the Bench and drier antecedant soil conditions following the irrigation season.

The total runoff volume for the June and September storms was estimated for the portion of the Muddy Creek basin between the USGS gaging stations at Power and near Vaughn (Gordon). The June storm produced about 1,160 af of runoff whereas the September storm produced about 420 af. The June storm produced nearly three times more runoff with lower average precipitation. Although differences in rainfall intensity could be a factor, much of the additional runoff in June is from wasted irrigation water.

The hydrographs of Figure 22 also indicate numerous other peaks not related to precipitation events. These are probably surplus irrigation water discharge.

6.2.5 Surface Water Quality

Surface water quality in the drains and in Muddy Creek reflects a mixture of fresh irrigation water and precipitation runoff and more mineralized ground-water baseflow. Water samples were collected for chemical analyses from 4 drains in May, 1982 (Appendix B). The USGS collected chemical water quality samples 9 times per year at their gaging stations on Muddy Creek near Vaughn (Gordon) and at Vaughn through water year 1982. In addition, they collected continuous SC and daily suspended sediment data at these two stations.

6.2.5.1 Specific conductance data

The variability of chemical water quality in the drains is illustrated in Table 10, which gives SC values for drain discharges taken on an intermittent basis in 1981 and 1982. The low SC values reflect the large component of canal wastewater and transient ground-water flow that occurs in the mid-irrigation season. The high values occur in mid-winter and early spring when flows are low and the ground-water baseflow component predominates.

The daily SC data for Muddy Creek at the USGS gaging station near Vaughn (Gordon) demonstrate trends similar to the small drains. In water year 1981, the lowest monthly average SC was 608 umhos/cm @ 25°C in August, and the highest average monthly SC was 1710 unhos/cm in April. In water year 1982 the lowest monthly average SC was 560 umhos/cm in August, whereas the highest monthly average SC was 1990 umhos/cm in March.

The monthly SC trend of the drains, and to some extent, daily fluctuations in SC during the irrigation season reflect the relative magnitude of surface water and ground-water contributions to Muddy Creek from the Bench. Low SC values are often associated with increased surface water runoff. Large runoff events, however, produced quite high SC values in Muddy Creek despite of the greater magnitude of surface water input. For example, on June 28, 1982 the mean daily flow of Muddy Creek near Vaughn (Gordon) was 275 ft^3/s and the SC was 928 umhos/cm. The storm runoff on June 29 gave an average daily flow of 679 ft^3/s and the SC was 2720 umhos/cm. This increase in SC probably results from dissolution of salts associated with the increased suspended sediment load and the saturation of fresh bank material at higher stream stage.

Table 10. Specific Conductance Values of Drains on the Greenfields Bench

	Low		High		All measurements		
Station (Figure 2)	umhos/cm @ 25°C	Date mo day yr	umhos/cm @ 25°c	Date mo day yr	$\bar{x}$	SD	n[1]
1	670	8-24-81	2261	3-22-82	1218	552	8
2	312	7-8-82	2638	3-22-82	1224	947	10
3	608	8-24-82	1390	4-13-82	954	311	10
4	435	6-24-81	1615	4-13-82	859	382	9
5	631	6-24-81	1702	4-13-82	973	382	10
6	468	6-24-81	1552	2-3-82	729	327	9
8 & 9	559	6-24-81	1248	1-7-82	869	248	12
10	424	8-19-81	1417	4-13-82	715	378	6
11	433	8-10-82	1371	10-30-81	886	381	9
12	300	8-6-81	1123	1-6-82	646	329	10
13	459	8-21-81	846	12-2-81	703	158	6

[1] $\bar{x}$ = Mean
SD = Standard deviation (n-1)
n = number of measurements

6.2.5.2 Chemical quality of water in drains

Water samples for dissolved chemical constituents were taken at four drains on May 13, 1982. Complete analyses are contained in Appendix B.

The general water chemistry reflects the relative mixtures of surface water and ground-water runoff. Samples at Flume #5 and Tank Coulee were a calcium, magnesium-sulfate type, indicating that at the time of collection, they were dominated by ground-water baseflow. Discharge was relatively low for both sites. Samples at Spring Coulee and Weir #3 were a calcium-bicarbonate type, indicating that at the time of sampling they were dominated by surface water runoff. Inspection of drain hydrographs indicated that these sites were affected by the runoff from the initial canal flushing at the start of the investigation season.

The ten water samples of Muddy Creek near Vaughn (Gordon) collected by the USGS in water year 1982 indicated a similar trend. The ratio of calcium to magnesium is higher during the high flow period of May through September and lower in the baseflow winter months. Sodium, sulfate and total dissolved solids concentrations also demonstrate some degree of inverse correspondence with magnitude of discharge.

Although Muddy Creek is well known for its high suspended sediment load, it also carries a relatively high dissolved solids load. Differences in the location of instream accumulation of sediment and dissolved solids loads between Gordon and Vaughn reflect the origin of these constituents. In water year 1982, the Gordon station measured 72,940 tons of dissolved solids, and 63,059 tons of suspended sediment, compared to 87,470 tons and 187,754 tons, respectively, at Vaughn. This represents a 17% increase in dissolved solids, as compared to an almost 300%

increase in suspended sediment. This indicates that most dissolved solids originate from the drains above Gordon while most suspended sediment is derived from the lower reaches of Muddy Creek between Gordon and Vaughn.

6.2.5.3 Suspended sediment

Suspended sediment samples of the drains were not collected, but they were observed to be relatively low in turbidity and suspended material. Bed load movement, however, appeared quite high in some drains, with most fragments probably derived from shale and sandstone outcrops on the edges of the Bench. Suspended sediment data for Muddy Creek was collected by the USGS from 1968 through 1982. Detailed investigations of the suspended sediment data for Muddy Creek was not an objective of this investigation, and only some general comparisons of the data were made.

The most significant observation of the data over the past ten water years was the strong relationship of peak flows in Muddy Creek to high suspended loads. Table 11 shows mean and annual peak streamflows and suspended sediment discharges for water years 1982-73. If the daily discharge peak and sediment load peak differed, the daily sediment peak was utilized in the table. The data show that at the Gordon and Vaughn stations, an average of 18.5% and 14.7%, respectively, of the total annual suspended sediment load was transported in the peak day of each year. Years with a single large peak flow tended to have a higher one-day load percentage than those with multiple peaks or years without a large peak. In most years, over 50% of the entire annual suspended sediment load is transported during the small number of days with high flows.

Table 11 Streamflow and Suspended Sediment Discharge in Muddy Creek[1]

Muddy Creek near Vaughn (Gordon)

Water Year	TOTAL DISCHARGE Water af	TOTAL DISCHARGE Sus. Sed. tons	1-DAY PEAK DISCHARGE Date	Water ft^3/s	% Annual Flow	Sus. Sed. tons/d	% Ann. Load
82	86,340	63,059	6-29	679	1.6	10,800	17.1
81	84,250	121,733	5-22	1,540	3.6	63,900	52
80	66,360	63,399	5-26	810	2.4	26,100	41
79	92,510	64,205	3-7	1,100	2.3	9,740	15.2
78	92,440	187,782	3-20	1,370	2.9	35,800	19.1
77	60,900	26,127	7-14	418	1.4	1,550	5.9
76	90,760	53,474	6-7	336	.7	2,790	5.2
75	108,100	250,575	5-7	2,250	4.1	48,000	19.2
74	76,280	37,524	8-9	682	1.8	2,320	6.2
73	68,640	32,834	6-20	325	.9	1,440	4.4
Mean	82,658	90,071					18.5

Muddy Creek at Vaughn

Water Year	TOTAL DISCHARGE Water af	TOTAL DISCHARGE Sus. Sed. tons	1-DAY PEAK DISCHARGE Date	Water ft^3/s	% Annual Flow	Sus. Sed. tons/d	% Ann. Load
82	110,300	187,754	6-30	839	1.5	15,800	8.4
81	107,700	330,835	5-22	1,740	3.2	127,000	38.4
80	90,910	139,149	5-26	1,080	2.4	41,900	30.1
79	119,700	197,299	3-7	1,200	2.0	17,500	8.9
78	117,000	377,531	3-20	1,510	2.6	58,300	15.4
77	78,770	69,851	7-14	506	1.3	3,110	4.5
76	114,400	57,679	6-9	490	.8	8,230	14.3
75	134,200	625,392	5-7	2,540	3.7	109,000	17.4
74	98,680	122,285	8-9	730	1.5	7,060	5.8
73	87,360	96,215	7-4	320	.7	3,590	3.7
Mean	105,902	220,399					14.7

[1] Data Source: USGS Water Resources Data for Montana, 1973-1982.

Individual summer months without major runoff peaks typically account for 5 to 30% of the total annual load. Winter months without runoff events usually account for less than 1% of the annual sediment load.

Water years 1981 and 1982 at the USGS station near Vaughn (Gordon) provide a sharp contrast in the mechanism of sediment transport. Water year 1981 had a slightly lower total annual discharge, but the peak flow was over two times greater than in 1982. The total suspended sediment discharge in 1981 was almost twice that of 1982, and the 1-day peak load in 1981 exceeded the entire annual load in 1982. In 1981 at the station near Vaughn, over 50% of the entire year's sediment load was transported in one day.

The lower reach of Muddy Creek between Gordon and Vaughn is experiencing much more severe channel erosion than above Gordon, and is the source of most of the sediment load. Although the Gordon station encompasses 90% of the drainage area and had 78% of the average discharge at Vaughn, it only passed 41% of the average annual suspended sediment load over the past 10 years. The average volumetric transport rate at Gordon was 1.09 tons per acre-foot, compared to 2.08 tons per acre-foot at Vaughn. The station at Vaughn had a somewhat lower percentage of the total annual load contained in the peak daily load.

It is likely that the greater availability of sediment sources in the lower channel allows for a higher rate of sediment pickup at all discharge rates. For example, the months of June, July and August in water years 1980 and 1981 contained no major runoff events. These three months accounted for an average of 16.2% and 16.6% of the total annual suspended sediment load, respectively, at the "near" Vaughn (Gordon) station. For the station at Vaughn however, these three months accounted for an average of 33% and 34.6%, respectively, of the total annual sediment load.

In summary, the reduction of peak discharge in Muddy Creek by a reservoir would substantially reduce the peak and total annual suspended sediment yield if sufficient reservoir capacity were always available. However, reduction in the total flow volume is also likely needed to reduce the high ambient suspended sediment yield of the lower channel.

7. RECHARGE AND RUNOFF SOURCES

The contributions of various elements of the irrigation system to ground-water recharge and surface water runoff require quantification so that water management techniques can be evaluated. The only natural recharge is water from precipitation which infiltrates to the water table. The irrigation water delivery system of canals and laterals as well as leakage from on-farm ditches, fields, and ponded tailwater during irrigations are major sources of man-caused recharge.

Surface water runoff sources include wasteage of canal water directly to drains, tailwater runoff from individual farms, and precipitation-induced runoff from intense storms or moderate storms on irrigation-saturated soils.

Ground-water recharge can be defined as the entry of water into the saturated zone at the water-table surface, producing a rise of the water table, together with the associated flow of ground water away from the water table within the saturated zone (Freeze and Cherry, 1979). Water-table fluctuations were measured with continuous recorders on observations wells located in the six study fields. These installations measured recharge from precipitation, and on-farm irrigation. The amount of water being recharged can be estimated by multiplying the height of water-table rise by the specific yield of the aquifer. The specific yield is the ratio of the volume of water released by gravity drainage to the volume of aquifer material, per unit surface area. For example, a water-table rise of 2 ft. in an aquifer with a specific yield of 0.12 means an input of 0.24 ft. of water to the saturated zone. Over one acre, the volume of recharge equals 0.24 acre-feet. The factors which promote ground-water recharge include: 1) high vertical permeability; 2) moist antecedent soil conditions; 3) prolonged, moderate-intensity rain storms or snowmelt; 4) a shallow water table. The existance of a shallow water table promotes recharge because there are less unsaturated sediments to wet and store the percolating recharge water.

7.1 Precipitation

Ground-water recharge resulting from precipitation was observed in at least one observation well from eight separate events in 1982 and from six events in 1983. No precipitation recharge was observed from July 18, 1981 through December 1981. The sum of all observable precipitation recharge per well ranged from zero to 4.81 ft. of water-level change during the investigation. The Grossman well consistently recorded the greatest amount of recharge whereas the McInerney well record lacked any specific recharge events linked to precipitation.

However, in the McInerny well, and occassionally in other observation wells, possible recharge induced by precipitation was obscured by other factors which also produced ground-water level changes. These factors included irrigation events and regional upward trends in the water level which could not be separated from possible precipitation recharge on the basis of the available information. Since most of the annual precipitation occurs in the irrigation season, such coincidence was inescapable. Only three of the fourteen observed precipitation recharge events in 1982 and 1983 occurred outside the irrigation season, including one in April 1982 and one each in September 1982 and September 1983.

During the irrigation season, recharge from irrigation sources and precipitation are not independent. The soil moisture and water-table conditions created by one, influence the potential recharge of the following event. If soils are near field capacity and the water table is close to land surface following application of irrigation water, a rainstorm in close succession will easily result in ground-water recharge and surface-water runoff. The same rainfall on an adjoining site which was not previously irrigated, would not experience recharge or runoff if all the moisture went to bringing the unsaturated zone to field capacity. Surface-water runoff from precipitation is enhanced by high-intensity storms and pre-saturated field conditions. For example, the June 29, 1982 rainstorm of 1.5 to 2 in. produced mostly surface runoff and very little recharge at the Konen and Grossman sites because the water table was already very near ground surface from previous irrigation and precipitation recharge.

The inter-dependence of irrigation and precipitation recharge makes it difficult to distinguish the two. In terms of the total recharge to the aquifer, however, the distinction is less important. Precipitation-induced recharge was interpreted as ground-water table increases differing from the regional trend and occurring during the period of the storm or snowmelt event, plus one day. The average precipitation recharge from five sites was 1.53 ft. of water-table rise in 1982 and 2.29 ft. in 1983. With an average specific yield of 0.11, the volume of precipitation recharge to the ground-water system over the 58,000 ac of the Bench equals about 9,760 af in 1982 and 14,610 af in 1983.

This estimate indicates that approximately 15 to 20% of the total annual precipitation contributed to ground-water recharge. This percentage is three to four times greater than expected in a semi-arid climate without irrigation, and indicates the catalytic effect of irrigation in inducing precipitation recharge.

7.2 Distribution System Losses

7.2.1 The GID Canal System

The irrigation water distribution system on the Greenfields Bench consists of 295 miles of main canals and laterals, as determined with a Calcomp 9,000 digitizer and 1:24,000 scale maps. Approximately 47 miles of canals were lined with concrete and 22 miles of buried pipe installed from 1978 to 1982 as part of the Greenfields Irrigation Districts Rehabilitation and Betterment Program . Canal lining work continue to add another 20 miles each year.

It is well known that most unlined irrigation canals lose considerable amounts of water. However, it has always been difficult to quantify these losses. Canal seepage losses are known to vary with head in the canal, permeability of the bed and bank material, depth to the water table and the sediment load of the water.

7.2.2 Canal Ponding Tests

Canal seepage tests were conducted by the GID and MBMG in September, 1982 on 13 reaches of canal on the Greenfields Bench. The results are summarized in Table 12, and were computed by a U.S. Bureau of Reclamation method (USDI, 1968). Locations of canal test sections are shown in Figure 23. The canal ponding sections were dammed on both ends, water

TABLE 12. CANAL PONDING TEST RESULTS FROM 1982[1]

	Lateral	Length[2] (Feet)	d[3] (Feet)	Time[4] (Hours)	Seepage Rate Cubic Foot per square foot per day	Loss per Mile (cfs)	Rank Order
1.	GM 59	2754	0.52	6	1.97	3.4	2
2.	GM 59	2984	0.72	6	2.84	4.7	1
3.	GM 62	1489	0.54	6	1.88	2.87	3
4.	GM 62	1320	0.33	6	1.28	1.88	6
5.	GM 62	1430	0.57	24	0.53	0.74	9
6.	GM 85	1000	0.34	12	0.49	0.59	11
7.	GM 85	1052	0.31	16.80	0.43	0.65	10
8.	GM100	814	0.64	12	1.21	1.26	7
9.	GM100	not measured	0.18	9	0.46	0.45	13
10.	GS 28	896	0.99	12	1.91	2.36	4
11.	GS 28	805	0.47	18.67	0.58	0.50	12
12.	GS 32	780	0.91	12	1.70	1.91	5
13.	GS 32	1030	.5	12	0.90	0.90	8

1 Data compiled by Greenfields Irrigation District.
2 Length of test section.
3 Drop in water surface.
4 Duration of test.

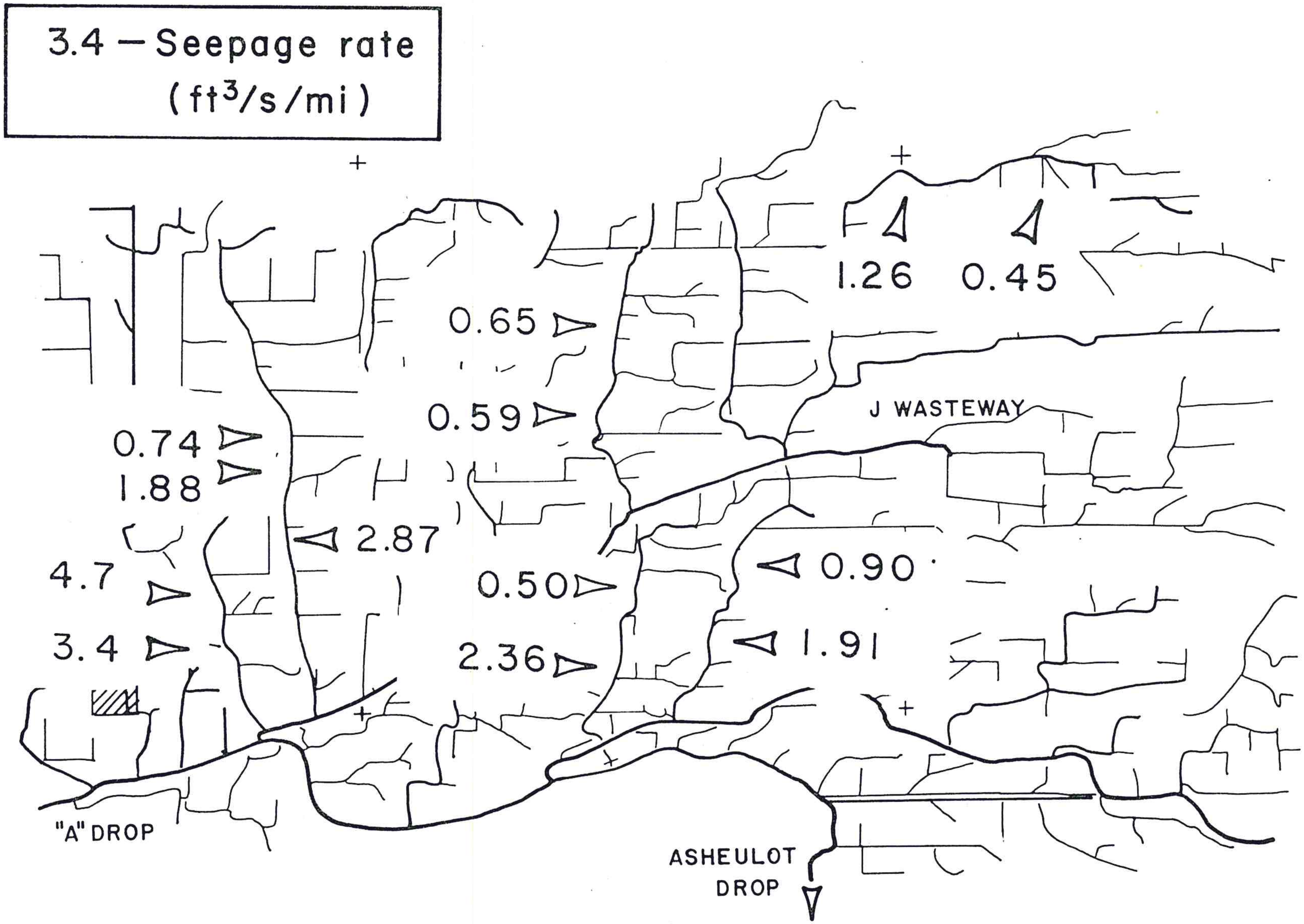


Figure 23 — Location of canal ponding tests.

was pumped in to fill the reach, and pre-saturated by filling for three to eight hours. Surface leakage losses were noted and periodically measured or repaired.

The values in Table 12 were calculated with the maximum wetted perimeter of the test when canals were near maximum capacity. Hence these seepage rates approximate the steady state conditions when canals are close to capacity. Higher rates could occur early in the irrigation when the water table is low, but lower rates will prevail over most of the season since the large canals are at maximum capacity for only about 30 days or about 23% of the average irrigation season.

7.2.3 Total Canal Seepage

An estimate was made of the total canal seepage loss for the 1982 irrigation season, using the ponding test data and assuming steady state conditions prevailed. An average maximum canal seepage rate of 1.5 ft^3/s per mile of canal was used. This rate was assumed to occur when the canals were at peak capacity, which is equivalent to a total inflow rate of 1200 ft^3/s at A-Drop. A seepage rate deceleration function was developed which decreased the average seepage rate as the inflow at A-Drop decreased. The function is graphed in Figure 24 and has the form: percent of maximum seepage rate = 0.0674 x Flow at A-Drop + 19.32. The rate of seepage decline with head and wetted perimeter was determined from the ponding test data of the GM-62 canal.

The length of canals in service was also decreased as flows at A-Drop decreased. Based on data from the on-farm irrigation studies, it was estimated that when inflows at A-Drop were at maximum (1,200 ft^3/s), 77% of the farms on the Bench were serviced with irrigation water. Of the total of 295 mi of canals on the Bench, 110 mi were assumed to always be in use whenever any inflows at A-Drop occurred. Of the remaining 185 mi, 69 mi were lined or replace with buried pipe, and assumed not to leak. The remaining 116 mi of canal were assumed to be used intermittently depending upon the rate of inflow at A-Drop.

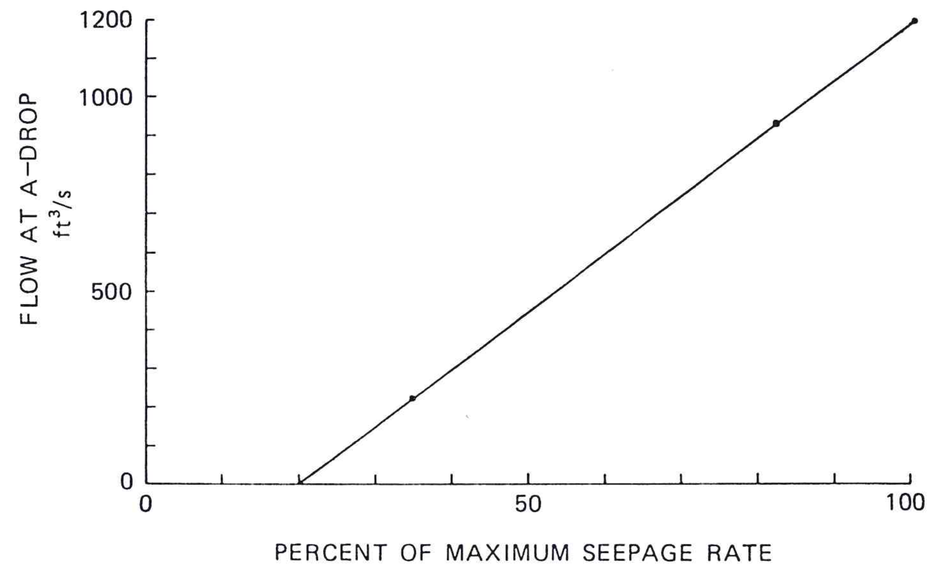
A canal length decline function was developed which decreased the total canal length linearly with the declining inflow rate at A-Drop. The function developed is graphed in Figure 24 and has the form: Canal length = 0.0935 x Flow at A-Drop + 86.8. An example calculation follows:

Inflow	Est. Delivery Efficiency	Delivered	Avg. Farm diversion	No. Farms	Total Farms
750 ft^3/s	0.60	450 ft^3/s	/ 3.90 ft^3/s	= 115	/ 300

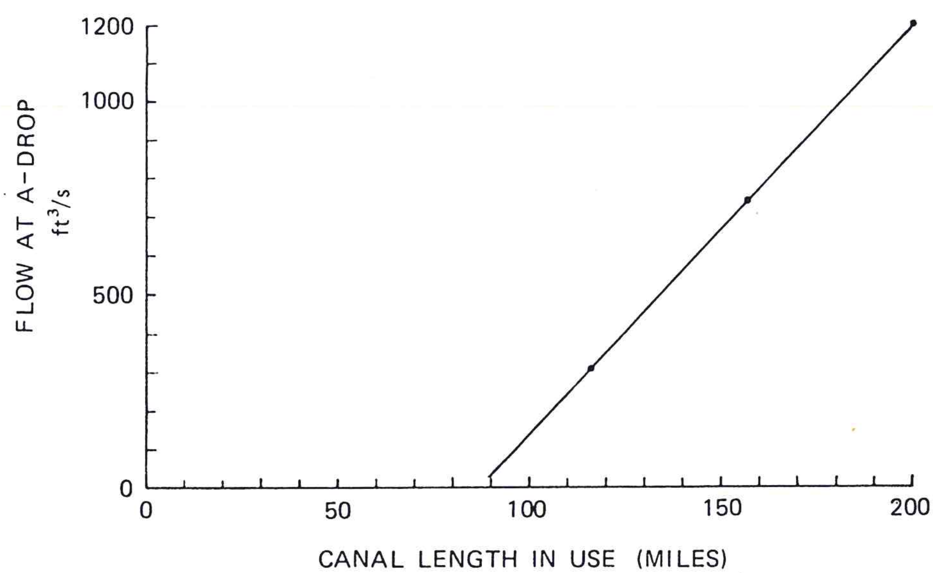
% Service	Total Intermit Canal length	Intermit Canal length	Continuous Canal length	Canal length @ 750 ft^3/s
= 38 x	116 mi	= 45 mi	+ 110 mi	155 mi

The estimated delivery efficiency was obtained from the GID (Nypen, 1983). The average farm diversion rate was obtained from the eight on-farm studies.

A summary of the canal seepage calculations is given in Table 13. The total volume of canal seepage losses was determined to be 37,136 af in 1982. Since data on early season canal losses were not available, the estimate may be too conservative. Soil moisture conditions and groundwater level observations point to the fact that proportionately greater seepage losses occur in May and June.



(a) Canal seepage rate deceleration function.



(b) Canal length deceleration function.

Figure 24 — Canal seepage rate and canal length deceleration functions.

TABLE 13. CANAL SEEPAGE LOSS ESTIMATE FOR 1982

Inflow @ A-Drop ft^3/s	Avg. Canal Length mi	% Max. Seepage Rate	Avg. Seepage Rate $ft^3/s/mi$	Total Seepage Rate ft^3/s	Seepage Volume af/d	No. of days 1982	Seepage Volume af
100-200	101	30	.45	45.4	90.0	4	360
200-300	110	37	.55	60.5	120	48	5750
300-400	120	43	.64	76.8	152	10	1521
400-500	129	50	.75	96.7	192	13	2490
500-600	138	56	.85	117	232	6	1393
600-700	148	63	.94	139	275	5	1377
700-800	157	70	1.05	165	326	12	3917
800-900	166	77	1.15	191	378	5	1890
900-1000	176	83	1.24	218	432	5	2161
1000-1100	185	90	1.35	250	494	9	4450
1100-1200	194	97	1.45	281	557	19	10583
1200-1300	204	103	1.54	314	622	2	1244
Totals						138	37136

7.2.4 Irrigation Waste Water

In addition to seepage losses, a considerable quantity of irrigation water is wasted directly into drains and coulees, particularly at the edges of the Bench.

One central waste-water discharge structure exists at J-wasteway, located about six miles above the mouth of Spring Coulee. At this point waste water from the Greenfields Main canal can be diverted directly into the coulee when a surplus occurs. Discharge records of J-wasteway have been kept by the GID, although the flow includes drain discharge other than direct waste water. The GID occassionally diverts the entire drain discharge into the GM-100 canal system for delivery to the northeast corner of the bench. The waste-water discharge into J-wasteway based on GID records was estimated to average 5,600 af per year for 1979 through 1983.

It is difficult to estimate the quantity of canal waste-water discharge to the other numerous drains and coulees around the Bench. This discharge is apparent as spikes on the hydrographs of the small drains, and to some extent on the Spring Coulee, Tank Coulee and Muddy Creek hydrographs. Several baseflow separation techniques were checked to delineate the waste water discharge including the hydrochemical method, logrithmic baseflow recession curves and hydrograph inspection. The daily SC data collected by the USGS at Muddy Creek near Vaughn was examined, however, the SC often varied directly with discharge, opposite to the expected inverse relationship. Normally, the surface water runoff component has lower conductivity than the ground-water component. In Muddy Creek though, apparently a greater proportion of solids are dissolved from the banks and the increased suspended sediment load at larger stream discharges than at smaller discharges, rendering the hydrochemical method unuseable in this case. Semi-logrithmic hydrographs were made of the Muddy Creek and drain discharge data. Except for the winter periods, the slope of baseflow recession curves for each station varied considerably and the short baseflow duration prevented adequate definition of equations for the curves. Finally, a hydrograph inspection approach was taken in which the hydrologist graphically constructs a baseflow curve, generally based on the troughs or low points of the hydrograph and knowledge of the runoff characteristics. The 1982 water year hydrographs of Muddy Creek near Vaughn and near Power were analyzed, and the baseflow (ground-water portion) discharge computed by graphical integration (Figure 25).

The separation of the Muddy Creek near Vaughn (Gordon) hydrograph gave 67% baseflow and 36% surface runoff whereas the Muddy Creek near Power station gave 65% and 35%, respectively (see Figure 24).

The total runoff from the Bench in 1982 was estimated to equal 102,350 af (see Section 8). Taking 35% of this for the surface runoff component gives 35,822 af. Based on the runoff at the Cordova station, precipitation runoff from the Bench in the absence of irrigation would equal 1890 af in 1982. Surface runoff from on-farm tailwater was estimated to equal about 13,000 af (see Section 8). Subtraction of these quantities leaves 20,930 af of surface runoff, due primarily to canal waste-water discharge. Precipitation runoff in addition to that which occurred on the dry-land drainages area of Muddy Creek is also contained in this estimate.

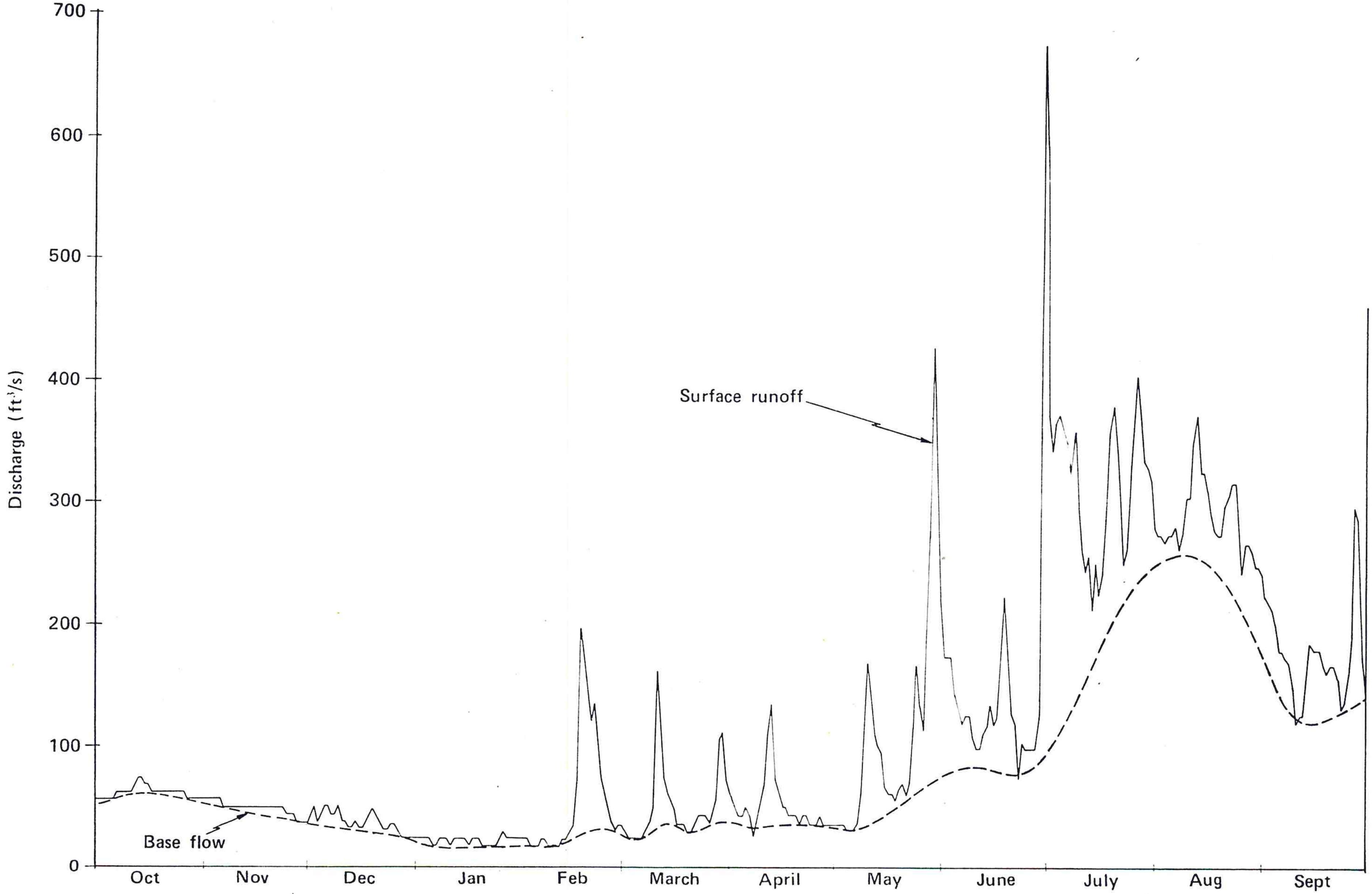


Figure 25 — Hydrograph separation for Muddy Creek near Vaughn, water year 1982.

7.2.5 Total Distribution System Losses

The estimated total canal system losses in 1982 are equivalent to the sum of the canal seepage losses (37,136 af) plus the canal wastewater discharge (20,930 af). The total loss of 58,070 of represents about 40% of the total irrigation water delivery to the Bench.

7.3 On-Farm Irrigation

Irrigation on farms is initiated by the diversion of water from a distribution canal or lateral into one or more head ditches that serve farm fields. The water may then be diverted to smaller farm ditches in the case of flood irrigation or applied to the field with a sprinkler system. Approximately 85% of the Bench is flood-irrigated, with the remainder irrigated by wheel-line and center-pivot sprinklers. The six study fields in this investigation were all irrigated by flooding methods.

7.3.1 Data Collection

Six fields were monitored intensively in 1982 by the MBMG and GID to prepare budgets of the total irrigation water input. Measurements of the inflow to the head ditch were made periodically with current meters. In 2 cases, irrigation applications on the study fields were estimated from application rates to larger fields by the same irrigator. Water-table response was monitored by a continuous recorder or periodic measurement of one or more observation wells in the field. Surface water runoff was measured in Parshall flumes installed at the tailwater ends of the fields. At the McInerney field, however, surface-water runoff was collected in a roadside borrow pit and measured volumetrically with a measurement of the ditch geometry and a water level recorder. The percentage of soil-moisture depletion at the beginning of irrigation, and water-holding capacity of the soil were taken from CES data in most cases. Estimates of antecedent moisture content were made for the deeper unsaturated zones below root depth at the McInerney and Johnson sites. Evaporation losses and crop water use during the irrigation period were assumed to be equal to the average evaporation rate measured by CES, applied over the entire field. A saturated soil surface was assumed to provide the entire evapotranspirational demand for the field during the period of irrigation.

7.3.2 Results and Interpretation

Irrigation water budgets for eight irrigation applications by six operators during 1982 are presented in Table 14. The values for most budget components and the estimated irrigation application come primarily from unrefined field data. Data accuracy was limited by uncontrolled field conditions, field measurement methods and extrapolation of point data over the entire study field. All parameters with the exception of unsaturated zone depth and ground-water rise were measured independently or derived from independent sources. Both unsaturated zone depth and ground-water rise were determined from water level measurements of observation wells. The evapotranspiration and surface water runoff components are relatively well known whereas the soil moisture and ground-water components are more uncertain.

TABLE 14. ON-FARM IRRIGATION WATER BUDGETS FOR 1982

IRRIGATOR	Period of Irrigation	t	Area	Water Applied	ET [1]	ET [2]	SWRO [3]	Unsaturated Zone DEPTH	AWHC [4]	Deplete [5]	SM [6]	Groundwater Rise	SY [7]	GWRE [8]	Budget Sum
	Mo Day Yr	days	Ac	Af	ft/d	Af	Af	ft	%	%	Af	ft		Af	Af
Grossman	6/23-26	2.5	30	13.7	.005	.39	0	1.57	15	30	2.12	3.62	.11	11.9	14.4
Johnson	6/27-7/30	30	146	298	.013	57.0	3.47	12.0P	13	40E	65.0	11.1P	.11	179.	304.
Konen	6/23-28	5.0	66	30	.010	3.32	3.21	1.94	13	30	5.03	3.50	.10	23.3	34.9
Konen	7/21-24	2.9	66	22.5	.018	3.50	5.53	.97	13	35	2.93	0.68	.10	4.52	16.5
McInerney	7/7-22	10.3	85	97E	.018	15.8	(1.33)[9]	10.0	13	35	25.4	6.0E	.13	66.0	107.
Ostberg	7/26-29	3.6	56	42.5	.014	2.81	3.53	3.79	13	70E	18.9	3.33	.10	18.6	43.8
Vervick	7/9-11	1.9	14	10.0	.011	.29	4.88	2.88	15	40	2.35	1.50	.10	2.10	9.62
Vervick	7/28-30	2.0	14	12.0E	.010	.28	6.75	1.40	15	40	1.18	2.75	.10	3.85	12.1

E - Some parameters required in calculations were estimated.
P - Value was adjusted for effects of precipitation occurring during the irrigation period.
1 - Average daily evaporation rate measured by Cooperative Extension Service
2 - Total evaporation loss = ET x Area x t.
3 - Surface water runoff volume measured in flumes or volumetrically at McInerneys.
4 - Available water holding capacity.
5 - Percent depletion of AWHC at start of irrigation period.
6 - Increase of moisture in unsaturated zone due to irrigation; SM = depth x AWHC x Deplete x Area
7 - Specific yield of aquifer
8 - Ground water recharge volume; GWRE = Rise x SY x Area.
9 - All surface water runoff is contained on-site and either evaporates or infiltrates.

The water-budget approach assumes that steady state conditons occur in the ground-water system during the period of irrigation although the water-table rise caused by irrigation certainly causes some change in ground-water flow out of the fields. The change in ground-water discharge during the period of irrigation is called transient flow, which is a runoff component not accounted for in a steady state water budget. A transient ground-water flow simulation of the Ostberg study field was conducted to check the magnitude of this component. The two-dimensional finite-difference ground-water flow model developed for the U.S. Geological Survey by Trescott, Pinder and Larsen (1976), was utilized on a VAX 11/782 computer. The results showed that the pre-irrigation flow through the study field was about 0.053 af/day and that flow at the peak of irrigation recharge was about 0.33 af/day. Over the 3.6 day irrigation period this amounted to a transient outflow of about 1.0 af, or 2.3% of the total on-farm irrigation water budget. (See Appendix C).

The Ostberg field was surrounded on three sides by drains and was situated so as to be influenced more than other fields by transient flow. However, the effect of greater permeability and longer irrigation periods in some of the other fields was not investigated at this time. Since most of the average on-farm irrigation water budget was based on small fields and short irrigation periods, it was assumed that transient ground-water flow could safely be neglected.

Significant precipitation occurred during the lengthy Johnson field irrigation period. The effective rainfall totaled 5.67 in. (Bauder and Jones, 1982), but was eliminated from the budget by decreasing both the unsaturated zone depth and water-table rise by the equivalent of one-half of the rainfall volume. Effective precipitation during other irrigations was less than 0.5 in., and was considered insignificant.

Considering the limitations of the data discussed above, the irrigation water budget sums are in reasonable agreement with the amount of water applied as measured at the head ditch. The data from Table 14 were converted to a volume per unit area basis and on-farm irrigation efficiencies were calculated; these results are given in Table 15. A graphical summary of the on-farm irrigation water budgets is shown in Figure 26. Applied irrigation water averaged 0.85 af/ac, and ranged from 0.34 to 2.04 af/ac. The high rate occurred on the Johnson site and was due to the prolonged irrigation period caused by the large field and shortage of labor help for the irrigator.

Evaporation or crop water use during the irrigation period averaged 0.10 af/ac or about 11% of the budget sum. It was a very small component most fields, but was quite large for the two longest irrigation periods. The actual source of the evapotranspirational water loss during irrigation is difficult to identify. In areas of the field not yet irrigated it comes from stored soil moisture, whereas in areas just irrigated it may come from free water on the surface or very shallow ground water. It was assumed for this study that all evapotranspirational water demand during the period of irrigation was satisfied by the applied irrigation water.

Direct surface water runoff was another small component, averaging 15% of the budget sum. It tended to be smallest on the large fields and largest on the small fields. This likely results from the need for more frequent moving of irrigation sets on small fields and the fact that

TABLE 15. ON-FARM IRRIGATION BUDGET SUMMARY AND EFFICIENCIES, 1982[1]

IRRIGATOR	Period of Irrigation	AREA Irrigated	Evapo-ration	Surface Water Runoff	RECHARGE		Sum	Water Applied	Absolute Difference	On-Farm Efficiency
					Unsat. Zone	Groundwater				
	Mo Day Yr	(Ac)	Ac-ft/Ac							%
Grossman	6/23-26	30	.01	0	.07	.40	.48	.46	.02	17
Johnson	6/27-7/30	146	.39	.02	.45E	1.23E	2.09	2.04	.05	40
Konen	6/23-28	66	.05	.05	.08	.35	.53	.45	.08	25
Konen	7/21-24	66	.05	.08	.04	.07	.24	.34	.10	37
McInerney	7/7-22	85	.19	(.02)[3]	.30E	.78E	1.27	1.14E	.13	39
Ostberg	7/26-29	56	.05	.06	.34	.33	.78	.81	.03	50
Vervick	7/9-11	14	.02	.35	.17	.15	.69	.71	.02	28
Vervick	7/28-30	14	.02	.48	.08	.27	.85	.86E	.01	12
MEAN (n=8)		60	.10	.13	.19	.45	.87	.85	.05	33
% of Sum			11	15	22	52	100			

[1] See footnotes in Table 14.

[2] On-Farm Efficiency = (Evaporation + Unsaturated Zone recharge) x 100/sum.

[3] All surface water runoff on the McInerney site is contained and either evaporates or infiltrates.

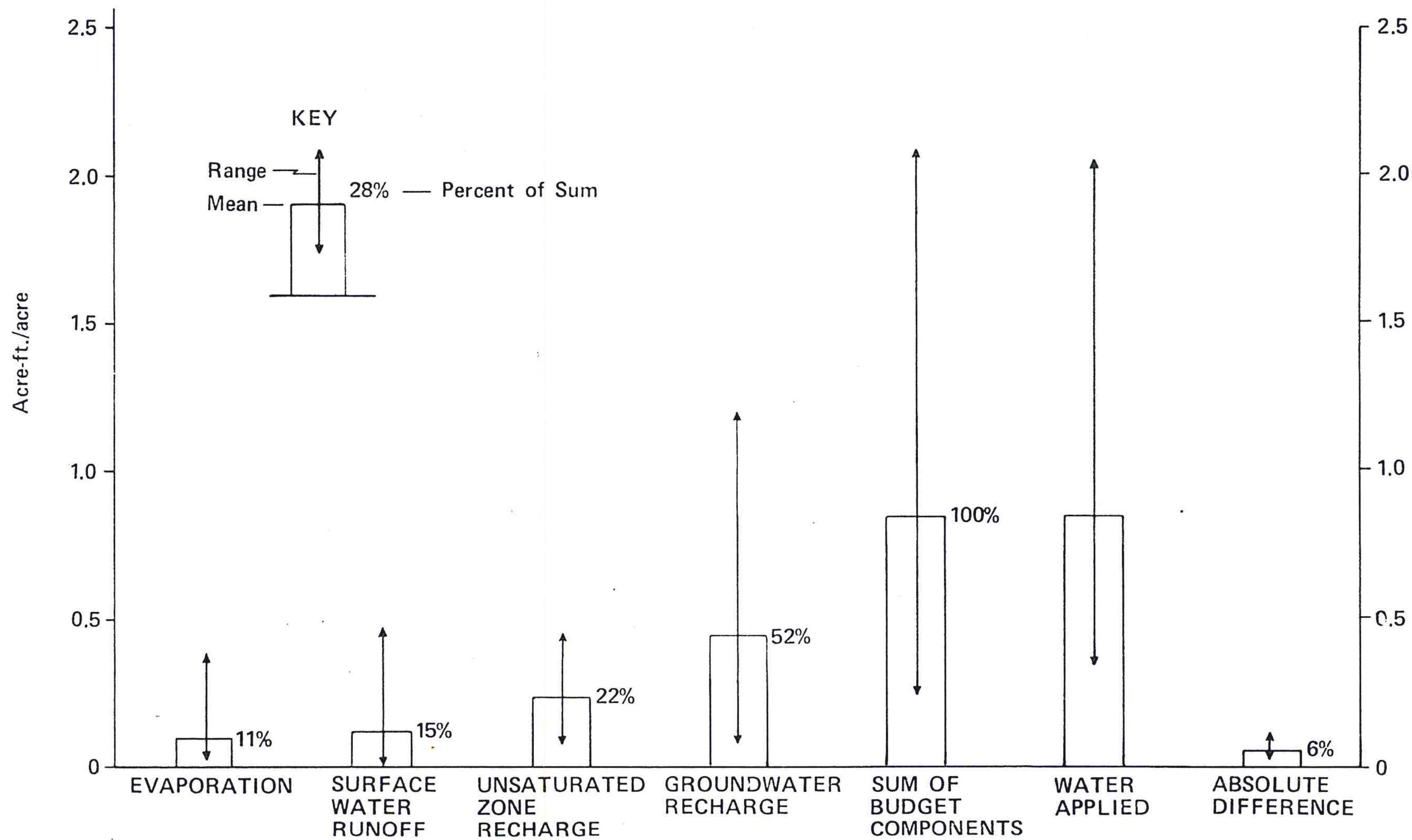


Figure 26 — On-farm irrigation water budget summary.

under flood irrigation, there is less area for water to infiltrate before reaching the lower end of the field or panel.

Unsaturated-zone recharge averaged 22% of the budget sum and ranged from 9 to 44%. The higher values occurred on fields having relatively deep water tables, in the case of McInerney and Johnson, or when the soil moisture was mostly depleted, as the Ostberg field. Both factors allow more irrigation water to be taken up by the unsaturated zone. The portion of the unsaturated zone below the crop root depth though, is not directly available to satisfy crop water demand. Indirectly, however, a deep unsaturated zone at field capacity prevents a decreasing moisture gradient with depth and prolongs the interval until the next required irrigation. Observation well records during all eight irrigation events indicated water-table responses, so that the entire unsaturated zone on each field was always brought to field capacity, if uniform wetting was achieved.

Ground-water recharge averaged 52% of the budget sum and ranged from 22 to 83%. It was proportionately the largest component on the Grossman site where the pre-irrigation water table was very shallow, vertical permeability was high and only a thin unsaturated zone existed. The Ostberg field contained eight observation wells which provided almost complete coverage of water-table fluctuations over the entire area, whereas other fields contained one to four observation wells. The Konen and Vervick observation wells were on the head ditch side of the fields, whereas the McInerney, Grossman and Johnson wells were on the lower end of the study fields.

The mean budget sum and mean water application rate are within about

2.4% indicating that the over-predictions and under-predictions tended to cancel. The mean absolute difference was 0.05 af/ac, approximately 6% of the applied water rate. Budget components varied substantially in magnitude from field to field, indicating that factors such as soil type, field size and layout, irrigation method and timing, depth to water table, pre-conditions and the irrigator all interact to provide a wide spectrum of responses to irrigation.

The on-farm irrigation efficiencies were calculated as the sum of the evaporation and unsaturated zone components divided by the budget sum. The average on-farm efficiency was 33% with the range from 12 to 50%. The unsaturated zone recharge taken alone give an average efficiency of 22%.

Data from Hertzog and Bauder's (1983) report on the 1983 CES monitoring of the Greenfields Bench indicated an average on-farm efficiency for 14 flood irrigators of 30.3%.

8. WATER BUDGETS

A water budget is an accounting of the inflow, outflow and change in storage during a specified time increment, for a given hydrologic unit. Having derived quantities or estimates for most of the major hydrologic components in previous sections, a water budget can be prepared for the Greenfields Bench.

A water budget equation for the Bench can be expressed in its simplest form as:

$$P + I = ET + RO + cS$$

where P = precipitation, I = irrigation water, ET = evapotranspiration, RO = total surface-water and ground-water runoff, and cS = all changes in water storage of surface water bodies, the unsaturated zone and the ground-water zone from the beginning of the period to the end.

If each quantity could be measured independently, a "checkbook" approach could be taken where the deposits (P + I) are compared to "withdrawals" (ET + RO + cS), and any difference would represent net effect of sampling limitations and measurement errors. In this investigation, only portions of some quantities were actually determined in the field, leaving portions to be estimated, and one quantity to be determined as a difference of the others.

The water budget was calculated for the 58,000 ac Greenfields Bench down to the depth of the bedrock, over the time interval of one year, (October 1, 1981 through September 31, 1982). The annual interval tends to even out the large temporary changes in the components like the water-table position or soil moisture content. The most complete data are available for 1982. As a result, however, any anamolous features of the components in 1982 must be considered before generalizing the conclusions.

8.1 The Hydrologic Budget

A water budget for 1982 using the equation of section 8. is given in Table 16.

Table 16. Generalized Hydrologic Budget for the Greenfields Bench, Water Year 1982

	Inputs			Outputs		ET + cS			
UNITS	P	I	TOTAL	RO	ET + cS	CD	cS-gw	cS-soil	ETO
cre-feet	62,600	144,000	206,600	102,350	104,250	67,880	6,570	6,880	22,920
TOTAL	29	71	100	50	50	33	3	3	11

= precipitation; I = irrigation water; RO = Surface water and ground-water runoff;
T + cS = evapotranspiration + change in total storage;
D = crop water demand; cS-gw = change in ground-water storage;
S-soil = change in unsaturated zone storage;
TO = off-season and non-crop evapotranspiration.

In this budget, precipitation is the average of the annual totals for the Fairfield, Power, and Sun River stations. Irrigation water input is that measured at A-Drop (160,744 af) minus outflow to the Asheulot Bench (17,000 af). Runoff is the sum of the annual discharge of Muddy Creek near Vaughn (86340 af) plus MBMG stations #1, #2 and #3 (8,308 af), plus diversions to Benton Lake (3,000 af), minus the dryland discharge to Muddy Creek (2,000 af), plus the drain discharge to Freezeout Lake (6,700 af).

The term ET + cS is the remainder when RO is subtracted from (P + I). The crop water demand (CD) was estimated independently by the CES and equalled 67,880 af over the Bench. Analysis of six ground-water hydrographs from five study fields gave an average of 1.03 ft. net increase in the water table over water year 1982. This was equivalent to a volume of about 6,570 af over the Bench. Subtraction of these two quantities gives a remainder of 29,800 af, which consists of off-season and non-crop evapotranspiration and changes in the soil moisture component in the unsaturated zone (ETO + cS-soil).

The remainder is difficult to differentiate because no direct measurements were available for either off-season (September-May) evapotranspiration or the change in moisture content of the unsaturated zone. Since both precipitation and irrigation diversions were greater in September 1982 than in September, 1981, it is probable that there was a net increase in water storage in the unsaturated zone. An estimate of unsaturated zone change in storage was made by comparing hydrologic conditions in September of 1981 and 1982, and assuming that unsaturated zone conditions were equivalent at the end of August for the two years.

The difference between 1981 and 1982 in average September precipitation, using the Fairfield, Power and Sun River stations was 1.79 in., which is equivalent to 8,650 af over the Bench. Since most of the September 1982 rain came in a single storm at the end of the month, ground-water hydrographs from five study fields and the Muddy Creek hydrograph were examined for that period and the runoff from those components calculated. Ground-water recharge averaged 920 af over the Bench and surface water runoff equalled 850 af at the station near Vaughn. Subtraction of these quantities left 6,880 af as the estimated increase in unsaturated zone storage in water year 1982.

The off-season, non-crop evapotranspiration component (ETO) is the difference between the sum of all other components and the total input. The 22,920 af is equivalent to 0.40 ft. or (4.7 in.) over the Bench. The sum of CD + ETO equals 90,800 af and represents the total evapotranspirational water loss during water year 1982. Over the area of the Bench it is equivalent to 1.57 ft. (18.8 in.), and is equal to 44% of the budget total.

The crop water demand in 1982 equalled 33% of the total precipitation and irrigation water input. It was equivalent to 47% of the irrigation water input alone. However, not all the crop water demand was supplied by direct irrigation as discussed in the next section.

8.2 Runoff Budgets for Precipitation and Irrigation

Although the water budget just developed is useful in the hydrologic sense, further specification of the components is needed to assess water management strategies. Therefore a second water budget approach was taken to segregate the three major input and runoff components: precipitation, canal system losses and on-farm losses.

The 1982 water-year hydrographs of Muddy Creek near Vaughn and near Power were analyzed to determine the precentage of annual flow occuring as ground-water base flow and as surface water runoff as discussed in section 7.2.4. The results indicated that approximately 65% of the total runoff occurred as ground-water base flow and 35% as surface water runoff. A runoff budget for water year 1982 can be prepared from this starting point and is given in Table 17.

The surface water runoff from precipitation was determined by prorating the dryland runoff as measured at Cordova, over the area of the Bench. As such, it represents the precipitation which would have occurred in the absence of any irrigation. In reality, the wetter soil conditions caused by irrigation cause more surface runoff during precipitation

TABLE 17. PRECIPITATION AND IRRIGATION WATER RUNOFF BUDGET FOR WATER YEAR 1982 ON THE 54,700 ACRE GREENFIELDS BENCH.

	Runoff in acre-feet			
	Surface water	Groundwater	Total	% of Total
1982 WY TOTAL	35,820	66,530	102,350	100
Precipitation	1890	9,760	11,650	11
Delivery Losses	20,930	37,140	58,070	
reduced for sub-irrigation	20,930	24,615	45,850	45
Total Delivery to farms			85,930	
On-Farm Losses	12,890	44,680		
reduced for sub-irrigation	12,890	32,155	45,045	44

events. This additional runoff is directly associated with canal waste-water discharges occurring at the same time. The surface water delivery loss value of 21,030 af includes both the precipitation-induced runoff plus canal waste-water. The 12,890 af of on-farm surface runoff was derived from the on-farm irrigation water budget in Table 15.

The precipitation-caused ground-water runoff was derived in Section 7.1 from well hydrograph analysis. Delivery losses to ground water were calculated with the ponding test data in Section 7.2.3 and equalled 37,140 af. Not all of this ends up as runoff, however, since a portion of the ground-water recharge is transpired by crops through sub-irrigation or else it evaporates. Similarly, the on-farm ground-water loss of 44,680 af represents 52% of the total on-farm delivery, as presented previously in Table 15. This quantity was also reduced by withdrawals through sub-irrigation. The total amount of sub-irrigation was estimated by first summing the total precipitation recharge, delivery losses and on-farm losses to ground water (9,760 + 37,140 + 44,680 af) and subtracting the total ground-water runoff (66,530 af). The difference of 25,050 af represents ground-water recharge which later met evapotranspirational demand or resulted in a change of storage. One-half of this difference was subtracted each from the delivery loss and on-farm loss to ground water to arrive at the adjusted values of 24,615 af and 32,155 af respectively.

The sources of runoff from the Greenfields Bench in water-year 1982 can be differentiated as follows: 11% of total runoff came from precipitation, 45% from canal system seepage, waste water and storm runoff, and 44% from on-farm surface and ground-water runoff. To some extent, the subtraction of the sub-irrigation component from any of the ground-water runoff categories is arbitrary. However, since precipitation is relatively small, and delivery loss is roughly equivalent to on-farm loss, the allocation of one-half the sub-irrigation estimate to each of the latter two categories is reasonable.

8.3 Irrigation Water Budget

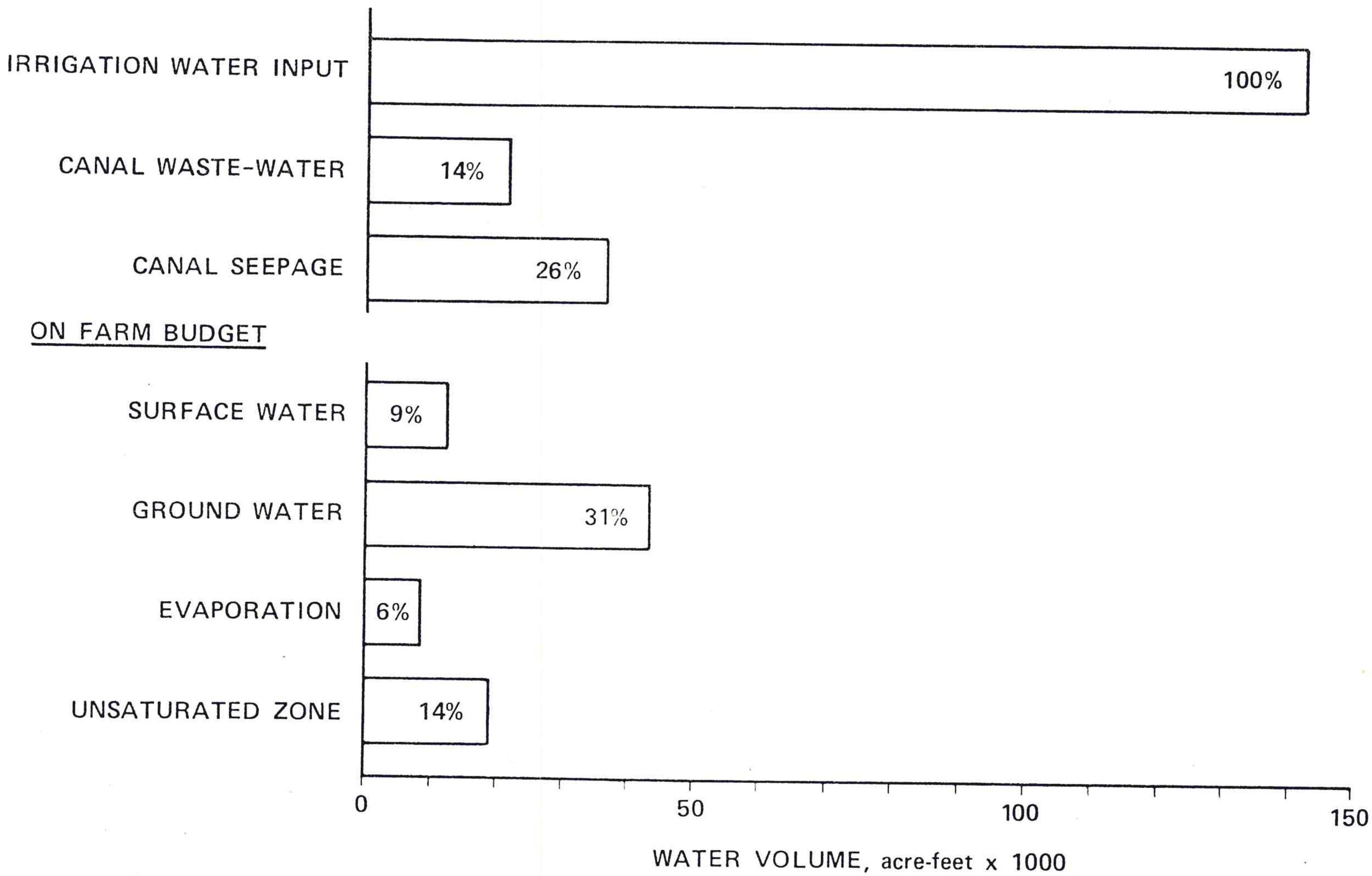
Delineation of the delivery system losses and on-farm losses permit a total irrigation water budget for 1982 to be prepared, given in Figure 27.

Of the total input of 144,000 af of irrigation water to the 52,000 irrigated acres on the Bench, about 40% was lost during delivery to the farms. This includes 14% canal waste and 26% seepage loss. On the farm, 9% was lost to surface tailwater runoff, and 31% to the ground-water system. Recharge of the unsaturated zone plus evapotranspiration during irrigation amounts to 28,360 af or about 20% of the 144,000 af input to the Bench. This was the overall apparent efficiency of the irrigation system in 1982, if sub-irrigation is not considered.

8.4 Crop Water Budget

The ultimate goal of irrigation is to supply the crop root zone with an optimum quantity of water at intervals sufficent to prevent moisture stress in the crop. The hydrologic and irrigation water budgets allow an estimation to be made of the sources of water used to grow the crop.

Extrapolation of the CES data indicated that a total of 67,880 af was consumptively used by the crops on the Bench. This calculation was



Irrigation water budget for 1982.

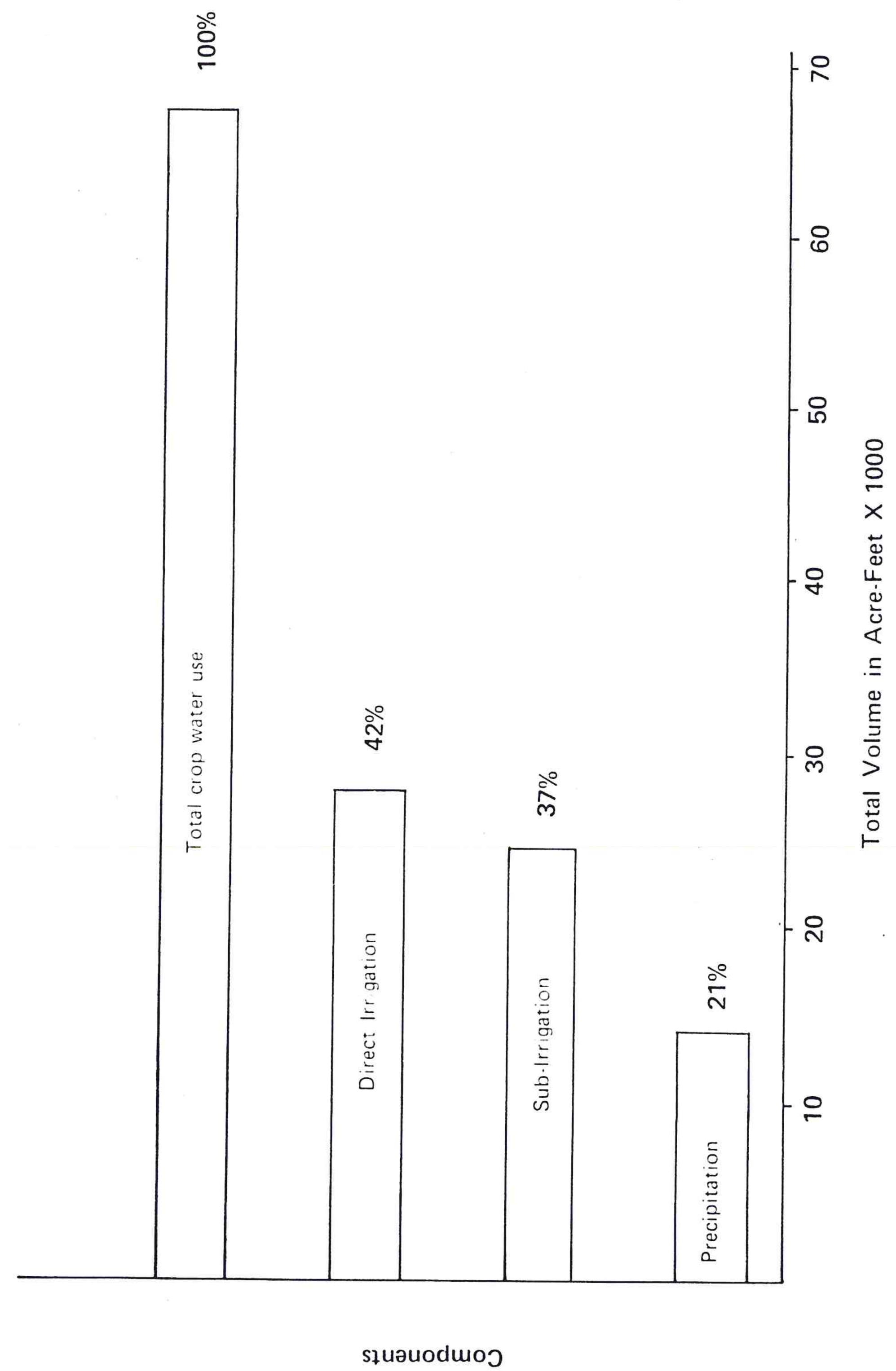
presented in section 4.4. The irrigation water budget accounted for 28,360 af of irrigation water which recharged the unsaturated zone, or directly reduced the evapotranspirational demand during irrigation. This leaves 39,520 af which was supplied by either precipitation or sub-irrigation. Stored soil moisture at the beginning of the irrigation season is also included in this figure, but assumed to have been supplied by precipitation earlier in the budget year.

In Section 8.2, it was pointed out that there was a significant difference between the total ground-water recharge and the ground-water-derived runoff. This difference was 25,050 af and represents the estimated volume of ground water which contributed to evapotranspirational demand. Since ground-water levels reach their peak in the growing season, it is probable that most of this quantity went to satisfying the water requirements of the crops and general evaporation demand.

With this assumption, about 14,470 af of the crop water demand was supplied by precipitation. In reality there may be a different proportion of the crop demand supplied by ground water and precipitation, which can not be distinguished. The estimated crop water demand budget is presented in Figure 28.

The results illustrate an observation made by agriculturalists working on the Greenfields Bench: namely, that the irrigation water directly applied by farmers was often less than the calculated irrigation requirement. Approximately 42% of the crop water needs was supplied by direct irrigation, the remainder was supplied by sub-irrigation and precipitation.

Sub-irrigation is a valid method of irrigation and is considered a



Crop use budget for 1982

beneficial use of water. If added to the direct irrigation component it can be said that approximately 79% of the crop water requirements in 1982 were directly or indirectly supplied by irrigation.

Sub-irrigation, whether intended or not, requires a high water table to enable ground water to be drawn by capillary and suction forces into the root zone where it can be used by crops. The widespread occurrence of a high water table over the bench throughout 4 to 5 months results in the large baseflow component of Muddy Creek. In addition, it promotes excessive surface runoff from precipitation events.

The combination of direct irrigation and sub-irrigation in use on the Bench is effective in growing crops, but as a side-effect, it results in excessive runoff from the Bench. The present irrigation system could be modified to reduce the excessive runoff and still produce desired crop yields.

9. RUNOFF CONTROL ALTERNATIVES

The approaches to control the irrigation-related runoff to Muddy Creek can be grouped under four categories: 1) optimizing irrigation frequency and volume, 2) improving both on-farm and canal system efficiencies, 3) reuse of runoff water, and 4) peak-reduction facilities. A brief summary of these alternatives is presented along with some pertinant considerations regarding runoff control.

9.1 Optimizing Frequency

Closer regulation of the timing and amount of irrigation on the farm or of the delivery of water to the Bench is probably one of the more cost-effective approaches for controlling runoff. Changes in facilities or basic methods are not required, only attention to the timing and quantity of water application is specifically needed. It can be done immediately by individual farmers with minimal expenditures of time or resources.

The on-farm irrigation scheduling program implemented by the CES was the first attempt to schedule on-farm irrigation to coincide with crop needs as opposed to strictly subjective criteria usually in use.

The amount of runoff savings if an on-farm irrigation scheduling program was implemented across the Bench is difficult to estimate. For example, however, if one-half the farmers and acreage on the bench were to forgo one complete irrigation, at the average application rate of 0.85 af/ac, about 21,000 af less would be required. However, it is not likely that there is a one to one reduction in runoff, because the delivery system, as is, operates less efficiently at lower capacity. In addition, although a reduction of 21,000 af represents 15% of the total 1982 irrigation water supply, the runoff reduction would not substantially diminish peak flow in Muddy Creek and hence, a relatively minor effect on sediment loads would be realized.

Unless operated on a site-specific basis, irrigation scheduling could have the negative effect of concentrating irrigation demand which could exacerbate peak shortages and off-peak surpluses. Individual farm scheduling, which accounts for crop-stage, soil characteristics and local weather conditions would alleviate this problem. The CES reports indicated that irrigation scheduling had other positive effects on irrigator's labor savings and crop yields, irrespective of runoff reduction.

With proper authorization, it is possible for the irrigation district to apply scheduling principles throughout the District, and attempt to operate the distribution system at the level warranted by their independent measurement of moisture conditions. For example, the date of first delivery to the Bench in May, could be delayed if the district (or another agency) conducted a Bench-wide reconnaissance survey of soil moisture conditions and found soils near field capacity at the start of the growing season. This could result in considerable direct runoff savings at the time when Muddy Creek frequently experiences its annual peak flow. The district could offer a soil moisture evaluation service to farmers at the beginning of the growing season, or upon request, whenever an irrigator called in to place a water order. Such a practice would entail some additional costs but may prevent over-irrigation.

9.2 Improvement of Efficiencies

The improvement of on-farm irrigation efficiency is a topic which is too diverse to address at length in this report. The lining of farm ditches, shortening panel or field lengths, land leveling, automated diversion devices, sprinkler systems, etc., all work to both benefit the farmer and reduce return flows. It is likely though, that by themselves, on-farm improvements would have to be widespread and intensive over the Bench to substantially reduce runoff and sediment production in Muddy Creek.

As an example, if one-half the Bench converted to sprinkler irrigation and operated at 70% efficiency, approximately 24,500 af less would be required, or about 28% of the 1982 on-farm deliveries. Once again, a reduction in runoff would occur, but at less than a one to one ratio because of reduced delivery efficiencies at lower canal capacities.

Improvement of the delivery system efficiency is an attractive measure since water savings from reduced seepage and canal wastage result in runoff savings closer to a one to one ratio. Concrete canal lining and buried pipe are two improvement methods currently being installed under the GID's rehabilitation program. Through 1983, 95 mi. of unlined canal have been replaced and an estimated water savings of 30,000 af per year realized (Nypen, 1983).

Once again, this savings reduces seepage losses to ground water and therefore reduces the baseflow runoff component. Peak flows and sediment production in Muddy Creek are probably only reduced by a minor amount. Canal lining will also lower the water table, particularly on the western end of the Bench, and in fields bordering the canals. However, this will reduce the contribution of sub-irrigation to crop growth and this may mean increased irrigation requirements for some farmers. In addition, lined canals and buried pipe allow for larger peak flows of waste water to reach Muddy Creek when farm diversions are temporarily reduced during storm events because of the lack of seepage losses. This would tend to exacerbate peak runoff and sediment production in Muddy Creek.

Canal lining must occur within the context of a comprehensive water-management plan. The largest rates of canal seepage measured in ponding tests occurred on the western end of the bench where the highest permeabilities generally occur. However, this area also has the deepest gravel deposits and can absorb greater losses without having an excessively high water table. Canals on the eastern edge of the bench leak at lower rates, but the gravels deposits are thinner, allowing for less storage of ground water and greater runoff. Additionally, water-table recharge on the east end more quickly reaches Muddy Creek. Other considerations include the average duration of flow in a particular canal, present state of repair and occurrance of water logging problems in adjacent fields.

9.3 Reuse

Surface water and ground-water runoff can be collected for re-use in the existing or in a modified irrigation system. The Greenfields Irrigation District uses five large turbine pumps to recycle drain water into the canal system, particularly to serve the sometimes water-short northeastern corner of the bench. Drain flows are diverted into irrigation canals at several points on the eastern edge of the Bench where irrigated land extends below the level of the drains and water supplies are sometimes short.

These existing runoff reuse facilities arose in response to occasional water shortages on the extreme ends of the Bench. This serves to point out the primary dis-incentive for expanding surface water and ground-water reuse: in most years, the Bench has a more than adequate supply of irrigation water from the Sun River. On other irrigation districts in the western U.S. where water supplies are more limited, reuse is a way of life.

One reuse of a given volume of surface water or ground-water runoff on the Bench would reduce on-farm runoff an average of 32% for each irrigation and also reduce canal deliveries and total seepage losses. It may provide additional benefits by recycling nutrients, particularly nitrate to the soil. By itself, reuse would not greatly diminsh peak flows and sediment transport in Muddy Creek. However, if coupled to a recharge and ground-water storage system, where storm runoff from precipitation and canal waste-water could be captured, stored temporarily and later withdrawn, a reuse system could significantly cut peak flows and sediment yield.

Reuse of runoff water on the Bench holds a large number of options which require a comprehensive feasibilty analysis not done in this report. A few of the possibilities include:

a) adding more pump stations on existing surface drains;

b) piping existing drain discharge by gravity flow from one bench to a lower one, or down-gradient on the same bench;

c) pumping ground water for direct irrigation or as input to canals;

d) installing deep, buried drains for ground-water collection and conveyance to canals or sprinklers;

e) use of drainflow or ground water from the bench for domestic, agricultural, industrial or environmental purposes at other locations.

A combined recharge-reuse system offers the advantages of a reservoir storage system which allows peak flow reductions, baseflow reductions and multi-purposes management of water supplies. The possibility of constructing special recharge structures or for utilizing existing canals, drains, farm fields or borrow pits as recharge facilities would have to be thoroughly investigated.

On the average, each 10 ft. rise or fall of the water table adds or releases about 700 af of water over a one mi^2 area. The western one-third of the bench may offer the greatest reuse potential since the gravel deposits are thickest and permeabilities the greatest.

Potential salinity increases in the reuse water would have to be considered. However, the ground-water runoff from the Bench generally is of acceptable quality for irrigation.

The possibilities of donating or marketing surplus water to areas off the Bench is an attractive reuse alternative. The Tri-County ground-water collector and pipeline is a prime example. It is possible that other high-volume water users could be found and additional runoff water directly exported without cost to the irrigation district, residents of the bench, or state taxpayers. Of course, the projected yield and possible side effects of such projects must be carefully considered.

9.4 Peak Reduction Facilities

Special facilities could be constructed to divert or store canal or drain water during large runoff events to reduce the peak flows in Muddy Creek. As indicated in the surface water section, peak flow reduction is an effective means of reducing the sediment discharge of Muddy Creek.

Alternatives in this category include most of those analyzed by the U.S. Bureau of Reclamation, such as the canal diversion to Freezeout Lake and the drain interceptor canal and reservoir on Muddy Creek near Power. Their special draft report on Muddy creek (USBR, 1983) summarizes these alternatives.

The advantage of these facilities is that they are relatively effective in reducing the sediment discharge of Muddy Creek. Disadvantages include their limited usefulness for other purposes and lack of direct benefits to farmers on the Bench. The Bureau of Reclamation estimated that the reservoir option would reduce the average annual sediment load by 60,700 tons per year or by about 28% of the current average load (an additional Benton Lake diversion could reduce the average load by 80,300 tons per year, or 38%). These facilities may most economically control sediment load up to the estimated percentages, but cannot go much beyond that. Other options or combinations, while incrementally less efficient at sediment control, may offer more sediment load reduction or benefits in the long run if carried out extensively.

9.5 Choosing Strategies

A comprehensive analysis of all runoff and sediment control options is needed, utilizing the results of this investigation. Any analysis must be predicated on a well-defined set of objectives and criteria so that sediment control as well as other benefits and costs of the alternatives can be fairly assessed.

The results of irrigation efficiency improvements and reuse projects are not straightforward in their impact on water savings, side-effects on irrigators or sediment reduction. It is recommended that hydrologic models be employed to check side effects and runoff savings of the various alternatives. Presumably, if the volume and timing of runoff savings can be estimated, the U.S. Bureau of Reclamation (or other) sediment model could be used to predict average sediment-load reduction. Irrigation changes on the Bench could first be modeled with the simple water budget approach given in this report. Final analyses may best be checked with a discretized dynamic computer model of the hydrologic system of the

Bench. All proposals must receive input from farmers on the Bench, environmental scientists and engineers, and governmental representatives of the State of Montana.

10. CONCLUSIONS

1. Irrigation of crops on the Bench is often not required in parts of May and early June because of the availability of stored soil moisture, immature crop stage, low evapotranspiration rates, and a high probability of receiving rainfall.

2. Irrigation water is supplied to the Bench in May and June at rates exceeding three times the crop water use requirement for the Bench. This leads to large canal seepage losses and waste water discharge to Muddy Creek and amplifies the peak runoff and sediment transport rates in Muddy Creek.

3. The gravel deposits of the Greenfields Bench are generally a good aquifer capable of rapid recharge and high yields. The aquifer is highly permeable on the western one-third of the Bench, but quite heterogeneous elsewhere, requiring site specific testing prior to development.

4. Most of the total sediment load of Muddy Creek is associated with a small number of peak flow days. An average of 15-20% of the total annual load occurs on a single day.

5. Approximately 65% of the total runoff in Muddy Creek is derived from ground-water discharge primarily to drains on the Bench. Peak flow reduction facilities would substantially reduce the peak sediment loads. Reduction of the baseflow component is needed to control high ambient sediment concentrations and facilitate channel stabilization.

6. The hydrologic budget for the Bench in water year 1982 is: P + I = RO + ET + cS; where: precipitation (P) = 62,600 af, irrigation water (I) = 144,000, runoff (RO) = 102,350, evapotranspiration (ET) = 90,800 and change in storage (cS) = 13,450 af.

7. Evapotranspiration is composed of the total crop water demands (CD = 67,880 af), and off-season evapotranspiration = 22,920 af.

8. The annual discharge of Muddy Creek near Vaughn was probably between 2,000 to 7,500 af.

9. Total runoff is over 100,000 af each year. Approximately 11% of the Greenfields Bench runoff is derived from precipitation, 45% from irrigation delivery system losses, and 44% from on-farm irrigation water losses.

10. Of the total irrigation water input to the Bench, about 40% is lost to canal seepage or wasted to drains.

11. On-farm irrigation efficiencies averaged 33% with 52% lost to ground-water recharge and 15% to surface water runoff.

12. About 30% of the total canal system and on-farm ground-water losses were consumptively utilized in sub-irrigation and evaporation during the same growing season.

13. Direct irrigation supplied an average of 42% of the total crop water demand in 1982. The remainder was supplied by precipitation and sub-irrigation. The seasonally high water table is an important element of the present irrigation system by satisfying about 37% of the annual crop water needs; however, it also is a major cause of the high runoff rate to Muddy Creek.

14. Irrigation scheduling by farmers and careful control of irrigation water delivery to the Bench by the GID are low cost ways of reducing runoff.

15. The construction of peak runoff control facilities, such as a reservoir on Muddy Creek could significantly reduce the sediment yield. However, it would not directly benefit farmers or agricultural productivity on the Bench.

16. Canal lining and on-farm efficiency improvements would primarily reduce the baseflow runoff component of Muddy Creek.

17. Irrigation efficiency improvements which substantially lower the water table in the growing season will require changes in irrigation frequency, timing or application rate by farmers on the Bench.

18. Attention to soil moisture conditions, indices of the evapotranspiration rate, and measurements of the water-table elevation by farmers and the Greenfields Irrigation District would entail additional effort, but little capital cost, and could substantially reduce irrigation diversions and return flow to Muddy Creek.

19. A ground-water recharge and reuse system which recharged excess irrigation water and withdrew it for later irrigation use, could reduce both peak and baseflow runoff in Muddy Creek.

20. A comprehensive analysis of all runoff control alternatives utilizing the hydrologic data from this investigation is needed.

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APPENDICES