WATER SALINITY STUDY FOR THE SOUTHERN SAN PITCH DRAINAGE SYSTEM IN SANPETE COUNTY, UTAH

by Janae Wallace, J. Lucy Jordan, Christian Hardwick, and Hugh Hurlow

SPECIAL STUDY 158
UTAH GEOLOGICAL SURVEY
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2017

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Cover photo: View upstream of the San Pitch River looking east toward the Wasatch Plateau.

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CONTENTS

FIGURES

TABLE

PLATES

WATER SALINITY STUDY FOR THE SOUTHERN SAN PITCH DRAINAGE SYSTEM IN SANPETE COUNTY, UTAH

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ABSTRACT

The Gunnison Irrigation Company would like to use existing surface water supplies in the lower San Pitch drainage in Sanpete County to provide water of suitable quality to all water users (irrigators). Salinity is known to affect water quality in the region, but previous studies lack sufficient detail to aid decisions on how to manage or treat poorer water quality while preserving and protecting better water quality sources. This study attempts to determine the sources and extent of salinity in the area by assessing hydrogeologic conditions through surface water analysis, detailed geologic mapping, and geophysical surveys.

This report outlines our findings with GIS maps that show flow, salinity, and salt load in surface water and groundwater along the San Pitch River and Twelvemile Creek drainages; 2D-Transient Electromagnetic Method (TEM) images and interpretations; and a simplified geologic map with a cross section. Overall, our maps emphasize areas of higher salinity and lower salinity sources.

We spent two field seasons (autumn 2014 and spring 2015) measuring water quality and quantity in the lower San Pitch River drainage along different reaches of the San Pitch River and Twelvemile Creek as well as nearby canals and springs. We estimated salt loading based on water quality measurements. We coupled that data with results of the geologic mapping of the Arapien Shale and of interpretations of 2D-TEM images of subsurface electrically conductive bodies to identify local sources of salinity. The best quality water exists in Highland and Pettyville Canals, Peacock Spring, Sixmile Creek, and Twelvemile Creek above the diversion to Highland Canal. The poorest water quality is (1) along the San Pitch River between the Highway 89 bridge and the confluence with Twelvemile Creek, (2) from a 20-acre marsh situated between the San Pitch River and Yardleyville Canal, (3) from a 10-acre marsh and seeps on Twelvemile Creek midway between the Twelvemile Diversion and the confluence with the San Pitch River, and (4) from low-flow seeps in the half-mile reach of the San Pitch River above the Highway 89 bridge.

Because the poorest and most saline water quality exists along the San Pitch River south of the Highway 89 bridge and above the confluence of Twelvemile Creek (which has better water quality), we recommend transferring higher-salinity water from the San Pitch River to the Highland Canal past the confluence with Twelvemile Creek. We also recommend lining or discontinuing the use of settling ponds near Highland Canal. We believe this will provide better quality water to the Old Field Canal. Below the confluence with Twelvemile Creek, the San Pitch River is a gaining stream and acquires significant flow from seeps and springs (~2 to 2.5 cfs) before it reaches the Old Field Canal. Water from the seeps and springs has relatively lower total dissolved solids and conductivity than the San Pitch River both above and below its confluence with Twelvemile Creek. The supply of water from the San Pitch River to Old Field Canal will sufficiently provide water to the ~15% of water users on the Old Field Canal.

INTRODUCTION AND SCOPE

Irrigators receiving water from the Old Field Canal, a diversion from the San Pitch River near Gunnison, are unable to use the water during periods of low flow due to high salinity. Gunnison Irrigation Company (GIC) suspects the source of salinity in the southern San Pitch River may be saline springs. GIC contracted the Utah Geological Survey (UGS) to quantify the sources and extent of salinity in the lower San Pitch River drainage and adjoining GIC canal system in southern Sanpete Valley. Utah Geological Survey personnel investigated the problem by characterizing the hydrogeologic setting, collecting flow and chemistry data throughout the problem area, and performing shallow geophysical analysis. The results of our study are compiled in this report. This study provides information necessary to make targeted management decisions to reduce salinity and provide a sustainable supply of usable irrigation water.

Study Area

The study area includes the southern San Pitch River Valley from Sterling, Utah, to Gunnison Siding (figure 1A and B).

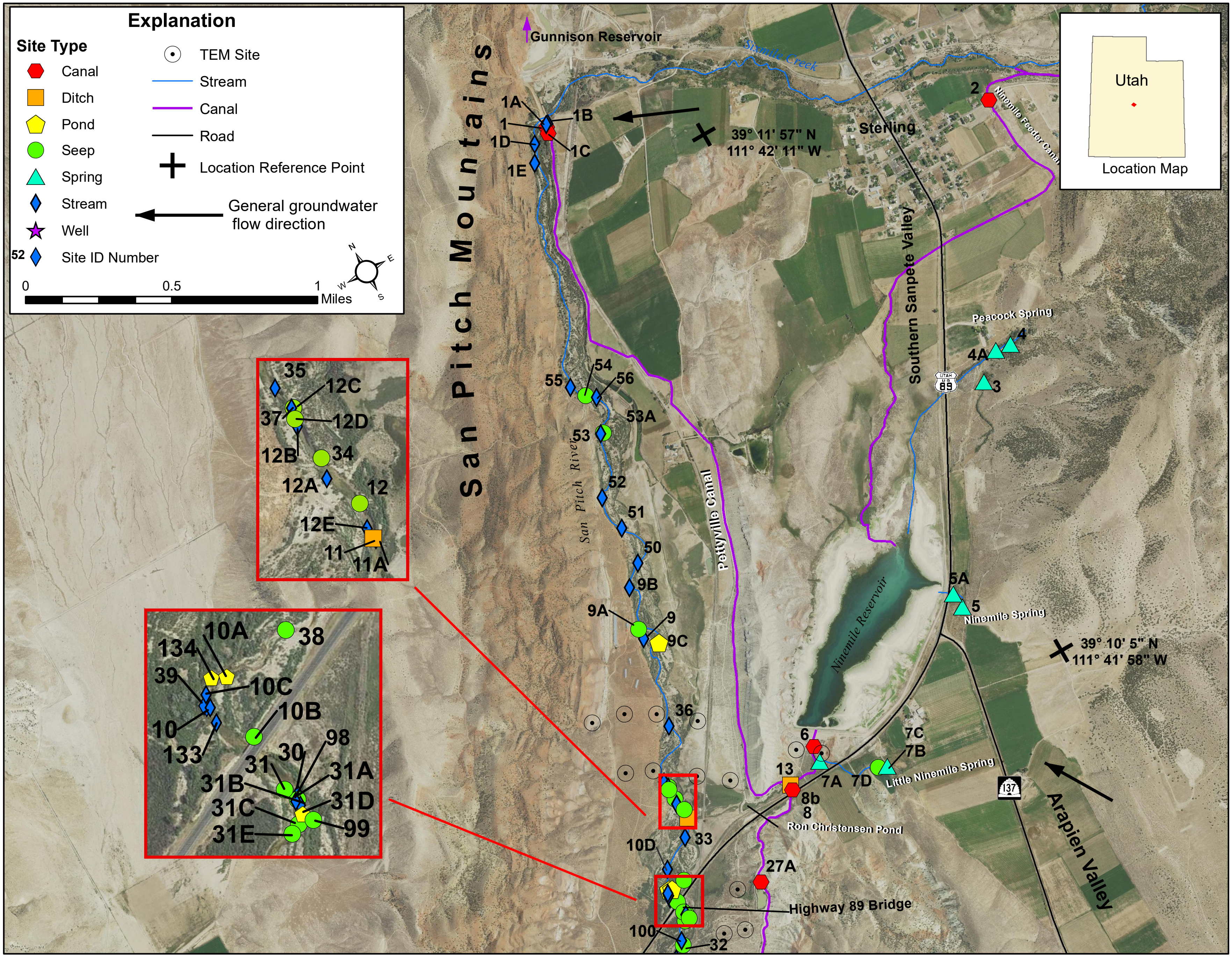

Figure 1A. *Northern portion of study area, site locations, and groundwater flow direction in the lower San Pitch River drainage.*

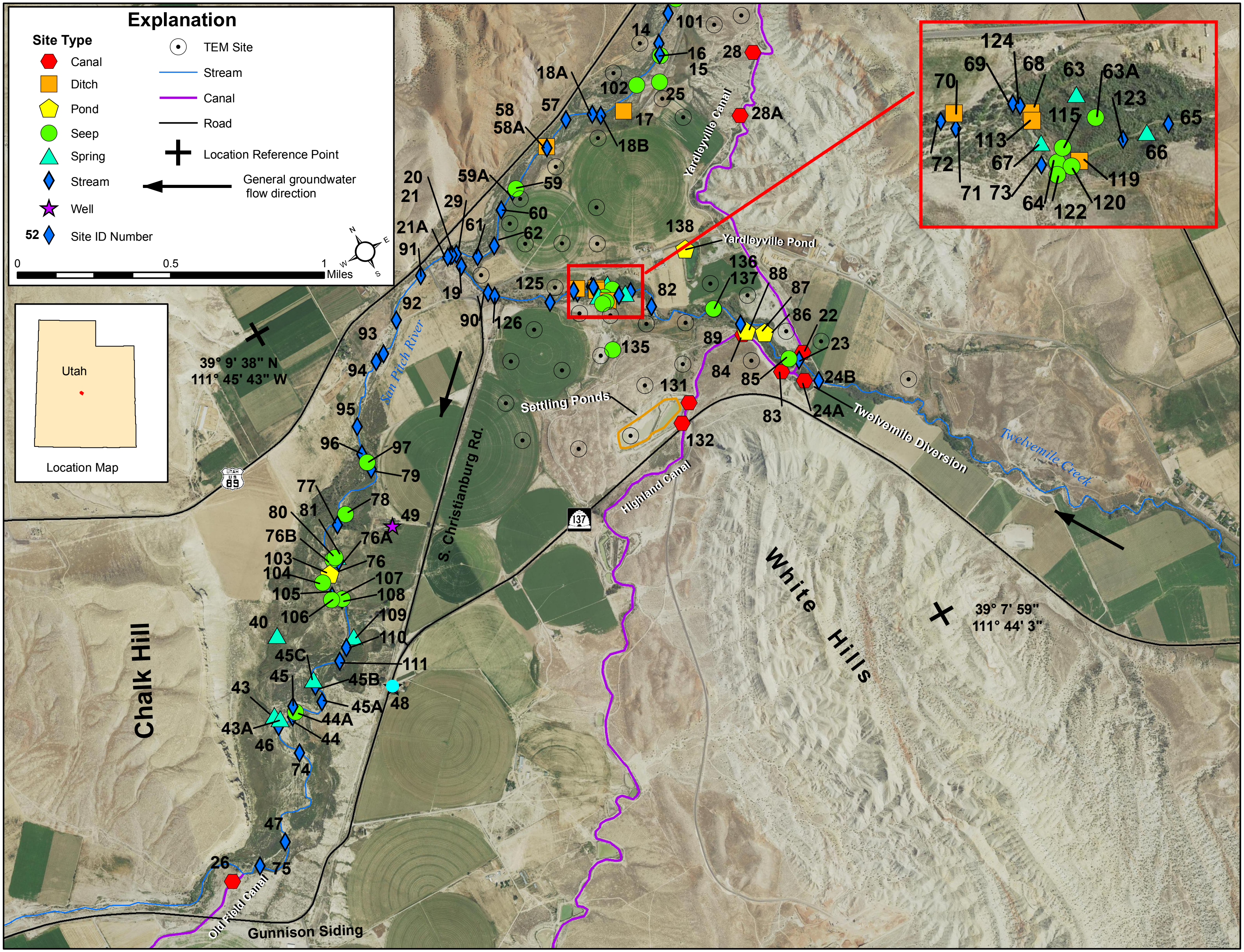

Figure 1B. Southern portion of study area, site locations, and groundwater flow direction in the lower San Pitch River drainage.

The study area is situated between three valleys: Southern Sanpete Valley, Arapien Valley, and central Sevier Valley in central and south-central Sanpete County, central Utah, about 100 miles (160 km) south of Salt Lake City. The Wasatch Plateau is east of the study area and the San Pitch Mountains are to the west. The White Hills are a low range of mountains separating the San Pitch River Valley from the Arapien Valley (figures 1 and 2). Important hydrologic features include the San Pitch River and its tributaries (Sixmile and Twelvemile Creeks), Ninemile Reservoir, major irrigation canals (Pettyville, Yardleyville, Highland, and Old Field Canals), and multiple large and small springs and seeps along the river bottoms. The San Pitch River flows generally southwest from Gunnison Reservoir, picking up the outflow from Ninemile Reservoir and Twelvemile Creek, before bending around the southern end of Chalk Hills (figure 1). Sixmile Creek, a tributary to the San Pitch River in this study area, flows west from the Wasatch Plateau through the town of Sterling, where it can be diverted into Gunnison Reservoir, Ninemile Reservoir, or continue on its natural course to the San Pitch River downstream of Gunnison Reservoir, where it can also be diverted into the Pettyville Canal. Twelvemile Creek, a major tributary to the San Pitch River, flows west from the Wasatch Plateau through the Arapien Valley and White Hills and enters the San Pitch River about 2 miles (3.2 km) southwest of Ninemile Reservoir (figures 1B and 3). After the creek passes White Hills, it can be diverted to the GIC canal system (Highland Canal). The portion of the southern San Pitch River in our study ranges in elevation from 5360 feet (1634 m) at the base of the Gunnison Reservoir spillway to 5140 feet (1537 m) at the Old Field Canal Diversion. The highest peak in the San Pitch Mountains west of the study area is 8780 feet (2676 m), and the drainage basins of Sixmile and Twelvemile Creeks in the Wasatch Plateau to the east reach maximum elevations of nearly 11,000 feet (3300 m).

Background Water Use

GIC delivers surface water from the San Pitch River, Sixmile Creek, Twelvemile Creek, and springs in southern Sanpete County and Sevier County. Since the late 1800s, water users have applied this water to crops, pasture land, and residential areas around the towns of Gunnison, Centerfield, and Axtell in Sevier County. Originally, GIC delivered water via four canals, but by switching from flood to pressurized irrigation in recent decades, they have narrowed the canal delivery into two major canals: Highland Canal (~85%) and Old Field Canal (~15%).

Previous Work

Poor water quality in the San Pitch River has been documented by several workers in the lower San Pitch drainage, with some reports identifying saline spring(s) as one probable source and others indicating the local bedrock (Arapien Shale) is affecting water quality in the region.

Hahl and Mundorff (1968) identified poor quality water in the Sevier Lake basin and attributed it to (1) concentration of salts from irrigated lands in irrigation return flow to the San Pitch and Sevier Rivers, (2) poor quality groundwater influx from aquifers having gypsum and halite derived from the weathering of the Arapien Shale, and (3) saline springs. They noted that the total-dissolved-solids (TDS) concentration of the San Pitch River above Gunnison Reservoir, north of the study area, decreased as discharge increased with the exception of one sample site near Manti where the quality was lower at higher flows; they attributed the difference to the site's high discharge to water composed mostly of irrigation return flow (Hahl and Mundorff, 1968). Lambert and others

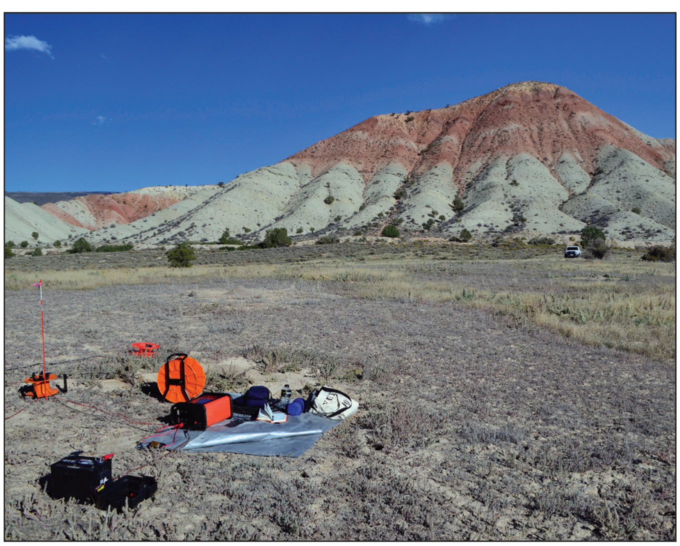

Figure 2. *View to the east of the White Hills. TEM survey equipment in the foreground.*

Figure 3. *The confluence of San Pitch River and Twelvemile Creek during winter. Staff are attempting to download transducer data.*

(1995) built on the work of Hahl and Mundorff by calculating the salt load of the Sevier River through discrete reaches from Sevier to Gunnison. They identified a significant increase in the salt load of the Sevier River between Richfield and Sigurd and between Redmond and Gunnison, which they attribute to groundwater inflow (Lambert and others, 1995). Brine Creek and a water well near Glenwood have water high in TDS and of sodium-chloride type, which they attribute to dissolution of halite in the Arapien Shale (Lambert and others, 1995). The dominance of the sodium cation in the reach between Redmond and Gunnison was also attributed to halite dissolution from the Arapien Shale.

A total maximum daily load (TMDL) study (Millennium Science and Engineering, 2003) approximated TMDL loads of the lower San Pitch River over two water seasons (1996 and 1997) and attribute most of the high TDS to natural geologic sources. The TMDL study recommended a site-specific load allocation for TMDL instead of nonpoint source calculation due to the natural, geologic contribution, especially from saline bedrock, to the watershed in this study area compared to the middle San Pitch River near Manti.

Lowe and others (2002) and Wallace (2010) evaluated groundwater quality in the aquifers of southern Sanpete and central Sevier Valleys, with emphasis on nitrate and TDS concentrations. Lowe and others (2002) associated the Arapien Shale in southern Sanpete and central Sevier Valleys with poor water quality; they reported TDS concentrations in wells as high as 2752 mg/L. High nitrate levels in groundwater have been documented locally, where many wells have historically yielded groundwater having greater than 10 mg/L nitrate concentration, including two wells drilled by the town of Centerfield and a public-supply spring (Little Ninemile Spring) that has had persistent nitrate concentration of about 7 mg/L. These studies were prompted by these historical incidents and by the concern of potential water-quality degradation in the growing communities of southern Sanpete County. Elevated TDS concentrations in groundwater are largely attributed to proximity to outcrops of the Green River Formation and the Arapien Shale and return irrigation water. No correlation between high-TDS wells and high-nitrate wells was found.

Wallace (2010) reported that the average nitrate concentration for groundwater in the valley-fill aquifer is about 6.5 mg/L. Of the water wells analyzed for nitrate, 51% yielded values greater than 5 mg/L, and 20% exceeded U.S. Environmental Protection Agency (EPA) drinking-water standards for nitrate (10 mg/L). Most of the high-nitrate wells were less than 150 feet (46 m) deep and contamination sources are likely within a short distance (3200 feet [1000 m]) of the high-nitrate wells. Overall water quality in southern Sanpete and central Sevier Valleys is good, the exception is areas that have elevated nitrate concentration. The highest quality of water in terms of low TDS and nitrate concentration occurs primarily along the margins in both valleys: along Sixmile and Twelvemile Creeks in southern Sanpete Valley and along the western margin of the San Pitch Mountains and the southeastern margin of the Valley Mountains in central Sevier Valley. A correlation is apparent between high-nitrate concentration in wells and proximity to current or pre-existing animal feedlot operations and irrigated agricultural areas, as supported by field observations of potential sources of nitrate upgradient of wells yielding high-nitrate groundwater. However, nitrogen isotope data indicated multiple sources could be responsible for the high-nitrate concentration in wells and that multiple nitrogen sources exist, including septic-tank systems, agricultural fertilizer, animal-waste products, and natural soil nitrate. Well log information indicated some high-nitrate wells may be isolated single-well contaminations, whereas other high-nitrate wells occur in relatively large areas of high-nitrate groundwater. Water chemistry data indicated high-nitrate wells may have a common source of groundwater recharge on a local scale. Data from nitrogen and oxygen isotopes in nitrate indicated most high-nitrate wells contain water derived possibly from human and/or animal sources, soil nitrate, ammonia in fertilizer and rain, and mixed sources. Wallace (2010) concluded that bedrock is not a source of high nitrate, but that fertilizer and animal manure were possible sources and septic-tank systems likely contributed nitrate to many of the wells.

Gunnison Irrigation Company, through their contractor Jones and DeMille Engineering, provided July and August 2013 field water-quality data. Field measurements estimated water quality (expressed as salinity in parts per million [ppm]) and flow estimates (in cfs) from eight different sites:

1. the San Pitch River just north of the Highway 89 bridge,
2. the San Pitch River below the Highway 89 bridge and above the confluence with Twelvemile Creek,
3. Twelvemile Creek above the confluence with the San Pitch River,
4. Twelvemile Creek above the diversion at the Twelvemile Canal flume,
5. Highland Canal adjacent to Twelvemile Creek,
6. seepage from a settling pond upgradient from Twelvemile Creek and the Highland Canal,
7. Chalk Hill Spring before it reaches the San Pitch River, and
8. Old Field Canal.

Salinity ranged from a low of 200 ppm at Twelvemile Creek above the diversion to a high of ~10,000 ppm at the settling pond. Flow estimates ranged from a low of 0.5 cfs at Chalk Hill Spring to a high of 7 cfs measured at Old Field Canal.

Geologic Setting

The San Pitch and Sevier River drainage basins are in the Basin and Range–Colorado Plateau transition zone (Stokes, 1977), which contains features characteristic of both the Basin and Range and Colorado Plateau physiographic provinces. Stratigraphic units exposed in the Sanpete Valley area range from Jurassic to Quaternary in age. The San Pitch Mountains and Wasatch Plateau both consist of Jurassic to Tertiary sedimentary rocks, capped by Tertiary limestone. The Cretaceous section consists mostly of Upper Cretaceous clastic sedimentary rocks. Underlying the Cretaceous units are the Jurassic Twist Gulch Formation and evaporite-bearing Jurassic Arapien Shale.

Sanpete Valley is bounded on the east by the 50-mile-long (80 km) Wasatch monocline, along which Upper Cretaceous and Tertiary strata dip steeply to the west below Sanpete Valley from their near-horizontal dip atop the Wasatch Plateau (Spieker, 1946, 1949a, 1949b). Some of these tilted beds have been cut by westward-flowing streams that form deep, sinuous canyons extending eastward into the Wasatch Plateau (Witkind and others, 1987). The westward dip becomes less steep beneath Sanpete Valley alluvium (Spieker, 1946, 1949a, 1949b).

Unconsolidated valley-fill deposits are at least 300 feet (100 m) thick in the center of southern Sanpete Valley (Snyder and Lowe, 1998). The valley fill is predominantly fluvial and alluvial-fan deposits consisting mainly of poorly sorted gravel, gravelly sand, and, locally, sand and sandy silt, interlayered with silt and clay. The valley-fill deposits generally become finer grained toward the valley center.

West of Sanpete Valley and northeast of central Sevier Valley, the north-south-trending San Pitch Mountains consist of sedimentary rocks that have been folded to form a southward-plunging syncline (Witkind and others, 1987; Witkind and Weiss, 1991). In southern Sanpete Valley, the White Hills are between the Wasatch Plateau and the San Pitch Mountains. The White Hills are a structurally complex antiform composed chiefly of the Jurassic Arapien Shale (Spieker, 1946).

In the northern White Hills, the Arapien Shale is about 2780 feet (850 m) thick and includes five members (plate 1) (Spieker, 1946; Hardy, 1952; Weiss, 1994). The depositional environment is interpreted as shallow-marine, and the unit includes abundant evaporite deposits (Sprinkel and others, 2011). Members A through D of the Arapien Shale are green-gray to red-gray mudstone, siltstone, fine-grained sandstone, and can contain local lenticular gypsum beds (Hardy, 1952; Weiss, 1994). Weiss (1994) describes local halite "pods" within member B. Member E is brick red, halite-bearing mudstone and sparse siltstone to fine sandstone (Hardy, 1952; Weiss, 1994). Doug Sprinkel of the Utah Geological Survey notes that, based on examination of petroleum-exploration well cores, halite in the Arapien Shale occurs as fine-grained crystals dispersed within the mudstone and siltstone, or as concentrated pods or beds and may occur in any of the members (verbal communication, May 26, 2015). Hardy (1952, p. 22) described an outcrop of member E in a gravel pit near Redmond, Utah, 10 miles southwest of the study area, that includes a 200-foot-thick bedded halite deposit. Petroleum-exploration wells northeast of the study area (Chandler 4-2 Barton, American Petroleum Institute [API] number 4303930012 and Mobil 1 Larson Unit, API number 4303930008) encountered halite deposits in the Arapien Shale (log data from Utah Division of Oil, Gas, and Mining). In summary, the Arapien Shale includes local halite deposits in either dispersed or bedded form, mainly in its upper member E but potentially throughout the formation at any given location. Gypsum occurs throughout the formation and is more common than halite (Hardy, 1952; Weiss, 1994).

Structurally, the White Hills are in the core of the northeast-southwest trending Sevier-Sanpete antiform (Sprinkel and others, 2011), and its north-plunging northern end separates the Wasatch Plateau monocline and San Pitch Mountains syncline in southwest Sanpete Valley. The Arapien Shale in the northern White Hills is complexly deformed by folds, thrust faults, and normal faults (plate 1) (Weiss, 1994). These structures formed during Cretaceous and Tertiary time. Folding and thrust faulting in the White Hills were related to west-directed motion on the west-vergent Sanpete Valley backthrust during Cretaceous deformation within the overall east-vergent Sevier fold-and-thrust belt (DeCelles and Coogan, 2006). The Sanpete Valley backthrust is concealed beneath younger sediments of the Wasatch Plateau. The folds and faults were likely re-activated and additional folds and normal faults formed during Tertiary time when the Arapien Shale moved upward as a diapir due to its buoyancy relative to surrounding rocks (Witkind, 1982; Weiss and Sprinkel, 2002). Witkind (1982), Witkind and others (1987), and Witkind and Weiss (1991) mapped the contact between the Arapien Shale and overlying rocks as an intrusive contact between the diapir and overlying rocks, and categorized the unit as "intrusive sedimentary rock." Halite is particularly mobile due to its higher buoyancy than the surrounding shale and sandstone, and may have formed concentrated pods during diapiric movement.

Groundwater Flow

Groundwater table elevation in the valley-fill aquifer in the study area is higher in the east and lower in the west. Water-table elevation is highest near Sterling (approximately 5450 feet) and Mayfield (approximately 5500 feet) and lowest near Gunnison and Centerfield (approximately 5090 feet) as reported in the U.S. Geological Survey's National Water Information System (NWIS) (U.S. Geological Survey, 2015). Water-level elevation in the San Pitch River valley south of the confluence with Twelvemile Creek and Gunnison Siding are intermediate at approximately 5200 feet (U.S. Geological Survey, 2015).

Groundwater-flow direction has been defined in southern Sanpete Valley (Wilberg and Heilweil, 1995) and northern Sevier Valley (Lambert and others, 1995), but has not previously been defined in the study area. Groundwater flows south in southern Sanpete Valley (Wilberg and Heilweil, 1995) following the drainage of the San Pitch River. Groundwater-flow direction at Sterling may follow the drainage of Sixmile Creek in a westerly direction, although Wilberg and Heilweil (1995) had sparse data in this area. Groundwater-flow direction is north in the Sevier River valley (Lambert and others, 1995). Based on our cursory examination of limited water-level information available in NWIS (U.S. Geological Survey, 2015), groundwater likely flows north in the Arapien Valley to the Highway 89 corridor and then southwesterly following the San Pitch River to the Sevier Valley (figure 1). Groundwater may also flow from the Arapien Valley through the Twelvemile Creek drainage to the San Pitch River valley.

METHODS

The methods we used to determine sources and extent of salinity in the southern San Pitch River drainage included targeted geologic mapping to identify geologic sources of salinity, measuring instream flow and chemistry to determine water volume and salinity contributions from groundwater and surface-water sources, and a near-surface geophysical survey to investigate the extent of low-resistivity areas in the shallow subsurface, which may be due to saline groundwater.

Geologic Mapping

We characterized the hydrogeologic setting of the regional groundwater system by compiling existing geologic maps (plate 1) (Weiss, 1994) and constructing a cross section through the central part of the study area (plate 2). We conducted field reconnaissance of the Arapien Shale, particularly members E and B that Weiss (1994) described as halite-bearing, to examine its lithology and structure. During reconnaissance for saline springs along Twelvemile Creek, we discovered outcrops of the Arapien Shale and overlying Twist Gulch Formation that were not shown on the original geologic map (Weiss, 1994). The outcrops helped constrain the positions of these units in the subsurface. From our evaluation of the hydrogeologic setting of the study area, we formed an initial hypothesis that the principal source of the saline springs is dissolution of halite in the Arapien Shale, particularly members E and B, by groundwater as it flows through outcrops below San Pitch River sediment and/or as it rises along faults. To test this hypothesis in part, we constructed a "subcrop" map of the Arapien Shale below the San Pitch River valley (plate 1), that shows the positions of the members of the Arapien Shale and possible faults below the river deposits.

River Salinity Mapping

We characterized the location, flow rates, and water chemistry of hydrologic features and diversions along the San Pitch River to constrain their relative importance to instream flow and salinity. We surveyed (walked the length of) the San Pitch River to assess changes in water quality and flow from the outflow of Gunnison Reservoir to the Old Field Canal. Similarly, we assessed flow and water quality conditions along the length of Twelvemile Creek from the diversion at the Twelvemile flume to the confluence with the San Pitch River. We used existing information from GIC, field investigations in autumn 2014 and spring 2015, and results from laboratory analyses on water samples to map and characterize these diversions.

We mapped the spring locations and other important hydrologic locations such as diversion points and potential saline seeps using high-resolution aerial photography (Google Earth™ and U.S. Department of Agriculture) and existing locations from the National Hydrologic Dataset (NHD), U.S. Geological Survey, and Utah Division of Water Rights data sets. Preliminary locations were field checked using a GPS-enabled tablet and/or handheld GPS unit that contained the location data, and which was edited as we conducted field investigations.

Flow Measurement

We measured or estimated discharge (flow) 83 times (measuring multiple times at some locations) at 53 unique locations. Location coordinates, site description, and flow are given in the appendix. We measured or estimated stream discharge (stream flow) at 17 locations along the San Pitch River, 5 locations along Twelvemile Creek, 13 locations in canals or ditches, 9 springs, and 9 seeps. At the larger discharge locations (approximately greater than 0.5 cubic feet per second [cfs]) we used a Swoffer 3000 current meter and the 0.6 depth method to measure velocity across a stream transect and compute the cross-sectional area (figure 4). The accura-

Figure 4. *Flow measurement in the San Pitch River above Chalk Hill Spring.*

cy of the current meter measurements is ± 15% except where noted in the text. At smaller seeps/springs, we measured flow volumetrically using a bucket and timer, a portable weir, or the neutral buoyant object (NBO) method, i.e., timing a buoyant object as it floats through a measured channel geometry. The accuracy of the NBO method measurements is ± 25%. Most discharge values less than 0.03 cfs (15 gallons per minute [gpm]) were estimated visually; therefore, the accuracy of these small flows is ± 50%. At or very near each flow location, we also measured field chemistry parameters: pH, specific electrical conductance (conductivity), and temperature. Total flow of the San Pitch River above the confluence with Twelvemile Creek was calculated by subtracting the input of Twelvemile Creek at the confluence from the flow of the San Pitch River below the confluence. Total flow of Twelvemile Creek below the input of an irrigation ditch from the Yardley property was calculated by adding the flow of the ditch and the creek immediately upgradient from the ditch input.

Field Chemistry Parameters

We recorded 216 water quality estimates (field parameters) from 172 different sites within the flow regime, measuring some sites multiple times, in autumn 2014 and spring 2015 (appendix). We used one Hanna brand and two pHTestr brand handheld multiparameter meters that measure pH, temperature (degrees Celsius), temperature-compensated conductivity (measured as microSiemens per centimeter [µS/cm]), and, depending on the meter, salinity or oxygen-reduction potential (figure 5). The meters were calibrated daily, or more often as needed, with standard solutions over the range of pH and conductivity we expected. Conductivity is used in this study as a proxy for TDS and to salinity in general. We had 24 samples analyzed for TDS at the lab for select sites. For other sites, TDS concentrations (salinity) were also calculated from conductivity data based on the mathematical relation of conductance to TDS from samples for which both types of data were measured (from field the laboratory measurements). For this study, we multiplied conductivity (µS/cm) by 0.59 to calculate TDS (mg/L).

Chemical Analysis

At 19 locations where we estimated water quality, we also collected 24 grab water chemistry samples for laboratory analysis, sampling 5 of the sites repeatedly in autumn and spring. During autumn, 2014, we sampled one canal, two springs, one seep, five stream samples, and two wells. During spring, 2015, we re-sampled five of the sites and added new sites from newly discovered seeps and springs issuing into the San Pitch River and Twelvemile Creek. Water chemistry data are summarized in table 1 (station ID refers to our identification for the location where field parameters were measured, and site number is an abbreviation of our station ID shown on most maps and which we refer to in the text to describe the location of a particular location of interest). Water samples were analyzed at the Utah Department of Health Laboratory for general chemistry (including TDS and salinity), selenium, and boron, and for environmental tracers (stable isotopes of oxygen and hydrogen in water) at the Utah State University isotope lab in the Department of Geology (Dr. Newell). Stable isotopes are useful tracers of groundwater flow paths (Kendall and Caldwell, 1998) and may indicate the source(s) of waters bearing similar isotopic signatures.

Continuous Monitoring Data

We installed two transducers to monitor salinity in the San Pitch River over a seven-month period (figures 6 and 7). We placed the transducers above and below an area that GIC knew to be of significant saline input; one was placed above the Highway 89 bridge and another immediately above the confluence with the less saline Twelvemile Creek, site numbers 39 and 29, respectively (figure 1). The transducers recorded temperature, conductivity, and relative river stage (level) on an hourly basis. We calculated the daily average conductivity and compared it to stage and temperature change.

River Gain, Interpolated Conductivity, and Salt Load Calculations

We calculated the gain or loss of a section of river between two discharge measurement points by finding the difference between measurements taken on the same date and dividing that number by the river distance between them as measured using geographic information system (GIS) methods along a polyline of the San Pitch River. The polyline was modified from the line included in the NHD dataset to better represent the path of the river as shown on the 2014 aerial photo. The gain or loss is expressed in cubic feet per second (cfs) per river mile.

Figure 5. *Measuring field parameters in a spring issuing into Twelvemile Creek.*

Table 1. *Water quality data from select sites for the lower San Pitch River drainage area.*

Station ID	Site No.	Source	Sample Date	Field Temp (°C)	Field Conductivity (µS/cm)	pH, Field	Longitude	Latitude	Lab Conductivity (µS/cm)	pH, Lab	Ammonia (mg/L)	$NO_2 + NO_3$ as Nitrogen (mg/L)	Total Dissolved Solids, residue @180°C (mg/L)	Boron (µg/L)	Bicarbonate (mg/L)	Bromide (mg/L)	Calcium (mg/L)
USPS1	1	Canal	9/22/14	19.5	630	8.80	-111.711546	39.203249	647	8.568	<0.035	0.349	388	63.2	270	0.0406	43.5
USPS1	1	Canal	4/20/15	12.6	1429	9.30	-111.711546	39.203249	1331	8.68	-	0.0319j	830	178	306	0.1621	39.1
USPS4A	4	Spring	4/20/15	18.4	1560	8.38	-111.693605	39.182583	1510	8.019	-	0.0307J	888	347	380	0.6091	40.7
USPS4A	4	Spring	9/23/14	19.8	1485	7.74	-111.693457	39.182607	1543	8.025	<0.035	<0.005	896	349	384	0.701	41.5
USPS8	8	Canal	9/24/14	20.8	900	8.55	-111.718651	39.168310	909	8.392	0.159	1.93	548	213	356	0.1169	49
USPS8b	8	Canal	4/21/15	13.8	1326	9.10	-111.718753	39.168548	1255	8.547	-	0.104	790	169	309	0.1381	39.8
USPS9	9	Stream	9/24/14	14.8	2400	8.24	-111.722153	39.178915	2420	7.95	<0.035	j0.0695	1364	140	580	0.12	73.1
USPS9	9	Stream	4/21/15	19.4	2400	8.34	-111.722212	39.178868	2450	8.12	-	0.123	1426	119	496	0.1169	69.5
USPS10	10	Stream	9/24/14	18.0	5080	8.40	-111.728981	39.167060	4880	7.582	<0.035	<0.005	2742	319	522	0.1494	103
USPS12	12	Seep	9/24/14	19.9	10870	7.24	-111.725366	39.170322	11300	7.923	j 0.046	<0.005	6386	756	468	0.6028	210
USPS19	19	Stream	9/25/14	13.3	3970	8.45	-111.748983	39.158499	3850	8.183	<0.035	8.15	2416	290	384	0.3999	140
USPS21A	21	Stream	4/22/15	12.8	7870	8.54	-111.749482	39.159209	7420	7.781	-	4.79	4234	454	358	0.887	163
USPS23	23	Stream	4/22/15	11.1	1954	7.49	-111.734072	39.146801	1853	7.747	-	12.2	1302	254	434	0.1877	149
USPS24B	24	Stream	4/23/15	12.6	460	8.51	-111.733580	39.145480	445	8.208	-	0.112	260	<30	278	<0.02	50.7
USPS25	25	Seep	9/25/14	22.7	>20000	8.28	-111.733051	39.161473	25100	8.484	<0.035	<0.005	15538	1870	107	0.3711	477
USPS26	26	Canal	4/23/15	8.1	4880	8.27	-111.779549	39.138504	4780	7.886	-	3.53	2884	319	388	0.5279	128
USPS43A	43	Spring	4/23/15	15.5	3220	8.62	-111.772169	39.144094	3240	8.259	-	2.94	1994	428	476	0.4081	75
USPS43	43	Spring	10/7/14	20.0	4070	8.34	-111.772373	39.144359	3680	8.435	<0.035	1.08	2282	439	417	0.4078	82.8
USPS48	48	Well	10/20/14	14.7	2840	7.00	-111.765242	39.142791	2660	7.91	<0.035	2.32	1598	274	392	0.186	118
USPS49	49	Well	10/20/14	16.1	2340	7.60	-111.760462	39.149414	2280	8.113	<0.035	2.43	1286	141	374	0.215	74.9
USPS64	64	Seep	5/20/15	17.6	22650	7.74	-111.742609	39.153784	21300	7.903	-	1.45	13170	413	436	<0.4	151
USPS76	76	Stream	4/23/15	18.7	6360	8.29	-111.764857	39.148932	6590	7.956	-	4.25	3902	405	356	0.7611	145
USPS84	84	Canal	5/19/15	9.8	600	9.25	-111.736225	39.149129	586	8.662	-	0.578	324	<150	265	0.0334	47.5
USPS108	108	Seep	5/20/15	14.0	2020	7.61	-111.765280	39.147577	-	7.727	-	2.23	1240	157	374	-	74.3

Table 1. *continued*

Station ID	Carbon dioxide (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Carbonate (CO_3) Solids (mg/L)	Hydroxide (mg/L)	Magnesium (mg/L)	Phosphate, total (mg/L)	Potassium, dissolved (mg/L)	Selenium, dissolved (µg/L)	Sodium, dissolved (mg/L)	Sulfate (mg/L)	Total Alkalinity (mg/L)	Total Suspended Solids (mg/L)	Turbidity (NTU)	δ^2H_{VSMOW*} (‰)	$\delta^{18}O_{VSMOW*}$ (‰)
USPS1	1	12	29.2	145	0	39.8	0.078	1.99	<1	40.6	68.3	241	4	8.74	-116.04	-15.59
USPS1	1	23	151	173	0	71.9	-	2.59	-	147	239	289	8.8	7.33	-	-
USPS4A	6	0	195	187	0	24.2	-	3.45	-	257	180	312	122	64.3	-	-
USPS4A	6	0	195	189	0	24.4	0.008	4.6	<1	264	179	315	11.2	50.4	-125.38	-17.11
USPS8	2	7	52	182	0	51.5	0.287	2.51	<1	76.5	104	303	285.3	231	-116.77	-15.88
USPS8b	1	20	136	172	0	69.8	-	2.56	-	139	221	287	57.2	15.2	-	-
USPS9	10	0	406	285	0	76.3	0.009	3.15	<1	331	153	476	5.6	2.4	-109.66	-14.21
USPS9	6	0	454	244	0	77.6	-	3.63	-	339	172	407	4.4	1.66	-	-
USPS10	22	0	1220	257	0	89.8	0.021	3.9	<1	825	225	428	<4	1.66	-110.57	-14.12
USPS12	9	0	2860	230	0	97.8	0.031	9.22	<1	2100	393	384	46	1.85	-104.17	-13.59
USPS19	4	0	846	189	0	102	0.021	5.62	<1	553	370	315	5	2.23	-118.52	-15.45
USPS21A	9	0	1930	176	0	106	-	8.01	-	1460	501	294	10.8	2.18	-	-
USPS23	12	0	143	214	0	98.6	-	4.35	-	124	445	356	26	13.6	-	-
USPS24B	3	0	4.33	137	0	23.2	-	1.15	-	28	17.7j	228	1012	640	-	-
USPS25	1	9	7520	62	0	208	0.009	24.1	<1	5020	1270	103	7.2	0.859	-102.26	-12.23
USPS26	8	0	1200	191	0	96	-	5.66	-	747	397	318	4.4	2.6	-	-
USPS43A	4	0	612	234	0	122	-	4.94	-	452	443	390	147.6	48.1	-	-
USPS43	2	12	671	217	0	135	0.009	4.81	3.71	500	528	362	<4	1.55	-106.86	-13.91
USPS48	8	0	430	193	0	81.3	0.008	2.92	4.524	322	399	321	<4	0.816	-116.81	-15.05
USPS49	5	0	429	184	0	64.6	0.009	2.21	2.739	294	191	307	<4	1.32	-117.85	-15.26
USPS64	9	0	7370	215	0	85	-	3.76	-	4620	307	358	171	19.4	-	-
USPS76	6	0	1810	175	0	105	-	7.3	-	1090	434	292	26	8.24	-	-
USPS84	1	15	33.7	146	0	34.1	-	1.7	-	49.2	51.6	243	324	172	-	-
USPS108	11	0	433	184	0	66.4	-	<1	-	334	179	307	-	-	-	-

"j" indicates lab analysis value was below detection level; "-" indicates no data

* (VSMOW) Vienna Standard Mean Ocean Water

Figure 6. *Transducer installation in the San Pitch River at site 39.*

Figure 7. *Transducer removal from the San Pitch River at site 29.*

Conductivity values of river, canal, and springbrook samples were interpolated to a 50-meter grid in ArcMap™ using the spline with barriers interpolation method. Barriers were inserted between closely spaced canals and river/creek stretches to prevent the search radius from using points from another water body when interpolating. For example, a barrier was placed between Twelvemile Creek and the Highland Canal so that canal samples would not be used to interpolate the values along Twelvemile Creek.

We calculated the salt load, or quantity of salt carried by the river per unit of time, using the same method Lambert and others (1995) used for the Sevier River. The salt load at a particular location is the TDS in mg/L multiplied by the discharge in cfs converted to grams per second (g/s). We used laboratory measured TDS where available and calculated TDS (conductivity x 0.59) for all other sites.

Regional Salinity Mapping Using Geophysics

We conducted a Transient Electromagnetic Method (TEM) geophysical survey (figure 8) to better define geology and water quality in the subsurface. TEM is an active source method that measures the attenuation signal of induced magnetic fields which correspond to changes in the electrical properties in the subsurface. We used this data to image the shallow subsurface which allows us to infer changes in the shallow groundwater system related to variations in groundwater salinity and aquifer characteristics across the San Pitch Valley. TEM measurements were made at 49 unique locations (figure 1) within the San Pitch study area using an ABEM WalkTEM ground loop system fitted with a 40 x 40-meter (m) transmitter antenna with high and low-frequency receiver antenna coils capable of simultaneous recording. Repeat measurements were carried out at specific locations to ensure data consistency and quality for the duration of the field survey period. The time spent at each station location was less than one hour with two to three measurements completed during that time as well as subsequent checking of the field data. All TEM stations yielded high-quality data with excellent signal-to-noise ratio; one station was deemed less useful due to very conductive surface conditions at the site location.

After initial data processing, one-dimensional (1D) inversion models for every station were created and improved until data fit was satisfactory. Using 1D TEM models and a Digital Elevation

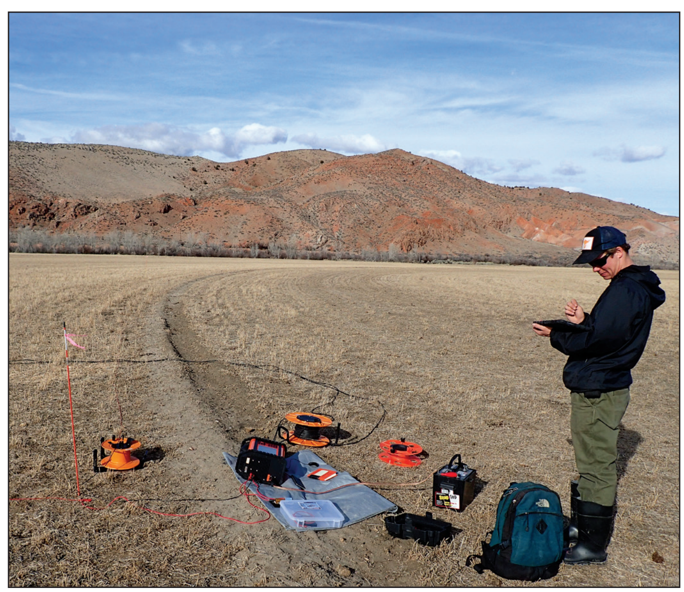

Figure 8. *TEM fieldwork.*

Model (DEM), pseudo two-dimensional (2D) maps of resistivity at specific depths below the land surface were created to aid interpretations. The pseudo-2D maps display the average resistivity over a specified depth or elevation interval and were constrained using the Depth of Investigation (DOI) parameter. DOI is unique for each station, relies on the physical properties of subsurface material, and indicates the maximum depth of resolution in regards to modeling. When extending modeling deeper than the DOI, resulting 1D and 2D models have less confidence below that depth. Early attempts to acquire gravity data to model the basin depth using 2D cross sections were made, but cultural interference and land-access restrictions precluded collection of the high-quality gravity data required for the task. The maximum attainable resolution of the gravity data resulting from the above limitations would not have added nearly as much value as the TEM surveys, so field efforts were adjusted accordingly.

RESULTS AND DISCUSSION

Discharge

We recorded 83 flow measurements ranging from ~0.001 cfs (about 0.5 gpm) from several seeps to 53.5 cfs at the start of the Pettyville Canal below Gunnison Reservoir Dam on April 20, 2015 (site 1). All flow measurements are reported in the appendix.

Of the 16 locations at which we repeated flow measurements in the autumn and spring seasons, about half had higher flow in autumn and the other half in the spring. Generally, the springs, canals, and Twelvemile Creek had higher flow in the spring, and the San Pitch River had higher flow in autumn. Hahl and Mundorff (1968) documented that higher flows in autumn in the San Pitch and Sevier Rivers were due to a significant portion of irrigation return flow to the rivers. The study area had been in moderate to severe drought conditions (streamflow between 6% and 20% of average and precipitation below normal) for at least a year prior to our investigation (National Drought Mitigation Center, 2015), and in spring 2015, snowpack melted out of the Twelvemile Creek drainage about a month earlier than normal (Natural Resource Conservation Service, 2015); therefore, discharge of the San Pitch River was likely less than typical for late April during our site visit. Flow measurements collected at two sites during both spring season field work periods (sites 19 and 21) show discharge was 10% to 20% higher on May 19–20, 2015, than April 20–23, 2015, likely due to precipitation before and during the May visit.

San Pitch River

Discharge of the San Pitch River ranged from no flow directly below Gunnison Reservoir during both autumn 2014 and spring 2015 field visits to 6.9 cfs on October 6, 2014, and 5.0 cfs on April 23, 2015, at the diversion into the Old Field Canal (100% of the river was being diverted to the Old Field Canal during our visits) (figure 9). Figures 9 and 10 show a subset of our data compiled to represent the most spatially complete overview of our flow and chemistry data; that is, the figures show 137 total site visits in April and May 2015 (the "spring 2015" set) and 44 total site visits from late August through early October (the "autumn 2014" set).

The San Pitch River was gaining during the period of study. Numerous visible springs and seeps along the stream banks and floodplains (figures 5, 11A, and 11B), many of which we documented by visual flow estimate and field chemistry measurement (figure 11C), plus groundwater inflow, cause the San Pitch River to gain approximately 0.7 cfs per river mile (cfs/mi) throughout the study area from Gunnison Reservoir to the Old Field Canal diversion (site 26) as measured on April 23, 2015. The upper reach from Gunnison Reservoir to the confluence with Twelvemile Creek (site 20) gained less than the lower reach from the confluence (site 21) to the Old Field Canal diversion, 0.2 cfs/mi versus 0.9 cfs/mi, respectively on April 23, 2015. The gain for the upper reach versus lower reach in autumn 2014 (September 25, 2014) was 0.3 cfs/mi and 1.0 cfs/mi, respectively, indicating the river gained more in autumn 2014 than spring 2015.

The middle reach of the San Pitch River between the Highway 89 bridge and the confluence with Twelvemile Creek gained ~0.2 cfs/mi in both spring 2015 and autumn 2014. Flow measurements in this area were complicated by the nature of the streambed: either shallow and rocky or deep pools filled with slow moving water. Consequently, the flow measurements within this reach (site 101, 57, 60, and 20) have an uncertainty of approximately 0.4 cfs, which does not allow us to calculate the gain through the area of highly saline input with sufficient accuracy.

The reach of the San Pitch River showing the greatest increase in discharge is west of the intersection of South Christianburg Road and Highway 137, near the Neilsen and Gregerson properties, where the river gained at a rate of 2.5 cfs/mi for 0.8 river miles on April 23, 2015 (2.4 cfs to 4.4 cfs; figures 11A and 9). The gain measured on May 20, 2015, was even greater (from 3.8 to 5.0 cfs) in a shorter length of that section of river, equating to a gain rate of 5.9 cfs/mi.

We measured or estimated flow 18 times from 14 seeps and springs along the San Pitch River (figure 10). Flow ranged from a trickle to 0.14 cfs (63 gpm) of channelized flow draining an area of saline marsh between the Highway 89 bridge and the confluence with Twelvemile Creek, entering the San Pitch River at site 17 (figure 10). We measured 0.05 cfs (24 gpm) of flow from a spring located about 400 feet east of the San Pitch River where it enters the San Pitch River at site 81 northwest of the intersection of S Christianburg Rd and Hwy 137. Another smaller spring complex, site 109, was contributing approximately 0.001 cfs (3 gpm) to the San Pitch River on May 20, 2015. Chalk Hill Spring (site 43 and 43A) (figure 11B) flow was measured at 0.002 cfs (0.5 gpm) and 0.01 cfs (2.5 gpm) in autumn 2014 and spring 2015, respectively.

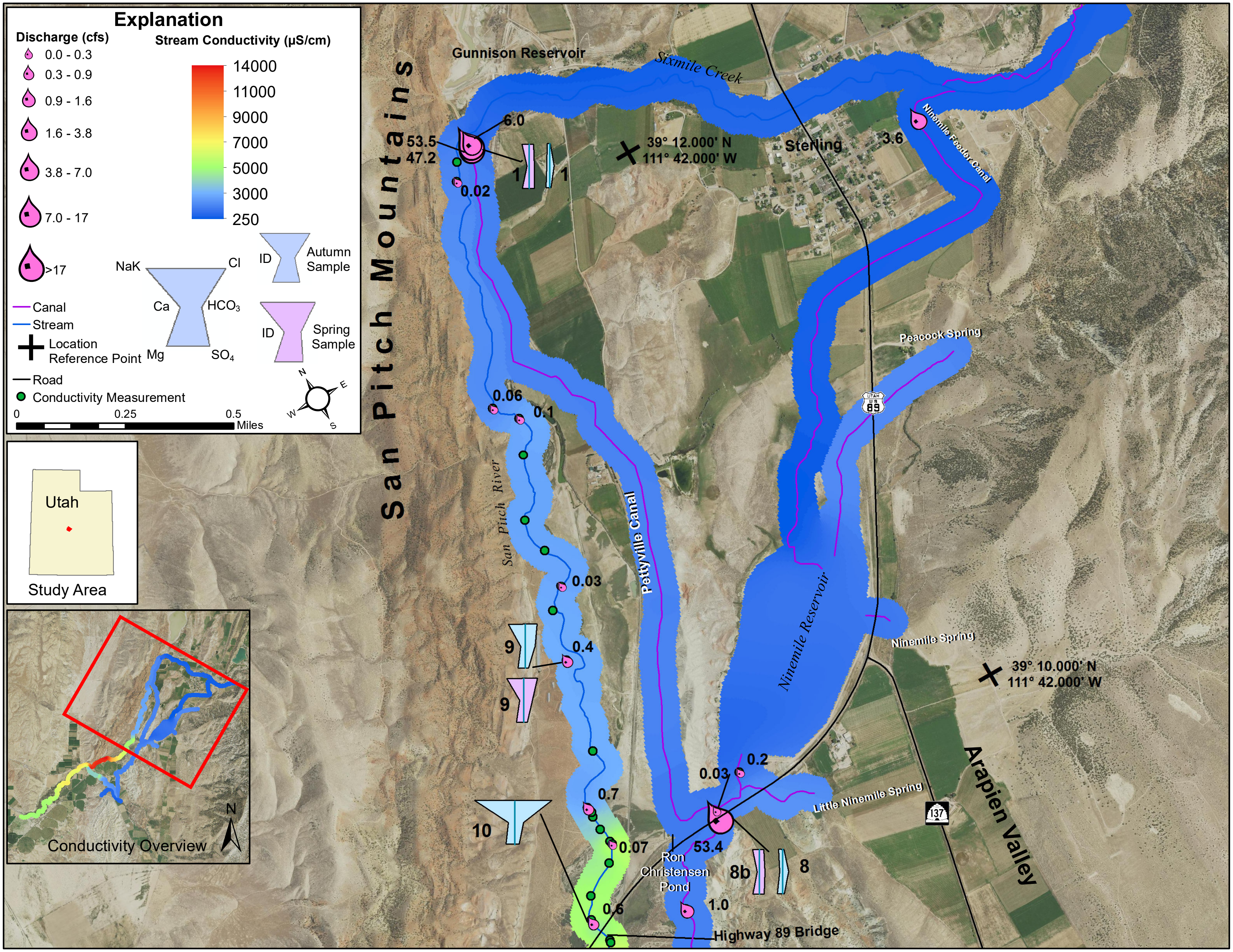

Figure 9A. Northern portion of study area. Discharge and electrical conductivity of the streams and canals in the lower San Pitch River and Twelvemile Creek drainages, and Stiff diagrams of stream and canal samples.

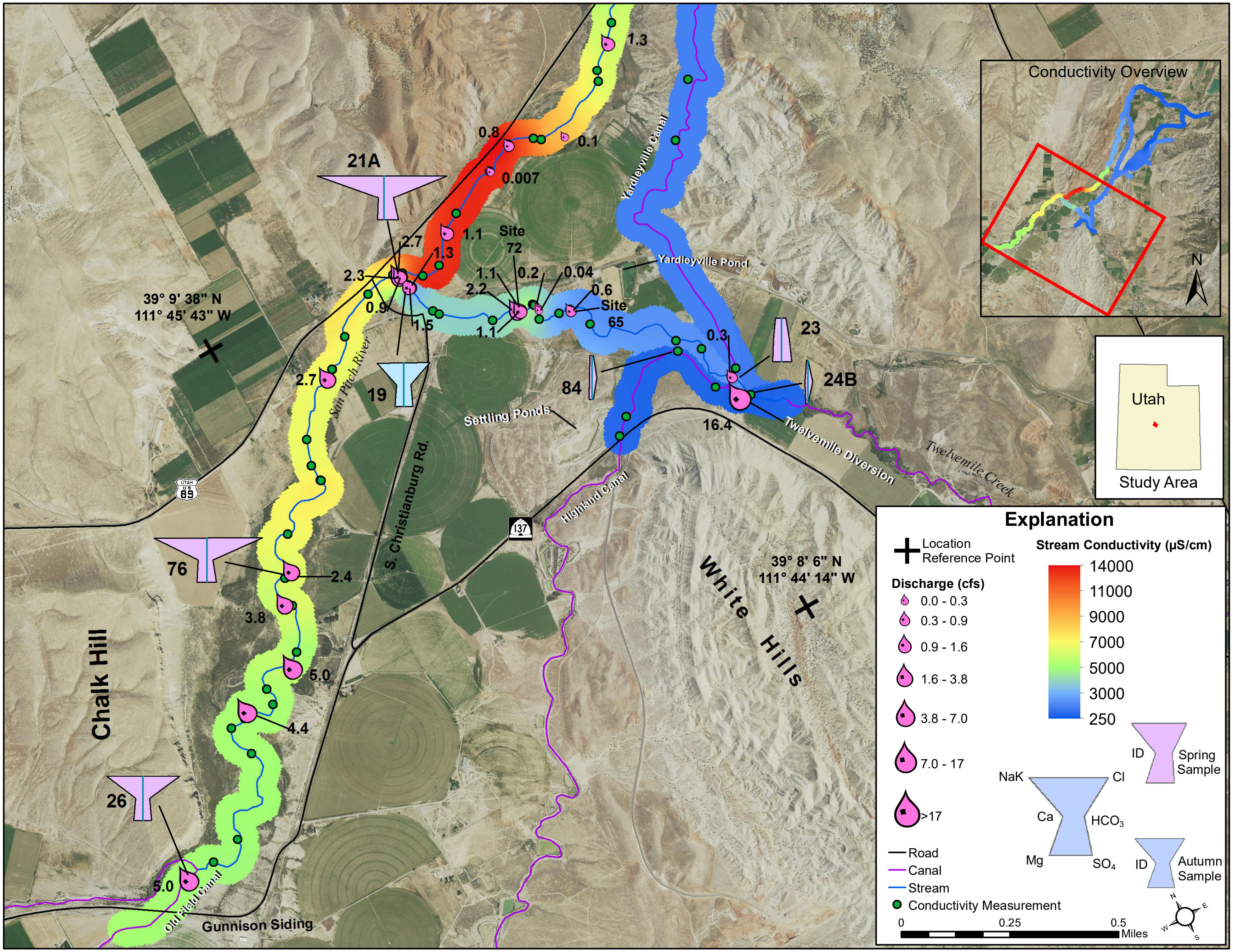

Figure 9B. *Southern portion of study area. Discharge and electrical conductivity of the streams and canals in the lower San Pitch River and Twelvemile Creek drainages, and Stiff diagrams of stream and canal samples.*

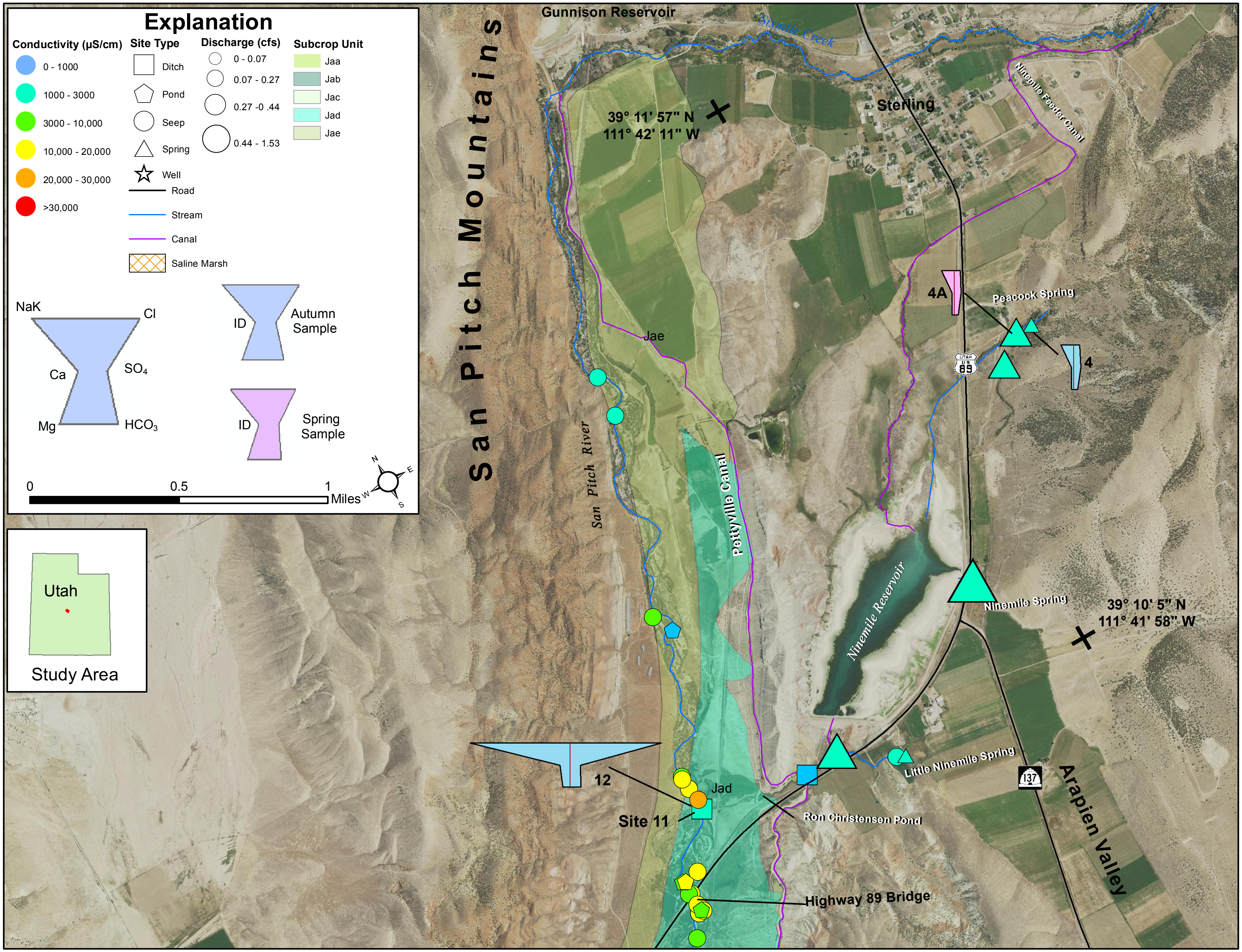

Figure 10A. *Northern portion of study area. Discharge and electrical conductivity of springs, seeps, ditches, wells, and ponds in the lower San Pitch River and Twelvemile Creek drainages, Stiff diagrams of springs and seeps, and Arapien Shale subcrop interpreted from Weiss (1994).*

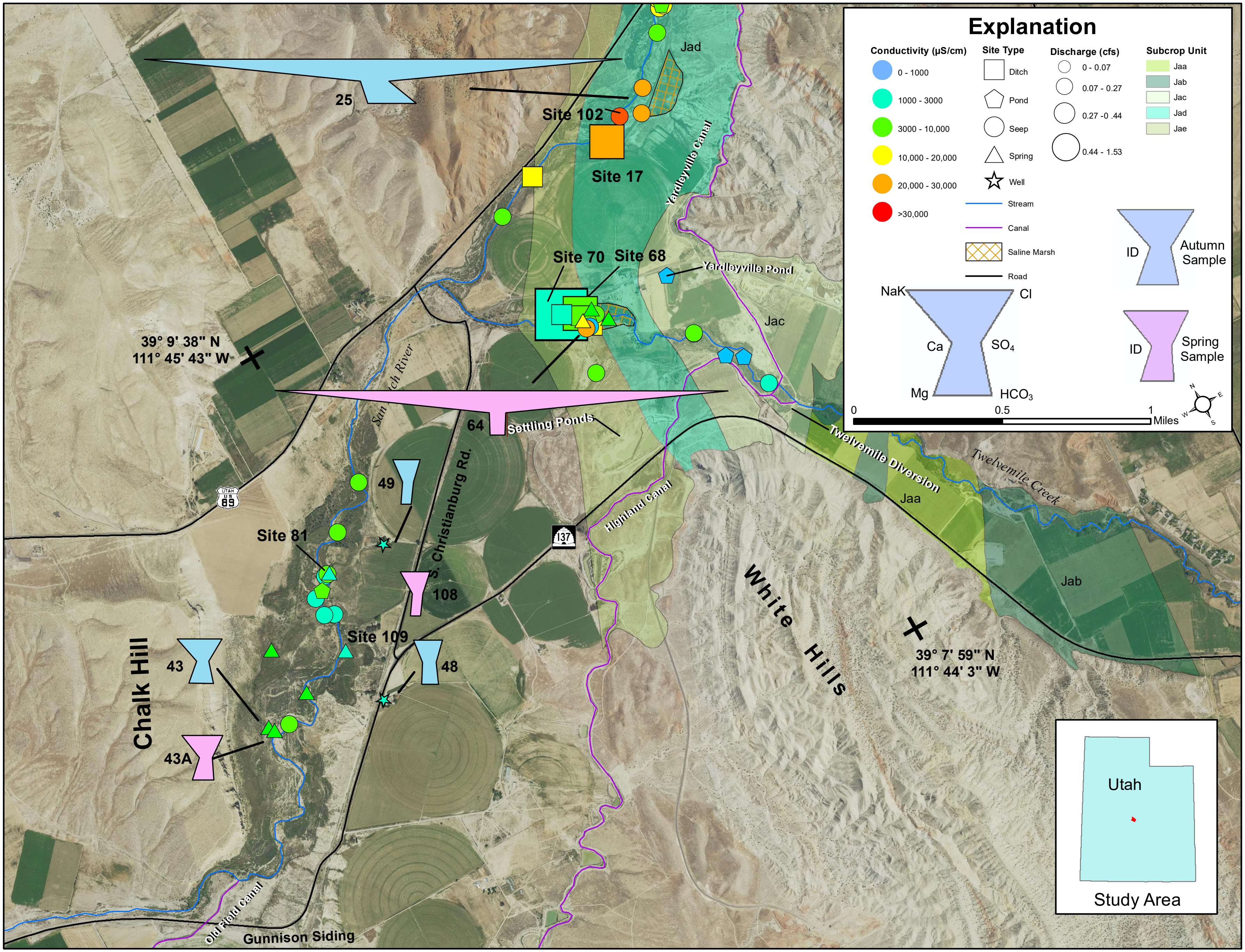

Figure 10B. *Southern portion of study area. Discharge and electrical conductivity of springs, seeps, ditches, wells, and ponds in the lower San Pitch River and Twelvemile Creek drainages, Stiff diagrams of springs and seeps, and Arapien Shale subcrop interpreted from Weiss (1994).*

A B C

Figure 11. *(A) Spring-fed channel flowing into the San Pitch River below the confluence with Twelvemile Creek. (B) Flow measurement with a v-notch weir at Chalk Hill spring. (C) Linear saline seep in the San Pitch River marked by rust and black organic material.*

Twelvemile Creek

As is typical, Twelvemile Creek was completely diverted to the Highland Canal at the Twelvemile Creek diversion structure (site 24, 24A, and 24B) during our visits. Therefore, all flow in Twelvemile Creek at the confluence with the San Pitch River was from seepage into the creek bed, seeps and springs along the lower reach, irrigation ditch return, or irrigation return flow (not distinguishable from seepage). Discharge of Twelvemile Creek ranged from 0.84 cfs immediately below the diversion (site 23) (figure 9B) on May 19, 2015, flow we observed to be bank seepage and general groundwater gain, to 1.2 cfs and 1.5 cfs at the confluence with the San Pitch River (site 19) on September 25, 2014, and May 19, 2015, respectively (appendix, figures 1B and 9B).

Twelvemile Creek gained an average of 0.7 cfs per river mile below the Twelvemile Creek diversion (site 23) to the confluence with the San Pitch River (site 19) as measured on April 23, 2015. A large portion of the gain in discharge on Twelvemile Creek (1.6 cfs) occurs in a short reach between river mile 0.9 and 1.1 (sites 65 and 72, respectively) (figures 1B and 9B), an area of highly saline groundwater input plus relatively good quality water in a ditch from the Yardley ranch (site 70) (figures 1 and 10B). We measured at least 0.25 cfs of poor quality water from springs, seeps, and streamlets entering Twelvemile Creek at sites through this reach; however, Twelvemile Creek actually gained 0.5 cfs in the 0.2 miles above where the ditch from Yardley ranch joins the creek (between site 65 and 70), a rate of gain of 2.3 cfs per mile, the highest rate of gain observed anywhere in the study area.

We measured or estimated flow six times from five seeps and springs along Twelvemile Creek (figure 10B), although many more diffuse seeps were visible along the creek, especially in the section adjacent to the Highland Canal and in the area of saline input. Flow ranged from a trickle to 0.19 cfs of channelized flow draining a highly saline 10-acre marsh about midway between the Twelvemile Creek diversion and the confluence with the San Pitch River (south of the Yardley ranch), entering the creek at site 68. A ditch southwest of the ranch, site 70, was doubling the flow of the creek (site 72) when we visited on April 23, 2015.

Temporal Changes in Conductivity, Temperature, and River Stage

We monitored conductivity, temperature, and relative stage (river level) from October 2014 to April 2015 at two locations on the San Pitch River: one just above the Highway 89 bridge (site 39, figure 1), upstream from an area of saline input, and the other just above the confluence with Twelvemile Creek (site 29, figure 1B), downstream from the saline input. As suspected, the location downstream from high-salinity groundwater inflow had much higher overall conductivity (average 10,460 µS/cm) relative to the upstream location (average 3570 µS/cm), and higher variability of 5000 µS/cm over the monitoring period relative to a variability of 2300 µS/cm at the upstream site (figure 12). Water quality variability was greater at both sites during springtime.

River stage varied by slightly more than one foot over the monitoring period, and increases in stage correlate with decreases in conductivity (figure 12). Stage increase can be caused by precipitation/runoff events or changes in volume released to the river from tributaries or reservoirs. Salt transported via surface runoff through and over the areas of high salinity, some of which had visible salt encrustations on the surface (figure 13), appears to be diluted by higher volumes of fresh water in the San Pitch after these stage increases. The upward conductivity trend in springtime at the downstream site is consistent with lower overall stream discharge.

Chemistry

Conductivity Measurements (Proxy for Salinity)

Water from 216 sites was measured for field parameters; 48 sites were measured during autumn 2014, 87 sites were measured only during spring 2015, and 74 sites were duplicate measurements taken during both seasons from streams, seeps, canals, springs, and wells. Conductivity measured for all sites ranged from 359 to 77,500 µS/cm, the lowest from Twelvemile Creek above the Highland Canal diversion and the highest from a seep along the banks of the San Pitch River. All field parameters are reported in the appendix; figures 9 and 10 present a subset of our data compiled to represent the most spatially complete overview of our flow and chemistry data; that is, 137 site visits in April and May 2015, and 44 visits from late August through early October 2014. Some of our repeat measurements taken during spring 2015 vary due to heavy rainfall during our May fieldwork.

Conductivity, a proxy for salinity, changes dramatically throughout streams and canals in the study area (figure 9), mostly due to the influence of good quality to very poor quality seeps and springs along the San Pitch River and Twelvemile Creek (figure 10). In the northernmost portion of the study area, Sixmile Creek has excellent water quality, as shown in the darker blue colors on figure 9A. The San Pitch River is characterized by relatively low-salinity water (based on a conductivity of 1453 µS/cm). The adjacent Pettyville Canal, fed by San Pitch River water mixed with higher quality Sixmile Creek, is characterized by TDS concentrations of 388 and 830 mg/L (the former was taken during autumn sampling where we measured more flow from Sixmile Creek than the San Pitch River; the opposite conditions were documented during our spring sampling). Springbrooks around Ninemile Reservoir (Peacock, Ninemile, and Little Ninemile) have generally good water quality, as do the major canals.

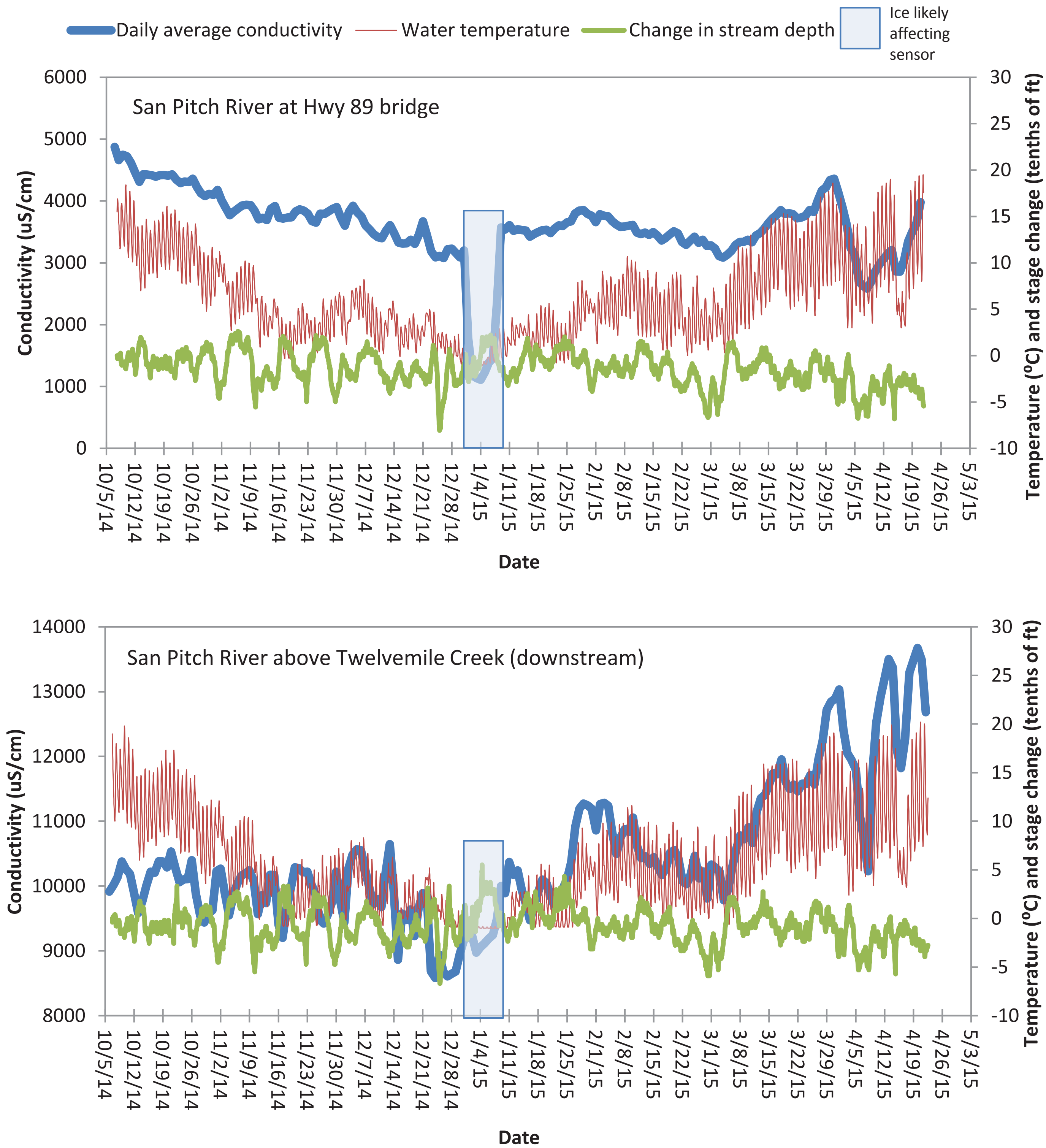

Figure 12. *Conductivity, temperature, and change in stream depth over time in the San Pitch River upstream (top graph) and downstream (bottom graph) of an area of high-salinity input. The downstream site had a much higher conductivity overall, had higher variability over the monitoring period, and increased during spring relative to the upstream site. Stage (depth) is inversely correlated to conductivity at the downstream site, i.e., water quality improves as stream flow increases and vice versa at the downstream site. Dilution by fresh runoff or flow routing for irrigation is likely the cause of water-quality improvement.*

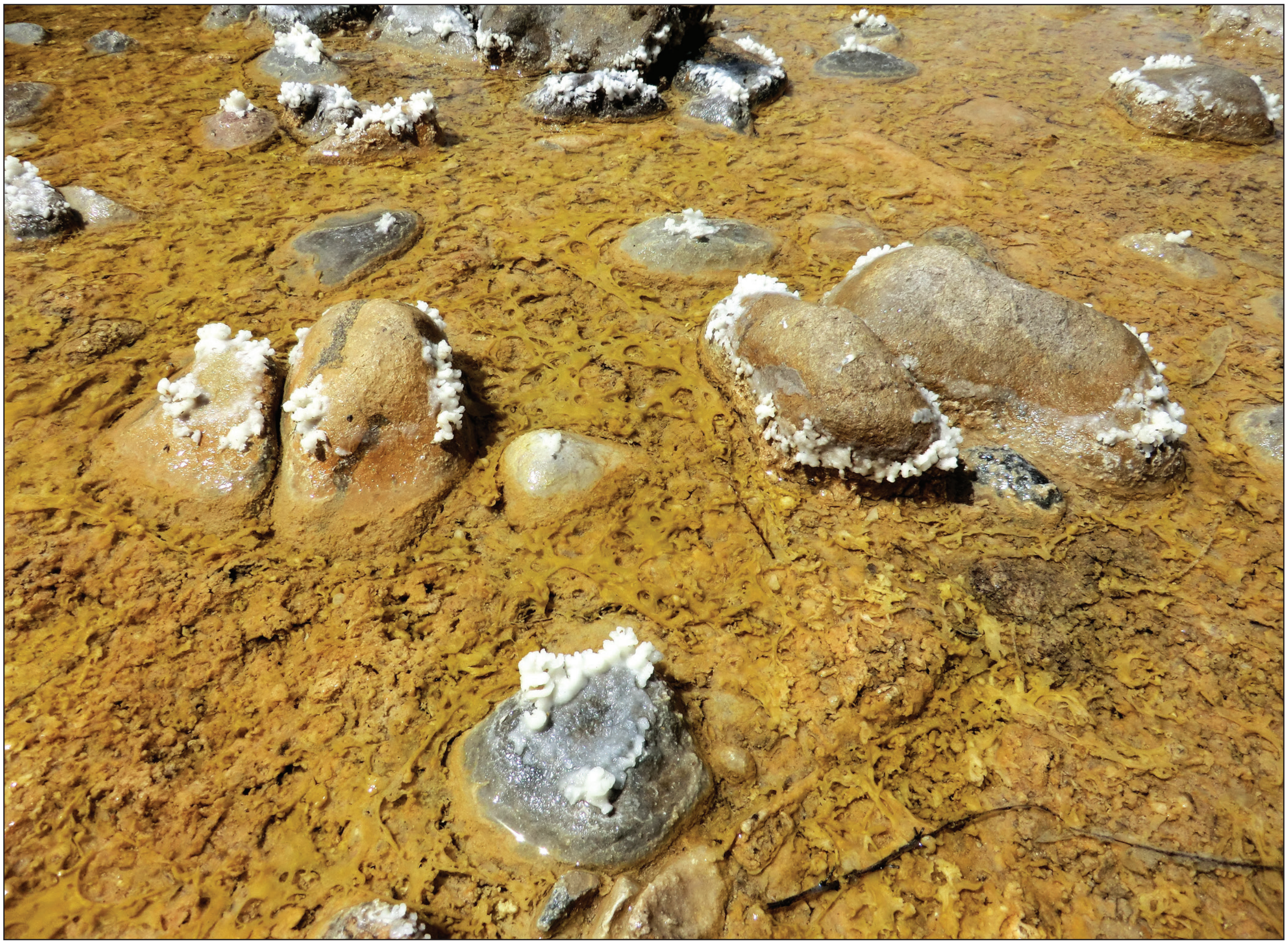

Figure 13. *Encrusted salt on clasts within the San Pitch River flow regime.*

San Pitch River quality declines downriver from ~1 mile south of Gunnison Reservoir (medium blue, figure 9) to the confluence with Twelvemile Creek (red) in a stepwise fashion. Some poor quality seeps and springs along the banks of the San Pitch in the northernmost reach were marked by linear features stained red from possible iron and black organic material (figure 11C). Return flow from Ron Christiansen pond (site 11) had relatively good water quality (figure 10A). South of the Highway 89 bridge, the San Pitch River has numerous saline springs and seeps mostly on the south side of the river and adjacent to a saline marshy area (site 25) that yields/contributes the highest conductivity water documented at all reaches of the stream (site 102) (figures 1B and 10B).

Twelvemile Creek above the Twelvemile diversion has excellent water quality, influencing the quality of water in the Highland Canal. Twelvemile Creek below the diversion has generally good water quality (medium blue) until an abrupt deterioration north of the settling ponds (green-blue) (figure 9B).

At the confluence with Twelvemile Creek, water quality of the San Pitch River improves due to mixing and input of less saline water from Twelvemile Creek (figure 9B); conductivity of water measured in Twelvemile Creek near the confluence at three different times during autumn and spring sampling events ranged from 3640 to 3970 µS/cm with a TDS concentration of 2416 mg/L (recorded during autumn 2014). The San Pitch River below the confluence of Twelvemile Creek is characterized by conductivity values of 7500 µS/cm and 7870 µS/cm and a TDS concentration of 4234 mg/L (the latter two values are from autumn 2014)—a decrease from the high conductivity value of 13,140 µS/cm measured on April 22, 2015, above the confluence.

About halfway between the confluence with Twelvemile Creek and the Old Field Canal diversion, water quality of the San Pitch River improves and has conductivity values generally in the 3000s (figure 9B) primarily due to better water quality from seeps and springs. Springs and seeps along this stretch/reach are characterized by lower water temperatures and in some cases, support watercress growth. The seeps and springs also have similar pH and conductivity as nearby water wells (sites 48 and 49), suggesting a groundwater source.

General Chemistry

Water quality in the study area varies with TDS concentrations primarily above 1000 mg/L (about 67% of sampled water), and unexpected elevated nitrate concentrations exist in some of the stream sample sites. About 21% of the water samples are above 3000 mg/L TDS concentration, a classification deemed by the Utah Water Quality Board as "Limited Use Water." TDS concentration data are from 24 samples from 8 streams, 6 canals, 4 springs, 4 seeps, and 2 wells. Five of the sites were sampled in autumn and repeated in spring. TDS concentration ranges from 260 to 15,538 mg/L, the lowest is from Twelvemile Creek before it is diverted to Highland Canal (site 24B; appendix and figure 9B) and the highest is from a saline seep from a marshy area (figure 14) adjacent to the San Pitch River located about 0.3 miles south of the Highway 89 bridge (site 25; appendix and figure 10B). Nitrate concentrations range from non-detect to 12.2 mg/L (site 19 from Twelvemile Creek above the confluence with the San Pitch River) (table 1).

Solute chemistry for 24 water samples taken from various locations throughout the study area is shown on Stiff diagrams (figures 9 and 10). Plots having similar shape reflect similar chemistry type and the width of the plot is proportional to the concentration of the constituents. The variability of the diagrams on figures 9 and 10 reflects the different and likely mixed sources of water in this part of the San Pitch drainage system. Conductivity values for streams and canals (figure 9) and seeps and springs (figure 10) emphasize the areas that have greater salinity (higher conductivity values) compared to the areas characterized by lower salinity (lower conductivity values). In general, the area that has the greatest salinity is in the reach of the San Pitch River between the Highway 89 bridge and the confluence with Twelvemile Creek (in the river itself, as well as from seeps, springs, and marshes in the adjacent floodplain of the river).

The distribution of water chemistry type based on major cations and anions for 24 water samples, including sites sampled over different seasons (figure 15), is shown in a Piper diagram. Water chemistry is variable throughout the area but is dominantly sodium-potassium-chloride-type and calcium-magnesium-bicarbonate-type water (figure 15), and sites (those sampled twice) maintain similar quality over the different seasons. In general, water quality from the canals (except Old Field Canal) and Twelvemile Creek have calcium-magnesium-bicarbonate-type water and all other sites have sodium-potassium-chloride type.

Nitrate

Nitrate was analyzed in 24 samples. Nitrate concentration values range from non-detect to 12.2 mg/L (table 1). Average nitrate concentration in the samples is about 2.0 mg/L with

Figure 14. *Saline marsh area south of the San Pitch River and south of the Highway 89 bridge.*

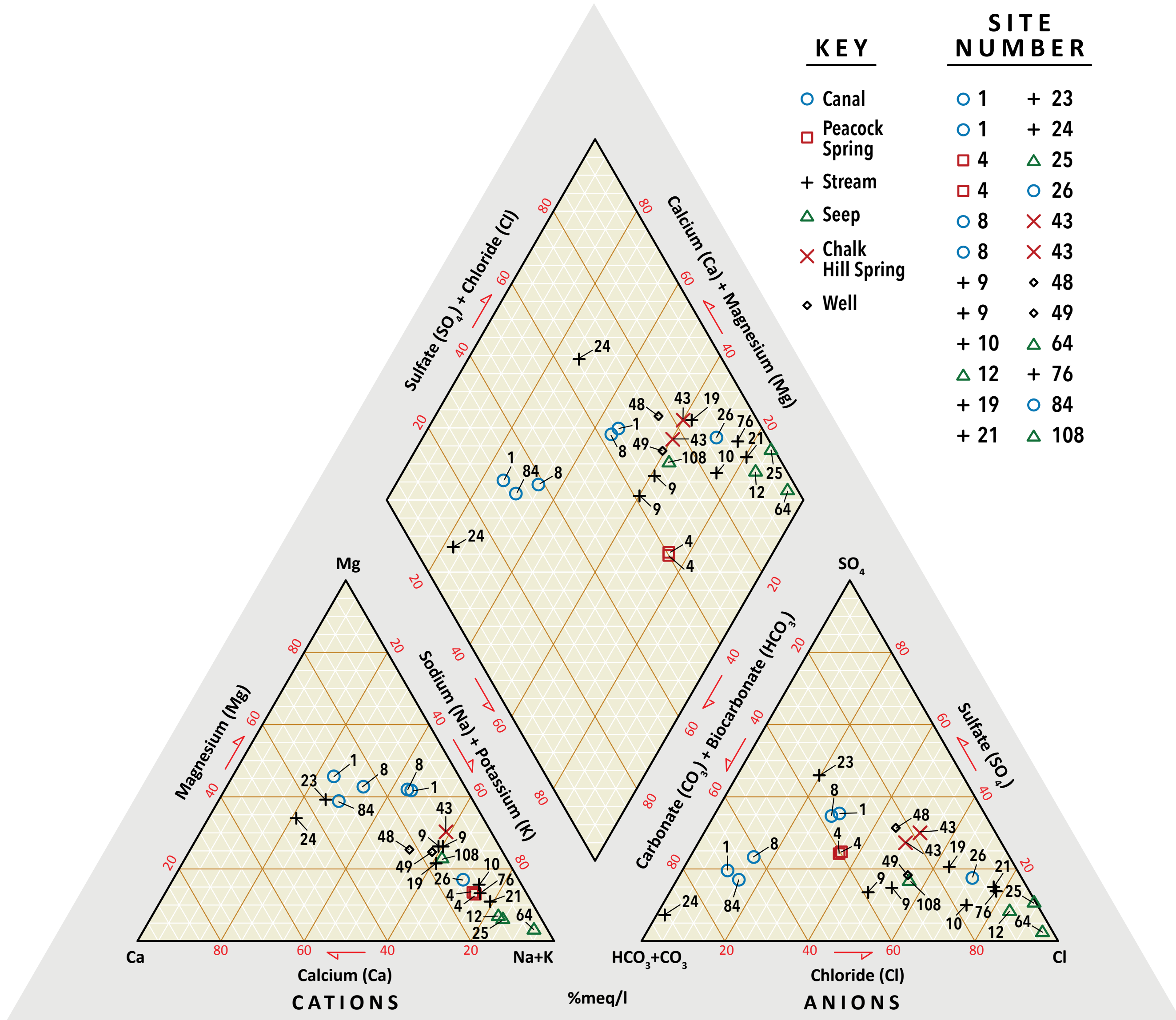

Figure 15. General solute chemistry for sampling sites in the lower San Pitch drainage for streams, canals, springs, seeps, and wells; some sites were sampled during autumn 2014 and spring 2015 (sites 1,4,8,9, and 43 in the text).

a median of 0.8 mg/L. Fifty-eight percent of the water analyzed for nitrate yielded values less than 2 mg/L, the range of samples with nitrate concentrations greater than 1 mg/L is 1.08 to 12.2 mg/L, averaging 4 mg/L (atypically high nitrate concentrations for surface water). One sample, Twelvemile Creek immediately below the diversion of Twelvemile Creek to Highland Canal (site 23), exceeded the EPA drinking water standard of 10 mg/L. The second highest nitrate concentration of 8.15 mg/L is also in Twelvemile Creek at site 19 above the confluence with the San Pitch River. The source of nitrate is unknown, but likely not inherent in Twelvemile Creek since the sample at site 24B (Twelvemile Creek above the diversion to Highland Canal) has nitrate concentration of 0.11 mg/L. Groundwater seepage from the Highland Canal likely contributes nitrate to Twelvemile Creek along the reach from site 23 to the confluence with the San Pitch River at site 19. Possible sources of nitrate include fertilizer, septic-tank effluent, and manure from nearby feedlots. Because the water with elevated nitrate concentration does not serve as a drinking water source, it is not considered deleterious to human health.

Boron

Boron was analyzed in 24 samples during both field seasons. Concentrations ranged from less than 30 µg/L (the detection level) in one sample to 1870 µg/L at site 25, a saline seep on the floodplain of the San Pitch River (table 1); average concentration in all 24 samples is 344 µg/L. Boron may be associated with dissolution of minerals from local geologic units (particularly the Green River Formation, which has been associated with potential dissolution of boron contributing to surface and groundwater samples in the Uinta Basin [Wallace, 2012]). All but one sample of the water analyzed for boron concentrations were above the detection level and two were above the Utah Division of Water Quality's (UDWQ) maximum contaminant level (MCL) (not a primary drinking water standard, but a surface water-quality standard based on the UDWQ's criterion for maximum boron concentration of 0.75 mg/L for Class 4 "Beneficial Use Designation" for agricultural use as reported by a TMDL study for the lower San Pitch drainage area [Millenium Science and Engineering, 2003]). The TMDL study indicated that irrigation on saline crops could increase the concentration of other dissolved constituents, including boron (if at elevated concentrations), and can be toxic to some crops. Boron is not known to pose a threat to human health.

Chloride/Bromide Ratio

Chloride/bromide mass ratios can be used to determine the source of surface and groundwater contamination. To determine whether water in the study area has been affected by subsurface influences (waters associated with a more saline source in the subsurface) from geologic units (i.e., the Arapien Shale), we analyzed concentrations of chloride and bromide in wells, canals, streams, and springs and compared this data to concentrations of the same species in waters from the saline sources (marshy springs and seeps). Chloride concentration in natural precipitation is generally less than 5 mg/L and Cl/Br ratio is less than 60. Higher concentrations and ratios indicate contamination or interaction with geologic materials (Davis and others, 1988). Water affected by the dissolution of halite will have higher ratios than other sources of contamination, generally 1000 to 10,000 (Davis and others, 1988). Samples in this study (figure 16) have exceptionally high chloride concentration and Cl/Br ratios, indicating dissolution of halite as the source of the chloride. In addition, the bromide-chloride data show a trend of increasing chloride to bromide ratio with increasing chloride concentration, indicative of more saline waters possibly mixing with fresher water.

Stable Isotopes

Stable isotopes of oxygen and hydrogen atoms in the water molecule are affected by latitude and temperature that can provide clues to the location of where the water was recharged (Clark and Fritz, 1997). The study area is small enough that latitude effects are negligible, but temperature will influence the ratio of heavy isotopes to light isotopes. Samples depleted in the heavier isotopes are characteristic of water recharged at a higher elevation (cooler temperatures), likely from snowmelt; whereas samples enriched in the heavy isotopes indicate water that is recharged at lower elevation (warmer temperatures) (Clark and Fritz, 1997). A graph of oxygen versus hydrogen isotope ratios from the San Pitch samples (figure 17) shows depleted samples farther down and to the left and enriched samples up and to the right but still near the meteoric water line. Departure to the right from the meteoric water line can indicate an increasing degree of evaporation.

The stable isotope results are helpful in determining the origin of the saline seeps. San Pitch samples plot generally along the meteoric water line (figure 17). Peacock Spring has the most depleted signature of the samples, indicating this spring is discharging water that was recharged at an elevation higher than other waters in the study area. Pettyville and Yardleyville Canals (fed primarily by Sixmile Creek water), Twelvemile Creek, and the two private wells have depleted signatures relative to the San Pitch River and the saline seeps. Rivers and groundwater tend to integrate all sources of precipitation, so it is not surprising that these sites have similar intermediate signatures. The saline seeps and Chalk Hill Spring have the heaviest isotope ratios, indicating the water from these sources recharged the groundwater system at low elevation. Canal and reservoir seepage and/or precipitation recharge on the valley floor are likely sources of the water that eventually emerges as saline seeps. One sample from a saline marsh approximately 0.3 miles south of the Highway 89 bridge between the San Pitch River and Yardleyville Canal (site 25) has an isotopic signature indicative of evaporated water. The stable isotope data do not point to deep groundwater flow originating in the surrounding mountains as the source of the seeps. The San Pitch River has isotope ratios intermediate between fresher groundwater and saline seeps, indicating mixing of those two sources in the San Pitch River.

Salinity Loading

The high-salinity sources identified above impact the quality of the San Pitch River and its irrigation diversions only as much as the total load they bring to the river, which is proportional to the concentration of salts multiplied by the discharge of the source. The symbols and values on figure 18 illustrate that the salt load of the San Pitch River generally increases with distance downstream (symbols changing from small blue to larger orange) and that the salt load for a given river sample location is typically higher in autumn (dark blue labels) than in the spring (black labels). Conversely, most of the tributary sources such as the springs south of Sterling, Pettyville and Yardleyville Canals, and Ninemile Reservoir carried a larger salt load in the spring because their flows were much greater than in autumn. The largest calculated salt loads are at Gunnison Reservoir, Pettyville Canal, and Yardleyville Canal in the spring because the discharge at these locations was an order of magnitude higher than any other measured flow, and not because they have high-salinity water.

A marked increase in salt load carried by the San Pitch River occurs near the Highway 89 bridge, where salt load increases from generally less than 100 g/s to over 100 g/s due to the influence of saline seeps and the gain of high conductivity groundwater, increasing both the flow and salinity of the river (figure 18). Salt load increases even more dramatically adjacent to the area of the saline marsh between the bridge and the

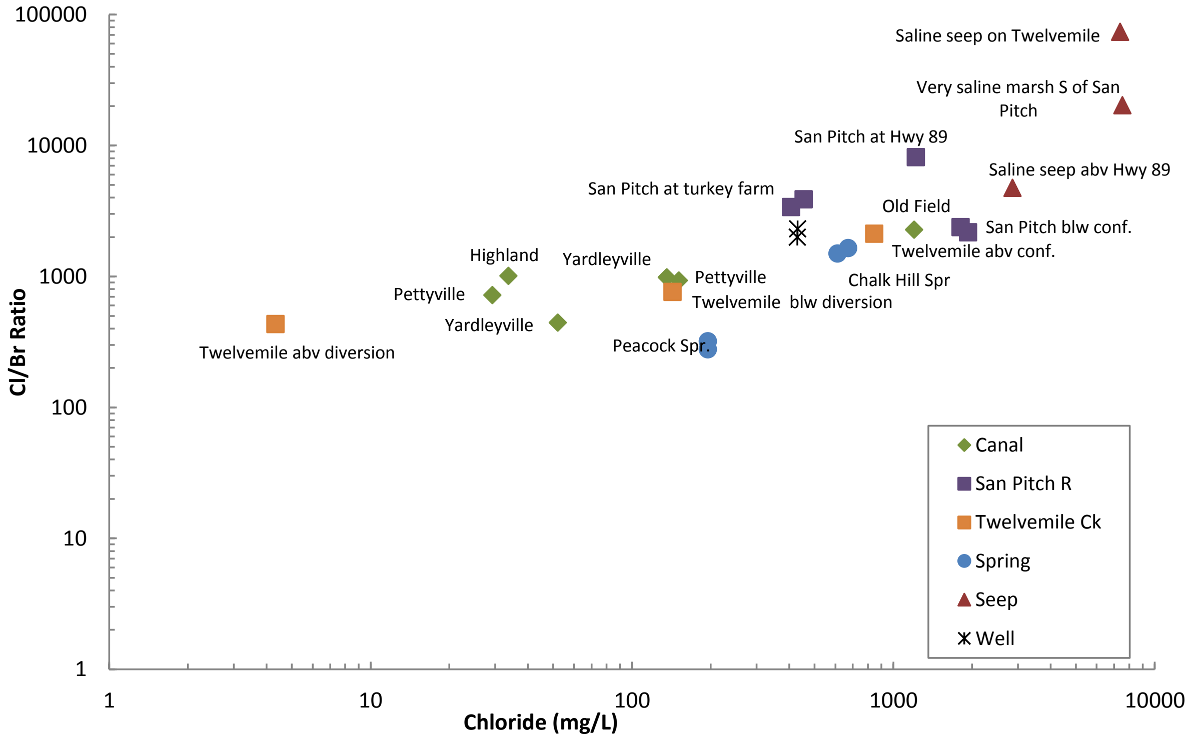

Figure 16. Chloride/bromide ratio in water samples in the lower San Pitch River and Twelvemile Creek drainages (note logarithmic scale). Chloride concentration in natural precipitation is generally less than 5 mg/L and Cl/Br ratio is less than 60. Higher concentrations and ratios indicate interaction with geologic materials or contamination. Water affected by the dissolution of halite will have higher ratios than other sources of contamination, generally 1000 to 10,000. Samples in this study had exceptionally high chloride concentration and Cl/Br ratios, indicating dissolution of halite.

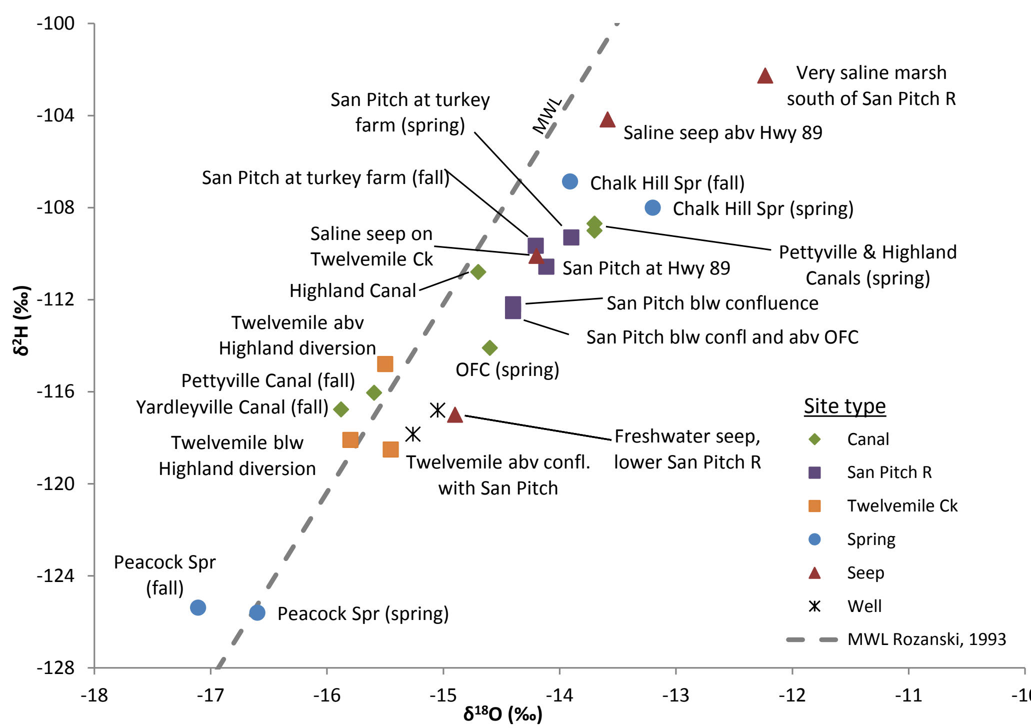

Figure 17. Stable isotopes of hydrogen and oxygen in water samples from the lower San Pitch River and Twelvemile Creek drainages. A depleted signature (farther down and to the left on the graph) is characteristic of water recharged at a higher elevation, likely from snowmelt (e.g., Peacock spring), whereas enriched signatures (toward the top and to the right) indicate water that is recharged at lower elevation. Departure to the right of the meteoric water line (MWL) can indicate an increasing degree of evaporation. The canals, wells, and Twelvmile Creek have a relatively high elevation recharge signature, likely indicating mountain recharge ending up as groundwater or runoff. A fresh water seep in the San Pitch River below the confluence with Twelvemile and before Old Field Canal has a similar signature to the well samples, suggesting a similar recharge source. The saline seeps and Chalk Hill spring have isotope signatures that suggest low elevation recharge, and in the case of the very saline marsh, some evaporation. The San Pitch River has a signature indicative of mixing of the saline groundwater input and the fresher surface water sources.

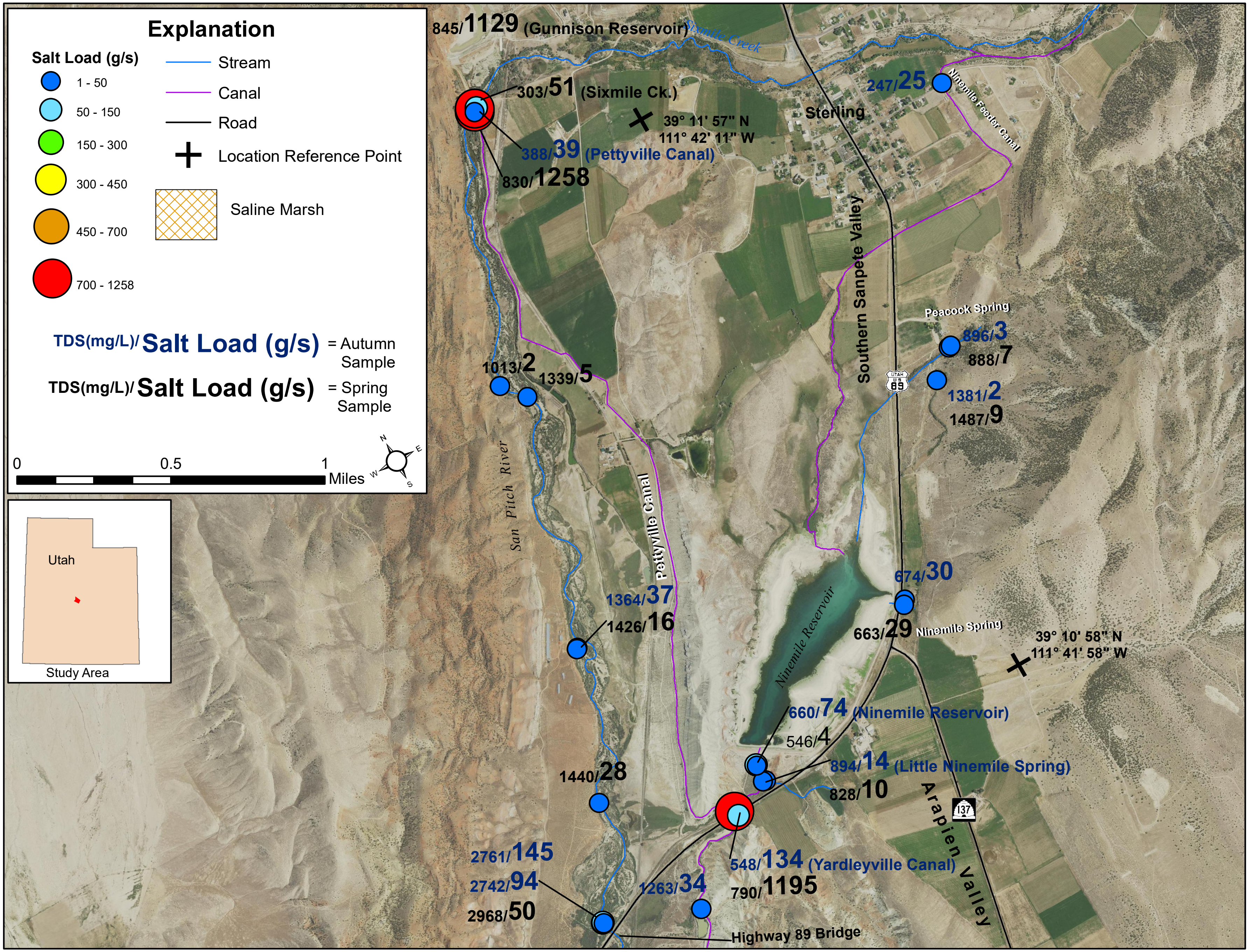

Figure 18A. Northern portion of study area. Salt load carried by the San Pitch River, Twelvemile Creek, and selected canals and springs.

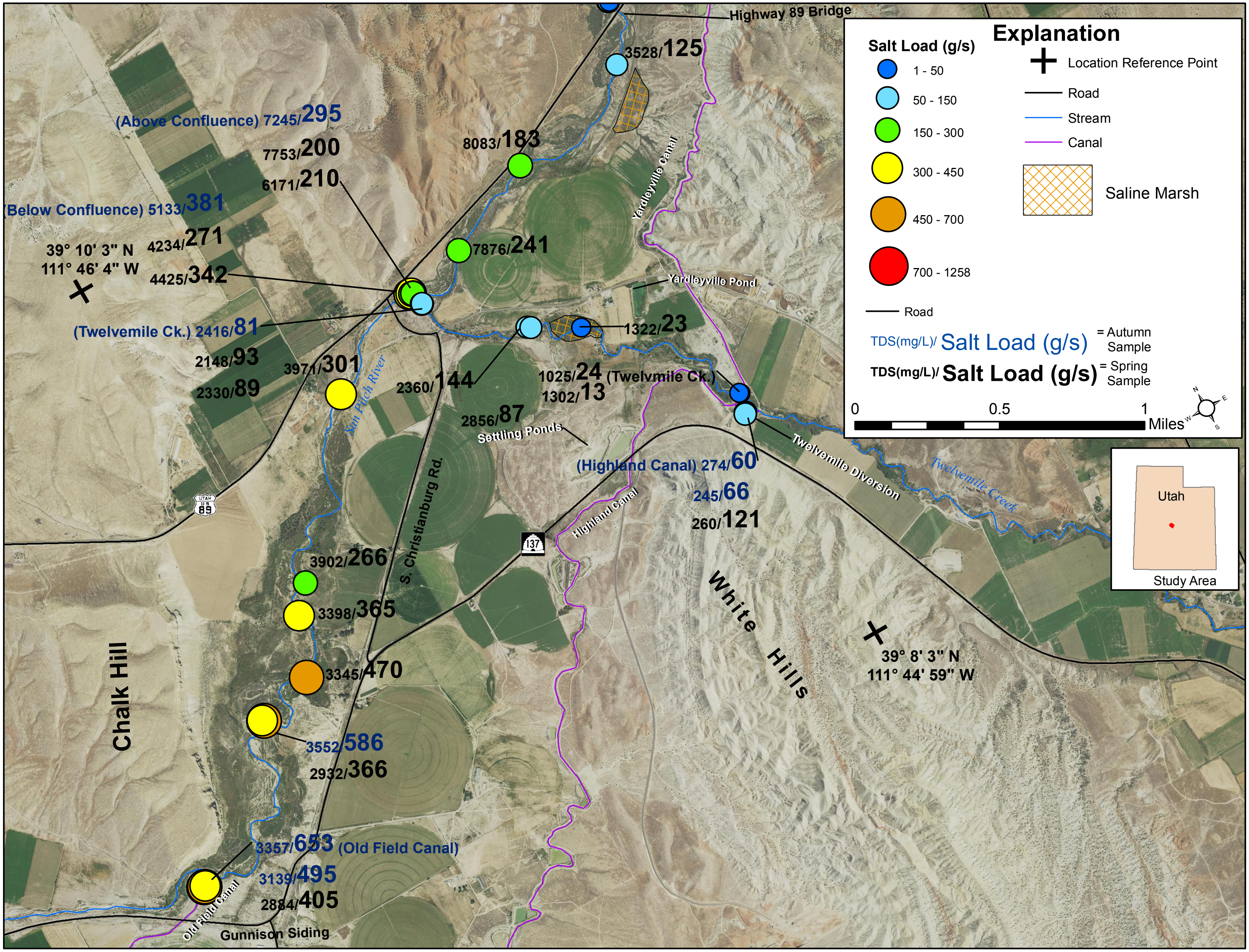

Figure 18B. *Southern portion of study area. Salt load carried by the San Pitch River, Twelvemile Creek, and selected canals and springs.*

confluence because, in addition to other saline seeps we have documented in this reach and groundwater inflow, the marsh is contributing significant flow (at least 0.14 cfs of channelized flow from the marsh measured at site 17 on September 25, 2014) of very poor quality water (a sample directly from the marsh via a culvert at site 25 had conductivity of 25,100 and TDS of 15,538 mg/L). The river gains enough flow and salinity in this reach (approximately 0.3 cfs gain and TDS increase from 2968 to 7753 mg/L on April 22, 2015) to almost triple the salt load to nearly 300 g/s before reaching the confluence with Twelvemile Creek (figures 18 and 19).

Twelvemile Creek carries negligible salt until it reaches the saline marsh north of the settling ponds and west of Yardley ranch. This marshy area contributes enough salt that the salt load of Twelvemile Creek at the confluence with the San Pitch River is approximately 80 g/s (in autumn) to 90 g/s (in spring) even considering the dilution by better quality water from an irrigation ditch off the Yardley ranch (figure 18B).

Although salinity (conductivity) decreases in the San Pitch River downstream from the confluence due to dilution by Twelvemile Creek (figure 9B), the salt load increases due to the additional flow supplied by Twelvemile Creek (figure 18B). Similarly, the better quality springs and groundwater inflow in the lower reach of the San Pitch River above the Old Field Canal (figure 10B) increase the discharge of the river and contribute some salt load themselves, which increases the overall salt load carried by the San Pitch to between approximately 400 g/s in spring to approximately 650 g/s in autumn at the Old Field Canal diversion (figure 18B).

TEM Survey

The DOI values for the study area range from 35 meters (114 ft) to 200 meters (656 ft) and have an average of 106 meters (347 ft). The pseudo-2D maps shown on figure 20 represent the average electrical resistivity at depth below the ground surface over specific depth intervals. Near-surface resistivity models agree fairly well with water sample data since coherent structures from modeling (observed as low-resistivity, conductive bodies) are found near areas of high water conductivity/salinity. Background values of resistivity within the study area range from 10 to 100 ohm meters (ohm-m) which is inferred as the signature of valley fill (sand and gravels mixed with clay). Figure 20B shows a prominent near-surface conductive body (1 to 10 ohm-m) within the study area between the settling ponds near Highway 137 and downgradient (northward direction) to Twelvemile Creek. The top of the conductive body is detected at less than 5 meters (16 ft) depth and is approximately 15 meters (50 ft) in thickness. Two more shallow conductive zones are observed which are adjacent to the Highway 89 bridge (over the San Pitch River channel) and Ninemile Reservoir. At a depth interval of 20 to 25 meters (figure 20C), the conductive zone near the settling ponds is no longer observable. However, a more prominent conductive zone (1 to 10 ohm-m) located to the northeast near Ninemile Reservoir is a much larger, continuous, and deeper structure (detected beyond 100 m depth) that trends NE-SW. This conductive zone is also the dominant feature on figure 20D.

Data collected from the wireline geophysical logs of regional oil and gas exploration wells indicate that the Arapien Shale

Figure 19. *High-salinity water and organic/chemical precipitates in the San Pitch River above the confluence with Twelvemile Creek.*

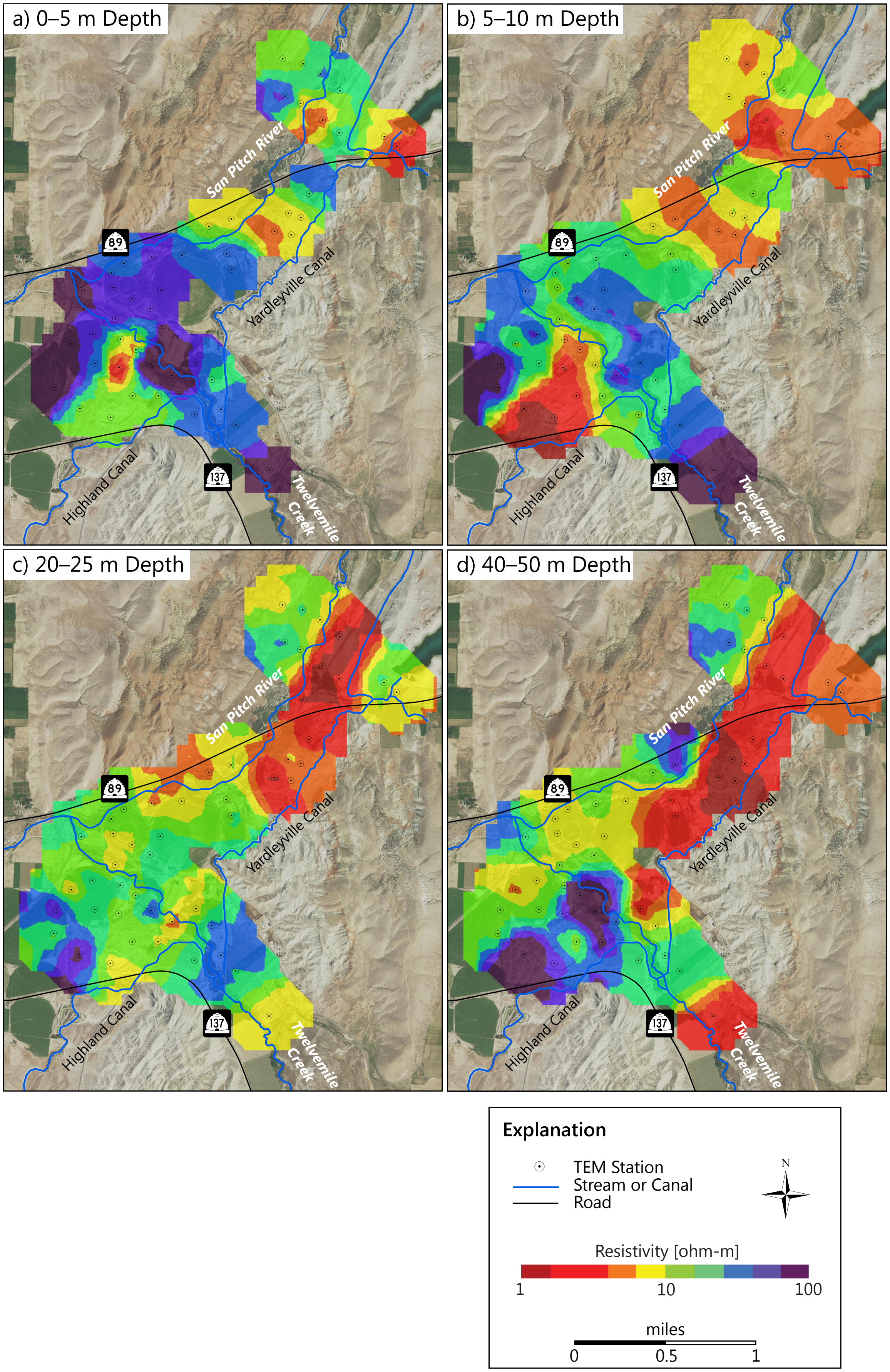

Figure 20. *Pseudo-2D maps of average resistivity at specific depth intervals below the land surface from TEM models.*

has electrical resistivity values ranging from 2 to 30 ohm-m, but less than 10 ohm-m in the majority of wells. This relatively small range of variation in resistivity can be attributed to a number of factors, the main conditions include (1) water saturation, (2) salt content of the shale, and (3) salinity of the pore fluids within the formation. As a reference, a typical range in resistivity for a generic shale is from 4 to 40 ohm-m (Palacky, 1987).

Resistivity models delineate two prominent conductive bodies in the study area. The first is interpreted as a shallow, finite-sized body likely related to groundwater flow or seepage at/from the settling ponds that moves downgradient (northward) locally. The second conductive body, a larger, continuous zone to the northeast near Ninemile Reservoir, is most likely the signature of a geologic unit such as the Arapien Shale. The modeled resistivity values of this zone (1 to 10 ohm-m) are within average resistivity values of shale as well as values from wireline logs.

Sources of Salinity

We conclude that most of the salt dissolved in the groundwater of the lower San Pitch River drainage and lower Twelvemile Creek is derived from interaction between shallow groundwater or canal seepage and the Arapien Shale. This conclusion is based on several lines of evidence:

1. The overall dominant sodium-chloride-type water quality characterizes San Pitch River samples and nearby seeps and springs.
2. Very high chloride/bromide mass ratios and chloride concentrations indicate halite as the source of sodium and chloride in the surface water.
3. Comparison of the subcrop map of the Arapien Shale below the San Pitch River deposits shows the spatial coincidence between the saline springs and members D and E of the Arapien Shale, and the lack of saline springs in areas not directly underlain by the Arapien (figure 10).
4. The isotopically enriched signature of water from saline seeps indicates that the recharge source for the springs is likely low elevation (local) precipitation or canal/reservoir seepage and is not likely sourced from higher elevation mountain recharge nor deeper groundwater flow along faults.
5. The existence of a shallow, electrically conductive body in the subsurface, interpreted as saline groundwater in a halite-rich part of the Arapien Shale, located between the reportedly leaky settling ponds along the Highland Canal and the location of saline seeps and marshes along Twelvemile Creek.
6. The existence of a larger, relatively deep, continuous conductive zone west and southwest of Ninemile Reservoir, underlain by Arapien Shale members, where shallow groundwater and/or seepage from Ninemile Reservoir likely interacts with halite-bearing Arapien Shale as it moves down valley.

Groundwater and canal seepage dissolve halite within the Arapien Shale bedrock and, possibly, alluvium or buried colluvial deposits derived from the Arapien Shale as it moves along the base of the river deposits. Two highly saline marsh areas (figure 18), one south of the San Pitch River about 0.3 mile downstream from the Highway 89 bridge and the other marsh north of Twelvemile Creek and west of Yardley ranch (about midway between the Twelvemile diversion and the confluence with the San Pitch River), may coincide with the locations of halite pods or high concentrations of fine-grained halite. The source of the water in the saline marsh south of the San Pitch River is likely a combination of shallow groundwater in the alluvium, runoff from irrigated fields to the southwest, surface runoff from the northern extension of the White Hills, and potentially some Yardleyville Canal seepage, which is impounded behind an old railroad grade and interacts with halite in underlying bedrock or colluvium and alluvium. Evaporation in this relatively stagnant area may further concentrate sodium and chloride in the water, as supported by the stable isotope ratio from sample site 25, which shows an evaporative signature.

The location of numerous other saline springs and seeps along the San Pitch River are likely controlled by contrasts in hydraulic conductivity among different sedimentary facies of the river deposits, implying that relatively thick deposits of low-hydraulic-conductivity sediment (such as mud and silt) impede lateral flow of the groundwater and force it toward the surface.

Linear alignment of saline springs along Twelvemile Creek suggests that faults within the Arapien Shale may concentrate shallow groundwater flow within the unit and force it toward the surface. The saline springs west of Yardley ranch lie along a rough north-south trend and are just east of an abrupt bend in the stream from east-west to north-south (sites 64, 67, 68, 113, 115, 120, and 122). The springs lie between the projected positions of a northeast-striking normal fault mapped to the southwest by Weiss (1994) and the inferred contact between members D and E of the Arapien Shale, which Weiss (1994) mapped as a thrust fault (plate 1). The springs may align with either fault. The 90-degree bend in the stream may follow relatively less resistant fault-compromised rock, or possibly a north-south trending halite pod. The source of the saline water in the springs and saline marsh along Twelvemile Creek, based on the subsurface position of the halite-bearing Arapien Shale member E and a shallow highly conductive body between the springs/marsh and the settling ponds, is likely seepage of high-quality water from the settling ponds and possibly shallow groundwater in Twelvemile Creek alluvium that dissolves salt from halite deposits in shallow Arapien Shale or lithologic variations in the alluvium.

Overall salt load varies throughout different reaches of the lower San Pitch River, and a general increase in salt load and corresponding TDS exceeds the site-specific TMDL allotment of 2400 mg/L (as outlined in officially submitted document by the Utah Division of Water Quality [2003 TMDL] under §303d of the CWA for EPA approval). The TMDL recommends continuous water-quality monitoring, which is supported and corroborated by our data.

RECOMMENDATIONS

We have evaluated water quality and quantity along the lower San Pitch River drainage to help GIC determine how to deliver suitable, higher-quality water to agricultural users. We have documented the salt load for different reaches along the San Pitch River and Twelvemile Creek to identify potential locations where GIC can modify their delivery system. Modifications can be accomplished through isolation (point-source reduction of saline sources) and diversion of higher-salinity water.

Steps to limit settling pond seepage, canal seepage, and or excess irrigation near areas with Arapien Shale subcrop should be taken to reduce the source of saline seeps. Settling ponds should be properly lined to prevent seepage. Canal seepage could be reduced by lining the Yardleyville Canal and northern portion of the Highland Canal. The fields between Twelvemile Creek and the San Pitch River should be irrigated efficiently to prevent infiltration past the root zone and prevent surface runoff. These steps likely will reduce some of the salt load to the San Pitch River.

Remaining salt load could be mitigated in the lower reach of the San Pitch River by transferring high salt load water from the river below the confluence with Twelvemile Creek to the Highland Canal, which has sufficient flow and high-quality water to dilute the salt load. The transfer of the higher-salinity water from the San Pitch River to the Highland Canal will also provide better water quality to the Old Field Canal than that currently being used. Below the confluence with Twelvemile Creek, the San Pitch River is a gaining stream and acquires significant flow from seeps and springs (~2 to 2.5 cfs) along both banks of the stream before it reaches the Old Field Canal. Water from the seeps and springs has relatively lower TDS and conductivity than the San Pitch River both above (proximal) and below its confluence with Twelvemile Creek. The supply of water from the San Pitch River to Old Field Canal will sufficiently provide water to the ~15% of GIC's water users on the Old Field Canal. Because the majority of water in the lower San Pitch River exceeds the recommended TMDL, we recommend continuous water quality monitoring along the reach from site 9 (above the bridge at Highway 89) to the diversion to Old Field Canal.

SUMMARY AND CONCLUSIONS

The goal of this project was to determine the sources and extent of salinity in the lower San Pitch River drainage and adjoining Gunnison Irrigation Company (GIC) canal system in southern Sanpete Valley. We spent two field seasons documenting water quality and quantity in the lower San Pitch River drainage along different reaches within the San Pitch River and Twelvemile Creek as well as nearby canals and springs. We used geologic mapping and geophysical techniques (TEM) to isolate and identify regions in the subsurface that likely have an influence on river salinity. The data collected for this study provide information necessary to make targeted management decisions to reduce salinity and provide for a sustainable supply of acceptable/suitable quality irrigation water for the GIC and its water users.

For this study, we produced GIS maps that show salinity concentrations and groundwater along the San Pitch River channel, 2D-TEM images and interpretations, and a simplified geologic map with a cross section. Overall, the maps emphasize the areas of higher and lower salinity. The best quality water exists in Highland and Pettyville Canals, Peacock Spring, Sixmile Creek, and Twelvemile Creek above the diversion to Highland Canal. The poorest water quality is along the reach of the San Pitch River between the Highway 89 bridge and the confluence with Twelvemile Creek; from a 20-acre marsh situated between the San Pitch River and Yardleyville Canal; from a 10-acre marsh and seeps on Twelvemile Creek midway between the Twelvemile Diversion and the confluence with the San Pitch River; and from low-flow seeps in the half-mile reach of the San Pitch River above the Highway 89 bridge. In general, nitrate concentrations are low, but elevated nitrate concentrations (8 and 12.2 mg/L) exist in Twelvemile Creek, which is unusual for surface water (which typically has nitrate levels less than 1 mg/L). The higher nitrate concentrations are possibly from fertilizer use on crops in the adjacent irrigated fields, runoff from feedlots to the northeast, or from septic-tank effluent from nearby homes.

The San Pitch River is gaining throughout the reach we studied. Below the Gunnison Reservoir, the river does not flow in its natural channel. At the point where it is completely diverted to the Old Field Canal, we measured 6.9 cfs during our autumn 2014 visit and 5.0 cfs during spring 2015, an average rate of gain of about 0.7 cfs per river mile measured from the Gunnison Dam to the Old Field Canal. Springs, seeps, and groundwater inflow are the source of the gain in discharge. The upper reach of the San Pitch River above the confluence with Twelvemile Creek had a gain rate of 0.2 cfs/mi, whereas the lower reach of the San Pitch River from the confluence to Old Field Canal had a gain rate of 0.9 cfs/mi during our April 2015 fieldwork. The lower reach gained a total of almost 3 cfs in autumn and 2.7 cfs in spring. The area of highest rate of gain (a rate of 5.9 cfs per river mile) is a short section of river west of the intersection of South Christianburg Road and Highway 137, and the source of the increase in discharge is better quality springs and seeps throughout this reach.

The reach of the San Pitch River between the Highway 89 bridge and the confluence with Twelvemile Creek is a major source of salt loading; salt load increases from mostly less than 50 g/s above the bridge to nearly 300 g/s above the confluence. An addition of 80 to 90 g/s salt load from Twelvemile Creek, which carries salt from a 10-acre saline marsh, combines to bring the overall salt load carried by the San Pitch River at the Old Field Canal between approximately 400 g/s in the spring to approximately 650 g/s in autumn at the Old Field Canal diversion.

Geologic mapping revealed that members D and E of the Arapien Shale are likely present in the subsurface beneath the areas where saline springs are found. Previous workers reported halite deposits in member E in the study area and indicate member D is known to contain halite in the general region. A TEM survey reveals a very shallow conductive body we interpret to be saline groundwater between the old settling ponds off of Highland Canal and Twelvemile Creek.

Our combined geologic, geophysical, and hydrologic assessment indicates the source of salinity in the San Pitch River and Twelvemile Creek is dissolution of salt from the Arapien Shale and its erosional remnants by groundwater and seepage from irrigation works. In consultation with Jones & DeMille Engineering staff, UGS recommends the following measures to mitigate the influence of the highly saline groundwater inflow:

1. Limit settling pond seepage, canal seepage, and irrigation return flow near areas with Arapien Shale subcrop. Do not use the settling ponds until properly lined to prevent seepage. Irrigate fields between Twelvemile Creek and the San Pitch River efficiently to prevent infiltration past the root zone and prevent surface runoff.
2. Divert high-salinity water out of the San Pitch River downstream of saline inputs and upstream of higher-quality springs and groundwater seepage. Install a pumping station on the San Pitch River below the confluence with Twelvemile Creek to remove river water and deliver it to the Highland Canal, which has sufficient flow and low salinity to dilute the San Pitch water. The San Pitch River gains 2 to 2.5 cfs of moderate to good quality water (calculated TDS ranging from about 1200 mg/L to 2400 mg/L) from seeps, springs, and groundwater inflow between the confluence with Twelvemile Creek and the Old Field Canal diversion; this would be the water available to users of the Old Field Canal.

Because our study involved a hydrogeologic assessment over two seasons (autumn 2014 and spring 2015—a time marked by drought conditions in Utah) and represents a snapshot in time, caveats to our work exist. Our data are based on a short-term analysis that seeks to solve a broader, long-term concern. Hence our recommendations may need to be modified as climatic conditions change. Changes in seasonal cycles (wet and dry periods) in the area could alter the dynamics of the hydrologic system. Wetter conditions could potentially provide higher-quality flow into the lower reach of the San Pitch River from seeps, springs, and higher water table conditions. Conversely, extreme drought conditions may yield negligible flow from these same sources, providing insufficient water for downstream users at Old Field Canal. During extreme droughts, the GIC may need to reduce the amount of water diverted out of the San Pitch at the proposed diversion. Similarly, any changes in irrigation practices based on seasonal variations in climate and/or any land-use changes that significantly alter the geohydrologic dynamics should be monitored for the impact they may have on stream salinity.

ACKNOWLEDGMENTS

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APPENDIX

SITE INFORMATION, FIELD WATER QUALITY, AND DISCHARGE MEASUREMENTS FOR THE LOWER SAN PITCH RIVER SALINITY STUDY

Appendix. *Site information, field water quality, and discharge measurements for the lower San Pitch River salinity study.*

Station ID[1]	Site No.	Source	Sample Date	Flow (cfs)	Temp (°C)	Conductivity (µS/cm)	pH	Site Description	Longitude	Latitude
USPS1	1	Canal	9/22/14	3.6	19.5	630	8.80	Start of Pettyville Canal, at flume below Gunnison Res	-111.7115465	39.2032486
USPS1	1	Canal	4/20/15	53.5	12.6	1429	9.30	Start of Pettyville Canal, at flume below Gunnison Res	-111.7115465	39.2032486
USPS1A	1	Stream	9/22/14	-	21.2	1690	9.34	Gunnison Reservoir outflow to Pettyville Canal before mixing with Sixmile Ck	-111.7114603	39.2033818
USPS1A	1	Stream	4/20/15	47.2	12.9	1433	9.20	Gunnison Reservoir outflow to Pettyville Canal before mixing with Sixmile Ck	-111.7114603	39.2033818
USPS1B	1	Stream	9/22/14	-	18.5	506	8.83	Sixmile Creek at culvert into Pettyville Canal	-111.7113552	39.2033923
USPS1B	1	Stream	4/20/15	6.0	16.0	513	8.80	Sixmile Creek at culvert into Pettyville Canal	-111.7113552	39.2033923
USPS1C	1	Canal	9/22/14	-	18.6	535	8.87	Pettyville Canal 100 feet downstream of Gunnison Reservoir and Sixmile Ck confluence	-111.7116554	39.2029445
USPS1C	1	Canal	4/20/15	-	13.3	1390	9.16	Pettyville Canal 100 feet downstream of Gunnison Reservoir and Sixmile Ck confluence	-111.7116554	39.2029445
USPS1D	1	Stream	4/20/15	-	13.3	1453	7.65	San Pitch River as it begins to flow downstream from Gunnison Res	-111.7127100	39.2028250
USPS1E	1	Stream	4/20/15	0.02	15.7	1485	8.14	San Pitch river as it begins to flow downstream from Gunnison Res	-111.7133410	39.2019950
USPS2	2	Canal	9/22/14	3.6	17.4	419	8.89	Ninemile Feeder Canal near Sterling	-111.6860900	39.1935720
USPS2	2	Canal	4/20/15	-	-	-	-	Ninemile Feeder Canal near Sterling; dry	-111.6860685	39.1935812
USPS3	3	Spring	9/23/14	0.06	15.7	2340	8.15	Wetlands and canal near spring on hill near Sterling	-111.6952420	39.1815113
USPS3	3	Spring	4/20/15	0.2	17.2	2520	8.30	Wetlands and canal near spring on hill near Sterling	-111.6952420	39.1815113
USPS4	4	Spring	9/23/14	-	19.8	1485	7.74	Peacock Spring diffuse springhead by rusty pipe	-111.6925754	39.1824959
USPS4A	4	Spring	9/23/14	0.1	18.1	1499	8.35	Peacock Spring in spring brook channel	-111.6934574	39.1826067
USPS4A	4	Spring	4/20/15	0.3	18.4	1560	8.38	Peacock Spring in spring brook channel	-111.6936049	39.1825830
USPS5	5	Spring	9/23/14	-	12.1	1330	7.71	Ninemile Spring at springhead	-111.7035485	39.1723041
USPS5A	5	Spring	9/23/14	1.6	12.7	1143	8.04	Ninemile Spring springbrook	-111.7034581	39.1732661
USPS5A	5	Spring	4/21/15	1.5	11.1	1123	7.90	Ninemile Spring springbrook	-111.7036458	39.1730912
USPS6	6	Canal	9/23/14	4.0	21.8	1118	8.59	Ninemile Reservoir outflow at flume	-111.7162336	39.1699618
USPS6	6	Canal	4/23/15	0.2	10.1	925	8.80	Ninemile Reservoir outflow at flume	-111.7162012	39.1699050
USPS7A	7	Spring	9/23/14	0.5	15.0	1515	8.39	Ninemile Spring in springbrook 1/4 mi. downgradient from spring	-111.7161727	39.1691022
USPS7A	7	Spring	4/21/15	0.4	10.3	1403	8.39	Ninemile Spring in springbrook 1/4 mi. downgradient from spring	-111.7163312	39.1691293
USPS7B	7	Spring	9/23/14	-	12.6	1610	7.87	Little Ninemile Spring Box public supply north outflow	-111.7127515	39.1672141
USPS7B	7	Spring	4/21/15	-	8.2	1682	8.09	Little Ninemile Spring Box public supply north outflow	-111.7127349	39.1672543
USPS7C	7	Spring	9/23/14	-	11.5	1547	7.47	Little Ninemile Spring box public supply south outflow	-111.7127876	39.1671890
USPS7D	7	Seep	9/23/14	-	13.3	1590	7.62	Seep on bank of springbrook	-111.7132530	39.1674290
USPS8	8	Canal	9/24/14	8.6	20.8	900	8.55	Yardleyville Canal after Pettyville and Ninemile Reservoir confluence	-111.7186506	39.1683097
USPS8B	8	Canal	4/21/15	53.4	13.8	1326	9.10	Yardleyville Canal after Pettyville and Ninemile Reservoir confluence	-111.7187526	39.1685480
USPS9	9	Stream	9/24/14	1.0	14.8	2400	8.24	San Pitch R near abandoned turkey barns	-111.7221533	39.1789146
USPS9	9	Stream	4/21/15	0.4	19.4	2400	8.34	San Pitch R near abandoned turkey barns	-111.7222122	39.1788683
USPS9A	9	Seep	4/21/15	-	21.0	3330	7.66	Seep area on left bank of San Pitch R	-111.7222008	39.1792050
USPS9B	9	Stream	4/21/15	-	-	2370	-	San Pitch R near abandoned turkey barns	-111.7214197	39.1813148
USPS9C	9	Pond	9/24/14	-	16.6	2830	8.08	Non-flowing pond east of San Pitch R	-111.7215290	39.1782030
USPS10	10	Stream	9/24/14	1.2	18.0	5080	8.40	San Pitch River 200 ft abv Hwy 89 bridge	-111.7289808	39.1670596
USPS10	10	Stream	4/22/15	0.6	17.8	5030	8.30	San Pitch River 200 ft abv Hwy 89 bridge	-111.7289561	39.1670172
USPS10A	10	Pond	9/24/14	-	18.7	15,000	7.64	Stagnant pond adjacent to San Pitch R	-111.7285790	39.1672050
USPS10B	10	Seep	8/26/14	-	23.7	14,200	8.60	Black saline seep on N side of Hwy 89 bridge, left bank of river	-111.7286560	39.1665489
USPS10B	10	Seep	9/24/14	-	21.4	8400	7.91	Black saline seep on N side of Hwy 89 bridge, left bank of river	-111.7287850	39.1665780
USPS10C	10	Stream	4/22/15	-	17.8	4980	8.30	San Pitch R in stream above Highway 89 bridge	-111.7289220	39.1671500
USPS10D	10	Stream	4/22/15	-	17.9	4940	8.29	San Pitch R in stream above Highway 89 bridge	-111.7281970	39.1681980
USPS11	11	Ditch	9/24/14	0.03	21.8	2780	8.57	Return flow from ponds below Ron Christensen pond	-111.7253968	39.1698532
USPS11	11	Ditch	4/21/15	0.07	14.1	2720	8.61	Return flow from ponds below Ron Christensen pond	-111.7254593	39.1699094
USPS11A	11	Stream	4/21/15	-	14.8	5340	8.16	San Pitch River before inflow from Ron Christensen pond	-111.7254298	39.1698849
USPS12	12	Seep	9/24/14	0.001	19.9	10,870	7.24	Rusty saline seep left bank San Pitch R	-111.7253657	39.1703216

Appendix. continued

Station ID[1]	Site No.	Source	Sample Date	Flow (cfs)	Temp (°C)	Conductivity (µS/cm)	pH	Site Description	Longitude	Latitude
USPS12	12	Seep	4/21/15	0.001	13.6	25,400	6.95	Rusty saline seep left bank San Pitch R	-111.7253735	39.1703508
USPS12A	12	Stream	9/24/14	-	-	3640	-	San Pitch R at mile 2.8 upstream of seeps	-111.7256140	39.1707900
USPS12A	12	Stream	4/21/15	-	16.0	3330	8.22	San Pitch R at mile 2.8 upstream of seeps	-111.7256304	39.1708046
USPS12B	12	Stream	9/24/14	-	-	3520	-	San Pitch R at mile 2.8	-111.7256240	39.1715210
USPS12C	12	Stream	9/24/14	-	-	2480	-	San Pitch R at mile 2.8	-111.7256430	39.1717170
USPS12C	12	Stream	4/21/15	-	17.3	2460	8.36	San Pitch R at mile 2.8	-111.7255611	39.1717440
USPS12D	12	Seep	9/24/14	-	-	16,000	7.25	Tiny seepage on both banks of San Pitch R	-111.7256280	39.1716360
USPS12D	12	Seep	4/21/15	-	18.2	11,020	7.34	Tiny seepage on both banks of San Pitch R	-111.7256036	39.1716106
USPS12E	12	Stream	9/24/14	-	23.0	5250	8.23	San Pitch R at mile 2.9 below seeps	-111.7254660	39.1700510
USPS13	13	Ditch	9/24/14	0.03	21.8	870	8.71	Diversion into Ron Christiansen pond from Pettyville Canal in 8" flume	-111.7186900	39.1688220
USPS13	13	Ditch	4/23/15	-	-	-	-	Diversion into Ron Christiansen pond from Pettyville Canal in 8" flume	-111.7186718	39.1687808
USPS14	14	Stream	9/24/14	-	23.2	6730	8.25	San Pitch R half mile below Hwy 89 bridge	-111.7319377	39.1630779
USPS15	15	Seep	9/24/14	0.001	24.4	>20,000	8.18	Salty seep left bank of San Pitch R below old bridge abutment	-111.7321908	39.1625716
USPS15	15	Seep	5/20/15	0.001	20.8	28,200	8.29	Salty seep left bank of San Pitch R below old bridge abutment	-111.7322068	39.1625286
USPS16	16	Stream	9/24/14	-	23.0	7060	8.27	San Pitch River downstream from salty seep	-111.7323077	39.1625046
USPS16	16	Stream	5/20/15	-	15.2	6440	8.43	San Pitch River adjacent/upstream from salty seep	-111.7322153	39.1625903
USPS17	17	Ditch	9/25/14	0.1	22.7	>20,000	8.28	Salty channel flow south of San Pitch R	-111.7358152	39.1611067
USPS18A	18	Stream	9/24/14	-	22.4	9950	8.24	San Pitch R abv confluence of the salty channel flow	-111.7371485	39.1614741
USPS18B	18	Stream	9/24/14	-	22.3	11,130	8.20	San Pitch R blw confluence of the salty channel flow	-111.7375585	39.1617141
USPS19	19	Stream	9/25/14	1.2	13.3	3970	8.45	Twelvemile Ck abv confluence with San Pitch R	-111.7489832	39.1584991
USPS19	19	Stream	4/22/15	1.4	12.3	3950	8.59	Twelvemile Ck abv confluence with San Pitch R	-111.7490387	39.1585035
USPS19	19	Stream	5/19/15	1.5	17.5	3640	8.57	Twelvemile Ck abv confluence with San Pitch R	-111.7489548	39.1584838
USPS20	20	Stream	9/25/14	1.4	16.0	12,280	8.28	San Pitch R abv confluence with Twelvemile Ck	-111.7491560	39.1591470
USPS20	20	Stream	4/22/15	0.9	13.7	13,140	8.40	San Pitch R abv confluence with Twelvemile Ck	-111.7491840	39.1591801
USPS20	20	Stream	5/20/15	1.2	21.6	10,460	8.31	San Pitch R abv confluence with Twelvemile Ck	-111.7491572	39.1591818
USPS21	21	Stream	9/25/14	2.6	15.5	8700	8.40	San Pitch R 15' blw confluence with Twelvemile Ck	-111.7493927	39.1592351
USPS21	21	Stream	4/22/15	2.3	-	-	-	San Pitch R 15' blw confluence with Twelvemile Ck	-111.7492881	39.1592005
USPS21	21	Stream	5/20/15	2.7	-	-	-	San Pitch R 15' blw confluence with Twelvemile Ck	-111.7492559	39.1592152
USPS21A	21	Stream	4/22/15	-	12.8	7870	8.54	San Pitch R 200' blw confluence with Twelvemile Ck	-111.7494820	39.1592093
USPS21A	21	Stream	5/20/15	-	20.8	7500	8.38	San Pitch R 200' blw confluence with Twelvemile Ck	-111.7495012	39.1592999
USPS22	22	Canal	9/25/14	-	15.3	961	8.63	Highland Canal 100 yds abv Twelvemile Ck diversion	-111.7337688	39.1468209
USPS22	22	Canal	4/22/15	-	13.2	1295	9.20	Highland Canal 100 yds abv Twelvemile Ck diversion	-111.7335840	39.1469901
USPS23	23	Stream	9/25/14	-	15.4	2080	7.50	Twelvemile Ck below diversion to Highland Canal	-111.7337939	39.1468708
USPS23	23	Stream	4/22/15	0.3	11.1	1954	7.49	Twelvemile Ck below diversion to Highland Canal	-111.7340716	39.1468010
USPS23	23	Stream	5/19/15	0.8	10.8	1738	7.58	Twelvemile Ck below diversion to Highland Canal	-111.7340489	39.1467514
USPS24	24	Stream	8/18/14	-	15.0	359	8.00	Twelvemile Creek diversion	-111.7337327	39.1454853
USPS24A	24	Canal	9/25/14	9.5	17.0	415	8.50	Twelvemile Ck diversion in flume	-111.7343830	39.1457790
USPS24A	24	Canal	10/6/14	7.7	13.1	465	8.68	Twelvemile Ck diversion in flume	-111.7344089	39.1457372
USPS24A	24	Canal	4/22/15	16.4	-	-	-	Twelvemile Ck diversion in flume	-111.7343399	39.1457843
USPS24B	24	Stream	4/23/15	-	12.6	460	8.51	Twelvemile Creek above Twelvemile Ck diversion	-111.7335800	39.1454798
USPS25	25	Seep	9/25/14	-	22.7	>20,000	8.28	Very salty side creek entering San Pitch from the S taken at culvert under RR grade	-111.7330514	39.1614726
USPS26	26	Canal	8/18/14	-	18.6	4900	8.27	Old Field Canal in 6' flume	-111.7795617	39.1385079
USPS26	26	Canal	9/25/14	5.6	19.6	5320	8.32	Old Field Canal in 6' flume	-111.7795840	39.1384710
USPS26	26	Canal	10/6/14	6.9	12.1	5690	8.38	Old Field Canal in 6' flume	-111.7796600	39.1384552
USPS26	26	Canal	4/23/15	5.0	8.1	4880	8.27	Old Field Canal in 6' flume	-111.7795491	39.1385035
USPS27A	27	Canal	10/6/14	1.0	17.4	2140	8.57	Flume below Antelope Pond diversion	-111.7233902	39.1653487

Appendix. *continued*

Station ID[1]	Site No.	Source	Sample Date	Flow (cfs)	Temp (ºC)	Conductivity (µS/cm)	pH	Site Description	Longitude	Latitude
USPS28	28	Canal	10/6/14	-	16.2	1865	8.57	Yardleyville Canal	-111.7272205	39.1605041
USPS28A	28	Canal	10/6/14	-	17.0	1803	8.71	Off Yardleyville Canal	-111.7298100	39.1582013
USPS29	29	Stream	10/6/14	-	18.8	10,700	8.08	Transducer, lower	-111.7489305	39.1591323
USPS30	30	Stream	10/7/14	-	11.3	5220	8.15	San Pitch R 200-300 feet downstream from Hwy 89 bridge	-111.7285255	39.1658401
USPS31	31	Seep	10/7/14	0.01	15.3	>20,000	6.88	Seep on San Pitch R 200-300 feet downstream from Hwy 89 bridge	-111.7286465	39.1659381
USPS31A	31	Seep	10/7/14	-	13.0	10,570	7.66	Seep in San Pitch R 200-300 feet downstream from Hwy 89 bridge	-111.7285655	39.1657911
USPS31B	31	Stream	10/7/14	-	11.6	5510	8.18	San Pitch R 200-300 feet downstream from Hwy 89 bridge	-111.7285695	39.1657291
USPS31C	31	Seep	10/7/14	-	11.9	16,300	6.92	Seep on left bank San Pitch R 200-300 feet downstream from Hwy 89 bridge	-111.7287045	39.1655711
USPS31D	31	Pond	10/7/14	-	11.7	5880	8.18	Outflow of pond downstream of other sites 31	-111.7286005	39.1656421
USPS31E	31	Seep	10/7/14	-	13.0	>20,000	-	Seep on left bank San Pitch R.	-111.7288395	39.1655211
USPS32	32	Seep	10/7/14	-	11.7	8300	8.13	Marshy area above left bank of San Pitch River	-111.7297022	39.1645180
USPS33	33	Stream	10/7/14	-	12.3	4560	8.12	Deep pond in San Pitch R	-111.7261941	39.1691453
USPS34	34	Seep	10/7/14	-	-	12,000	-	Seep with bubbles	-111.7255464	39.1710495
USPS35	35	Stream	10/7/14	-	14.1	2540	8.22	San Pitch R at mile 2.7	-111.7256375	39.1721661
USPS35	35	Stream	4/21/15	0.7	18.8	2440	8.41	San Pitch R at mile 2.7	-111.7256358	39.1720487
USPS36	36	Stream	10/7/14	-	14.4	2530	8.15	San Pitch R at mile 2.5 upstream from cutoff channel	-111.7235475	39.1743821
USPS36	36	Stream	4/21/15	-	18.2	2440	8.32	San Pitch R at mile 2.5 upstream from cutoff channel	-111.7235890	39.1743500
USPS37	37	Seep	10/7/14	-	-	>10,000	-	Seep on San Pitch R at mile 2.8	-111.7255405	39.1717341
USPS38	38	Seep	10/7/14	-	-	>20,000	-	Seep on San Pitch R at mile 3.1	-111.7276265	39.1673141
USPS39	39	Stream	10/7/14	1.9	15.3	4680	8.18	Transducer, upper	-111.7290115	39.1670621
USPS40	40	Spring	10/7/14	-	17.5	3740	8.06	Stagnant water near base of Chalk Hill cliff	-111.7698395	39.1475901
USPS43	43	Spring	10/7/14	0.002	20.0	4070	8.34	Chalk Hill spring brook before entering San Pitch	-111.7723735	39.1443591
USPS43A	43	Spring	4/23/15	0.01	15.5	3220	8.62	Chalk Hill spring brook before entering San Pitch	-111.7721689	39.1440943
USPS44	44	Stream	10/7/14	-	17.6	6010	8.08	San Pitch R abv confluence of Chalk Hill Spring	-111.7714565	39.1438981
USPS44A	44	Seep	10/7/14	-	-	4120	-	Seep on left bank of San Pitch R above confluence with Chalk Hill spring	-111.7711485	39.1440051
USPS45	45	Stream	10/7/14	5.8	17.5	6020	8.02	San Pitch R abv confluence of Chalk Hill spring	-111.7710295	39.1442391
USPS45	45	Stream	4/23/15	4.4	15.2	4970	8.24	San Pitch R abv confluence of Chalk Hill spring	-111.7711123	39.1443036
USPS45A	45	Stream	10/7/14	-	17.5	5980	-	San Pitch R abv confluence of Chalk Hill spring	-111.7694275	39.1437361
USPS45A	45	Stream	4/23/15	-	15.8	5020	8.18	San Pitch R abv confluence of Chalk Hill spring	-111.7694418	39.1438205
USPS45B	45	Stream	10/7/14	-	-	6080	-	San Pitch R abv confluence of Chalk Hill spring	-111.7692705	39.1445711
USPS45B	45	Stream	4/23/15	-	16.6	5070	8.21	San Pitch R abv confluence of Chalk Hill spring	-111.7693180	39.1446156
USPS45C	45	Spring	4/23/15	0.002	14.1	3470	7.57	Spring on S bank of San Pitch R	-111.7692301	39.1449321
USPS46	46	Stream	10/7/14	-	17.6	5950	8.05	San Pitch R below Chalk Hill spring inlet	-111.7724815	39.1438001
USPS46	46	Stream	4/23/15	-	13.2	4960	8.25	San Pitch R below Chalk Hill spring inlet	-111.7724787	39.1438117
USPS47	47	Stream	4/23/15	-	11.0	4800	8.28	San Pitch R 0.25 mile abv Old Field Canal diversion	-111.7755799	39.1389110
USPS48	48	Well	10/20/14	-	14.7	2840	7.00	Christensen well, 30 ft well	-111.7652416	39.1427910
USPS49	49	Well	10/20/14	-	16.1	2340	7.60	Nielsen well, 52 ft well	-111.7604617	39.1494141
USPS50	50	Stream	4/21/15	0.03	23.0	2290	8.48	Small tributary or split of San Pitch R at mile 1	-111.7201954	39.1821664
USPS51	51	Stream	4/21/15	-	18.8	2260	8.28	San Pitch R nr Patterson ranch 100 ft upstream from road crossing	-111.7199805	39.1840827
USPS52	52	Stream	4/21/15	-	18.8	2210	8.24	San Pitch R at mile 1.5	-111.7201285	39.1858667
USPS53	53	Stream	4/21/15	-	19.2	2270	8.25	San Pitch R at mile 1.3	-111.7181900	39.1886830
USPS53A	53	Seep	4/21/15	0.01	10.8	2200	7.42	Cooler seep on left side of San Pitch R	-111.7180140	39.1886490
USPS54	54	Seep	4/21/15	-	8.8	1843	7.58	Groundwater inflow seep on San Pitch R at mile 1.1	-111.7178060	39.1906900
USPS55	55	Stream	4/21/15	0.06	18.0	1717	8.16	San Pitch R at mile 1	-111.7184070	39.1914220
USPS56	56	Stream	4/21/15	0.1	12.4	2270	7.70	San Pitch R at mile 1.1	-111.7172820	39.1903520
USPS57	57	Stream	4/22/15	0.8	8.8	13,700	8.12	San Pitch R downstream from salty marsh input, at mile 1.9	-111.7391269	39.1620962

Appendix. continued

Station ID[1]	Site No.	Source	Sample Date	Flow (cfs)	Temp (°C)	Conductivity (µS/cm)	pH	Site Description	Longitude	Latitude
USPS58	58	Ditch	4/22/15	0.007	9.0	16,950	8.36	Side channel of high salinity water entering right bank San Pitch R	-111.7409644	39.1614384
USPS58A	58	Stream	4/22/15	-	9.8	13,480	8.19	San Pitch R abv salty side channel of site 58	-111.7409781	39.1613843
USPS59	59	Seep	4/22/15	-	8.1	6460	8.10	Groundwater seep down from Yardley irrig field	-111.7438373	39.1604264
USPS59A	59	Stream	4/22/15	-	11.2	13,380	-	San Pitch R	-111.7441032	39.1603864
USPS60	60	Stream	4/22/15	1.1	11.7	13,350	8.13	San Pitch R	-111.7452494	39.1599046
USPS61	61	Stream	4/22/15	-	13.1	13,240	8.39	San Pitch R upgradient from confluence with Twelvemile Ck	-111.7478856	39.1585161
USPS62	62	Stream	4/22/15	-	13.7	13,220	8.40	San Pitch R upgrad. from confluence	-111.7466790	39.1585822
USPS63	63	Spring	4/22/15	-	10.9	6230	7.37	Side creek in wetland W of Yardley ranch	-111.7418498	39.1543722
USPS63A	63	Seep	4/22/15	-	16.8	5820	7.83	Standing water in wetland marsh S of Yardley ranch	-111.7417635	39.1540219
USPS64	64	Seep	4/22/15	-	17.0	23,800	8.90	Seep in marshy salty wetland adj to Twelvemile Ck right bank	-111.7426089	39.1537842
USPS64	64	Seep	5/20/15	-	17.6	22,650	7.74	Saline seep	-111.7426089	39.1537842
USPS65	65	Stream	4/23/15	0.61	14.2	2240	8.31	Twelvemile Ck	-111.7408524	39.1535331
USPS66	66	Spring	4/23/15	-	8.1	6050	7.12	Spring on left bank of Twelvemile Ck	-111.7412051	39.1535712
USPS67	67	Spring	4/23/15	0.01	13.1	13,850	7.92	Stream from wetland N side of Twelvemile Ck	-111.7426721	39.1540827
USPS67	67	Spring	5/20/15	0.02	21.4	13,253	7.99	Side stream into right bank Twelvemile Ck	-111.7426728	39.1540815
USPS68	68	Ditch	4/23/15	-	11.2	6110	-	Side creek from near pheasant pen	-111.7425829	39.1544506
USPS68	69	Ditch	5/20/15	0.2	12.8	8940	7.33	Side stream into right bank Twelvemile Ck	-111.7425829	39.1544506
USPS69	69	Stream	4/23/15	-	12.7	4850	8.24	Twelvemile Ck	-111.7427561	39.1546460
USPS70	70	Ditch	4/23/15	1.1	12.6	2280	8.52	Ditch return through Yardleys ranch before entering Twelvemile Ck	-111.7436261	39.1548602
USPS70	70	Ditch	5/20/15	-	17.6	2102	8.36	Ditch return through Yardleys ranch before entering Twelvemile Ck	-111.7436261	39.1548602
USPS71	71	Stream	4/23/15	1.1	12.5	4840	8.26	Twelvemile Ck abv addition of Yardley ditch below saline inputs	-111.7436530	39.1547786
USPS71	71	Stream	5/20/15	-	20.7	3930	8.14	Twelvemile Ck abv addition of Yardley ditch below saline inputs	-111.7436530	39.1547786
USPS72	72	Stream	4/23/15	2.2	12.3	4000	8.40	Twelvemile Ck blw addition of Yardley ditch below saline inputs	-111.7438400	39.1548880
USPS72	72	Stream	5/20/15	-	19.5	3330	8.21	Twelvemile Ck blw addition of Yardley ditch below saline inputs	-111.7438400	39.1548880
USPS73	73	Stream	4/23/15	-	13.7	3720	8.39	Twelvemile Ck	-111.7428393	39.1538517
USPS74	74	Stream	4/23/15	-	12.6	4940	8.21	San Pitch R between Chalk Hill spring and Old Field Canal diversion	-111.7721543	39.1422474
USPS75	75	Stream	4/23/15	-	16.7	4730	8.42	San Pitch R abv Old Field Canal diversion	-111.7776278	39.1385117
USPS76	76	Stream	4/23/15	-	18.7	6360	8.29	San Pitch R W of Nielsen ranch	-111.7648571	39.1489319
USPS76A	76	Stream	4/23/15	2.4	19.8	6400	8.27	San Pitch R W of Nielsen ranch	-111.7643629	39.1492075
USPS76B	76	Seep	4/23/15	-	14.7	2240	7.58	Irrigation seepage? into San Pitch w of Nielsen ranch	-111.7646145	39.1494222
USPS77	77	Stream	4/23/15	-	21.5	6960	8.47	San Pitch R	-111.7633416	39.1507443
USPS78	78	Seep	4/23/15	-	9.5	7300	-	Seeps on left bank of San Pitch R	-111.7625913	39.1509893
USPS79	79	Stream	4/23/15	-	20.9	7500	8.40	San Pitch R	-111.7598767	39.1522529
USPS79	79	Stream	5/20/15	-	17.9	7350	8.64	San Pitch R	-111.7598616	39.1522233
USPS80	80	Seep	4/23/15	-	13.3	3550	7.37	Seep on right bank of San Pitch	-111.7644253	39.1494477
USPS81	81	Spring	4/23/15	0.05	14.4	2450	7.70	Rivulet from spring entering San Pitch R on left bank below Nielsen field	-111.7643067	39.1494536
USPS82	82	Stream	8/18/14	-	23.7	2010	8.18	Twelvemile Ck at 4WD rd crossing	-111.7402109	39.1524190
USPS83	83	Canal	5/19/15	-	9.7	605	9.26	Highland Canal blw confluence of Twelvemile Ck and Yardleyville Canal in 12 ft flume	-111.7352858	39.1466813
USPS84	84	Canal	5/19/15	-	9.8	600	9.25	Highland Canal below Jac outcrop	-111.7362246	39.1491290
USPS85	85	Seep	5/19/15	0.001	10.8	1962	7.47	Seep on left bank of Twelvemile Ck	-111.7344551	39.1469500
USPS86	86	Stream	5/19/15	-	13.5	1749	8.16	Twelvemile Ck in concrete flume where pipe/head gate comes in	-111.7348665	39.1486529
USPS87	87	Pond	5/19/15	-	15.8	1095	8.39	Stagnant desilting pond between Highland Canal and Twelvemile Ck	-111.7350024	39.1487075
USPS88	88	Pond	5/19/15	-	14.8	1407	8.59	Long impounded pond between Highland Canal and Twelvemile Ck	-111.7359242	39.1492044
USPS89	89	Stream	5/19/15	-	13.4	1886	8.29	Twelvemile Ck at fence	-111.7360081	39.1496205
USPS90	90	Stream	5/19/15	-	17.7	3640	8.58	Twelvemile Ck at bridge on Christianburg Rd	-111.7484205	39.1567881
USPS91	91	Stream	5/19/15	-	18.4	7330	8.57	San Pitch R below Christianburg Rd bridge	-111.7514674	39.1590776

Appendix. *continued*

Station ID[1]	Site No.	Source	Sample Date	Flow (cfs)	Temp (°C)	Conductivity (µS/cm)	pH	Site Description	Longitude	Latitude
USPS92	92	Stream	5/19/15	-	18.4	7340	8.57	San Pitch R abv fields near trailer graveyard	-111.7540874	39.1578041
USPS93	93	Stream	5/19/15	-	18.2	6720	8.55	San Pitch R adjacent to ranch on Hwy 89	-111.7557802	39.1567161
USPS94	94	Stream	5/19/15	2.7	18.1	6730	8.57	San Pitch R adjacent to ranch on Hwy 89	-111.7563875	39.1565709
USPS95	95	Stream	5/20/15	-	18.1	6740	8.58	San Pitch R	-111.7593547	39.1543366
USPS96	96	Stream	5/20/15	-	17.8	6740	8.59	San Pitch R	-111.7599215	39.1530917
USPS97	97	Seep	5/20/15	-	19.9	7370	9.15	Potential seep on left bank of San Pitch R adjacent to fields	-111.7598925	39.1526088
USPS98	98	Stream	5/20/15	-	12.6	4820	7.50	San Pitch R 100' downstream from Hwy 89 bridge	-111.7285340	39.1660450
USPS99	99	Seep	5/20/15	-	13.1	18,940	7.10	Seep on left bank of San Pitch R	-111.7285180	39.1655350
USPS100	100	Stream	5/20/15	-	13.5	6020	8.51	San Pitch R	-111.7296542	39.1647620
USPS101	101	Stream	5/20/15	1.3	15.4	5980	8.57	San Pitch R	-111.7305327	39.1640946
USPS102	102	Seep	5/20/15	0.004	14.1	77,500	7.06	Seep left bank San Pitch	-111.7343410	39.1618717
USPS103	103	Pond	5/20/15	-	20.0	3950	8.69	40 feet from San Pitch R in pond that is likely groundwater fed	-111.7652206	39.1489062
USPS104	104	Seep	5/20/15	0.02	11.3	2480	7.63	Diffuse seep on right bank of San Pitch R	-111.7658402	39.1486920
USPS105	105	Stream	5/20/15	3.8	21.6	5760	8.38	San Pitch R below Nielsen ranch	-111.7657565	39.1479472
USPS106	106	Seep	5/20/15	-	16.0	2200	-	Diffuse seep on right bank of San Pitch R	-111.7658760	39.1477929
USPS107	107	Stream	5/20/15	-	20.5	6330	8.12	San Pitch R	-111.7653128	39.1475701
USPS108	108	Seep	5/20/15	0.001	14.0	2020	7.61	Bubbling seep along left bank of San pitch R	-111.7652800	39.1475770
USPS109	109	Spring	5/20/15	0.001	13.3	2500	7.48	Two spring heads flow into side channel into San Pitch R	-111.7658231	39.1457654
USPS110	110	Stream	5/20/15	-	19.7	5000	8.29	San Pitch R adjacent to spring input	-111.7665296	39.1454812
USPS111	111	Stream	5/20/15	5.0	19.9	5670	8.19	San Pitch R below Gregerson ranch and above Chalk Hill spring	-111.7672823	39.1450762
USPS113	113	Ditch	5/20/15	0.04	12.0	7530	7.41	Side stream into right bank Twelvemile Ck	-111.7426295	39.1543611
USPS115	115	Seep	5/20/15	-	16.6	8925	7.92	Saline seep	-111.7424279	39.1539028
USPS119	119	Ditch	5/20/15	-	22.5	11,400	7.98	Trickle of flow	-111.7423097	39.1536693
USPS120	120	Seep	5/20/15	0.002	-	-	-	Trickle flow on left bank	-111.7424485	39.1536594
USPS122	122	Seep	5/20/15	-	11.7	25,620	7.96	Trickle flow into left bank	-111.7427031	39.1536578
USPS123	123	Stream	5/20/15	-	18.4	2154	8.01	Twelvemile Ck upstream from left bank seepage zone	-111.7415687	39.1536380
USPS124	124	Stream	5/20/15	-	18.9	3685	8.08	Twelvemile Ck	-111.7426764	39.1545855
USPS125	125	Stream	5/20/15	-	20.0	3489	8.22	Twelvemile Ck upstream from Jae outcrops	-111.7454364	39.1549469
USPS126	126	Stream	5/20/15	-	19.2	3505	8.25	Twelvemile Ck 50 ft upstream of bridge	-111.7481727	39.1565063
USPS130	130	Pond	8/18/14	-	34.0	9840	9.93	Old settling pond	-111.7431090	39.1525355
USPS131	131	Canal	8/18/14	-	22.3	623	9.51	Highland Canal at diversion into settling pond	-111.7411039	39.1475801
USPS132	132	Canal	8/18/14	-	23.7	644	8.51	Highland Canal	-111.7420825	39.1468972
USPS133	133	Stream	8/26/14	-	21.0	4200	8.30	San Pitch R	-111.7289850	39.1668552
USPS134	134	Pond	8/26/14	-	23.3	7000	-	Pond of higher conductivity water	-111.7287547	39.1672691
USPS135	135	Seep	5/19/15	-	16.2	>3999	7.30	Wet ground, dug pit, water slightly turbid	-111.7435487	39.1515258
USPS136	136	Seep	5/19/15	-	12.2	3300	7.36	Trickle seep above left bank Twelvemile Ck	-111.7369914	39.1508556
USPS137	137	Seep	5/19/15	-	11.6	3320	7.28	Trickle seep above left bank Twelvemile Ck	-111.7369915	39.1508646
USPS138	138	Pond	8/18/14	-	24.2	2240	8.20	Yardley pond	-111.7366840	39.1540020

[1]Station ID refers to our identification for measurement locations and site number is an abbreviation of our station ID shown on most maps and in the text to describe the location of a particular site of interest.

UTAH GEOLOGICAL SURVEY
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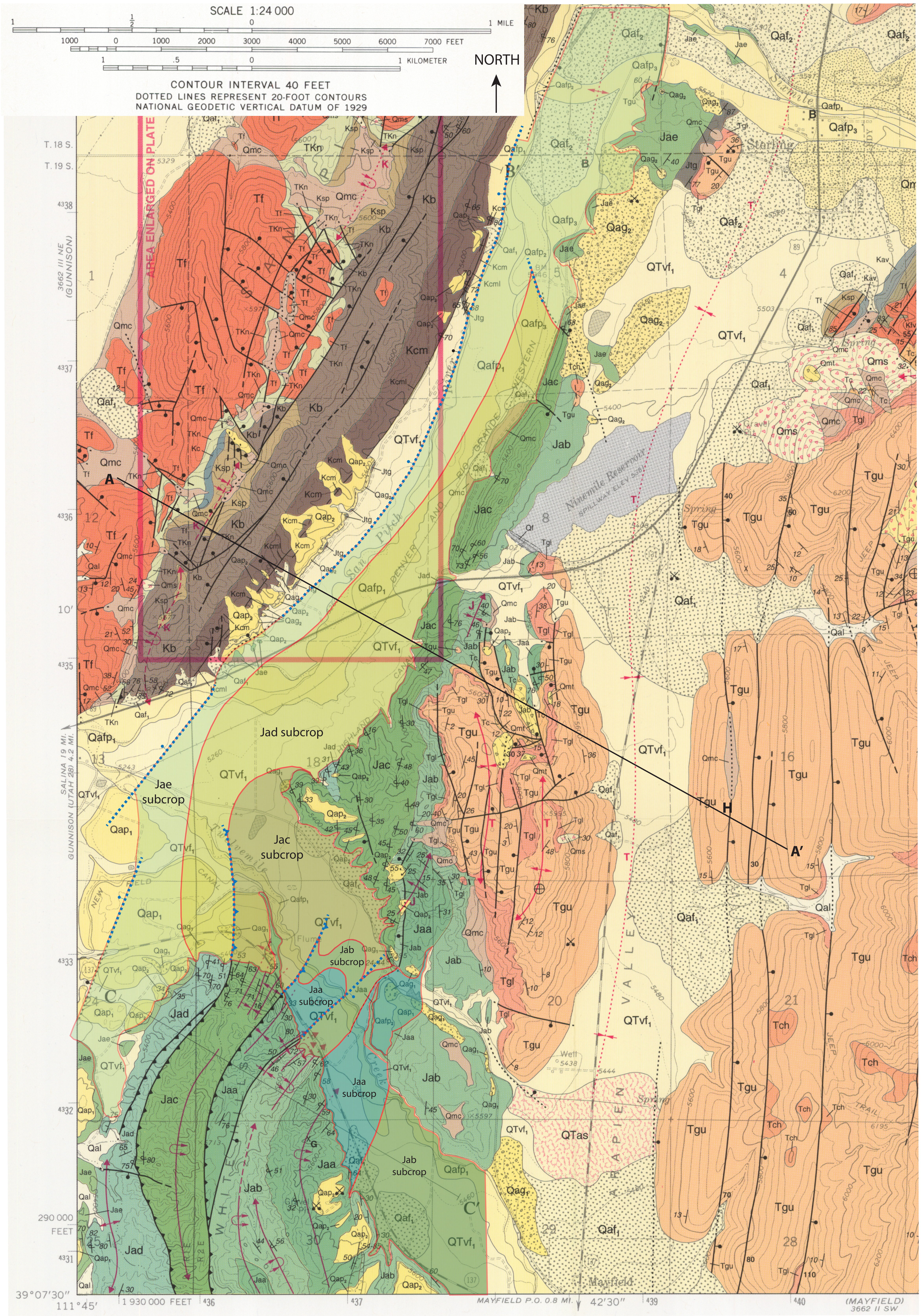
Utah Department of Natural Resources

SOUTHEAST QUARTER OF THE GEOLOGIC MAP OF THE STERLING QUADRANGE (WEISS, 1994)

Interpretation by the authors of geologic units below the San Pitch River alluvial fill are superposed on the original map, and are labeled "subcrop" and shown with orange boundaries. Interpreted faults are shown in blue and are thicker than faults on the original map. See plate 2 for explanation of geologic units and map symbols.



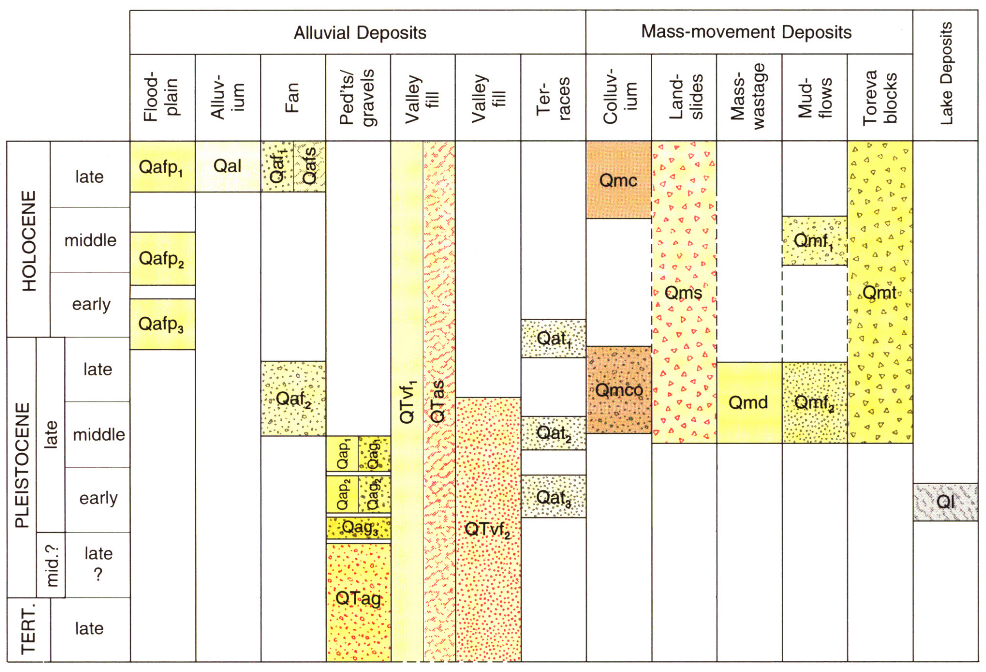
Base map from the U.S. Geological Survey, Sterling 7.5' Quadrangle, 1966

UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

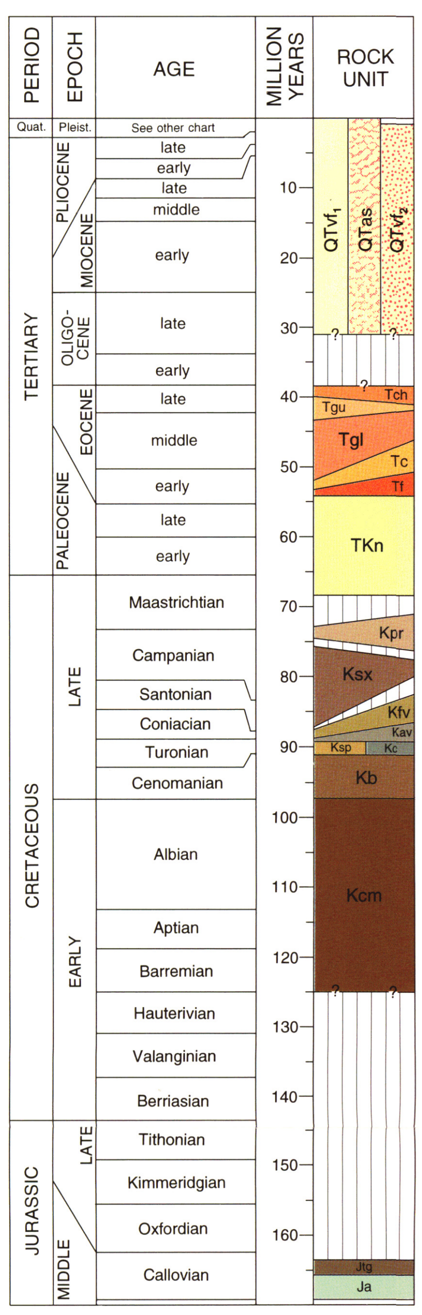
Plate 2
Utah Geological Survey Special Study 158
Water Salinity Study for the Southern San Pitch Drainage System in Sanpete County, Utah

LITHOLOGIC COLUMN, CORRELATION AND DESCRITION OF GEOLOGIC UNITS, MAP SYMBOLS, AND CROSS SECTION

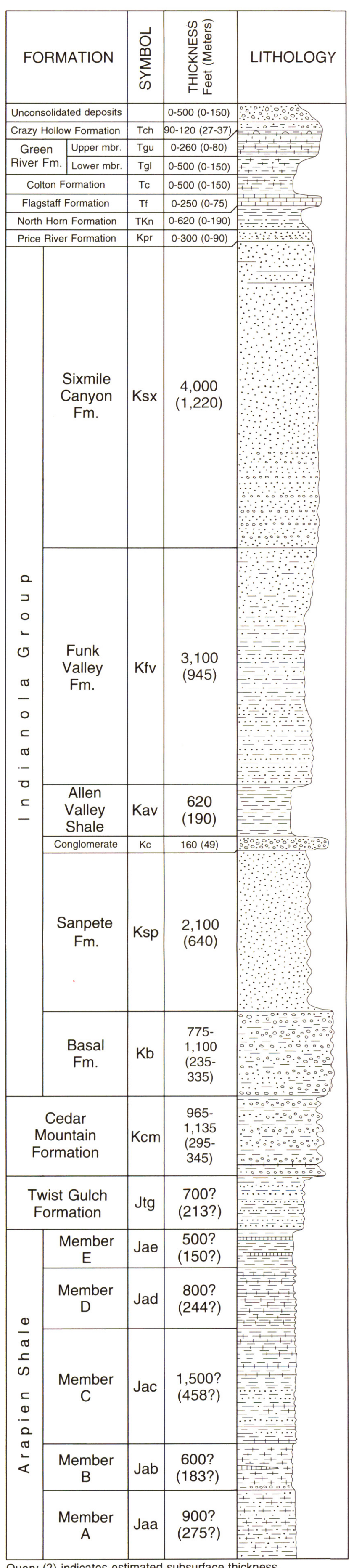
CORRELATION OF QUATERNARY UNITS



CORRELATION OF BEDROCK UNITS

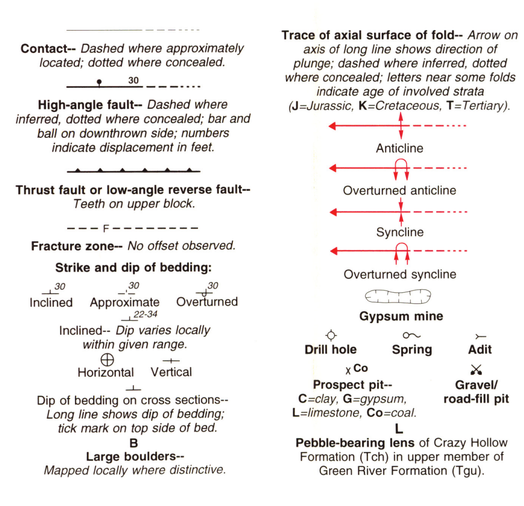


LITHOLOGIC COLUMN



Query (?) indicates estimated subsurface thickness.

MAP SYMBOLS



SUBSURFACE FEATURES INTERPRETED BY THE AUTHORS

Concealed by San Pitch River alluvium and other surficial deposits

- Normal fault
- Thrust fault
- Jae - Member E of Arapien Shale
- Jad - Member D of Arapien Shale
- Jac- Member C of Arapien Shale
- Jab - Member B of Arapien Shale
- Jaa - Member A of Arapien Shale

DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

Qf Artificial fill (modern)-- *Earth-fill dams.*

ALLUVIAL DEPOSITS

Qafp1 Floodplain deposits (late Holocene)-- *Alluvial material; brown and brownish-gray, poorly sorted, and close in both area and level to the principal streams; coarse fraction mostly in point bars; thickness probably less than 30 feet (9 m).*

Qafp2 Older floodplain deposits (early-middle Holocene)-- *Like the modern floodplain deposits, but grayer; found as remnants 15 to 20 feet (4.5-6 m) above Qafp1; thickness is unknown.*

Qafp3 Oldest floodplain deposits (Pleistocene-Holocene)-- *Like Qafp2, but lying 30 to 40 feet (9-12 m) above Qafp1; thickness is unknown.*

Qal Alluvium (late Holocene)-- *Fluvial material; dark-brown to gray clay, silt, sand, granules, pebbles, and sparse cobbles; thin- to thick-bedded, locally massive and cross-bedded; along intermittent streams and at upper ends of fans; forms broad, even surfaces of low relief; thickness is varied, commonly less than 50 feet (15 m).*

Qaf1 / Qafs Alluvial-fan deposits (late Holocene)-- *Light-brown to brown, locally gray, unconsolidated to semi-consolidated, moderately well-sorted silt, sand, granules, pebbles, or cobbles at the mouths of canyons; commonly lobate; thickness is uncertain: large fans to 70 feet (21 m), small fans less than 30 feet (9 m); grade to alluvium upstream and valley fill downstream. Mapped as Qafs where it includes salt marsh deposits.*

Qaf2 Older alluvial-fan deposits (late Pleistocene)-- *Like the younger alluvial-fan materials, but so deeply dissected by modern drainages that the surface is no longer building; however, the surfaces do grade to modern valley-fill surfaces; to 30 feet (9 m) thick.*

Qat1 Alluvial-terrace deposits (Holocene and Pleistocene)-- *Gray and brownish-gray alluvial deposits mixed with North Horn and Flagstaff colluvium; the upper surface stands 160 to 170 feet (49-52 m) above Sixmile Creek; thickness unknown.*

Qat2 Older alluvial-terrace deposits (middle late Pleistocene)-- *Alluvial deposits of boulders, cobbles, and local sand lenses; lower edge of surface is more than 40 feet (12 m) above Sixmile Creek, and the terrace parallels the stream gradient; underlies Qmf2 and Qaf2; maximum exposure is 30 feet (9 m) thick; total thickness is unknown.*

Qat3 Oldest alluvial-terrace deposits (early late Pleistocene)-- *Like the other terrace deposits, but the surface stands 40 to 150 feet (12-46 m), distally to proximally, above Sixmile Creek; thickness is unknown.*

Qap1 Pediment-mantle deposits (middle late Pleistocene)-- *Alluvial deposits spread on stream-cut rock surfaces; brown, gray, or locally reddish brown; massive to crudely bedded; unconsolidated mixture of silt, sand, granules, pebbles, cobbles, and boulders; surfaces are even and slope from uplands (proximal) toward the streams (distal); deposits are 30 to 60 feet (9-18 m) thick; surfaces range from about 20 to 50 feet (6-15 m), distally to proximally, above Twelvemile Creek.*

Qap2 Older pediment-mantle deposits (early late Pleistocene)-- *Deposits like Qap1, but deformed by tilting (35-45 degrees) or by elevation above the younger surfaces by as much as 70 feet (21 m); deposits are about 40 feet (12 m) thick; above the water table the deposits are well cemented in some layers, and are yellowed by limonite.*

Qag1 Stream gravel (middle late Pleistocene)-- *Limestone and chert cobbles and pebbles from the Flagstaff Limestone; found in streaks and patches within and bordering the younger pediments (Qap1); 10 to 20 feet (3-6 m) thick and at the same elevations as Qap1.*

Qag2 Older stream gravel (early late Pleistocene)-- *Moderately sorted cobble and pebble gravels with little sand, mostly limestone and chert of the Flagstaff Limestone; less than 15 feet (5 m) thick west of river and averaging 30 to 40 feet (9-12 m) east of river.*

Qag3 Alluvial (?) gravel (middle to early late Pleistocene)-- *Gray and brownish gray, mostly pebble gravels with some fines; poorly bedded with numerous poorly sorted layers; mostly limestone and chert from the Flagstaff; 20 feet (6 m) thick at maximum.*

MASS-MOVEMENT DEPOSITS

Qmc Colluvium (Holocene)-- *Gravity and slopewash sediments; gray to brown; unconsolidated to semi-consolidated; deposits mantle lower valley walls and accumulate at the base of some steep cliffs; grades to alluvium, valley fill, or fans as slopes lessen; thickness ranges from 0 to 50 feet (0-15 m).*

Qmco Older colluvium (late Pleistocene)-- *Gray, but otherwise like Qmc; occurs as sharply dissected aprons of weakly consolidated, mostly Flagstaff Limestone debris; larger in area than Qmc and 0 to 100 feet (0-30 m) thick.*

Qms Landslide deposits (Holocene and late Pleistocene)-- *Gravity deposits; brown to dark-brown and gray fragments of diverse sizes and shapes; hummocky topography with concentric ridges; includes small toreva blocks; thickness ranges from 0 to perhaps 60 feet (18 m).*

Qmd Debris-flow deposits (late Pleistocene)-- *Brown to gray masses of broken rock of diverse sizes and shapes; non-stratified; locally includes small earthflows and rock falls; hummocky and irregular surface; thickness ranges widely, but does not exceed about 300 feet (90 m). Mapped in three subdivisions, according to source: Qmd (Tg), Qmd (Tc), and Qmd (TKn).*

Qmf1 Mudflow deposits (middle Holocene)-- *Gray and brownish-gray, very poorly sorted, angular debris moved by mudflow; fine material is from the North Horn and most of the coarse material is Flagstaff Limestone; hummocky surface; thicknesses range up to 200 to 300 feet (60-90 m).*

Qmf2 Older mudflow deposits (late Pleistocene)-- *Similar to Qmf1 in texture and composition but much longer; dissected by both Funk and Sixmile Creeks; thickness ranges from 0 to 150 feet (45 m).*

Qmt Toreva blocks (Holocene-late Pleistocene)-- *Masses of rock that slumped with little internal disturbance; small toreva blocks are lumped with colluvium and are probably Holocene in age; large blocks are probably older; thickness is unknown.*

LACUSTRINE DEPOSITS

Ql Lake deposits (early late Pleistocene)-- *Marl, clay, thin sands, and some pebble bands; fossiliferous; little cementation; base not exposed, but apparently lies on Arapien Shale; overlain by Qag2; 12.8 feet (3.9 m) exposed.*

QUATERNARY AND TERTIARY DEPOSITS

QTag Older alluvial(?) gravel (middle Pleistocene)-- *Material and structure like Qag3, but has been turned on edge, in angular unconformity beneath Qag3; maximum thickness exposed is less than 50 feet (15 m). Regionally this unit is older.*

QTvf1 Valley-fill deposits (Holocene at surface; Tertiary at depth)-- *Gray and brownish-gray, poorly sorted, unconsolidated alluvial and colluvial debris in large valleys; grades to fans, colluvial and alluvial deposits at valley margins; probably 0 to 700 feet (0-215 m) thick.*

QTas Salt marsh deposits on valley fill (Holocene at surface; Tertiary at depth)-- *Same material as QTvf1, and has a concordant surface, but is water-saturated and contains local pond sediments; thickness like QTvf1; probably 0 to 700 feet (0-215 m) thick.*

QTvf2 Older valley-fill deposits (late Pleistocene at surface; Tertiary at depth)-- *Material and origin like those of QTvf1, but surface is 15 to 30 feet (4.5-9 m) higher than the younger valley fill and associated deposits; probably 0 to 700 feet (0-215 m) thick.*

TERTIARY ROCKS

Tch Crazy Hollow Formation (late Eocene)-- *Red to reddish-brown mudstone; red, light-yellow-brown, and locally white sandstone, shaly siltstone, and some conglomerate; sandstone and conglomerate that are not red are marked by grains and pebbles of black chert, giving a "salt and pepper" look; locally contains lenses of dense, micritic, light-gray, pink, or dark-gray to black limestone; mostly fluvial, but locally pond or lacustrine deposits; thickness is 0 to 120 feet (37 m).*

Green River Formation (Eocene)

Tgu --Upper member-- *White to yellowish-gray, thin-bedded, platy, micritic, well-cemented limy mudstone, and ostracodal and oolitic limestone interbedded with thin shale layers; yellowish-orange near the top, with silicified stromatolite beds and some tuffs; interfingers with Crazy Hollow Formation. Maximum thickness in quadrangle is 180 to 260 feet (55-80 m).*

Tgl --Lower member-- *Light-gray and greenish-gray, shaly mudstone with thin layers of limestone, some siltstone, and minor sandstone; 0 to 300 feet (0-90 m) thick in central area and to 500 feet (150 m) thick in the southeast corner; pinches out over Jurassic rocks.*

Tc Colton Formation (early Eocene)-- *Claystone and mudstone variegated in shades of reddish brown, light gray, violet, or light greenish gray; locally includes beds of yellowish-gray to yellowish-brown siltstone and sandstone; sparse, thin beds of platy, light-gray, micritic, lacustrine limestone; pinches out over the disturbed belt of Mesozoic rocks, but is 280 feet (85 m) thick in the central area and about 500 feet (150 m) thick in the southeast.*

Tf Flagstaff Limestone (Eocene)-- *Light-gray to yellowish-gray limestone; pinkish or grayish orange near base where unconformable on Jurassic or Cretaceous beds; numerous shale partings and mudstone interbeds; micritic beds are slabby limestone; finely sacharoidal, massive beds are commonly dolomitic or dolomite; deposits in northwestern part of quadrangle are fossiliferous, high-calcium micrites; thin- to thick-bedded, locally massive; contains oncolites locally near the base; contains subordinate, interbedded, dark-gray, gray, and greenish-gray shale; forms resistant ledges and prominent hogbacks; ranges widely in thickness from 0 to 400 feet (0-122 m); average maximum thickness is about 250 feet (75 m).*

TERTIARY AND CRETACEOUS ROCKS

TKn North Horn Formation (Maastrichtian to early Eocene)-- *Claystone, sandstone, conglomeratic sandstone, conglomerate, and sparse limestone; units alternate irregularly; mudstones are thick-bedded to massive; sandstones range from thin to thick bedded and many are cross-bedded; fine to medium grained; limestone beds are thin, dense, and locally arenaceous; thickness varies abruptly; forms slopes, slides, and flows easily; ranges in thickness from pinchout to 620 feet (190 m).*

CRETACEOUS ROCKS

Kpr Price River Formation (Late Cretaceous)-- *Gray to light-gray or yellowish-brown conglomerate, conglomeratic sandstone, and sandstone, with minor shale; thin to thick bedded; locally massive; commonly well cemented; coarse conglomerates contain well-rounded clasts of light-brown and purple quartzite, and red-and-white striped quartzite, light-gray quartz, light-gray chert, and sparse dark-bluish-gray limestone; sandstones are fine to coarse grained; forms steep slopes and low cliffs; ranges in thickness from 0 to 300 feet (90 m).*

Indianola Group

Ksx Sixmile Canyon Formation (Late Cretaceous)-- *Three intergrading parts are distinguished: a lower interval (slightly more than half the formation) of sandstone with some conglomerate and conglomeratic sandstone; a middle interval (slightly less than one-fourth) of fine sandstone, shale, carbonaceous shale, and coal; and an upper interval (slightly less than one-fourth) of coarser sandstone with minor conglomerate and a few coal beds; the formation is perhaps 4,000 feet (1,220 m) thick.*

Kfv Funk Valley Formation (Late Cretaceous)-- *Three intergrading parts are distinguished: 900 to 1,000 feet (275-304 m) of thick beds of sandstone interbedded with shale; 1,300 feet (395 m) of an easily weathered, finer grained, muddy sandstone with 550 feet (165 m) of mudstone near the middle; and an upper sandstone unit like the lower one, but 800 to 900 feet (245-275 m) thick.*

Kav Allen Valley Shale (early Late Cretaceous)-- *Gray, fossiliferous, marine shale with thin layers of bentonitic mudstone, siltstone, and limy siltstone; thickness is 620 feet (190 m).*

Kc Conglomerate beds (early Late Cretaceous)-- *A massive, well-cemented, gray conglomerate present only locally on top of the Sanpete Formation west of the San Pitch River; gray in outcrop with colored Precambrian quartzite clasts; outcrop is only about 1,500 feet (455 m) long with an exposed thickness of 160 feet (49 m).*

Ksp Sanpete Formation (early Late Cretaceous)-- *Grayish-orange weathering, marginal marine sandstone with shale interbeds, some about 100 feet thick; sand has a range of grain sizes and sorting is moderate to good; rock is reasonably well cemented, and limonitic, particularly west of the San Pitch River; thickness is about 2,100 feet (640 m).*

Kb Basal formation of Indianola Group, new unit (early Late Cretaceous)-- *Reddish-brown and gray, thick-bedded to massive, well-cemented conglomerate with interbeds of sandstone and some mudstone; granules, pebbles, and well-rounded cobbles and boulders 3 to 6 feet (1-2 m) in diameter of white, red, red-striped, purple, green, grayish-green, and light-brown quartzite, light-brown to light-gray chert, white quartz, and some gray and dark-bluish-gray limestone; thickness 775 to greater than 1,100 feet (235-335 m). Equals "Gunnison Formation" of Roche (1985), upper Pigeon Creek of Schwans (1989), and upper Cedar Mountain of Witkind and others (1986).*

Kcm / Kcml Cedar Mountain Formation (Early Cretaceous)-- *Mudstone, variegated in shades of red-orange, yellowish-gray, gray, purple, and green; massive to thick bedded; a few lenses and thin layers of limy sandstone occur; limy mudstone beds with lime nodules and oncolites are a signature of the unit; a few pebble and cobble conglomerate layers 10 to 30 feet (3-9 m) thick are present near the base and close to the top; exposed thickness is 965 to 1,135 feet (295-345 m). A conspicuous layer, 20 to 40 feet (6-12 m) thick, of white-weathering, pale-pink limestone (Kcml) lies near the base of the unit.*

JURASSIC ROCKS

Jtg Twist Gulch Formation (Middle Jurassic)-- *Reddish-brown shale and silty mudstone with some thin to thick beds of reddish-gray to light-gray, gritty sandstone that weathers light brown; feldspathic; unfossiliferous; about 3,000 feet (915 m) thick regionally and 1,667 feet (510 m) locally.*

Ja Arapien Shale (Middle Jurassic)-- *Mudstone, calcareous, commonly light-gray, with red, salt-bearing beds and lenses; in places entirely drab gray, elsewhere wholly reddish brown; thin to medium bedded; evenly bedded; locally amorphous; has intercalated thin, lenticular beds and seams of yellowish-gray to light-brown siltstone and sandstone; sparse limestone beds have few fossils; contains thick beds of rock salt (halite), gypsum, and minor evaporites; abundant selenite crystals; formation is complexly deformed, with much shearing; erodes to badland topography with little vegetation; thickness uncertain. Unit is divisible into five intergrading members:*

Jae --Member E: *Brick-red, silty shale; locally salt-bearing; bedding obscure where deformed; exposed thickness incomplete, about 500 feet (150 m) locally.*

Jad --Member D: *Alternate layers of bluish-gray and red, gypsiferous shale; locally blotchy because of lenticular beds and facies changes; about 800 feet (244 m) exposed locally.*

Jac --Member C: *Light-gray, calcareous shale and limy mudstone; all thin-bedded; contains a few thin and medium beds of dense, sandy, fossiliferous limestone, and local pods of gypsum; local thickness may be about 1,500 feet (458 m).*

Jab --Member B: *Bluish-gray and red, gypsiferous shale; blotchy and streaked like member D, but has more red mudstone with local pods of halite; minimum local thickness is 425 feet (130 m) but may reach 600 feet (183 m).*

Jaa --Member A: *Light-yellowish-gray shale and thin-bedded limestone; some red gypsiferous shale, and light-gray, argillaceous limestone with large local pods of gypsum concentrated near the top; local thickness indeterminate, but about 900 feet (275 m).*

All material on this plate except the cross section are from Weiss (1994). The cross section is original work by the authors, with structural interpretation based on section C-C' of Weiss (1994). Not all units and features shown on this plate appear on plate 1.