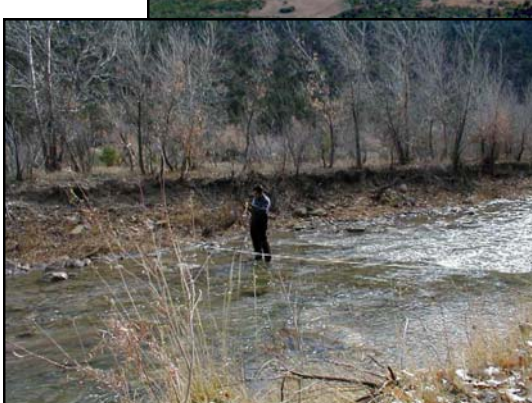
Mancos Valley Salinity: Hydrologic Study Report

Crystal Creek Ditch

Montezuma County, Colorado
March 2004

Mancos Valley



Mancos River

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NORTHERN PLAINS ENGINEERING TEAM
Lakewood, Colorado

March 22, 2004

Mancos Valley Salinity: Hydrologic Study Report

Job Number: Co0102
Short Job Description: Mancos Valley Salinity Study
Location: in the vicinity of Mancos, Montezuma County, Colorado

Summary: A hydrologic study was performed to quantify the dissolved salt loading from the Mancos Valley. This report details the findings of this study.

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ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance provided by numerous individuals in this effort, including Dalton Montgomery and Casey Sheley of the NRCS who accompanied me on my synoptic tours of the watershed; Phil Alcon of the U.S. Bureau of Reclamation, discharge master for the synoptics; and Al Albin and Bob Rasely of the NRCS for their geologic wisdom. Also to be thanked are Tim Sweeney and Nyle Jordre of the NRCS Colorado State Office for their assistance with background of the salinity program and all of their parallel work for the Mancos Valley Salinity Control Proposal; and Frank Riggle, Assistant State Conservationist for Water Resources, for his motivation and intellectual inspiration that led to a completed report.

The many unnamed individuals with the U.S. Geological Survey, Colorado Department of Public Health and Environment, Colorado Department of Natural Resources, National Park Service, Bureau of Reclamation, and the Ute Mountain Reservation who collected and analyzed the many water quality samples used in this analysis, as well as the dedicated NRCS soil conservationists and scientist who collected the soils information, are all greatly appreciated for their efforts.

INTRODUCTION

The Mancos Valley of Eastern Montezuma County, Colorado is being considered by the Natural Resources Conservation Service and the Colorado River Basin Salinity Control Forum for irrigation improvements to reduce the agricultural contribution of dissolved salts to the Colorado River. The Mancos Valley is an agricultural valley to the immediate north east of Mesa Verde, encompassing the town of Mancos. This community is the namesake of the Mancos Shale, a well known source of salts in the Colorado Basin. Portions of the Valley have exposed layers of Mancos Shale, with associated salty soils. Much of the saltiest areas of the valley are not used in agriculture, due to soil conditions and limited water availability, but numerous salt-rich areas have been and continue to be used in irrigated agriculture.

The Mancos River, a tributary to the San Juan River, is the main stem stream that drains this valley. Tributaries to this river include the East, Middle, and West Mancos Rivers; Chicken Creek; East and West Mud Creeks; Weber Canyon (and drainage); and East Canyon.

Irrigation improvements to control salinity have been considered in the Mancos Valley for at least two decades. Unnamed persons with the Natural Resources Conservation Service, Agricultural Stabilization and Conservation Service, and the Agricultural Research Service produced an irrigation improvements study in 1984 that quantified the total dissolved salts leaving the valley and contributed a portion of these salts to agricultural practices. This study also divided the agricultural sources of salt between on farm and transmission sources. Documentation of how these values were produced was not provided in this report. Salt loading (per irrigated acre) was lower than expected and the project was not pursued at that time.

In early 2001 the NRCS Northern Plains Engineering Team was asked to provide assistance to revisit this salinity study to verify the results of the previous study, since the relatively poorly documented study produced such unexpectedly low values in a region well endowed with Mancos Shale. This new study performed a number of tasks to quantify the salt loading of this area. The irrigated agriculture, geology, and soils of the basin was documented; the existing streamflow and relevant constituent concentrations data was mined from various databases and interpreted; several salinity synoptics were performed; and the existing streamflow and water quality data were analyzed to quantify the total and baseflow total dissolved solid mass flux from the basin. This hydrologic report documents the findings of this analysis, as well as how the values were specifically attained. The Summary and Conclusions section provides an overview of the results.

MANCOS VALLEY OVERVIEW

The Mancos Valley is an agricultural valley situated in the middle and lower portions of a 203 square mile watershed of the Mancos River (Figure 1), in the vicinity of Mancos, Montezuma County, Colorado. The watershed, with elevations ranging from 6,200 ft to 13,192 ft, consists of semi-arid high valleys, canyons, forested mountains and alpine tundra. The watershed is bound by Mesa Verde National Park in the southwest, the Ute Mountain Reservation to the south, the ridge of the Montezuma-La Plata county line in the southeast, the La Plata Mountains in the northeast, and a low ridge line to the northwest. Mean annual precipitation ranges from 16 inches in the valley to 40 inches on the ridges (Figure 1). Agriculture is primarily limited to the lower elevations of the valley and composed of irrigated grass-pasture and alfalfa production.

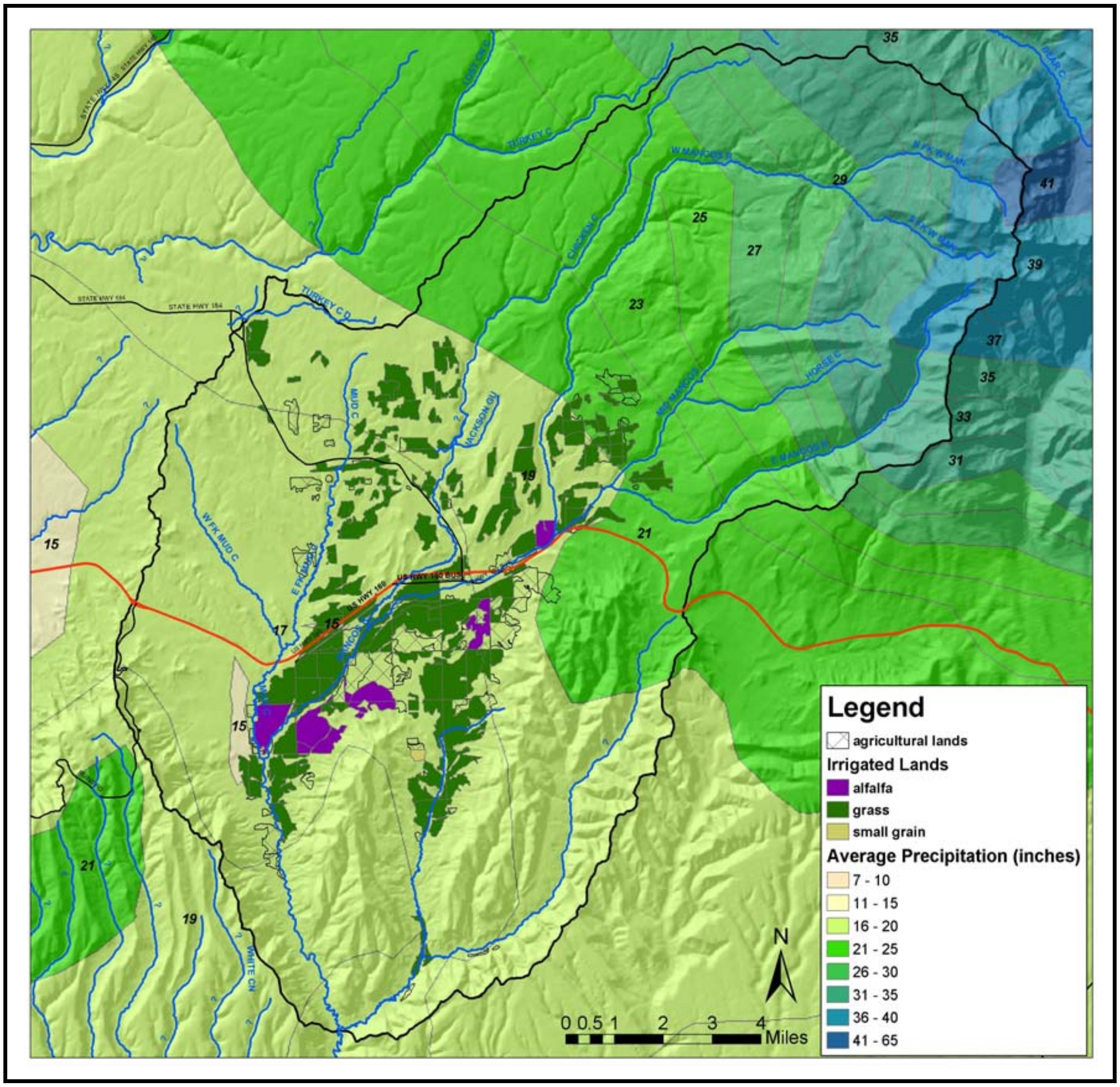

Figure 1: Mancos River Watershed, with irrigated lands by crop type and average precipitation. Agricultural data (circa 1994) was provided courtesy of the US Bureau of Reclamation.

The higher elevations of the watershed are dominated by Ponderosa, Spruce, Fir, and Aspen. On non-agricultural land, the vegetation of the lower elevations of the valley is dominated by Sage and Piñon-Juniper, with willows in riparian areas and large stands of invasive Tamarisk in the Mancos Canyon.

Mancos River flow is dominated by precipitation falling on the higher elevations in the northeast portion of the watershed, in the San Juan National Forest (Figure 1). The East, Middle, and West branches of the Mancos River and Chicken Creek drain these higher precipitation areas. Mud creek drains the lower elevations in the northwest. The lower valley is divided by Weber and Menefee Mountains, between which the Weber Drainage flows. The confluence of the Mancos River and Weber drainage marks the lower end of the valley. Immediately below the valley is the Ute Mountain Reservation, through which the Mancos River flows to its confluence with the San Juan River in New Mexico.

Wetlands that are likely the result of leakage from unlined irrigation canals can be found in the lower valley.

Irrigated Agriculture

According to a US Bureau of Reclamation GIS study (U.S. Bureau of Reclamation 1994) agriculture in the valley is composed of 14,900 acres, with 11,700 acres irrigated (9900 acres by flood practices and 1800 acres sprinkled). The spatial distribution of this agricultural land is presented in Figure 2. A breakdown of the acreage is provided below:

(a) Irrigated: 11,695 acres
- (1) Flood: 9900 acres
  - a. alfalfa: 280 acres
  - b. grass: 9541 acres
  - c. orchard: 41 acres
  - d. small grain: 38 acres
- (2) Sprinklers: 1795 acres
  - a. alfalfa: 948 acres
  - b. grass: 847 acres
  - c. Fallow: 61 acres
  - d. Intermittent: 80 acres

(b) Not Irrigated: 2996 acres

There are approximately 46 diversions of water for Mancos Valley agriculture. Locations and ID's of these diversions are provided in Figure 2, while Table 1 list each of the diversions by name, ID, irrigated acreage, five-year average withdrawal rate, and depth of water diverted (assuming all fields in use). Thirty six of these ditch diversions from the Mancos River and its tributaries provide water directly to 9290 acres of agricultural lands. Eight reservoir diversions provide water to an additional 2092 acres. Jackson Gulch, the primary storage reservoir for the valley, provides flow augmentation captured by a number of the 36 ditch systems. Additionally, there is one transbasin diversion for 289 acres from water district #71. According to Colorado Department of Natural Resources (DNR) records, this diversion has not been utilized since 1986 (Colorado Decision Support System 2001).

Annual, monthly, and daily diversion quantities were downloaded from the Colorado Department of Natural Resources (Colorado Decision Support System 2001) for 1974 through 2000, by irrigation year (Nov-Oct). Annual diversion totals (assuming that reservoir inflows equal outflows over each individual irrigation year) were at a maximum in 1975 at 67,700 ac-ft, a minimum in 1977 of 14,600 ac-ft, an average of 42,100 ac-ft, and median of 39,900 ac-ft. Average irrigation efficiency for the valley was computed to be 32 percent for 1991 through 1995, which well reflect the range of wet and dry years of the entire record. Within these five years of record, system efficiency ranged from 19 to 48 percent, with lower efficiencies during wet years. These estimates were computed using a simple water budget with evapotranspiration values computed using Blaney-Criddle and precipitation estimates from the Mesa Verde and Cortez climate stations.

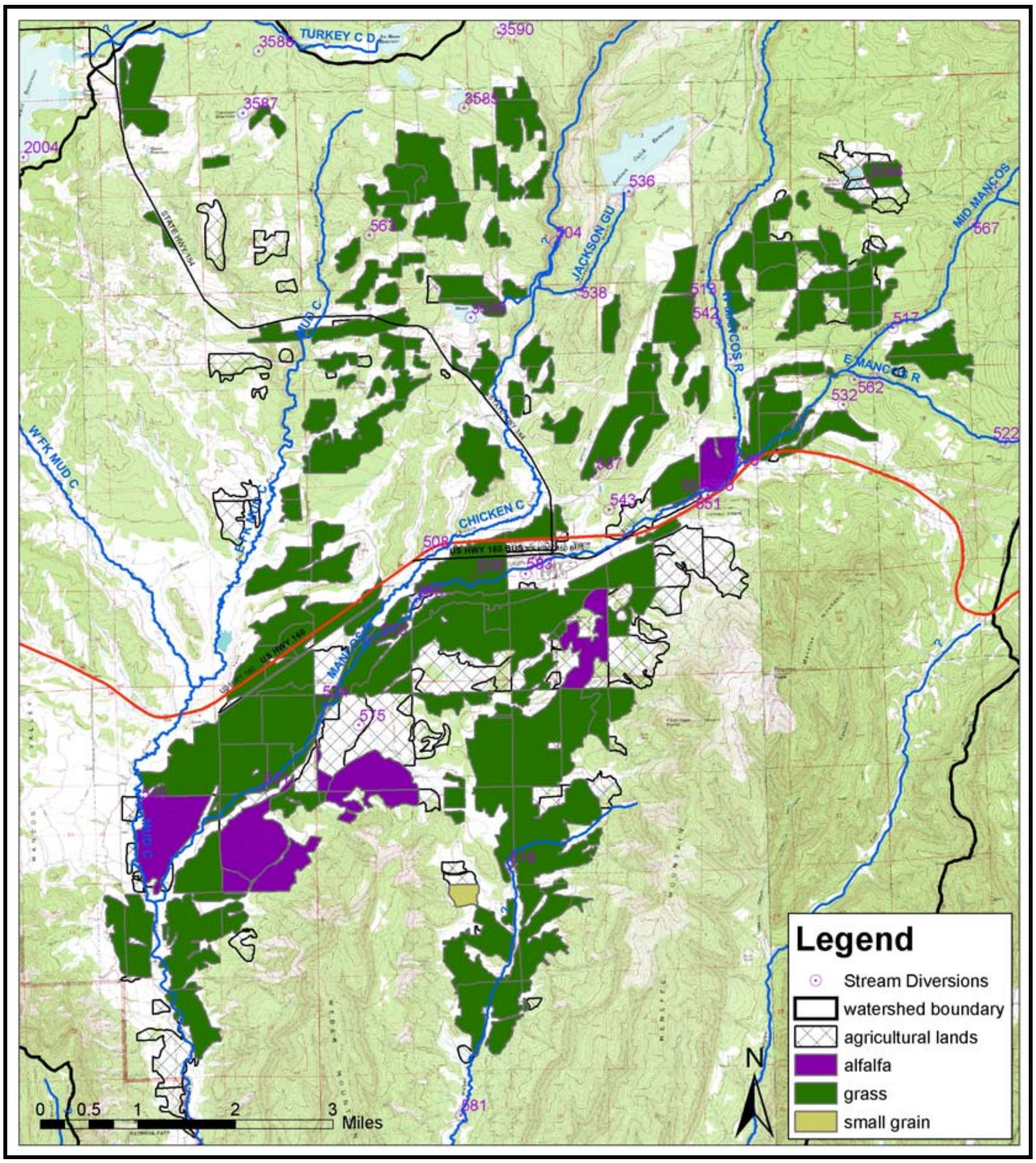

Figure 2: Agricultural land of the Mancos Valley, including numbered stream diversion locations. Agriculture data from US Bureau of Reclamation.

Table 1: Agricultural diversions from the Mancos River. The average volume diverted and depth diverted are for the years 1991 through 1995, which well reflect the precipitation range for the entire record. The symbol "----" indicates that no data is available.

ID	Name	Irrigated Area (acres)	Average Volume Diverted (ac-ft)	Average Depth Diverted (ft)
504	Bauer Reservoir No. 2 Inlet	----	1157	----
505	Beaver Ditch	238	1477	6.2
506	Boss Ditch	162	1056	6.5
508	Carpenter and Mitchell Ditch	367	705	1.9
513	Crader Ditch	----	399	----
514	Crystal Creek	332	896	2.7
517	Davenport Ditch	54	173	3.2
519	Doerfer Ditch	15	248	17.1
522	East Mancos Highline Ditch	----	719	----
524	Exon Ditch	66	369	5.6
525	Field Ditch	63	243	3.8
527	Frank Ditch	40	640	16.2
530	Giles Ditch	164	1180	7.2
531	Glasgow & Brewer Ditch	397	1503	3.8
532	Graybeal Ditch	38	99	2.6
534	Henry Bolen Ditch	478	2798	5.9
535**	Jackson Gulch Inlet	----	6629	----
537	Jim Beam Ditch	----	64	----
538	John Carter Ditch	159	511	3.2
542	Lee & Burke Ditch	281	946	3.4
543	Lee Ditch	330	807	2.4
544	Long Park Ditch	338	699	2.1
546	Mathews Ditch	193	0	0
551	No. 6, Nanna Spring and Seepage	----	----	----
552	No. 6 Ditch	344	1181	3.4
554	Retliff & Root Ditch	1806	4358	2.4
559	Robbins Ditch	10	94	9.4
562	Samson Ditch	69	144	2.1
563	Sellers Waste Water Ditch	34	102	3.0
565	Sheek Ditch	598	1932	3.2
566	Smith Ditch	139	367	2.6
567	Smouse Ditch	34	174	5.1
569	Spencer Ditch	292	0	----
575	Weaver Seepage Ditch	62	288	4.7
576	Webber Ditch	1700	5958	3.5
577	Weber Reservoir Inlet	116	753	6.5
581	Willden & Brinckerhoff Ditch	118	398	3.4
582	Williams Ditch	199	137	0.7
583	Willis Ditch	185	925	5.0
2004	Summit Irrigation System	289	0	0
3585	Bauer Reservoir No 1	846	207	0.2
3586	Bauer Reservoir No 2	620	941	1.5
3587	Coppinger No 1 Reservoir	17	0	0
3588	Coppinger No 2 Reservoir	30	0	0
3590	L A Bar Reservoir	153	36	0.2
3594	Weber Reservoir	310	423	1.4

** Jackson Gulch inlet diversions also accounted for in individual ditch systems during flow augmentation.

Geology

A geologic site visit was performed in May of 2002 by Bob Rasely, Geologist with the NRCS Utah State Office; Al Albin, Geologist with the NRCS Northern Plains Engineering Team; and Steve Yochum, Hydrologist with the NRCS Northern Plains Engineering Team. Bob Rasely's report on this visit (dated September 13, 2002) is provided in Appendix B.

A portion of the Colorado State Geologic Map, courtesy of the U.S. Geologic Survey (Tweto 1979), is provided in Figure 3.

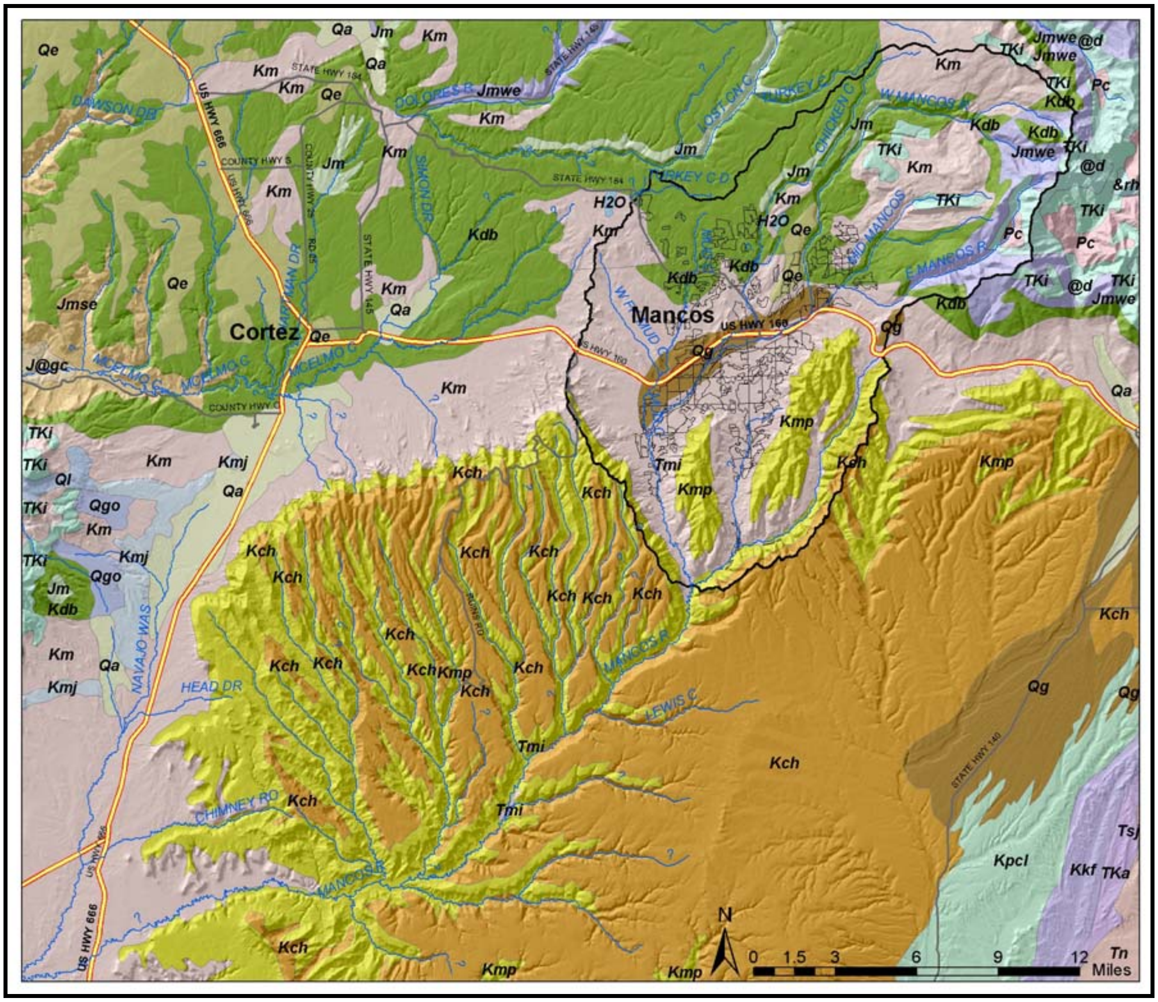

Figure 3: Geology in the vicinity of the Mancos River. Agricultural lands are shown within the Mancos watershed boundary. Qg – gravels and alluviums; Qe – eolian deposits; Tki – Laramide Intrusive Rocks; Km – Mancos Shale; Kdb – Dakota Sandstone and Burro Canyon Formation: Kch – Cliffhouse Sandstone; Kmp – Menefee Formation and Point Lookout Sandstone; Jmwe – Morrison, Wanakah, and Entrada formations (Tweto 1979).

A geologic description of the Mancos Valley, as quoted from Rasely's report in Appendix B, is provided:

> *The middle and lower portions of the watershed are underlain by salt bearing sedimentary rock units of the Mancos Shale (gypsum and sodium salts) and the Dakota Sandstone (calcium carbonate). The rocks in the watershed dip about 10 degrees to the south as is typical of the Colorado Plateau. The geomorphology is characterized by low lying hills of the more resistant Dakota Sandstone being overlain by erosive, salt laden, base of the Mancos Shale. There are low, gentle folds in the rock units and faults in the rocks. The axis of the folds is oriented north-south and the faulting is mostly in the middle watershed area. The faults have an uplift of a few hundred feet or less. These features are directly related to salt yield from the watershed. The folds and faults caused the uplifted lower Mancos Shale and Dakota Sandstone to be exposed multiple times in the watershed area.*
>
> *The Mancos Shale is dark gray and the Dakota Shale is red. Each exposure of a low hill of red sandstone had an exposure very salty, gray shale directly to the south of it for a few thousand feet. This relationship repeated throughout the middle and lower watershed area. It appears the lower portion of the thickness of the Mancos shale is extremely salty, while the units above it contain moderate or low levels of salt. The relationship of the red sandstone and gray salty shale is important to understanding the salt yield from the watershed.*

Soils

As detailed in the Mancos Valley Salinity Control Study of 1984 (SCS 1984), the soils of the agricultural portion of the valley can be grouped into three types: terraces and floodplains; alluvial fans; and hillsides and escarpments. The lower terraces and floodplains along the Mancos River and its tributaries have deep well-drained to moderately poorly drained soils. Much of this soil is formed in alluvium from various outflow events. Slopes range from 0 to 3 percent. The higher terraces are deep and well to poorly drained. They are formed in fine textured eolian material and alluvium. Surface textures are loam, clay-loam, and silty clay loam. Slopes range from 0 to 10 percent. The soils forming on the alluvial fans are deep and well-drained. They formed in fine textured alluvium derived from reworked eolian material and shale. Surface textures are clay loam, loam, and silty clay loam. Slopes range from 3 to 12 percent. The soils forming on hillsides and escarpments are shallow to deep, and well to poorly drained. They formed from alluvium and colluvium, dominated by shale, mudstone, and sandstone. Surface textures are variable and include rock fragments. Slopes range from 12 to 80 percent.

A soil conductivity map is provided in Figure 4. This map, derived from the NRCS Soil Survey (Natural Resources Conservation Service 2003), can be of use in identifying problem areas to concentrate effort in a salinity reduction program. It is important to note that this map only indicates surficial conditions. The alluvium that is abundant in the middle of the valley (Figure 3) may overlay additional problem zones. Any deep percolation that occurs would contact such zones and liberate available salts.

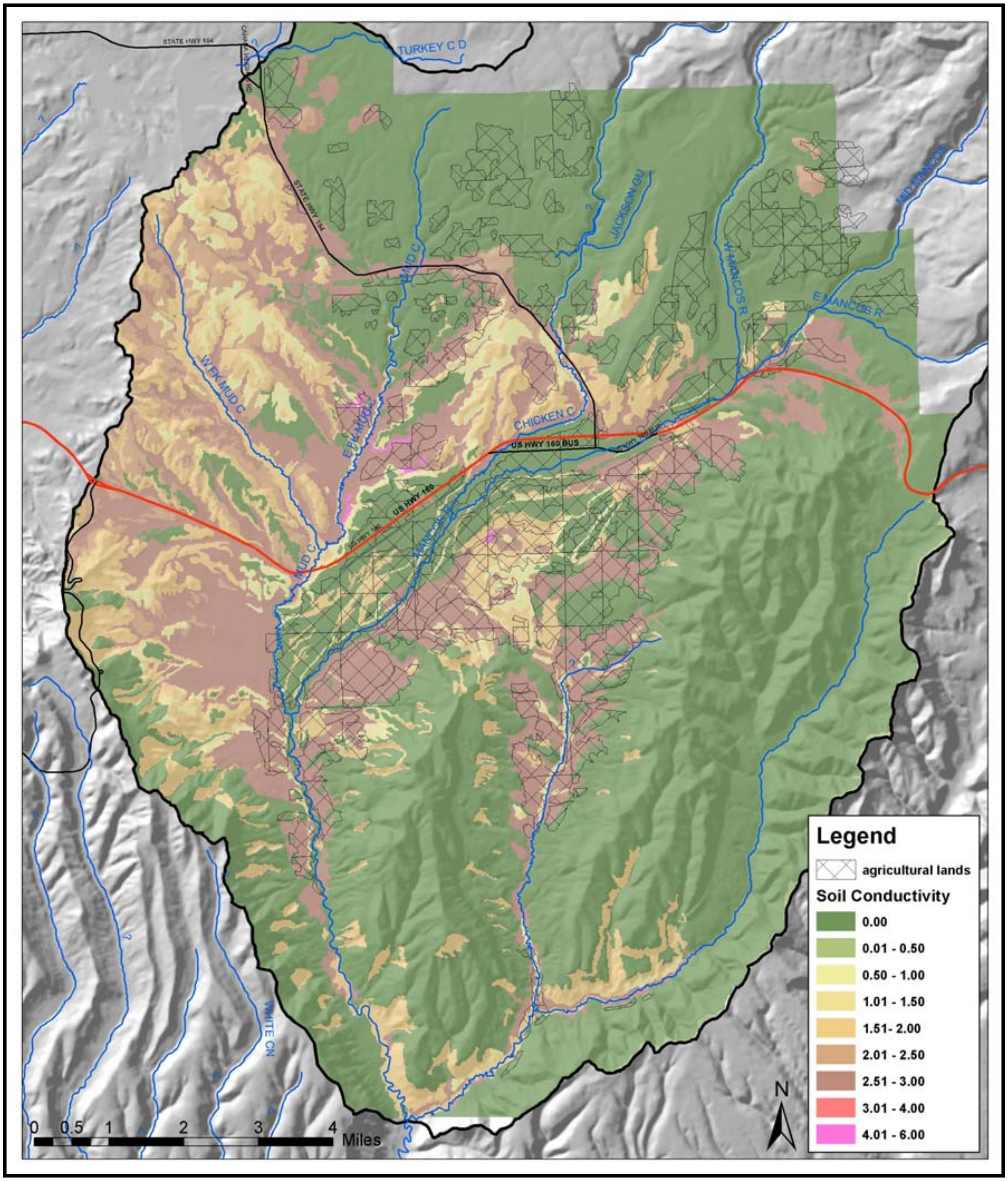

Figure 4: Soil conductivity of the Mancos Valley (in mmhos/cm). Watershed boundary and agricultural lands are also shown.

HYDROLOGY

The hydrologic analysis of the Mancos River consists of interpretations based upon existing water quantity and quality information and three synoptics performed in 2001. Two long-term streamgages exist on the river: the Mancos River at Mancos (currently operated by the Colorado Division of Water Resources, ID MANMANCO) and an additional gage on the Mancos, downstream of Mesa Verde, at Rt. 666 (operated by the USGS, ID 09371000). Water-quality information is available at both of these gages. Additionally, various agencies and the Ute Mountain Reservation have collected water-quality information throughout the area. To supplement these existing data, three synoptics were performed by NRCS. These data-gathering trips consisted of conductivity and temperature measurements for all three synoptics and discharge data for two of the synoptics. To tie the data into the Rt. 666 gage, the synoptic data was collected through the Mancos Canyon to the gage. Figure 5 indicates the locations of the streamgages and synoptic measuring points.

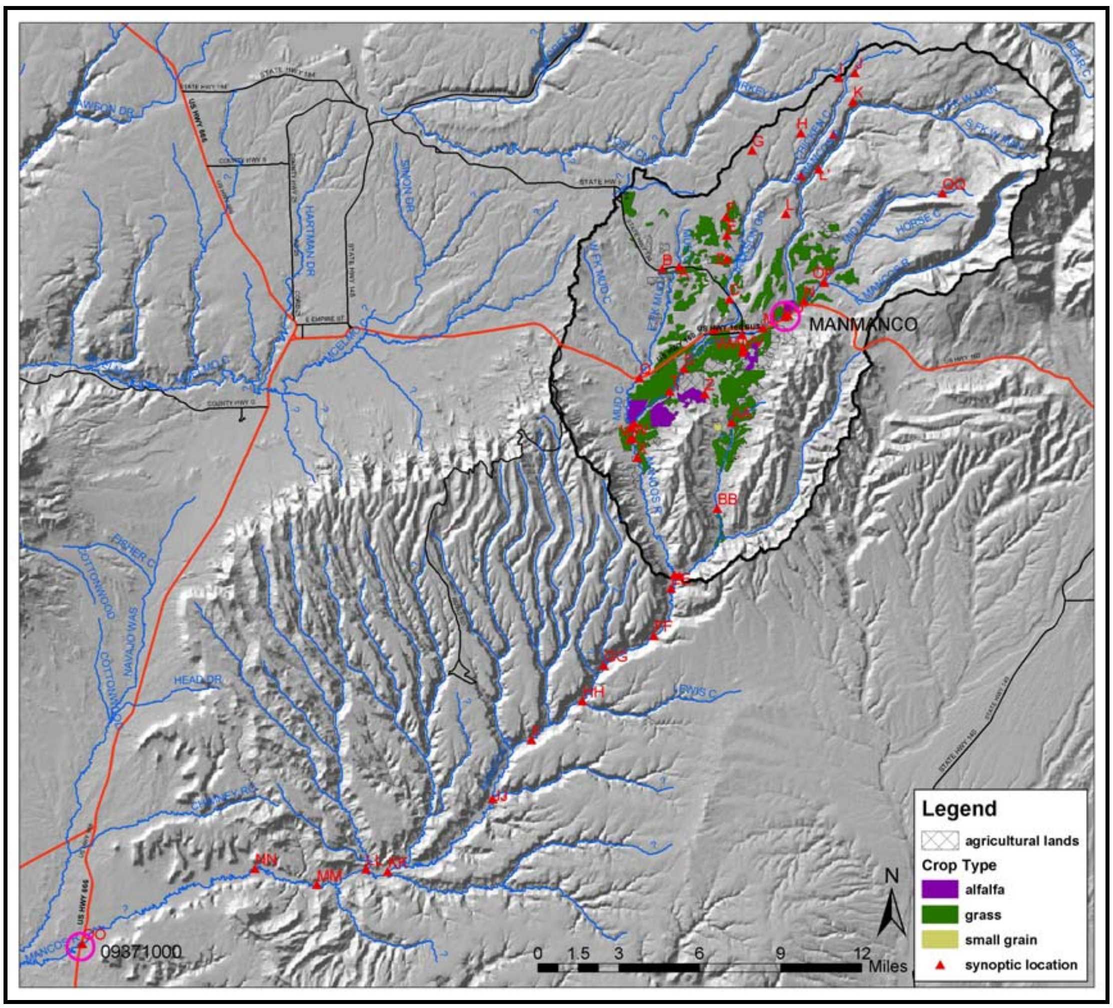

Figure 5: Locations of water quantity and quality data gathering points. Triangles indicate NRCS synoptic locations, some of which have additional data from other agencies and tribes. The two long-term gaging stations are circled. A larger version of this figure has been provided in Appendix A.

Streamgage Data

The Mancos River at Rt. 666 gage has the most information available for quantifying salt loading from the Mancos Valley. This gage has been operated continuously from 1951 to present. Its drainage area is 526 square miles, with the Mancos Valley contributing 203 square miles. The intervening drainage area is relatively dry, with average precipitation ranging from 9 to 21 inches, in comparison to the 15 to 41 inches of the upper Mancos watershed (Figure 1).

The statistics of flow at the Rt. 666 gage are provided below:

- Mean daily mean discharge = 48 cfs
- Median daily mean discharge = 16 cfs.
- Maximum daily mean discharge = 1890 cfs on 9/6/1970.
- Minimum daily mean discharge = 0 cfs, with 2,321 occurrences in 25,749 days of record (9.0 %), occurring from May through November.

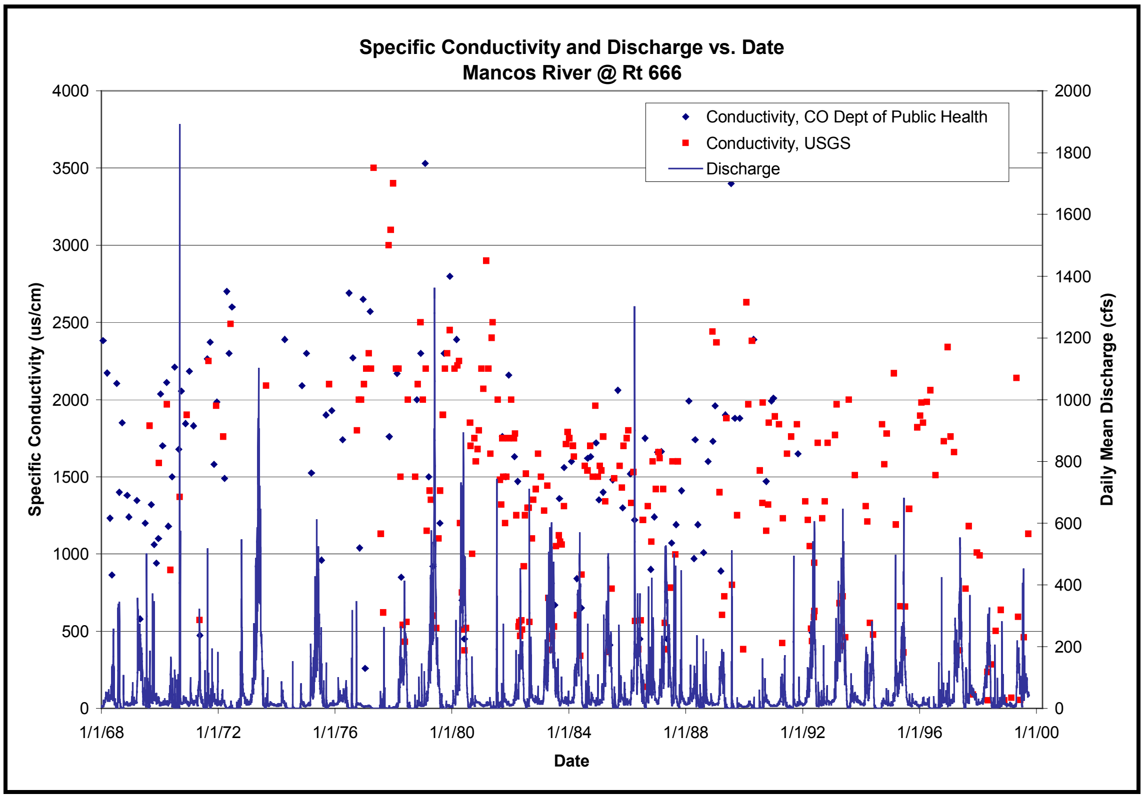

Figure 6: Specific Conductivity and Discharge of the Mancos River at Rt. 666 gaging station.

Water quality data at the Rt. 666 gage, collected by the USGS and the Colorado Department of Health and Environment, consists of approximately 400 field measurements and water sample analyses. Field measurements typically consisted of temperature and conductivity and at times also included pH and dissolved oxygen. Water sample analyses consisted of many parameters, including conductivity, pH, alkalinity, total dissolved solids, major ions, common dissolved metals, and occasionally such parameters as selenium and uranium. Discharge and conductivity measurements are provided in Figure 6.

The gage on the Mancos River at Mancos, currently operated by Colorado Department of Natural Resources (ID MANMANCO) and historically operated by the USGS (ID 09370000), has been operated intermittently from 1931 to present. It has a drainage area of approximately 72 square miles. The statistics of flow for the available record are provided below:

- Mean daily mean discharge = 41.6 cfs
- Median daily mean discharge = 9.7 cfs.
- Maximum daily mean discharge = 1040 cfs on June 15, 1975.
- Minimum daily mean discharge = 0 cfs, with 72 occurrences in 12,446 days of record (0.6%).

It is notable that despite the much smaller drainage area of the Mancos River at Mancos compared to the Rt. 666 gage (72 square miles versus 526 square miles), the mean and median discharges are relatively close in magnitude and the Mancos gage has much less frequent periods of zero surface flow (0.6 versus 9.0 percent). This is likely due to the drier lower portions of the Rt. 666 watershed and the large proportion of the upper water yield being used for irrigation.

Several other gages have been periodically established within the region of interest. These gages have been located on the West Mancos River near Mancos (09368500), the East Mancos River near Mancos (09369000), the Middle Mancos River near Mancos (09369500), the Mancos River near Cortez (09370800), and the Mancos River below Johnson Canyon (09370820). Water quality data have been collected at these locations as well as numerous other sites within the stream system. The constituents analyzed for are similar to those described at the Rt. 666 gage.

Total Dissolved Solids and Major Ion Distribution

Total dissolved solids analyses were performed by the U.S. Geological Survey and the Colorado Department of Health for the Mancos River at Mancos and the Mancos River at Rt. 666 gages. At the Mancos River at Mancos site, the raw (non-weighted) mean is 237 mg/l and the median is 230 mg/l. At the Mancos River at Rt. 666 site, the raw mean is 1425 mg/l and the median is 1345 mg/l. This represents an increase in average total dissolved solids concentration of 500% within this extensive reach.

According to U.S. Geological Survey data at the Mancos River at Rt. 666, typical total dissolved solids content is primarily composed of (in order of highest to lowest contribution) sulfate, calcium, sodium, magnesium, chloride, and potassium. As an example, a sample was collected on July 17, 1990 and was found to have a total dissolved solids content of 1260 mg/l. Dissolved solids content is primarily composed of major ions, which were found to be: 740 mg/l sulfate, 160 mg/l calcium, 87 mg/l sodium, 64 mg/l magnesium, 9.2 mg/l chloride, and 6.1 mg/l potassium.

National Park Service data near the downstream limit of the valley indicates that water leaving the valley has a similar major ion composition to the USGS gaging station.

According to Colorado Department of Health data, the chemistry of the Mancos River at Mancos is a bit different than the two downstream sites. (The Mancos River at Mancos sampling station is upstream of much of the irrigated cropland.) These waters have a much smaller amount of sulfate in the water, with calcium typically having a higher concentration. Also, there is typically more magnesium than sodium in these waters. As an example, a sample was collected on May 7,1980 and was found to have a total dissolved solids concentration of 180 mg/l with major ion concentrations of 92 mg/l total calcium, 45 mg/l total sulfate, 14 mg/l dissolved chloride, 8 mg/l total magnesium, and 5 mg/l total sodium.

Selenium Concentrations

Selenium measurements have been made on samples collected at the Mancos River at Rt. 666 and the Mancos River at Mancos gages, as well as at a number of additional locations within the basin. The Mancos River at Rt. 666 gage has 75 measurements, with a maximum of 12 ug/l and the majority of the data indicating non-detectable concentrations. (The Colorado State Water Quality Control Commission has designated a chronic criteria of 5 ug/l while the EPA's drinking water maximum contaminant level is 50 ug/l.) The Mancos River at Mancos has 24 measurements, with a maximum of 5 ug/l and the majority of the data indicating non-detectable concentrations. A few data points exist for the Mud Creek sub-basin. A spring near the Mesa Verde National Park, near the basin divide, has consistently shown high levels in the 8 samples collected. Concentrations range from 12 to 104 ug/l. Additionally, two other data points, one on the main stem of Mud Creek and another on a tributary, have concentrations of 53 ug/l and 31 ug/l, respectively in March of 1994.

Total Dissolved Solid Concentration Estimates from Specific Conductivity

Specific conductivity was used in this study to estimate total dissolved solids concentration. Regression equations were generated from concurrent conductivity and total dissolved solids measurements made at the Mancos River at Mancos (1971 through 1992, 99 data points) and the Mancos River at Rt. 666 data (1969 through 1992, 113 data points). The equation used to estimate total dissolved solids is a composite of two regression equations: one for higher concentrations and another for lower concentrations. Higher concentration data was from the Rt. 666 site and lower concentration data was from the Mancos site. Specifically, conductivity data for the Mancos and Rt. 666 sites ranged from 150-890 us/cm and 410 to 3530 us/cm, respectively. The equations are as follows:

- If conductivity < 601.85: TDS = $-11.4924 + 0.6932(\text{cond.})$, $R^2 = 0.94$
- If conductivity $>= 601.85$: TDS = $-186.1499 + 0.9834(\text{cond.})$, $R^2 = 0.92$

This equation was verified by comparing computed total dissolved solid concentration with actual values at the Rt. 666 gage. This comparison showed an average error of 9.6 percent and median error of 7.7 percent. Such an error was considered reasonable for this study.

Synoptics

To gain a greater understanding of how location within the watershed impacts basic stream chemistry and discharge, three synoptics were performed. These synoptics were all performed within two day periods, providing a snapshot of the hydrology of the basin at three times of year, in the spring, summer and autumn of 2001. Measurements were limited to conductivity (total dissolved solids), water temperature, and discharge. Synoptics are useful in defining the location of sources and sinks of flow and salt within a watershed, illuminating details of hydrologic processes expected with knowledge of the geology and soils of the watershed. Stream lengths (not valley length) were used to compute the total dissolved solids gradients. These gradients were computed between each of the main stem synoptic sampling sites. Such a method was helpful to illuminate both irrigation-related and natural salinity sources, since measurements were taken upstream, within, and downstream of the agricultural lands.

Measurements gathered during these three synoptics are provided in Appendix A, along with two detailed figures illustrating measurement locations. In addition to the data gathered in these three synoptics, the conductivity and temperature data gathered by NRCS from 1978 to 1981 are also provided.

Synoptic 1

Conductivity and temperature were measured at forty-one sites throughout the Mancos Valley and Canyon, to the Rt. 666 USGS monitoring station (to tie-in to the extensive data at this gage). This synoptic was conducted during spring runoff season, on May 8 and 9, 2001. The weather was sunny with temperatures ranging from 70-85 degrees F. Approximately 3 inches of snow fell upon portions of the watershed four days before the synoptic.

The synoptic crew consisted of Steve Yochum, Hydrologist; and Dalton Montgomery, District Conservationist. Equipment consisted of a Corning 316 conductivity meter (calibrated @ 0 & 1413 us/cm) and a Garmin GPS III Plus unit.

Figure 7 provides the concentration gradients for synoptic 1. Agricultural lands, generalized geology, and soil conductivity measurements are also provided in this figure.

Conductivity measurements ranged from 63 to 2710 us/cm (32 to 2480 mg/l), with main stem Mancos River conductivity ranging from 73 to 713 us/cm (39 to 515 mg/l). These main stem values are a bit low in comparison to measurements made in synoptics 2 and 3. This is likely due to dilution from spring flow. Mud creek, whose basin does not typically accumulate a snow pack, had concentrations ranging from 1043 to 2800 us/cm (840 to 2570 mg/l). Webber drainage, which also doesn't normally accumulate a snow pack, had concentrations ranging from 595 to 1770 us/cm (400 to 1550 mg/l). The peak 2710 us/cm measurement reflects an irrigation return flow at site Z. During this synoptic, salts were predominantly entering the creek along the lower elevation agricultural lands in the Mud Creek basin, the Mancos River downstream of Mancos, and lower Webber drainage. This is where irrigation return flow would be expected. During this synoptic, salts were also picked up along the Mancos River from the lower end of the valley to Rt. 666, with conductivity increasing from 446 to 713 us/cm (300 to 520 mg/l).

The upper Weber drainage was found to be flowing at site AA at the Doerfer driveway, which was a bit surprising considering the dry condition of the adjacent and larger watershed of East Canyon. It appears that the Weber drainage flow was from irrigation return flow and ditch wasteway flows. Concentration of this flow was 400 mg/l during this synoptic.

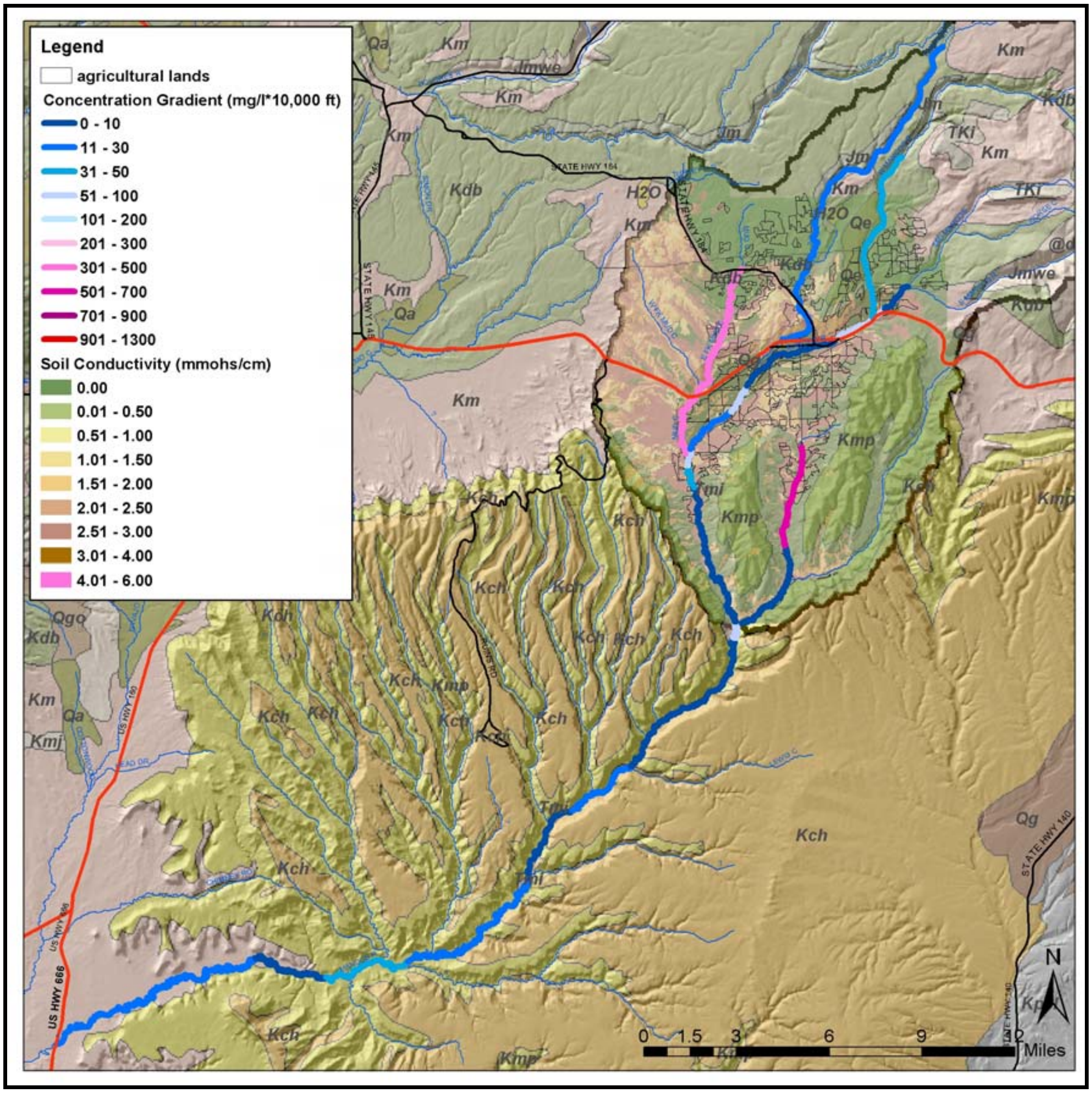

Figure 7: Synoptic 1 salinity concentration gradients. Soil conductivity and generalized geology are also provided. Qg – gravels and alluviums; Km – Mancos Shale; Kdb – Dakota Sandstone and Burro Canyon Formation (Tweto 1979).

Synoptic 2

Conductivity and temperature were measured at forty-four sites throughout the Mancos Valley and Mancos Canyon, to the Rt. 666 USGS monitoring station. (Five of these sites were dry at the time of sampling.) Discharge was also measured at a number of the sites. This baseflow synoptic was conducted during the summer, from August 7 to August 8, 2001. The weather was partly cloudy, with temperatures from 70-85 degrees F. Thunderstorms occurred during the afternoon and evening of August 6th in the general area. Mild to moderate rain also occurred in the general area during the afternoon of August 7th. The synoptic crew consisted of Steve Yochum, Hydrologist; and Dalton Montgomery, District Conservationist, and Phil Alcon, Hydrological Technician,

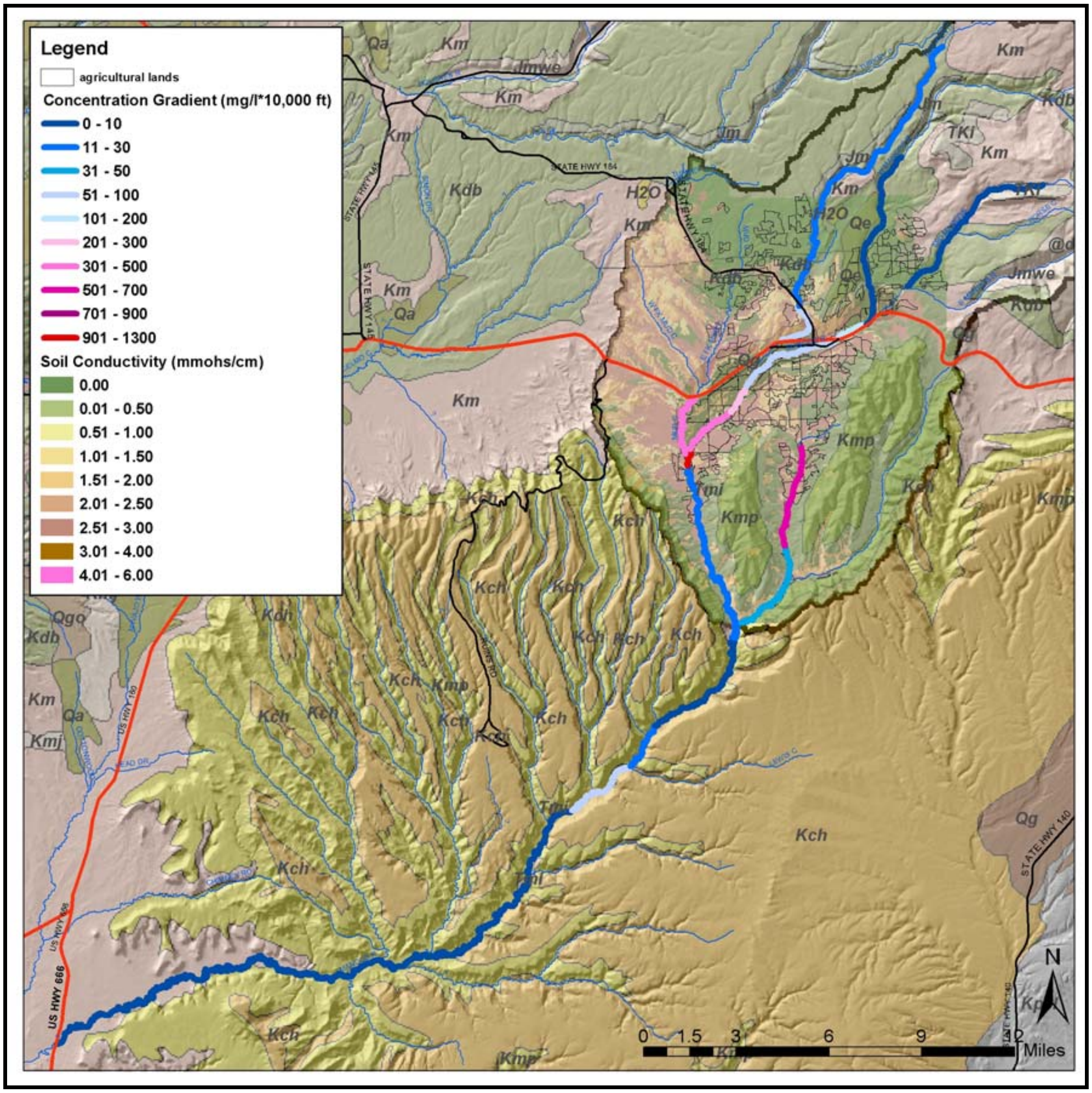

Figure 8: Synoptic 2 salinity concentration gradients. Soil conductivity and generalized geology are also provided. Qg – gravels and alluviums; Km – Mancos Shale; Kdb – Dakota Sandstone and Burro Canyon Formation (Tweto 1979). Figure 10 provides a detail of the Mancos Valley.

U.S. Bureau of Reclamation. Equipment consisted of a YSI 30 conductivity meter (calibrated at 1000 us/cm), a Garmin GPS III Plus, and streamgaging equipment.

Figure 8 provides the concentration gradients for synoptic 2. Agricultural lands, generalized geology, and soil conductivity measurements are also provided in this figure.

Conductivity measurements ranged from 107 to 2562 us/cm (63 to 2333 mg/l), with main stem Mancos River conductivity ranging from 165 to 1755 us/cm (103 to 1540 mg/l). Mud creek had conductivity ranging from 1398 to 1966 us/cm (1190 to 1750 mg/l), with the upper most synoptic site being dry and flow of 3.6 cfs at the mouth. This flow and concentration represents a significant salt load, with an instantaneous mass flux of 11,300 kg/day. Webber drainage had concentrations ranging from 940 to 1708 us/cm (740 to 1490 mg/l), with flow at the mouth of 3.1 cfs and an instantaneous load of 11,330 kg/day).

Mancos River discharge ranged from 21.3 cfs at the gaging station (with an instantaneous salt load of 5980 kg/day), 10.2 cfs at Mancos (5410 kg/day), 5.1 cfs upstream of the Mud Creek confluence (12,200 kg/day), 11 cfs downstream of Webber drainage (38,060 kg/day), and 9.0 cfs upstream of the Ute Mountain diversion upstream of Rt. 666 (12,600 kg/day). Hence, during this synoptic salt loading on the Mancos River increased from 5400 to 38,800 kg/day between Mancos and the end of the Mancos Valley. This salt loading increase, which should be mostly from baseflow and direct irrigation return flow, represents a 620 percent increase in salts, with the upper baseflow load only representing 14 percent of the load at the end of the Valley.

The salinity concentration gradients indicate that salts were predominantly entering the creek along the lower elevation agricultural lands in the Mud Creek basin, the Mancos River downstream of Mancos to approximately the limit of irrigated agriculture, and the lower Webber drainage. These concentration gradients also indicate that the Mancos Shale underlying the alluvium of the central Mancos Valley (Figure 3) may be a significant source of salt. Deep percolation in this area may be a problem even though the soil salinity is minimal (Figure 4).

A hypothesis that most of the baseflow salt loading is contributed from irrigated agriculture is supported by findings of high salinity gradients and substantial increases in salt loading at such locations. Surface, shallow and deep irrigation return flow would be expected at just such locations.

Stream baseflow contributions along drier lower stream reaches with adjacent irrigated agriculture can be considered deep percolation return flow. These baseflow contribution concentrations were computed using a stream segment mass-budget method. For reach PP-M on the Mancos River just upstream of Mancos, a concentration of 1150 mg/l was computed. For reach S-Y on the Mancos River just above the Mud Creek confluence, a concentration of 3000 mg/l was computed. The return flow spring near the town of Weber (site Z) indicates likely diluted flow of 929 mg/l when compared to the 2480 mg/l of synoptic 1 and the results from synoptic 3. Combined with the salinity gradients of Figure 8, these computations and measurements indicate a moderate salt source zone above the town of Mancos and a moderate to severe salt source zone near the confluence of Mancos and Mud Creeks and in the upper Webber drainage.

The upper Weber drainage was found to be flowing again, supporting the hypothesis that flow in this drainage is from irrigation return flow and ditch wasteway flows. Concentration of this flow was 740 mg/l during this synoptic.

Fundamental to the appropriateness of a baseflow synoptic is verifying that it is actually measuring baseflow conditions, with little to no surface runoff. This criteria can be difficult to meet during Southern Colorado's summer monsoon season. As mentioned above, some rain occurred in the general area the day before and during the synoptic. However, if such rain generated significant runoff during the synoptic, this should have shown up in the data as a substantial increase in flow and decrease in salinity at some point. Such a peak was not found, instead a gradual increase in flow and salinity was measured in areas where irrigation return flow was expected. The Rt. 666 gage was also monitored to look for a passing flow wave. From August 7 at 2300 to August 9 at 0630 there was little change in flow noted, indicating baseflow conditions. A rapidly rising (in 15 minutes) peak flow of 322 cfs did pass through this gage early (0215) on August 7th, but such a large flow had no sign in the synoptic in the upper basin, indicating that this event occurred in the lower watershed or passed though the upper watershed in advance of the synoptic measurements. A much smaller peak of 40 cfs also occurred on August 9th at 0700 but this peak is also greater than any flows measured in the lower watershed the previous day. This event likely occurred after the synoptic. Hence, this synoptic has likely measured predominantly baseflow conditions, but there is a bit of uncertainty in such a claim. Due to this uncertainty, conclusions drawn from this synoptic should be verified with the results from another synoptic (synoptic 3).

It is not known what processes were causing the flow, load, *and* salt concentration to decrease along the Lower Mancos River, from the bottom of the Valley to Rt. 666. The salt concentration decreasing while flow decreased is especially odd. The extensive stands of Tamarisk along this reach on a hot, sunny summer day may have something to do with this (due to transpiration), but this suggestion is pure conjecture.

Synoptic 3

Conductivity and temperature were measured at fifty-one sites throughout the Mancos Valley and Mancos Canyon, to the Rt. 666 USGS monitoring station. (Seven of these sites were dry at the time of sampling.) This baseflow synoptic was conducted from November 14th to 15th, 2001 after irrigation ceased. However, some ditches still had flowing water, probably due to headgate leakage and stock water runs. Scattered thunderstorms occurred during the afternoon of November 13th. The weather was partly cloudy on the days of the synoptic. On November 14th, Cortez had a high of 60 degrees and a low of 29 degrees. Mesa Verde had a high of 54 degrees and a low of 30 degrees, with trace of precipitation. On November 15th, Cortez had a high of 63 degrees and a low of 28 degrees. Mesa Verde had a high of 59 degrees and a low of 31 degrees. The synoptic crew consisted of Steve Yochum, Hydrologist; and Casey Sheley, Soil Conservationist; and Phil Alcon, Hydrological Technician, US Bureau of Reclamation. Equipment consisted of a YSI 30 conductivity meter (calibrated at 1000 us/cm), a Garmin GPS III Plus, and streamgage equipment.

Figure 9 provides the concentration gradients for synoptic 3. Agricultural lands, generalized geology, and soil conductivity measurements are also provided.

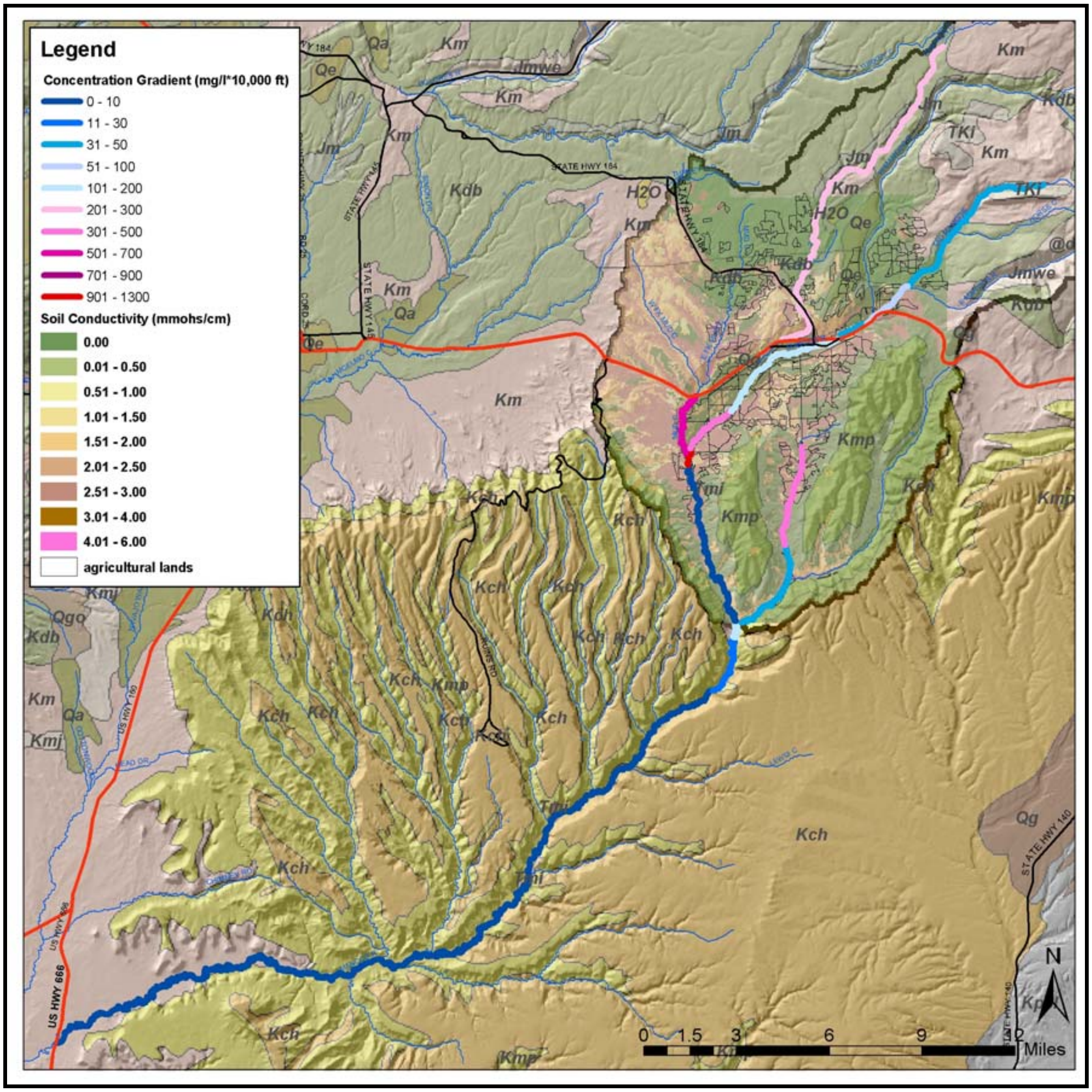

Figure 9: Synoptic 3 salinity concentration gradients. Soil conductivity and generalized geology are also provided. Qg – gravels and alluviums; Km – Mancos Shale; Kdb – Dakota Sandstone and Burro Canyon Formation (Tweto 1979).

Conductivity measurements ranged from 110 to 3028 us/cm (65 to 2790 mg/l), with main stem Mancos River conductivity ranging from 360 to 1746 us/cm (238 to 1531 mg/l). Mud creek had conductivity ranging from 2201 to 3028 us/cm (1978 to 2792 mg/l), with the upper most synoptic site being dry and flow of 1.5 cfs at the mouth. This flow and concentration represents a significant salt load, with an instantaneous mass flux of 10,500 kg/day. Webber drainage had concentrations ranging from 1012 to 2096 us/cm (810 to 1880 mg/l), with flow at the mouth of 2.3 cfs and an instantaneous load of 10,300 kg/day.

Mancos River discharge ranged from 2.8 cfs at the upper gaging station (with a concentration of 300 mg/l and an instantaneous salt load of 2070 kg/day), 3.1 cfs at Mancos (320 mg/l, 2390 kg/day), 4.5 cfs upstream of the Mud Creek confluence (990 mg/l, 11,000 kg/day), 10.9 cfs downstream of Webber drainage (1500 mg/l, 39,900 kg/day), and 8.7 cfs upstream of the Rt. 666 gaging station (1520 mg/l, 32,300 kg/day).

Hence, during this synoptic salt loading on the Mancos River increased from 2070 to 39,900 kg/day between Mancos and the end of the Mancos Valley. This salt loading increase, which should be mostly from baseflow and direct irrigation return flow, represents a 1830 percent increase, with the upper baseflow load only contributing 5 percent of the load at the end of the Valley (excluding upper Chicken Creek).

The lowest discharge location shows the stream was losing water to subsurface flow in at least a portion some of the lower reaches. This flow either reappeared above the gage to produce 13 cfs, as recorded by USGS, or the rating curve at low flow is inaccurate.

The salinity concentration gradients shown in Figure 9 indicate that salts were predominantly entering the creek along the lower elevation agricultural lands in the Mud Creek basin, the Mancos River downstream of Mancos to about the limit of irrigated agriculture, and the lower Webber drainage. As in synoptic 2, these concentration gradients also indicate the Mancos Shale underlying the alluvium of the central Mancos Valley (Figure 3) may be a significant source of salt. Deep percolation in this area may be a problem even though the soil salinity is minimal in this area (Figure 4).

The hypothesis that most of the baseflow salt loading is contributed from irrigated agriculture is supported by substantial increases in salt loading and high salinity gradients at such locations. Surface, shallow and deep irrigation return flow would be expected at just such locations.

Stream baseflow contributions along dry lower stream reaches with adjacent irrigated agriculture can be considered deep percolation return flow. These baseflow contribution concentrations were computed using a stream segment mass-budget method. For reach PP-M on the Mancos River just upstream of Mancos, a concentration of 320 mg/l was computed, which is considerably lower than the 1150 mg/l computed in synoptic 2. The synoptic 3 value may have been tainted by unidentified direct return flow from a diversion headgate leak or stock run. For reach S-Y on the Mancos River just above the Mud Creek confluence, a concentration of 3540 mg/l was computed, which compares well with the 3000 mg/l computed in synoptic 2. Chicken Creek reach C-R just north of Mancos indicates a return flow concentration of 1830 mg/l. Mud Creek reach Q-U just upstream of the Mancos River confluence indicates a concentration of 3370 mg/l. The Mancos River reach FF-HH just downstream of the valley indicates a return flow concentration of 1560 mg/l. The return flow spring near the town of Weber (site Z) had a measured concentration of 3070 mg/l, which compares well with concentration of 2480 mg/l during synoptic 1. Combined with the salinity gradients of Figure 8, these computations and measurements indicate a moderate salt source zone above the town of Mancos and a moderate to severe salt source zone near the confluence of Mancos and Mud Creeks and in the upper Webber drainage.

The upper Weber drainage was found to be flowing again, again supporting the hypothesis that flow in this drainage is from irrigation return flow and ditch wasteway flows. Concentration of this flow was 810 mg/l during this synoptic.

Several irrigation ditch leakage rates were measured for Crystal Creek Ditch in the National Forest as well as a ditch just southeast of Mancos. Rates of leakage of 0.11 and 0.18 $ft^3/day/ft^2$ were measured for Crystal Creek Ditch and 0.16 $ft^3/day/ft^2$ for the lower ditch.

Synoptic 3 was performed over two days. To assure connectivity between the two days of record, site DD (Mancos River just upstream of the confluence with Weber) was measured on both days. Discharge was measured to be 9.84 cfs on November 14th at 1400 and 9.90 cfs on November 15th at 1215.

Fundamental to the appropriateness in the use of baseflow synoptic data is that it is actually measuring baseflow conditions, with little to no surface runoff. As mentioned above, some rain occurred in the general area the day before and during the first day of the synoptic. If such rain generated significant runoff during the synoptic this should have shown up in the data as a substantial increase in flow and decrease in salinity at some point. Such a peak was not at all apparent and instead a gradual increase in flow and salinity was measured in areas where irrigation return flow was expected. The Rt. 666 gage was also monitored to look for a passing flow wave. From at least 2400 on November 12th to 0300 on November 19th, flow maintained a consistent magnitude at this gage. This indicates that this synoptic was performed during a true baseflow condition. Also, the general agreement of the results of this synoptic with synoptic 2 indicates that synoptic 2 was generally performed during a baseflow condition.

General Synoptic Interpretations

The 2001 synoptics provided conductivity values ranging from 63 to 3306 us/cm, which reflect computed total dissolved solid (salinity) values of 32 to 3070 mg/l. The results from the earlier synoptics indicate a similar range, with an notable exception of Mud Creek and Weber Drainage, which had peaks of 6500 us/cm (May 13, 1981) and 4000 us/cm (April 22, 1981), respectively. A summary of the measurements are provided in Table 2. The data are provided in Appendix A.

The differences between the upper North Fork of Mancos and Chicken Creek with the upper East and Middle Forks of the Mancos River are interesting. All four of these watersheds indicate Mancos Shale within their upper reaches. This shows that either these different portions of the Mancos contain different levels of salts, or that some other process is occurring.

Chicken Creek near Mancos typically shows high salinity during periods of low flow (Autumn and Winter) and low salinity levels during periods of high flow (Spring and Summer). This variation is expected with spring and summer snowmelt and rain events. The baseflow (high) levels do indicate significant salt contribution in the Lower Chicken Creek.

The Mancos River near Mancos reach shows less variability and lower concentrations than the Chicken Creek near Mancos reach. The higher concentrations again occurred during the Autumn and Winter periods while lower concentrations were prevalent during the Spring and Summer periods. Interestingly, the Mancos River near Mancos and the Upper East and Middle Forks of the Mancos show similar variability and range in salt concentration, which may indicate that salts in this reach may be predominantly from the upper watershed. In any case, the consistently lower baseflow salinity concentrations in this reach (than Chicken Creek) show that the agricultural land above and along this reach contribute much less salt load to the system.

Table 2: Summary (ranges) of synoptic measurements. Cond. = Conductivity, Conc. = Concentration.

Description of Reach	Synoptics 1-3		older NRCS synoptics (1978-'81)	
	Cond. us/cm	Conc. mg/l	Cond. us/cm	Conc. mg/l
North Fork of Mancos River and Chicken Creek, near National Forest Boundary(1)	67 - 165	35 - 103	----	----
Upper East and Mid Forks of the Mancos River, near National Forest Boundary	165 - 530	103 - 360	----	----
Chicken Creek near Mancos	190 - 1966	120 - 1750	145 - 2700	110 - 2470
Mancos River near Mancos	182 - 562	115 - 378	120 - 1160	72 - 960
Mancos River between Mud and Chicken Creeks	206 - 1197	130 - 990	150 - 2000	92 - 1780
Mud Creek	895 - 3028	690 - 2790	115 - 6500	68 - 6210
Webber Drainage	595 - 2096	401 - 1875	2000 - 4000	1780 - 3750
Mancos River in Canyon, downstream of Valley to Rt. 666	446 - 1746	300 - 1530	----	----

(1) the Chicken Creek site was higher in the watershed, due to access problems

The Mancos River between the Chicken Creek and Mud Creek confluences exhibit high variability in concentration, again reflecting dilution by snowmelt and rain events. The three sites in this reach were measured by all synoptics (new and old) for a total of 87 measurements. Averages computed for each site show steadily increasing concentrations, specifically 519 mg/l at site S, 741 mg/l at site T and 941 mg/l at site Y. The high and steadily increasing concentrations indicate that this reach is a primary receiver of salt in the Mancos Valley. This would likely be due to the prevalence of irrigated agriculture (and return flow) along this reach and the content of salt in the soils and underlying geology in the vicinity of this reach.

Mud Creek measurements indicate very high salt concentrations within this watershed. Typically, there is low variability in measurements at individual sites indicating that little baseflow dilution occurs. Two of the four sites in this reach were measured by the earlier synoptics for a total of 60 measurements within this watershed. Averages for the two sites with the most data (Q, U) show average salt concentrations of 1290 and 2740 mg/l, respectively. These high averages, especially at the lowest most Mud Creek sampling site (U), indicate that Mud Creek is a primary source of salt in the Mancos Valley. As discussed earlier, this watershed may also be a significant source of selenium.

Webber drainage measurements indicate consistently high salt concentration, with relatively little variability at individual sites. The most downstream site, which has 30 recorded measurements, has a range of 1493 to 3750 mg/l of total dissolved solids and average of 2310 mg/l. It appears that little natural baseflow dilution occurs in this drainage. When comparing this drainage to East Canyon (to the immediate east), which has a larger drainage area but only intermittent flow, the perennial flow in this drainage appears to be most likely artificial, with ditch wasteway and return flow supplying the discharge. Variation in the measurements may be due to availability of wasteway flow to dilute return flow. The high concentrations of the return flow indicate that Weber drainage drains a zone of irrigation occurring on salty soils and geologic units.

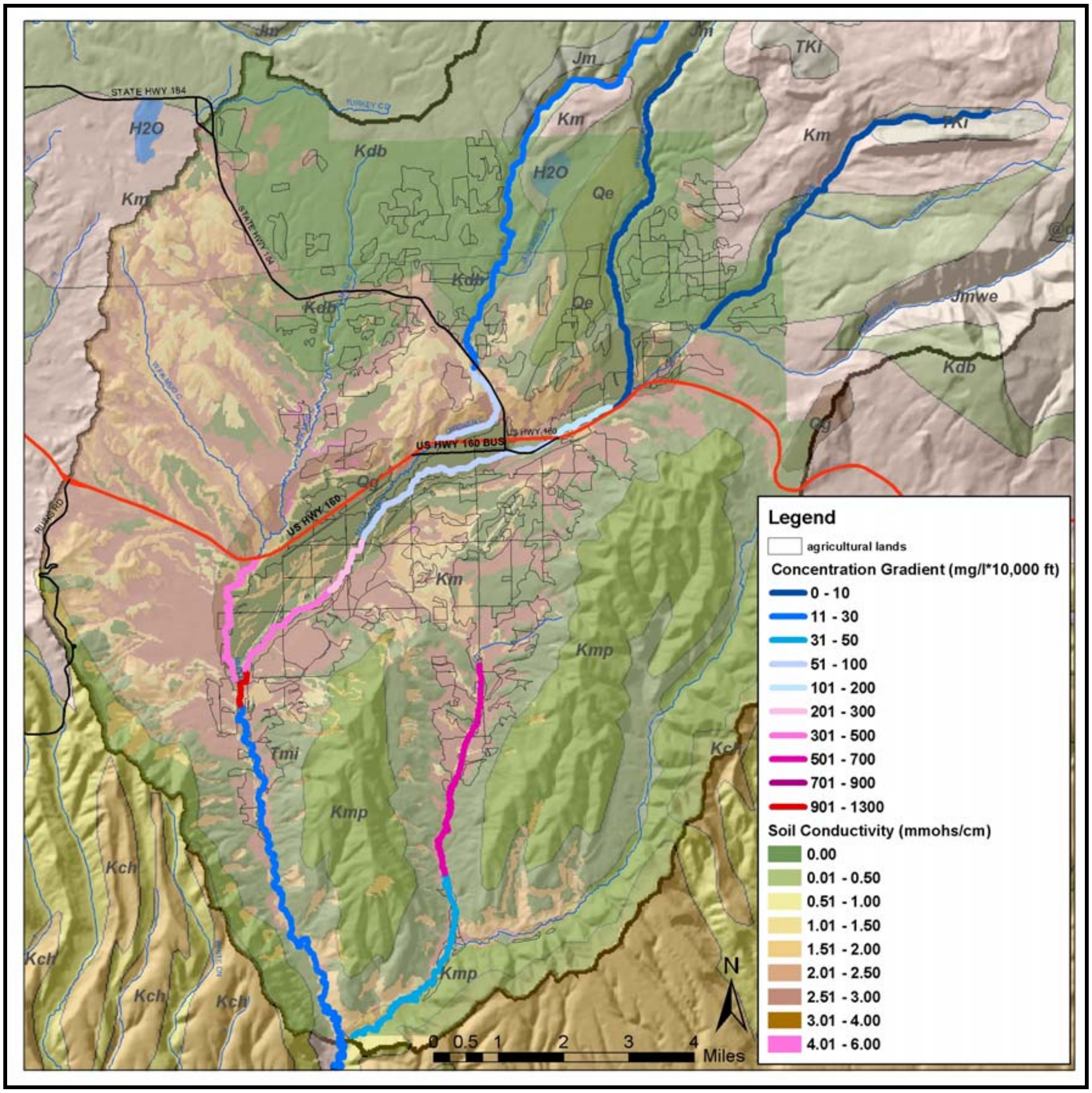

Figure 10: Synoptic 2 salinity concentration gradients detail. (Thin blue lines represent streams, not the thick lines of the gradient indicators.) Soil conductivity and generalized geology are also provided. Qg – gravels and alluviums; Qe – eolian deposits; Tki – Laramide Intrusive Rocks; Km – Mancos Shale; Kdb – Dakota Sandstone and Burro Canyon Formation: Kch – Cliffhouse Sandstone; Kmp – Menefee Formation and Point Lookout Sandstone; Jmwe – Morrison, Wanakah, and Entrada formations (Tweto 1979).

The Mancos River between the Valley and Rt. 666 shows average concentrations of 364 mg/l while spring flow exceeded diversion capacity and diluted baseflow in synoptic 1. Synoptic 1 shows some increase in concentration within this long reach, but the rates of increase are not high (Figure 7). Synoptics 2 and 3, with an average concentration of 1350 mg/l, indicate that baseflow is dominant for much of the year. The concentrations did not increase as flows proceeds through the canyon to Rt. 666 for synoptics 2 and 3, indicating that little additional high salt return flows was entering the river in this long reach, at least during these synoptics. There is no irrigated agriculture along this reach so any additional salty baseflow would be from natural stream recharge and regional salty recharge returning to the stream. It does not appear that either of these sources are significant in the Lower Mancos, at least at the times of these synoptics in August and November of 2001.

To show these concentrations visually, concentration gradients were computed and plotted. The in stream salinity gradients (rates of increase in concentration, per stream length, in mg/l/10,000 ft) were computed to demarcate zones of salinity increases and associate these "hot zones" with land use, soils and geology. Figures 7 through 9 provide plots for synoptics 1 though 3 while a detail of the Mancos Valley is provided in Figure 10 for synoptic 2. Important to note in Figure 10 is that salinity concentration most rapidly increases in three reaches: the lower Mud Creek; the Mancos River between Mancos and the Mud Creek Confluence; and the upper Weber Canyon. These are areas of expected return flow from agricultural land located on portions of Mancos Shale. These gradients show that most of the concentration increases in the Mancos River are occurring from agricultural return flow.

Mancos River salt loading increased during synoptic 2 from an instantaneous load of 5980 kg/day at the Mancos gaging station to 12,200 kg/day upstream of the Mud Creek confluence to 38,060 kg/day downstream of the Webber drainage. This salt loading increase represents a 620 percent increase in salts, with the upper baseflow load only representing 14 percent of the load at the end of the Valley. The results from synoptic 3 are similar. During synoptic 3, the load increased from 2070 kg/day at the gaging station to 11,000 kg/day upstream of the Mud Creek Confluence to 39,900 kg/day downstream of the Webber drainage. This salt loading increase represents a 1830 percent increase, with the upper baseflow load contributing only 5 percent of the load at the end of the Valley (excluding upper Chicken Creek). Hence, it appears that most of the baseflow salt load leaving the valley enters the stream along irrigated agriculture reaches and is from irrigation return flow.

As noted in the synoptic 3 discussion, several irrigation ditch leakage rates were measured. This was done for Crystal Creek Ditch in the National Forest as well as a ditch just southeast of Mancos. Rates of leakage of 0.11 and 0.18 $ft^3/day/ft^2$ were measured for Crystal Creek Ditch and 0.16 $ft^3/day/ft^2$ for the lower ditch. These values are a bit lower than what was expected from soil texture predictions, but this variation could be explained by the sealing that tends to occur over time in unlined irrigation canals (Riggle, personal communications 2004). Such "sealed" rates may be most appropriate for computing ditch leakage rates in later analyses.

To assess the quality of water being used for irrigation, diversion water quality is of interest. Total dissolved solid concentrations on streams being diverted near the point of diversions during primary periods of water withdrawal (spring and summer) are appropriate to use for this purpose. For most of the volume diverted, sites N (Middle/East Mancos River), L' (West Mancos River at Jackson Gulch reservoir diversion), J (upper Chicken Creek, in National Forest), PP (Mancos River at Mancos Gage), M (Mancos River at Mancos at Route 160), and C (Chicken Creek at Route 184) are useful for this application. The locations of these sites are provided in Figure A-1. Measurements taken from May through August are judged most suitable for this application. Data available include synoptics 1 and 2 as well as some of the measurements made by NRCS from 1978 to 1981. Table 3 provides the relevant data and statistics.

Table 3: Diversion inflow concentrations.

Site ID	Site Description	Date	TDS (mg/l)	Average (mg/l)
N	Middle/East Mancos River	05/08/2001	102	----
N	Middle/East Mancos River	08/07/2001	dry	102
L'	W. Mancos River at Jackson Gulch diversion	05/08/2001	39	----
L'	W. Mancos River at Jackson Gulch diversion	08/07/2001	103	71
J	upper Chicken Creek, in National Forest	05/08/2001	35	----
J	upper Chicken Creek, in National Forest	08/07/2001	66	51
PP	Mancos River at Mancos Gage	07/16/1980	141	----
PP	Mancos River at Mancos Gage	08/20/1980	127	----
PP	Mancos River at Mancos Gage	05/13/1981	162	----
PP	Mancos River at Mancos Gage	06/17/1981	151	----
PP	Mancos River at Mancos Gage	07/15/1981	217	----
PP	Mancos River at Mancos Gage	08/20/1981	169	----
PP	Mancos River at Mancos Gage	08/07/2001	115	155
M	Mancos River at Mancos at Route 160	05/08/2001	190	----
M	Mancos River at Mancos at Route 160	08/07/2001	216	203
C	Chicken Creek at Route 184	05/14/1980	110	----
C	Chicken Creek at Route 184	06/18/1980	335	----
C	Chicken Creek at Route 184	07/16/1980	169	----
C	Chicken Creek at Route 184	08/20/1980	190	----
C	Chicken Creek at Route 184	05/13/1981	207	----
C	Chicken Creek at Route 184	06/17/1981	148	----
C	Chicken Creek at Route 184	07/15/1981	196	----
C	Chicken Creek at Route 184	08/20/1981	196	----
C	Chicken Creek at Route 184	05/08/2001	120	----
C	Chicken Creek at Route 184	08/07/2001	170	184

Stream baseflow contributions along dry lower stream reaches with adjacent irrigated agriculture can be considered deep percolation return flow from irrigated lands and conveyance systems. These baseflow contribution concentrations were computed using a stream segment mass-budget method for synoptics 2 and 3, when discharge measurements were taken. Table 4 provides the results from these computations. From these results, it appears that the Valley can be divided into three zones: a relatively low concentration of return flow along the upper valley reaches above Mancos, a medium concentration in the middle valley reaches in the Mancos area, and high concentrations in the lower valley reaches in the vicinity of the Mud Creek and Mancos River confluence, and in the upper Webber drainage. Below the lower valley, the baseflow concentration decreases to a moderate to low level. These results agree with the findings from the concentration gradients found for all three synoptics, the return flow concentration at site

Z for synoptics 1 and 3 (2480 and 3070 mg/l), as well as the expectations derived from the geology and soils of the valley (Figures 3 and 4).

Table 4: Baseflow salinity concentrations within the Mancos Valley and Canyon. For reach locations, see Figure A-1.

Stream	Reach	Description	Date	Upstream Discharge (cfs)	Inflow Discharge (cfs)	Inflow Concentration (mg/l)
Mancos River	PP-M	Upper Valley	08/07/2001	21.3	1.1	1150
Mancos River	PP-M	Upper Valley	11/14/2001	2.8	1.4	320*
Chicken Creek	C-R	Middle Valley	11/14/2001	0.16	0.63	1830*
Mud Creek	Q-U	Lower Valley	11/14/2001	0.63	0.90	3370
Mancos River	S-Y	Lower Valley	08/07/2001	7.1	1.5	3000
Mancos River	S-Y	Lower Valley	11/14/2001	3.9	0.6	3540
Mancos River	FF-HH	Mancos Canyon	01/15/2001	10.9	2.8	1560

* may be biased by irrigation or ditch return flow

From individual concentration measurements, concentration gradients, load computations, baseflow concentration computations, and geology and soils information, it appears that the impact of salinity and irrigated agriculture varies by several zones throughout the watershed. Specifically, low salinity contributions, a “cool zone”, occurs in the upper Valley down to the town of Mancos. At this point a strip of medium salinity contributions, a “warm zone”, occurs between Chicken Creek to the Mancos river above Chicken Creek and on towards (but not up to) the Webber Drainage boundary. Below this is a zone of high salinity contributions, a “hot zone”, that occur in the Mud Creek basin, the Lower Mancos from Chicken Creek to a bit below the Mud confluence, and in the Upper Weber drainage to a point a bit north of the upper Weber watershed boundary. Below this hot zone, salinity contributions decrease to warm or cool zone levels.

Dissolved Solid Mass-Flux Analysis

The mass flux of total dissolved solids (TDS) passing through the Mancos River at Rt. 666 flow and water-quality monitoring station was computed using a log-linear regression model. This seven-parameter log-linear regression model, known as Estimator, was designed to characterize concentration data and estimate annual and monthly loads of dissolved and suspended water quality constituents, which fits in nicely with an objective of quantifying dissolved salt loading from a watershed. This model is used by the USGS for such projects as the Chesapeake Bay River Input Monitoring Program, which quantifies nutrients and suspended sediment loading in the Chesapeake Bay from major riverine sources (Yochum 2000).

The Estimator Model

Estimator was developed by Tim Cohn of the U.S. Geological Survey. It incorporates a Minimum Variance Unbiased Estimator (MVUE) for correcting the bias induced by log transformation as well as an Adjusted Maximum Likelihood Estimator (AMLE) for data sets containing censored observations. Descriptions of the Estimator model can be found in Yochum (2000), Darrell and others (1999), and Cohn and others (1992). The MVUE procedure is discussed in Gilroy and others (1990), Cohn and others (1989), and Bradu and Mundlak (1970). The AMLE procedure is discussed in Cohn and others (1992) and Cohn (1988).

The load estimation procedure involves two primary steps -- the fitting of the model to the concentration data using ordinary least-squares regression, and load estimation from the fit model (Darrell and others, 1999). The model has the following form:

$$\ln[C] = \beta_0 + \beta_1 \ln(Q/\overline{Q}) + \beta_2 \ln(Q/\overline{Q})^2 + \beta_3(T-\overline{T}) + \beta_4(T-\overline{T})^2 + \beta_5 \sin(2\pi T) + \beta_6 \cos(2\pi T) + \varepsilon$$

where:

ln[.]	=	natural logarithm function;
C	=	constituent concentration, in milligrams per liter (mg/l);
β	=	model coefficients;
Q	=	mean daily discharge, in cubic feet per second (cfs);
$\overline{Q}$	=	centered streamflow;
T	=	time, in decimal years;
$\overline{T}$	=	centered time;
sin	=	sine function;
cos	=	cosine function;
ε	=	independent, random error.

Daily concentration and load estimates are computed using the MVUE algorithm and the daily loads are summed to provide the monthly and annual fluxes (Darrell and others, 1999).

Application to Mancos Valley

The available conductivity measurements that USGS and the Colorado Department of Public Health made from 1967 through 1999 were compiled. These data constituted 366 data points. These conductivity measurements were converted to total dissolved solid concentration estimates using the two regression equations discussed in a previous section. The seven-parameter model was then run using these concentration estimates and daily discharge values. The model was stable and provided a concentration R^2 of 0.62 and load R^2 of 0.94.

Annual, monthly, and daily load estimates are produced by Estimator. Daily load estimates have the largest uncertainty in their prediction while annual estimates have the least uncertainty. Annual and monthly load estimates are provided in Appendix C, alongside their 95% confidence intervals, standard errors, and standard errors of prediction. On average, 42,300 tons/year (with a 95% confidence interval of 38,400 to 46,500 tons/year) of total dissolved solids pass through the channel of the Rt. 666 streamgage. The estimated annual load varied from 10,400 US tons/year in 1977 (a low discharge year) to 77,500 tons/year in 1987 (a high discharge year), with a median of 40,400 tons/year and standard deviation of 20,300 tons/year. Results are plotted in Figures 11 and 12. The baseflow load component (explained below) is also shown in these figures.

A standard error of prediction was generated by Estimator to indicate how well the estimated regression model fits a "true" regression model. The standard error of prediction is a measure of the expected difference between an individual estimate and the estimated daily load (measured concentration multiplied by the average daily discharge). This standard error of prediction is a function of the variability between the estimated and computed loads only on the days of measurement; hence, the standard error will be biased if there is any systematic sampling bias in the concentration data. Also, the standard error may not account for the variability on days without monitoring or from any systematic bias incorporated into the source concentration data set (Robertson and Roerish, 1999). Possible sources of this bias include sampling techniques and designs that do not adequately represent the true environmental variability. The standard errors are provided with the load predictions in Appendix C.

As alluded to in Bob Rasely's Geology discussion (Appendix B), this load computation method is limited by the timing of the conductivity (concentration) measurements and the measurement of only dissolved salt portions of flux. Specifically, few if any of the measurements used in the analysis were taken during the first flush of summer monsoon events, hence the load estimates do not include salt mass flux from such processes. Also excluded from the loading estimates are any not yet dissolved salts that may have passed the Rt. 666 gage within suspended sediment and bedload.

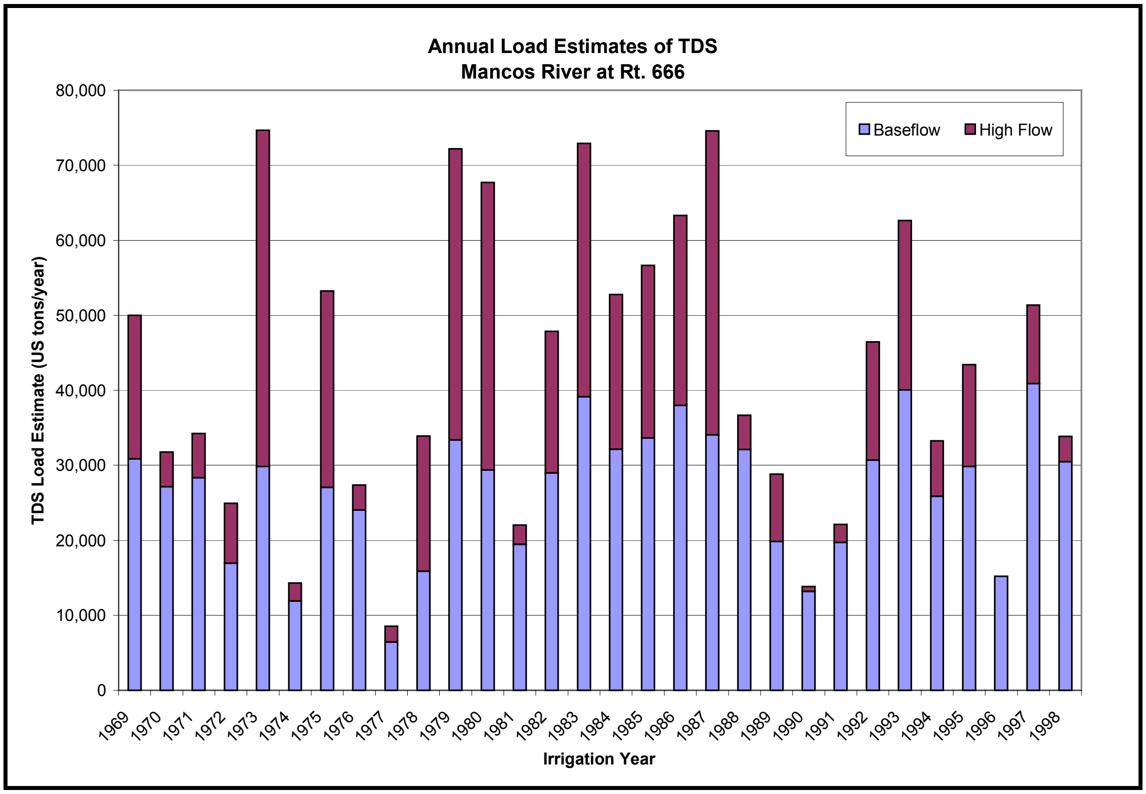

Figure 11: Total dissolved solids (TDS) load estimates for the Mancos River at Rt. 666. Both total flow and baseflow loads are shown.

Baseflow Dissolved Solid Mass-Flux Analysis

The August and November (2001) synoptics indicate that irrigation return flows (deep percolation and tailwater runoff) take the form of Mancos baseflow. From these synoptics, it is believed that most of the baseflow in the Mancos River is from such irrigation return flows. To quantify the salt load passing from the valley during baseflow conditions, a baseflow dissolved solid mass-flux analysis was performed. The baseflow load represents the possible salt load from irrigation return flow. Any load over and beyond such baseflow represents load associated with spring melt and summer monsoon events. The overland flow from such events liberate salts during the flush of in-channel precipitate (see geology discussion in appendix B) and sediment. These sources are not likely relevant for quantifying loads due to irrigation return flow.

To develop a baseflow total dissolved solid load estimate, a baseflow separation technique was used. For the 30 years of salt loading estimates, average daily discharge at the Rt. 666 gage was separated into either storm flow or baseflow using a simple linear technique. Baseflow-specific conductivity measurements (and their computed total dissolved solid concentration estimates) were also separated from the total record.

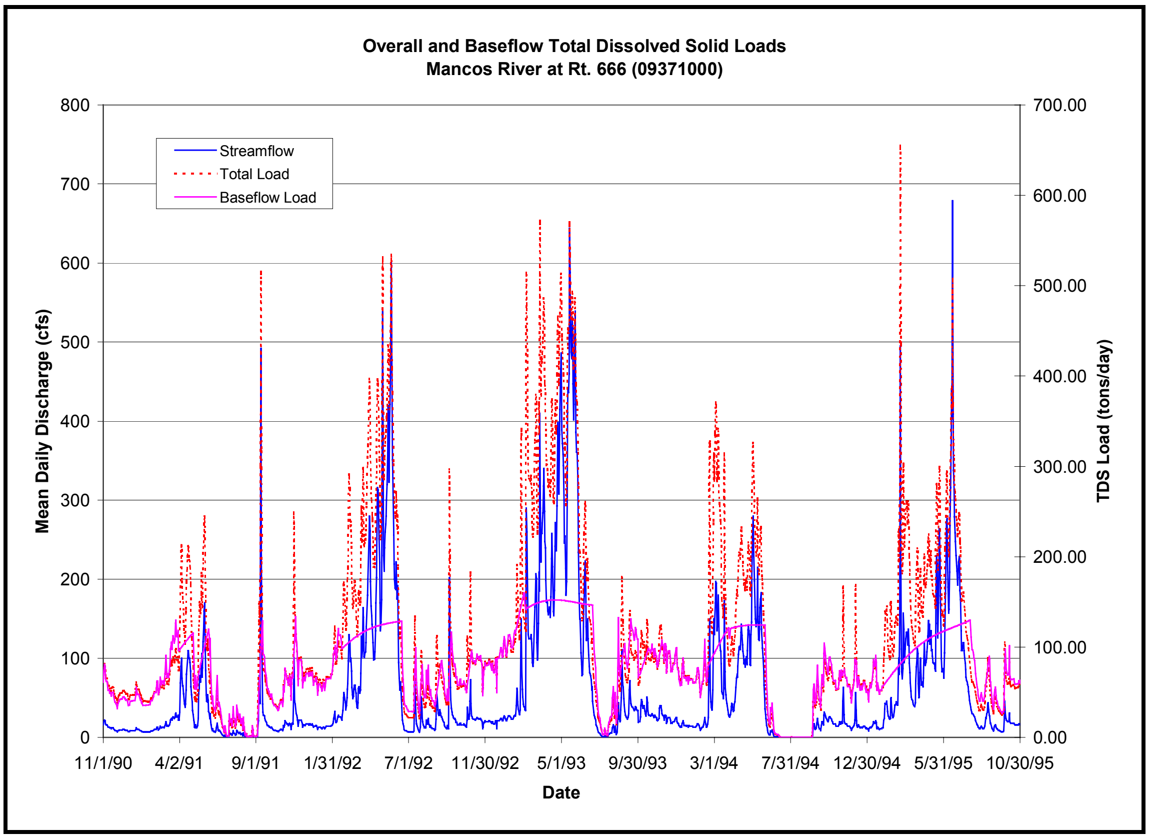

Figure 12: Hydrograph, total daily loads, and baseflow daily loads, 1991-'95.

Using these baseflow values and concentration estimates, an additional Estimator model was computed to provide estimated baseflow loads. Five years of results from this analysis are shown in Figure 12. Annual and monthly baseflow load estimates are provided in Appendix C, alongside their 95 percent confidence intervals, standard errors, and standard errors of prediction. On average, 26,200 tons/year (95% Confidence Interval of 24,000 to 28,700 tons/year) of baseflow-associated total dissolved solids pass through the channel of the Rt. 666 streamgage. The estimated annual load had a variation of 8000 tons/year in 1977 (77 percent of the total load) to 38,700 tons/year in 1983 (53 percent of the total load) for the 30 years of record. The median was 28,000 tons/year and the standard deviation was 8500 tons per year. Baseflow percent of total load varied from 41 to 100 percent (actually, a bit above 100 percent, which reflects some inaccuracies in this baseflow separation loading technique).

The average loading value of 26,200 tons/year changed slightly from the previous estimate of 26,800 tons/year due to the use of a water year average (October through September) instead of an irrigation year average (November through October). Due to limitations in the Estimator coding, this change was necessary to provide confidence limits and standard errors of prediction for the estimates. Considering the uncertainty involved in such analyses, these two numbers should be considered identical.

According to the analysis, the maximum likely irrigation return flow contribution to salinity averages 26,200 tons per year from 1969 through 1998. This 26,200 tons, or 62 percent of the total load of 42,300 tons/year, can be considered the return flow total dissolved solid upper limit.

Additional Baseflow Dissolved Solid Mass-Flux Computations

Sparse discharge and total dissolved solid concentration measurements have been taken in the lower Mancos Valley, on both Mancos River and Webber Drainage just above their confluence. These data can be analyzed to determine an approximate baseflow contribution to total flow. Since these values are sparse, they do not represent the full range in magnitude of baseflow expected from the valley. However, such an estimate can be helpful for verification purposes.

Weber Creek has had 39 data points collected for total dissolved solids, with an associated 20 measurements of discharge. Data for concentration was collected from 1980-2001, with discharge related measurements taken from 1997-2001. No significant quarterly variation in TDS concentration and discharge was observed. Hence, spring runoff flow and summer monsoon flow are not evident in the record and the majority of this flow in Webber Creek is probably from irrigation sources. Using the average values of 1924 mg/l total dissolved solids and 3.36 cfs, and assuming that this average flow represents 1.8 cfs of irrigation return flow and 1.6 cfs tailwater runoff, average baseflow load is 6400 US tons/year.

Mancos River has 43 data points collected for total dissolved solids, with an associated 20 measurements of discharge. Data for concentration was collected from 1972-73, 1980-81, and 1995-2001, with discharge related measurements taken from 1972-73 and 1995-2001. Data were collected during both high and low runoff periods. Low and high discharge data were separated and averages for the baseflow period (9 data points) were computed. Using the average low flow values of 1599 mg/l total dissolved solid concentration and 5.06 cfs, and assuming that 1/5 of the flow (likely high, considering the synoptics) is from natural sources, 2.16 cfs is from deep percolation, 1.89 cfs is from tailwater runoff, and 1.01 cfs is natural baseflow, the average load from irrigation in the Mancos River above Weber Drainage is 7800 tons/year.

From this, the estimated total average irrigation load from Mancos and Weber creeks is 14,200 tons/year, or 34% of the annual average salt load at Rt. 666. Due to the limited data and necessary assumptions, this estimate should be considered very approximate. But it does provide a likely lower range limit for irrigation contribution to salt loading in the Mancos River.

SUMMARY AND CONCLUSIONS

The Mancos Valley is an agricultural valley located in the lower portions of a 203 square mile Mancos River watershed. As of 1994, there were 14,900 acres being used for agriculture, of which 11,700 acres were irrigated. Of this irrigated area, 9900 acres are irrigated by flood practices while 1800 acres are irrigated by sprinklers. Irrigation water is diverted at approximately 46 locations of the Mancos River and its tributaries with an average diverted volume of 42,100 ac-ft. The average system efficiency was found to be 32 percent.

Exposures of Mancos Shale are extensive in the watershed. The low gentle folds of this formation are interspersed by faults and uplift of a few hundreds of feet or less. These uplift features appear to have a direct relationship to salt yield from the watershed. It appears that the lower portion of the unit is extremely salty while upper portions contain moderate to low levels of salt. This variability in salt availability can also be observed in soil conductivity data collected throughout the valley.

Water quantity and quality data have been collected by various federal and state agencies and the Ute Mountain Reservation. In addition to this, several synoptics were conducted in 2001. These data were interpreted to quantify and partition (between sources) salt loading in the valley.

Typical dissolved solids content in the Mancos River consists of (from the typical highest to lowest contribution) sulfate, calcium, sodium, magnesium, chloride and potassium. The upper reaches (above most of the irrigated agriculture) tend to have more magnesium than sodium content and a much lower sulfate proportion.

A relatively sparse selenium record has been gathered in the Mancos Watershed. Seventy-five samples on the main stem Mancos have found a maximum concentration of 12 ug/l, though the majority of the samples collected had undetectable concentrations. Mud Creek basin values were the highest, at up to 104 ug/l. The Colorado State Water Quality Control Commission has designated a chronic criteria of 5 ug/l while the EPA's drinking water maximum contaminant level is 50 ug/l.

The synoptics of 2001 indicated total dissolved solid concentrations ranging from 32 to 3070 mg/l. The results from earlier (1979-81) NRCS synoptics indicate a similar range, though some higher values were noted in the Mud and Weber watersheds. Baseflow concentrations, load, and concentration gradients all indicate a zone of high salinity contribution (a "hot zone") in a strip of land passing from the northwest to the southeast, with lesser to little contribution outside of this zone. For example, instantaneous total dissolved solid load during synoptic 3 increased from 2070 kg/day at the Mancos River at the Mancos gage, to 11,000 kg/day above the Mud Creek confluence, to 39,900 kg/day below the Weber Drainage confluence. Below this point the salt concentration increased from 1470 mg/l to only 1530 mg/l, despite passing through 40 miles of stream channel. The synoptic collected load data across the hot zone, illuminating areas of high salt contribution. Specifically, the Mud Creek reaches, the Mancos River reach between Mancos to a bit below the Mud Creek confluence, and the upper Weber Drainage appear to be large salt contribution areas. Agricultural land to the immediate northeast of this zone appears to be a moderate contributor of salt, while land above the town of Mancos appears to contribute only slightly to the river's salt load. There does not appear to be significant contribution of salt downstream of the agricultural portion of the watershed. These observations and interpretations agree with the geologic mapping and soil conductivity levels in the basin. Interestingly, the soil conductivity measurements also shows this hot zone continuing across the drainage divide into the vicinity of Dolores, which has been shown in previous salinity control studies to be a large contributor of salt.

The streamgage on the Mancos River at Rt. 666, with a drainage area of 526 square miles, has the most data available for analysis. The watershed between the Mancos Valley and this gage is relatively dry, with average precipitation raging from 9 to 21 inches, in comparison to the valley's watershed range of 15 to 41 inches. Mean daily flow at this gage is 48 cfs, with a peak average daily flow of 1890 cfs. On average, 44,400 ac-ft of water pass this gage per year. This volume is only slightly more than the average flow diverted in the Mancos Valley. Approximately 400 field measurements and water sample analyses were performed at this site. Using this data, total dissolved solid load was computed using a seven-parameter regression model for thirty years of record and an average load of **42,300 tons/year** was estimated. This value agrees remarkably well with the previous estimate of 43,000 tons/year (SCS 1984). A baseflow separation was also performed and an average load of **26,200 tons/year** was estimated. These load estimates may not account for all sources, specifically the first flush of salts from stream channels and any salts not yet dissolved in suspended sediment and bed load passing the gaging station. Additionally, it should be noted that this average baseflow load changed slightly from the previous estimate of 26,800 tons/year due to the use of a water year average instead of an irrigation year average. This change was necessary to provide confidence limits and standard errors of prediction for the estimates. Considering the uncertainty involved in such analyses, these two numbers should be considered identical.

The baseflow concentrations, load, and concentration gradients of the synoptics support a hypothesis that a major majority of baseflow salt load leaving the Mancos Valley is from irrigation return flow. These synoptics also indicate that little additional baseflow is yielded from the lower Mancos at Rt. 666 watershed. The exclusion of first flush salt flows and undissolved salts derived from sediments mobilized from crop and range lands from the load computations adds support to the selection of this relatively high salt yield. Hence, the baseflow dissolved salt loading estimate of 26,200 tons is a reasonable estimate for irrigation return flows

Therefore, this study recommends the use of an average annual load estimate from irrigation practices of **26,000 tons**. The value was rounded to two significant figures to reflect the appropriate degree of certainty. This recommendation is based upon best professional judgement, using available data. If greater certainty is desired, additional data and analysis will be required.

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