ONE-DIMENSIONAL HYDRAULIC MODEL OF VERDE RIVER NEAR

CAMP VERDE, ARIZONA

INCLUDING IRRIGATION DITCH DISCHARGE

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ABSTRACT

ONE-DIMENSIONAL HYDRAULIC MODEL OF VERDE RIVER NEAR CAMP VERDE, ARIZONA INCLUDING IRRIGATION DITCH DISCHARGE

ROBERT P ROSS

The middle Verde River system is a complex area, due in large part to undefined diversions of river base flow by irrigation ditches. To better understand the behavior of the riverine system, a comprehensive geographical information system (GIS) was compiled, irrigation ditch diversion and return flows were calculated, and a one dimensional hydraulic model was created with the U. S. Army Corps of Engineers Hydrologic Environmental Center River Analysis System (HEC-RAS).

Hypotheses for this work are that middle Verde River irrigation ditch diversions minimally disrupt regional river base flows, locally negatively impact river base flows, and conservative changes in management and delivery can maintain water user demands while minimizing effects on river base flows.

GIS data for the region were acquired from varied sources, and were compiled in a common projection in a single database. These data were edited by overlaying orthorectified high resolution (one meter) aerial photographs using ESRI ArcGIS. The data were then imported into HEC-RAS via Aquaveo, LLC's Watershed

Modeling System (WMS) module to create a one-dimensional hydraulic channel flow model. Detailed channel surveys were conducted to provide channel elevation data, and irrigation ditch diversions and return flows were monitored with pressure transducers to calculate discharge over a minimum of one year for flow change inputs to the system. A steady-state flow model was created for June 23rd, 2009, during a period of low-flow and minimal fluctuation in the system when all ditches were being monitored. The resulting data indicated a local disruption of hydraulic parameters such as velocity, flow area, discharge, and hydraulic radius, among others, due to flow diversion.

Similar systems such as the middle Rio Grande River Valley Conservation District (MRGRVCD) have had good results in the past with increasing efficiency with conservation-oriented management decisions. The results from the middle Verde River study serve as a general guide to the interactions of the area's irrigation ditches and riverine system, and may aid in future management decisions.

Acknowledgements

I would like to acknowledge the many people and agencies that assisted with and made this work possible. The Water Advisory Committee of Yavapai County (YC-WAC) provided generous funding enabling this study, and its Technical Advisory Committee (YC-WACTAC) provided consistent guidance and feedback to the work in progress. The Nature Conservancy (TNC), Salt River Project (SRP), and Arizona Department of Water Resources (ADWR) provided valuable data and commentary during the course of study. The management of the Eureka, Diamond S, OK, and Verde Ditches provided full cooperation with the study of irrigation diversions, and without them, this study would have been much more difficult, if not impossible. Also invaluable were Drs. Abe Springer, Charlie Schlinger, Rod Parnell, and Paul Grams; many thanks for providing many hours of review, support, advice, and the opportunity to do this work (Paul, thank you for your Excel expertise). The NAU Geology department provided me with the tools necessary to succeed in my professional endeavors, and Susan and Meredith made my life easier even when I made their's more difficult.

I would also like to thank my family and friends for all of their patience and support, especially my wife Kat and daughter Lily for putting up with my frequent field work on the Verde and Colorado Rivers, late nights writing and consorting with my mistresses Excel and HEC-RAS, and sandy/smelly laundry.

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Chapter 1 - Introduction, geologic setting, and background

1.1 Introduction

Interaction of natural rivers and anthropogenic impacts of diversion and modification creates complex riverine systems. These complexities make full, integrated understanding of riverine systems difficult. Understanding the interactions of the river system is essential to stakeholders and water users, as well as to land managers, ecology and resource agencies, and is important for recreational users of the river system. To better understand the relationships between the components of the Verde River system, the Water Advisory Committee of Yavapai County (YCWAC) desires a current and accurate collection of geospatial information relevant to the area. The Technical Advisory Committee (TAC) of the YCWAC has been instrumental in the pursuit of this goal. Finally, these data were used to create a surface-water flow model for the middle Verde River Watershed, which has predictive capabilities for hydrologic and land-use management applications, and can provide boundary constraints to regional and local groundwater flow models.

The Verde River runs through the Verde Valley from its headwaters near Paulden, AZ to the confluence with Salt River near Fountain Hills, AZ (Fig. 1). The selected model area and study reach is approximately 20 river miles and 14 linear miles, and comprises the Camp Verde area of the Verde River, along with four major irrigation ditches (Fig. 2).

The creation and interpretation of a geospatial database and hydraulic model will enable a more thorough understanding of the complex interactions of the natural

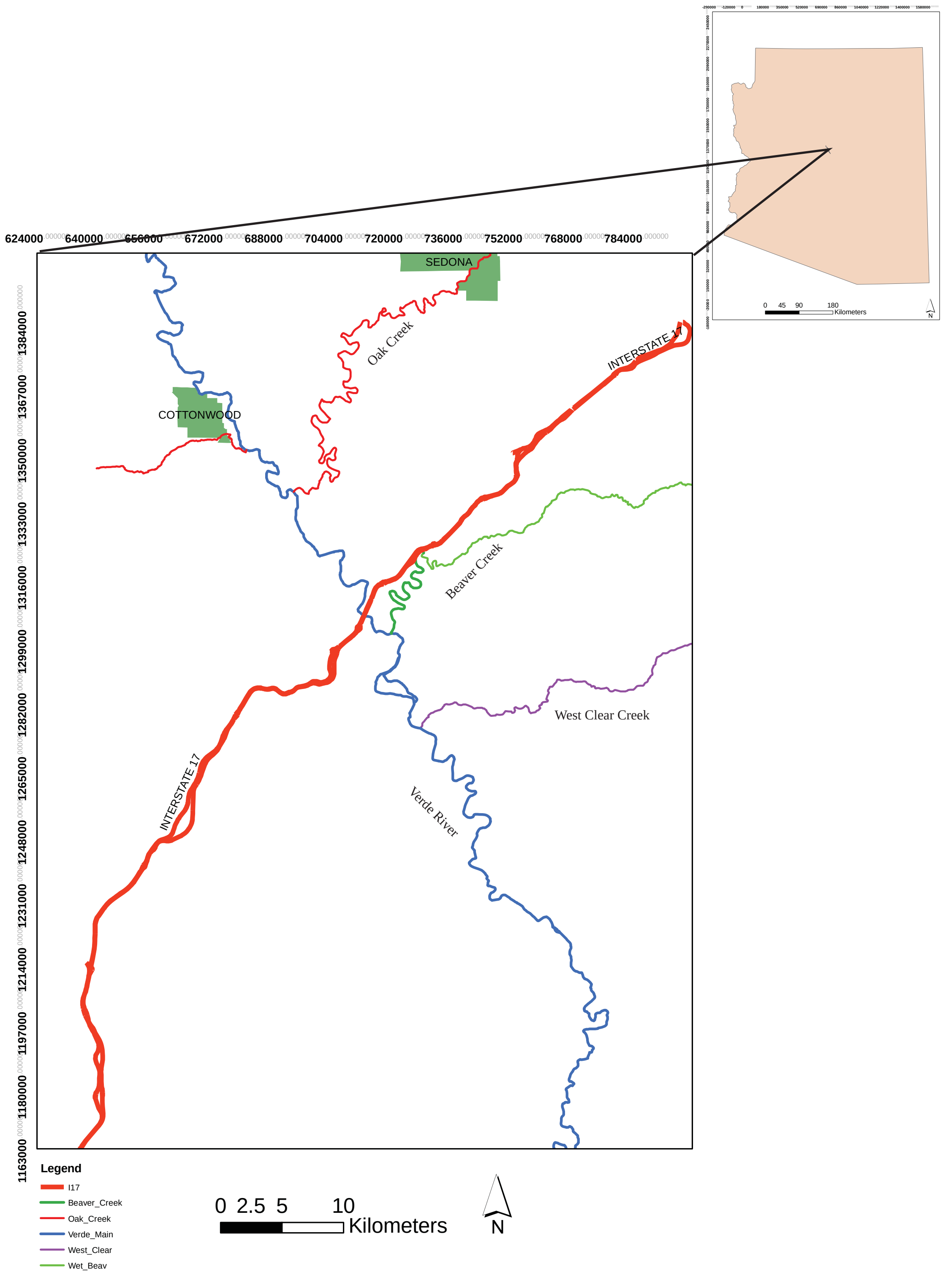

Figure 1 - Location map of the Verde River, central Arizona. Coverages of Interstate 17 and city boundaries are included for spatial reference.

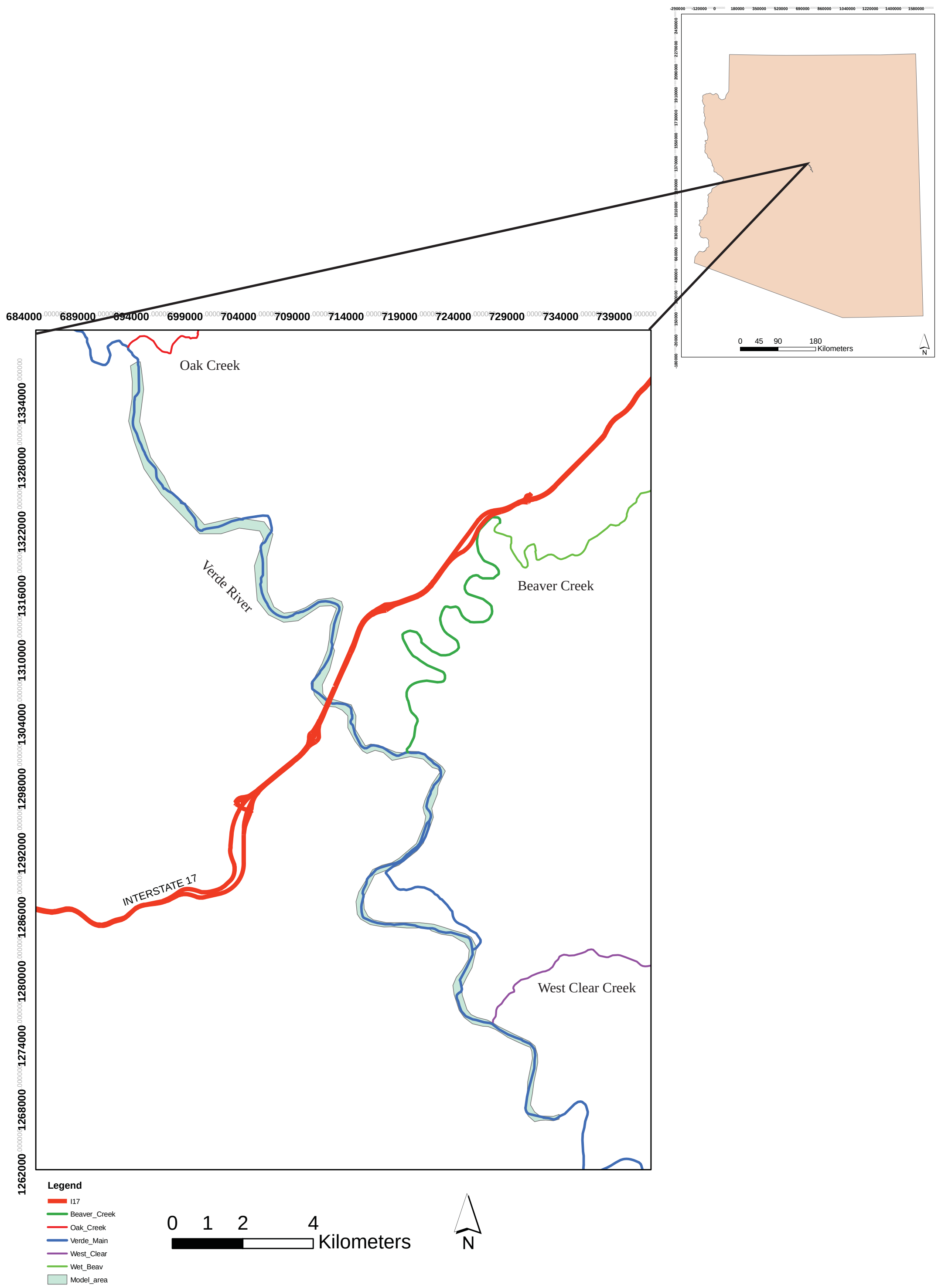

Figure 2 - Location map of study area within Verde River corridor, central Arizona. Interstate 17 and relevant tributaries are included for spatial reference. Blue polygon surrounding main channel is study area.

riverine system and the anthropogenic impacts of irrigation diversion by qualitatively and quantitatively examining the effects of different input scenarios to the system. To create the necessary components, the following objectives were used:

- GIS database.
    - Attributed spatial data for rivers, ditches, laterals, diversions, and return flows.
- Irrigation ditch stage/discharge data.
    - Hourly logged stage and discharge measurements at headgates/return flows for selected ditches.
- Steady-state low flow hydraulic model.
    - Step-iterative hydrographs along river.
    - Input and output discharge data.

Our hypotheses for the study are as follows:

- Middle Verde River ditch diversions minimally disrupt regional river base flows.
- Increased irrigation diversion will locally negatively impact river base flows.
- Conservatively managed diversion/delivery will locally increase river base flows.
- Engineered diversions and/or head gates will assist management.

The Verde River in the Verde Valley is unique in that the interactions of the irrigation ditches with the river and tributaries have never been monitored or modeled. However, a Modeling and Simulation (MODSIM) priority model exists for the potential ranking of water shares from precedent right/economic impact (Newell, 2007), and studies have been conducted on the irrigation ditch systems from a survey and measurement standpoint (Alam, 1997; Tinlin, 1977). Of the ditch studies, one (Alam, 1997) relied on information provided by the irrigation ditch companies in response to survey questionnaires, while the other provides a table of highest measured discharge at or near the headgates of all local irrigation ditches in the summer of 1977 (Tinlin, 1977). Both of these studies provide valuable data, but only provide averages or temporal snapshots of the range of diverted flow. They also do not provide data for the return flow of the ditches, or any estimation of actual evapotranspiration (ET) or consumptive use by each ditch.

Arizona Department of Water Resources (ADWR) published a comprehensive report on the middle Verde River watershed (ADWR, 2000), which provides a discussion of the geology, hydrology, economics, and demographics of the Verde Valley. Many of the data presented in therein are not current, and this study updates the statistics presented therein (such as population and demographic data) with current data from Arizona Department of Commerce, as well as compares projected future statistics to the current statistics available. Geologic maps and reports are also available for surficial geology of the Verde River (House and Pearthree, 1993), the geologic/geomorphologic setting of the Verde River (Pearthree, 1993), historical geomorphology of the Verde River (Pearthree, 1996), and a geologic map of Arizona (Richard, et al., 2000).

1.2 Geology, Settlement, and Demographics of the Verde Valley

1.2.1 Geology

Arizona is divided into three main physiographic regions; the Basin and Range deserts of southern and western Arizona, the mountainous Central Highlands, and the Colorado Plateau of northern Arizona. The Verde Valley is a NW-SE trending terrain in the Transition Zone of central Arizona (Richard, et al., 2000) (Fig. 3). The Transition Zone is characterized by a series of narrow valleys separating steep mountain ranges dividing the Central Highlands to the south from the Colorado Plateau to the north. The Verde River watershed is located in central Arizona, and covers parts of Yavapai, Coconino, and Gila Counties. The Verde River Basin encompasses approximately 5500 square miles, and is divided into the Big Chino, Verde Valley, and Verde Canyon sub-basins (ADWR, 2000).

The geology of the Verde River Watershed varies widely, with igneous, metamorphic, and sedimentary rocks ranging in age from Precambrian to Quaternary (Richard, et al., 2000). The lithology can be grouped by age into four broad categories: Precambrian rocks, Paleozoic rocks, Tertiary and Quaternary volcanic rocks, and Tertiary and Quaternary basin fill alluvium (ADWR, 2000). Locally, the basement is made up of Precambrian intrusive igneous and metamorphic rocks, including metamorphosed volcanic and sedimentary sequences, granite, quartzite, schist, diorite, and quartz porphyry (Twenter and Metzger, 1963). Paleozoic rocks overlie the Precambrian basement, comprising the Supai Formation, Coconino Sandstone, Toroweap Formation, Kaibab Limestone, Redwall Limestone, Martin Formation, and Tapeats Sandstone. The units above the Redwall Limestone contain

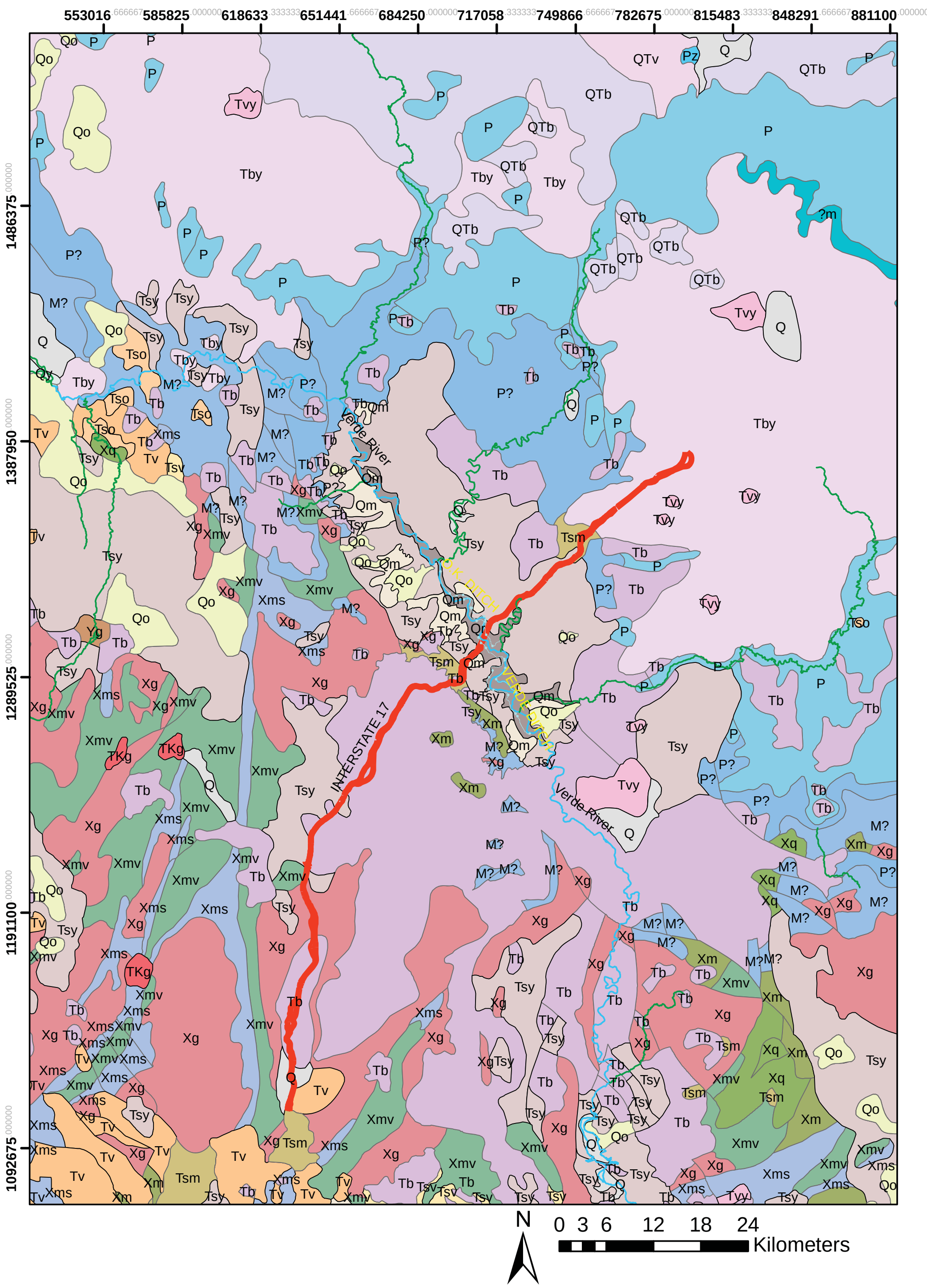

Figure 3 - Geologic map of the Verde Valley, central Arizona (after Richard, et al., 2000).

Map Unit Legend

Q	Quaternary Surficial deposits, undivided (0-2 Ma)
QTb	Holocene to middle Pliocene Basaltic rocks (0-4 Ma)
QTv	Holocene to middle Pliocene Volcanic rocks (0-4 Ma)
Qr	Holocene river alluvium (0-10 ka)
Qy	Holocene Surficial Deposits (0-10 ka)
Qm	Late and Middle Pleistocene Surficial Deposits (10-750 ka)
Qo	Early Pleistocene to latest Pliocene surficial deposits (0.75-3 Ma)
QTs	Early Pleistocene to late Miocene basin deposits (0.75-10 Ma)
Tvy	Pliocene to middle Miocene Volcanic rocks (2-12 Ma)
Tsy	Pliocene to middle Miocene deposits (2-16 Ma)
Tby	Pliocene to late Miocene Basaltic Rocks (4-8 Ma)
Tb	Late to middle Miocene Basaltic Rocks (8-16 Ma)
Tsv	Middle Miocene to Oligocene Volcanic and Sedimentary rocks, undivided (11-32 Ma)
Tsm	Middle Miocene to Oligocene Sedimentary rocks (11-32 Ma)
Tv	Middle Miocene to Oligocene Volcanic rocks (11-38 Ma)
Tg	Middle Miocene to Oligocene Granitic rocks (14-26 Ma)
Ti	Middle Miocene to Oligocene Shallow Intrusions (14-35 Ma)
TXgn	Tertiary to Early Proterozoic Gneissic rocks (15-1800 Ma)
Tso	Oligocene to Paleocene[?] Sedimentary rocks (30-65 Ma)
TKgm	Early Tertiary to Late Cretaceous Muscovite-bearing Granitic rocks (50-80 Ma)
TKg	Early Tertiary to Late Cretaceous Granitic rocks (50-82 Ma)
Kv	Early Tertiary to Late Cretaceous Volcanic rocks (50-82 Ma)
KJo	Orocopia Schist (Cretaceous - Jurassic, 65-165 Ma)
KJs	Cretaceous to Upper Jurassic Sedimentary rocks with minor volcanic rocks (80-160 Ma)
Kmv	Sedimentary rocks of the Upper Cretaceous Mesaverde Group (84-88 Ma)
Ks	Cretaceous Sedimentary rocks (about 88-97 Ma)
Jm	Morrison Formation (Late Jurassic, about 145-160 Ma)
Jsv	Jurassic Sedimentary and Volcanic rocks (150-170 Ma)
Jg	Jurassic Granitic rocks (150-180 Ma)
Jv	Jurassic Volcanic rocks (160-200 Ma)
JTR	Jurassic and Triassic Sedimentary and Volcanic rocks (160-240 Ma).
MzTR	Jurassic to Cambrian Metamorphosed Sedimentary rocks (160-540 Ma)
Js	San Rafael Group (Late to Middle Jurassic, about 160-180 Ma)
Jgc	Glen Canyon Group (Early Jurassic, about 180-210 Ma)
TRc	Chinle Formation (Late Triassic, 210-230 Ma)
TRcs	Shinarump Conglomerate Member
TRm	Moenkopi Formation (Middle(?) and Early Triassic, 230-245 Ma)
Pz	Paleozoic Sedimentary rocks (248-544 Ma)
P	Permian Sedimentary rocks (270-280 Ma).
PP	Permian to Pennsylvanian Sedimentary rocks (280-310 Ma)
MC	Mississippian, Devonian, and Cambrian Sedimentary rocks (330-540 Ma)
Ys	Middle Proterozoic Sedimentary rocks (700-1300)
Yd	Middle Proterozoic Diabase (1050-1150 Ma)
YXg	Proterozoic Granitic rocks (1400-1800 Ma)
Yg	Middle Proterozoic Granitic rocks (1400-1450 Ma)
Xg	Early Proterozoic Granitic rocks (1600-1800 Ma)
Xms	Early Proterozoic Metasedimentary rocks (1600-1800 Ma)
Xq	Early Proterozoic Quartzite (1650? -1700 Ma)
Xmv	Early Proterozoic Metavolcanic rocks (1650 to 1800 Ma)
Xm	Early Proterozoic Metamorphic rocks (1600-1800 Ma)

Contacts

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Faults

Faults

Figure 3, continued

groundwater and form a regional aquifer (Owen-Joyce, 1984). The units below the Redwall Limestone contact thick groups of Tertiary and Quaternary sedimentary and volcanic rocks in the central basins in the watershed (Richard et al, 2000). Tertiary and Quaternary volcanic rocks are the upper most and commonly exposed units. The volcanics are predominantly basalt, including the Perkinsville and Hickey Formations. Tertiary and Quaternary basin fill alluvial deposits overlie the Precambrian to Tertiary age rocks in the area, with extensive deposits of basin fill alluvium in the Chino and Verde Valleys. This young alluvium consists of unconsolidated sand, gravel, and silt deposited by the Verde River and tributaries within present stream channels as floodplain alluvium and channel fill. Channel deposits in the Camp Verde area are coarse-grained, and reach thicknesses of approximately 60 to 100 feet thick (Fig.4). These deposits typically consist of unconsolidated gravel, sand, clay, and silt (Owen-Joyce, 1984).

The Verde Formation in the Verde Valley is composed of chalky lacustrine limestone and siltstone deposits, along with Tertiary lava. It is believed to have been deposited between three and six Ma in freshwater lakes created by the damming effect of lava flows. The Verde Formation extends over about 325 square miles, and is a local near-surface aquifer (Owen-Joyce and Bell, 1983).

The river valley exposes Mississippian sedimentary rocks, Tertiary basaltic rocks, and Tertiary sedimentary rocks (e.g., the Hickey and Perkinsville Formations, the Verde Formation) (Richard et al., 2000) (Fig. 5).

Soils in the Verde Valley generally occur on gently sloping mesas, plains, and floodplains, with soil associations generally comprising one or more major soils and

Figure 4 - Channel deposit thickness in the Verde Valley within the study area. Partial exposure of channel deposit along Verde River near Camp Verde, central Arizona. This low terrace exposure is about 3 meters, and displays the low end of the typical local channel deposit thickness, ranging from 2 to 30 meters.

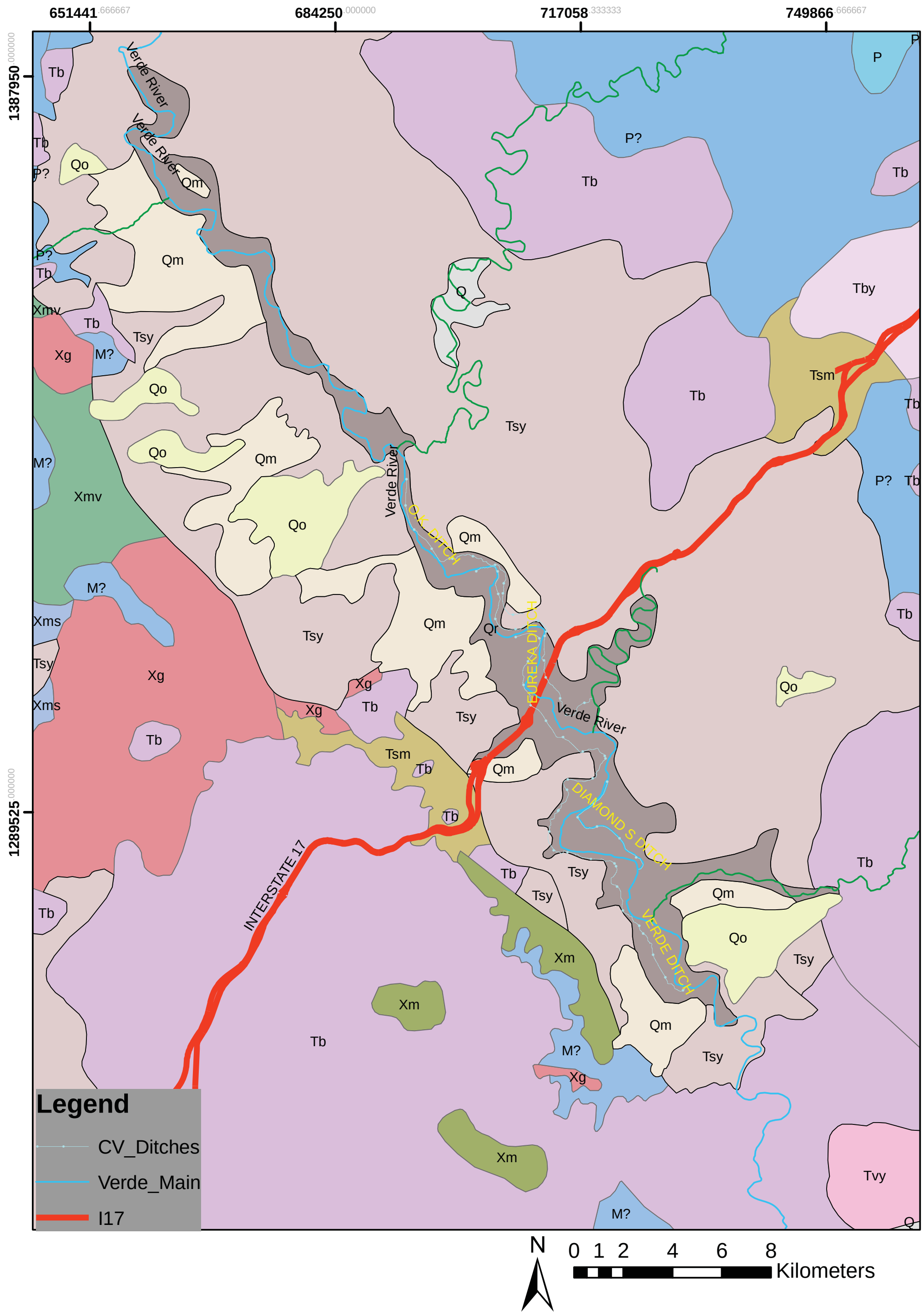

Figure 5 - River valley exposures of the Verde River, central Arizona (after Richard, et al., 2000). Refer to Figure 3 for map legend.

at least one minor soil (ADWR, 2000). In places, several soil features, such as low permeability and poor topsoil, restrict farm and irrigation development. Soil associations include Mesic Semiarid and Thermic Semiarid types, including the Penthouse-Latene-Pinaleno and Lithic Torriothents-Lithic Haplustolls-Rock Outcrop, and Tortugas-Purner-Jacks, respectively (USDA, 1975) (Fig. 6). These soils are well-drained and formed from alluvium and erosional material, and occur on surfaces ranging from nearly level to very steep. These associations generally have low permeability and low to moderate water capacity (USDA, 1975).

The channel and floodplains of the Verde River and its tributaries contain channel and terrace deposits of poorly-sorted, fine to coarse gravel and boulders, with silt, sand, gravel, and unconsolidated stratified clays are present in the terraces (USDA, 1975).

The headwater region of the Verde River consists of a large series of ephemeral washes in the Prescott/Chino Valley area, along with the Big Chino Wash. Perennial flow of the river begins at its confluence with Granite Wash, about 2 miles downstream of Paulden, Arizona. Major tributaries of the Verde River are Chino Wash, Williamson Valley Wash, Walnut Creek, Granite Creek, Hell Canyon, Sycamore Creek, Oak Creek, Beaver Creek, and West Clear Creek (Springer and Haney, 2008) (Fig. 7).

The Verde River consists of two distinct reaches; the upper Verde River and the middle Verde River, defined by distinct physiographic and anthropogenic characteristics.

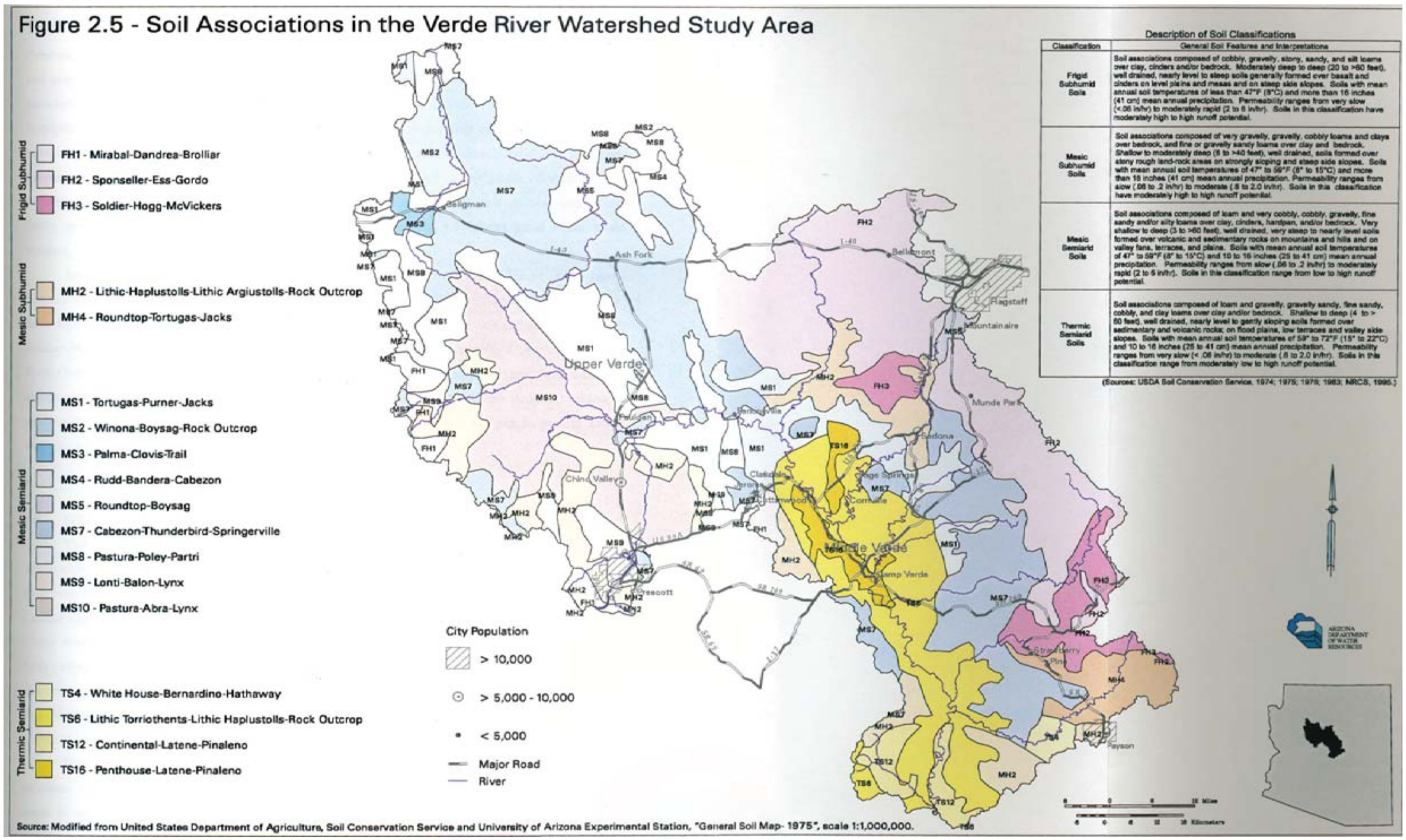

Figure 6 - Soil map of the Verde Valley, central Arizona (from ADWR, 2000; after USDA, 1975).

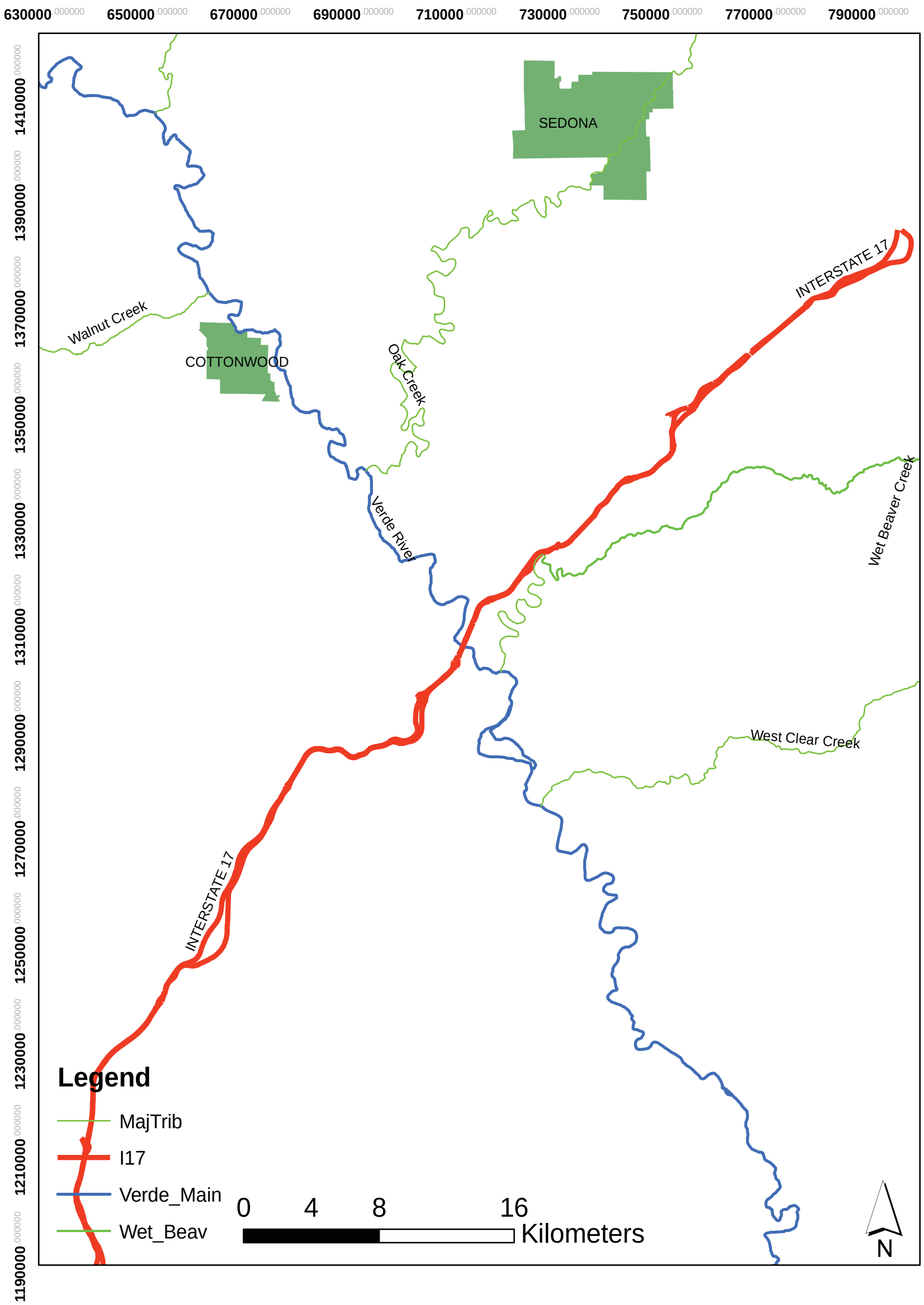

Figure 7 - Map of major tributaries of the Verde River, central Arizona. Interstate 17 and city areas for Cottonwood and Sedona are included for spatial reference.

The upper Verde River is sustained by surface runoff and groundwater discharge from the upper Verde Springs (Big Chino and Little Chino aquifers, Wirt et al., 2005). Spring contributions to the Verde River baseflow are an important port of the system; variable spring contributions are an indicator of climatic effects of changes in precipitation and temperature, although the “lag-time” between precipitation change and spring flow change has been found to be as much as 1 to 2 years (Rice, 2007). This upper reach of the river flows through largely undeveloped canyon terrain from below Paulden to the USGS Sycamore Canyon stream gage.

The middle Verde River is sustained by surface runoff, base flow of the upper Verde River, groundwater discharge from the Verde Formation in the Verde Valley, and significant contributions from spring-fed tributaries in the middle Verde watershed. This alluvial reach flows through the much more densely developed Verde Valley from the USGS Sycamore Canyon stream gage to the USGS stream gage below Camp Verde (Springer and Haney, 2008).

The Verde River fluvial system can be divided into 4 geomorphic components; the low-flow channel, flood channel, low terraces, and bounding landforms (Pearthree, 2008). The low-flow channel is the most persistent of components, as it conveys base level discharge through the larger flood channel. Pool/riffle sequences are common in this feature, with channel bed material generally comprising silt, sand, and fine gravel.

The flood channel is a dynamic feature, and is shaped by the timing and size of the prior flood events. The flood channel is defined as the channel areas directly adjacent to the low-flow channel, within heavily vegetated and higher floodplain/terrace features. Sand dominates the channel bed material in these features, but they may include pebbles, cobbles, silt, and clay in gravel bars and swales. Vegetation type, size, and density vary with temporal spacing between flood events. Width of the flood channel can vary significantly, ranging from 30 to 260 meters (Pearthree, 2008). The size and route of the flood channel can rapidly and significantly change in alluvial sections, while it stays consistent in canyon reaches. Low terraces intermittently bound the flood channel in canyon reaches, and are generally quite long and continuous along the alluvial reaches. Inundation of these terraces is dependent on their elevation relative to the flood channel, and vegetation type and density vary accordingly. Silt/sand packages cover most of these forms, with localized gravel bars; lateral cuts tend to display stacked flood deposits (Pearthree, 2008).

The Verde River is bounded by landforms ranging from bedrock cliffs to alluvial fans. In the Verde Valley, river incision into the moderately resistant Verde Formation provides a measure of topographic control of the river. Alluvial fans formed at the confluences of the Verde River's perennial tributaries are generally fine river sands and smaller gravels, while flood events from the smaller ephemeral tributaries and washes produce alluvial fans of coarser materials. The river may then either divert flow around these deposits, or cut through them and rework them into downstream deposits. As is common in southwestern US river systems, flood events are the predominant control on the morphology of the river channel and adjacent floodplains (Pearthree, 1993). Anthropogenic causes directly affect the morphology of the Verde River; increased impervious area of the rapid urbanization of

Cottonwood and Camp Verde increase runoff contribution to the river channel. This increase in discharge quantity and power leads to increased scouring and sediment transport, resulting in channel widening. These changes are due to a lack of stormwater discharge planning, which can and should be addressed by planners and stakeholders in the Verde River system (Masek-Lopez, 2009).

1.2.2 Settlement

Prehistoric settlement occurred along the Verde River between 3000-4000 BCE (Byrkit, 1978). Hohokam and southern Sinagua cultures established agricultural bases by 700 CE, with rapid population growth around 1100 CE (Beard, 1990). The Tuzigoot Phase peaked between 1300 and 1400 CE, and these settlements were abandoned c. 1425 CE, synchronous with the arrival of the Tonto Apaches and the Yavapai. The first Europeans came to the Verde Valley searching for copper mines in 1583 and 1598, but the Spanish deemed the ore deposits to not be worth developing (Masek-Lopez, 2001).

The first European settlement occurred in the early 1800s, when fur trappers came to procure beaver pelts. Trapping ceased in the 1830s when the market for beaver pelts dropped (Beard, 1990). In 1865, a group of European settlers began farming at the confluence of Clear Creek and the Verde River. This settlement became Camp Lincoln, which became Camp Verde in 1871. By 1875, the Yavapai had been relocated to the San Carlos Reservation. Cattle ranching was introduced to the area in 1875, with tremendous overstocking occurring in the 1880s (Masek-Lopez, 2001). In the aftermath of the cattle boom, settlers turned to farming, leading to irrigation system development and the town of Cottonwood.

The neighboring town of Clarkdale was formed as a company town for United Verde Copper Company (Masek-Lopez, 2001), which subsequently sold to Phelps-Dodge, and most recently, Freeport McMoRan. Mining operations caused environmental degradation, including untreated slag heaps, sulfur dioxide fumes, and over cutting of timber to provide fuel, exacerbating the deforestation caused by overgrazing (Beard, 1990).

The Verde River is currently used for irrigation purposes, both through diverted flow into irrigation ditches, as well as floodplain irrigation. It is a popular recreational resource, and is commonly used for fishing, hunting, kayaking and canoeing, and for other outdoor activities. In addition, it is a desirable location for residential properties.

1.2.3 Demographics

The population of the Verde Valley has rapidly increased in the past 30 years. Between 1980 and 1994, the population of Camp Verde increased by 89%, with some forecasts estimating a 128% increase by 2040 (Arizona Department of Economic Security [ADES], 1991). Recent projections call for growth to 23,120 by 2055; an increase of 70% over 2000 population estimate (US Census Bureau, 2010). Yavapai County experienced a total growth of 48% from 1980 to 1997 (Arizona Department of Commerce [ADOC], 1997). Estimates from 1997 predict that Yavapai County's population will exceed 325,000 by 2050 (ADES, 1997). This projection more recently has been estimated as 432,501 by 2055 (ADES, 2008).

Yavapai County as a whole had an estimated population of 167,517 in 2000, increasing 35% to 227,348 in 2008 (U.S. Census Bureau, 2010). Assuming an average annual growth rate of 3%, the 1997 ADES population projection is extremely conservative, leading to increasing concern over the availability of water resources. The employed population of ages 16 and over estimated for Yavapai County in 2008 is 92,128. The employment of this population is distributed over several sectors, including agriculture and mining, construction and manufacturing, trade, services, finance and real estate, and professionals (Table 1). The most significant sectors are education and health services, construction and manufacturing, and wholesale/retail trade, with relevant shares of 19.89%, 18%, and 16.6%, respectively (ADES, 2008). In Camp Verde, the employment sectors are divided into professional/management, service industry, sales/office positions, agriculture, construction, production and transportation, and government (Table 2), with professional/management, service, and sales/office positions making up the top three employment sector (21.5%, 21.4%, and 28.3%, respectively). These percentages differ significantly from the state averages in the professional/management and service sectors (Table 3) (US Census Bureau, 2008).

1.3 Water shares, use, and conflicts

1.3.1 Water demand and supply

The Central Yavapai Highlands Water Resource Management Study (CYHWRMS, 2010) developed estimates of current and projected water demand and availability for several regions, including Camp Verde. The reported resources included contributions from surface water and production well supplies, and segregated demand by municipal/domestic, commercial/industrial, and agriculture needs (Table 4). Demand for Camp Verde as of 2006 was 11,804 AF/yr, with a

Table 1 - Employment statistics by sector of Yavapai County, AZ workforce (Arizona Department of Economic Security [ADES], 2008)

Subject	Total	Margin of Error (+/-)	Male	Margin of Error (+/-)	Female	Margin of Error (+/-)	Median earnings (dollars)	Margin of Error (+/-)
Civilian employed population 16 years and over	**92,128**	**1,858**	**53.7%**	**1**	**46.3%**	**1**	**26,264**	**766**
Agriculture, forestry, fishing and hunting, and mining:	2,957	728	71.6%	10.1	28.4%	10.1	28,543	8,211
Agriculture, forestry, fishing and hunting	1,504	619	62.6%	18.6	37.4%	18.6	18,539	3,141
Mining, quarrying, and oil and gas extraction	1,453	389	80.9%	7.8	19.1%	7.8	43,222	4,413
Construction	11,207	1,196	89.3%	3.3	10.7%	3.3	30,313	2,523
Manufacturing	5,487	771	68.9%	6.3	31.1%	6.3	31,767	2,161
Wholesale trade	2,177	564	79.5%	9.1	20.5%	9.1	32,083	2,516
Retail trade	13,085	1,198	50.5%	3.9	49.5%	3.9	22,824	2,083
Transportation and warehousing, and utilities:	2,970	552	74.9%	7.8	25.1%	7.8	44,096	6,662
Transportation and warehousing	2,084	429	74.9%	8.2	25.1%	8.2	38,833	6,452
Utilities	886	378	75.1%	16.7	24.9%	16.7	54,413	8,100
Information	1,307	311	61.4%	13.1	38.6%	13.1	28,093	5,888
Finance and insurance, and real estate and rental and leasing:	4,838	660	36.4%	7.1	63.6%	7.1	31,415	1,582
Finance and insurance	1,929	401	25.8%	9.6	74.2%	9.6	33,622	7,087
Real estate and rental and leasing	2,909	559	43.5%	9.9	56.5%	9.9	30,042	9,641
Professional, scientific, and management, and administrative and waste management services:	8,789	1,164	55.4%	6	44.6%	6	27,546	2,030
Professional, scientific, and technical services	4,197	735	53.7%	6.4	46.3%	6.4	31,923	2,757

Table 1, continued.

Management of companies and enterprises	43	49	44.2%	55.8	55.8%	55.8	-	**
Administrative and support and waste management services	4,549	903	57.0%	10.1	43.0%	10.1	23,335	3,268
Educational services, and health care and social assistance:	18,281	1,254	31.1%	3.4	68.9%	3.4	28,229	2,816
Educational services	7,128	1,001	38.7%	6	61.3%	6	23,095	5,421
Health care and social assistance	11,153	1,123	26.2%	4	73.8%	4	30,623	1,602
Arts, entertainment, and recreation, and accommodation and food services:	12,395	1,302	48.2%	5.7	51.8%	5.7	16,487	1,206
Arts, entertainment, and recreation	2,740	535	44.5%	9.5	55.5%	9.5	19,817	4,180
Accommodation and food services	9,655	1,243	49.2%	6.4	50.8%	6.4	16,050	1,201
Other services, except public administration	4,731	773	48.9%	6.9	51.1%	6.9	17,143	3,331
Public administration	3,904	839	42.3%	7.4	57.7%	7.4	40,527	3,423

Table 2 - Employment by sector of Camp Verde, AZ workforce (ADES, 2008).

Geographic area	Management, professional, and related occupations	Service occupations	Sales and office occupations	Farming, fishing and forestry occupations	Construction, extraction, and maintenance occupations	Production, transportation, and material moving occupations	Agriculture, forestry, fishing and hunting	Manufacturing	Percent government workers (local state, or federal)
Camp Verde town, Yavapai County	21.5	21.4	28.3	1.6	15.3	12	1.8	5.1	17.6

Table 3 - Employment by sector of Camp Verde, AZ workforce compared to statewide Arizona workforce (ADES, 2008).

Geographic area	Management, professional, and related occupations	Service occupations	Sales and office occupations	Farming, fishing and forestry occupations	Construction, extraction, and maintenance occupations	Production, transportation, and material moving occupations	Agriculture, forestry, fishing and hunting	Manufacturing	Percent government workers (local state, or federal)
Arizona	32.7	16.2	28.5	0.6	11	10.9	1	10.2	15.2
Camp Verde town, Yavapai County	21.5	21.4	28.3	1.6	15.3	12	1.8	5.1	17.6

Table 4 - Central Yavapai Highlands Water Resources Management Study (CHYWRMS resource demand and availability (CHYWRMS, 2010).

Verde Valley Sub-Basin
Status Quo

Water Planning Area[1]	2006 Population [2]	2050 Population [2]	Pop. Change	2006 Mun/Dom Demand[3]	2006 Com/Ind Demand[3]	2006 AG Demand[3]	Total 2006 Demand	2006[4]	Estimated Available Water Supply[5]	2050[6]	2050 Mun/Dom Demand[6]	2050 Com/Ind Demand[7]	2050 AG Demand[8]	Total 2050 Demand	2050 Water Supply +/-
				(AF/yr)	(AF/yr)	(AF/yr)		GPPD	(AF/yr)	GPPD	(AF/yr)	(AF/yr)	(AF/yr)	(AF/yr)	(AF/yr)
Camp Verde	12,497	23,277	10,780	1,597	887	9,320	11,804	114	11,804	112	2,920	887	6,215	10,022	1,782
Clarkdale	3,999	22,460	18,461	478	3	31	512	107	512	75	1,887	300	31	2,218	-1,706
Cottonwood	20,400	77,630	57,230	3,370	1,782	1,137	6,289	147	6,289	125	10,870	1,782	760	13,412	-7,123
Jerome	510	800	290	282	0	0	282	494	282	255	229	53	0	282	0
Sedona	11,080	16,300	5,220	3,794	40	278	4,112	306	4,112	300	5,478	40	185	5,703	-1,591
Big Park CDP	7,731	8,810	1,079	1,361	1,153	0	2,514	157	2,514	198	1,954	1,153	0	3,107	-593
Cornville CDP	4,075	7,448	3,373	927	32	2,823	3,782	203	3,782	185	1,544	32	1,880	3,456	326
Lake Montezuma CDP	4,237	8,308	4,071	631	752	537	1,920	133	1,920	120	1,117	752	360	2,229	-309
Ctn-Verde Village CDP	3,373	11,706	8,333	118	1	1,124	1,243	31	1,243	125	1,639	1	750	2,390	-1,147
Verde CCD	1,700	4,525	2,825	501	731	1,322	2,554	263	2,554	235	1,191	731	880	2,802	-248
Mingus Mtn CCD (portion)*	510	1,357	847	138	226	487	851	242	851	215	327	226	325	878	-27
Humboldt CCD (portion)**	225	600	375	48	5	759	812	190	812	170	114	5	506	625	187
Total	70,337	183,221	112,884	13,245	5,612	17,818	36,675		**36,675**		29,270	5,962	11,892	**47,124**	**-10,449**
Water Balance Method															
VV Sub-Basin (with net natural recharge)	See Blasch, 2006, pg. 82. Inflow (167,000) - baseflow out (144,100)								22,900					47,124	-24,224
VV Sub-Basin (with 1997 demands)	See ADWR, 2000 pg. 5-23. Sum of Dom., Other/Industrial, Municipal, and AG								26,660					47,124	-20,464

1. See Demand Analysis and Data Sources Documentation for discussion of WPA boundaries. Note: Many municipal boundaries vary from the WPA boundaries.
2. See Population Comparisons for 2006 and 2050 population assumptions.
3. See CYHWRMS - Water Planning Area - Water Use and Available Supply Summary Table for all 2006 Demand Estimates. (Note: Mun/Dom demands include Com/Ind demands delivered by water providers. Column F
4. 2006 Gallons Per Person per Day is calculated by dividing the 2006 Mun/Dom demand by the 2006 population (conversion formula: AF/person * 325,851gal/AF / 365day/year = gal/person/day (GPPD)).
5. This data represents the "Status Quo method" - See CYHWMRS – Water Planning Area – Water Use and Available Supply Summary Table for supporting data per Water Planning Area.
6. 2050 GPPD was provided for each Water Planning Area. The value is multiplied by the 2050 population to calculate 2050 Municipal/Domestic Demand (conversion formula: person * gal/person/day / 325,851gal/AF *
7. 2050 Commercial/Industrial Demands are held in Status Quo for 2050 for WPAs outside of the PrAMA (except Clarkdale and Jerome who provided their own estimate and 240 AF was added to the Verde CCD for new
8. Outside the PrAMA 2050 Agricultural Groundwater Demand is assumed to be a percentage (67% - Verde Valley Sub-Basin, 50% - Big Chino Sub-Basin) of the 2006 Agricultural Demand (except Clarkdale and Jerome

projected decrease to 10,022 AF/yr by 2050. This decrease in demand is based on a decrease in agricultural demand, presumably projecting current trends of conversion of agricultural land to residential/non-cropped land. Projected demand for residential areas increases, but the magnitude of increase is less than that of the decreased demand of agricultural areas. Current available resources are determined by status quo and assured and adequate methods, with available surface water supply increased in assured and adequate measurement (1923.86 AF/yr vs. 952 AF/yr). These totals use an averaged amount of 0.33 AF/yr for exempt wells, and 0.50 AF/yr for non-exempt wells. Exempt wells are generally for residential use, and produce less than 35 gpm, while non-exempt wells generally produce more than 35 gpm (ADWR, 2000). Commercial/industrial use was considered the same for the projected values as the status quo, and agricultural use was assumed 60% of the current value (CYHWRMS, 2010). It is unclear whether the contributions of the irrigation ditch systems were considered.

1.3.2 Ditch systems overview

Irrigation ditches have been a part of the Verde River system since pre-European settlement, although the majority of the ditches were constructed in the 1800s and early 1900s. The ditches are generally open earth-lined channels fed by large diversion structures comprising river sediment and riprap bulldozed to form an embankment downstream of the diversions. Presently, these diversions do not provide for diverted flow metering; they have the primary function of diverting enough flow from the river to feed the ditch. All four of the ditch diversions in the study area have a large over-flow spillway just above the headgates, where extra diverted flow (often in excess of 50% of the diverted flow) is returned to the main stem of the river (Fig. 8).

The ditch substrate is generally clay-rich soil, and no significant seepage has been detected over the ditch lengths, other than when the channel base has been disturbed during maintenance operations (Alam, 1997). The headgates of each ditch are opened to varying heights to allow flow into the ditch. Lateral structures are used to deliver water to users, and can be concrete-lined culverts, open earthen channels, or sub-grade pipes. Most ditches use some combination of the three conveyance channel types.

Spillways may occur along the operational length of the ditch, with increased likelihood of these structures with increasing length. The Verde Ditch has upwards of six spillways (A. DePuoy, pers. comm., 2009). These spillways are generally active only during seasonal high-flow conditions, to prevent structural breaches within the ditches or lateral conveyance systems. Each ditch has a primary return flow to the Verde River (Beaver Creek in the case of the Eureka Ditch) after the terminal water user.

These ditches are largely unregulated, due to their long tenure and operation within the Verde Valley. They are operated under a “grandfathered” exclusion of Section 404 of the Federal Clean Water Act; installation of any permanent structure would require a 404 permit, as well as several other state and federal permits. The process would take at least three years, and the ditch companies would incur significant expenses from the process (Alam, 1997). The permitting produces a

Figure 8 - Verde Ditch head gate and spillway. Initial spillway is on right side of picture, while the head gate is on the lower left side. Note the large percentage of flow that the spillway is returning to the river. Blue arrows indicate flow direction.

significant challenge to the ditch companies, especially as they currently operate without undergoing any new permitting.

Potential future conflicts may arise between the ditch companies, agencies concerned with ecological impacts of ditches on the main stem river flows and riparian habitats, and agencies concerned with maximizing downstream water resources to southern Arizona municipalities. The irrigation ditches are primarily concerned with delivering the needed water to their stakeholders; most would likely be open to permanent structures and metered delivery if the required time and expense could be minimized. The following sections deal with the irrigation ditches around Camp Verde; they were chosen to provide the longest possible continuous river reach for modeling purposes.

Eureka Ditch

The Eureka Ditch was built in 1893, and irrigates about 421 acres and supplies 180 water users over its eight-mile length. It diverts at 703014.85 E 1321698.12 N (Fig. 9) on the northeast side of the Verde River, and returns flow to Beaver Creek near Camp Verde 718581.86 E 1304733.14 N (Fig. 10). The diversion is about 50 feet in length, and is less than three feet high. The Eureka ditch management reports an average flow of 15 ft^3/s at the diversion. John McReynolds is the ditch boss (2006 - present), and the ditch is operated by an association (Alam, 1997). The ditch is generally closed from late November until early March for maintenance, including repair and reinforcement of structure, and removal of vegetation within the ditch channel. A large wash (Grandpa Wash) above the

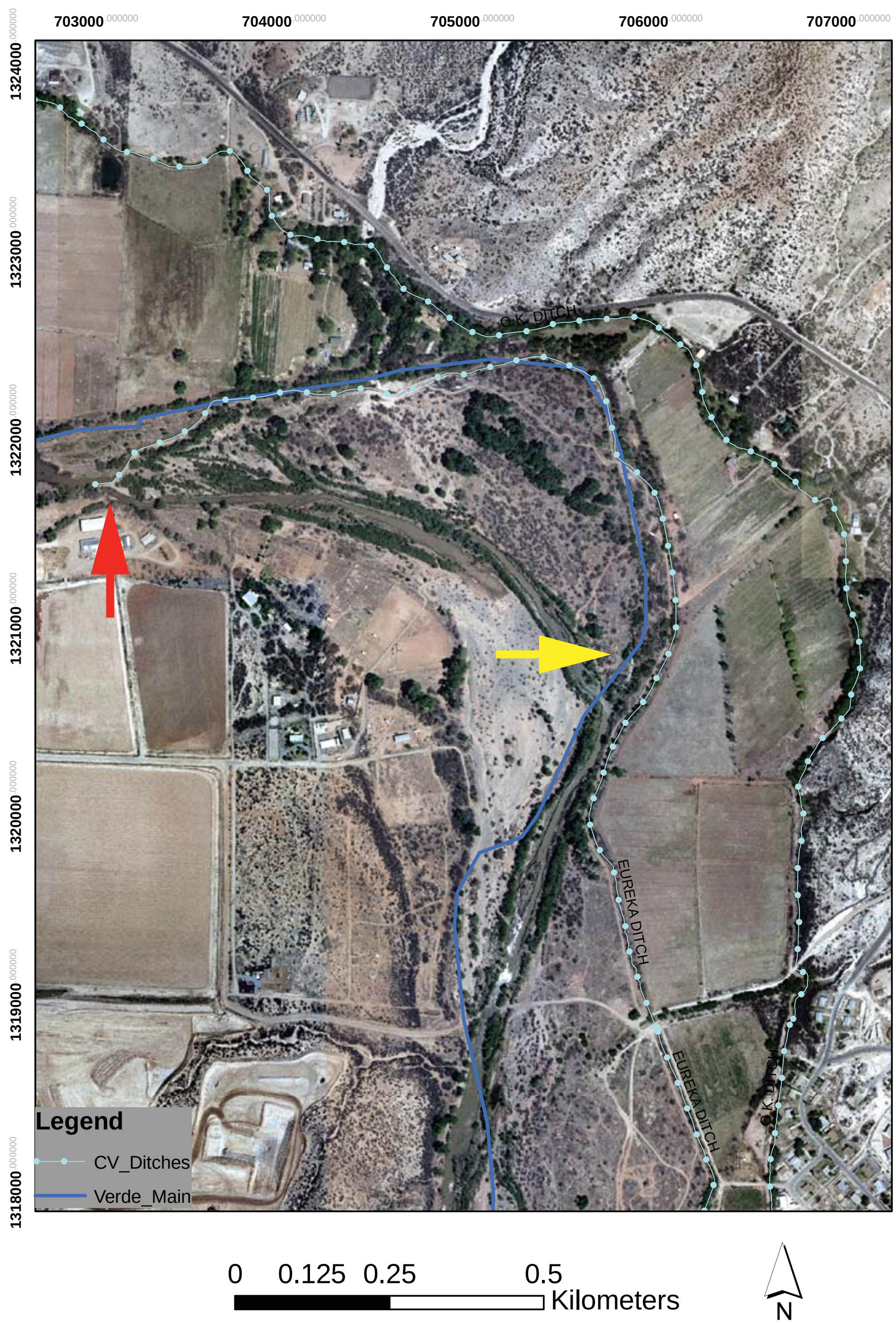

Figure 9 - Location map of Eureka Ditch diversion and head gates, Camp Verde, central Arizona. The first major spillway in on the ditch before the head gates control flow diverted into the ditch proper. Red arrow is diversion, and yellow arrow is location of head gates.

Figure 10 - Location map of Eureka Ditch return flow to Beaver Creek, Camp Verde, central Arizona. Red arrow is return location.

headgates sometimes deposits sediment to form a natural dam, which needs to be mechanically cleared to maintain flow (J. McReynolds, pers. comm., 2008).

OK Ditch

The OK Ditch was constructed in 1873, and serves 107 users (including the Camp Verde Indian Reservation) and 620 acres over its six-mile length (Alam, 1997). It diverts on the northeast side of the Verde River at 693675.92 E 1334149.55 N (Fig. 11), and returns flow to the Verde alongside Grandpa Wash 704427.8 E 1322975.68 N (Fig. 12). It diverts flow about one mile south of the Oak Creek/Verde river confluence, and has a reported average diverted flow of 30 ft^3/s. Bob Kovacovich is the ditch boss (2000-present), and the OK Ditch is operated by an association. The OK is closed for a short annual maintenance period, but flow is maintained for most of the year, depending on the needs of water users (B. Kovacovich, pers. comm., 2010). The diversion structure of the OK Ditch uses larger rocks from external sources as well as river sediment and riprap to maintain a three-foot-high structure that is highly flood-resistant due to its resilient foundation (Alam, 1997).

Diamond S Ditch

The Diamond S Ditch is operated by an association, which is managed by a board of directors. Frank Geminden is the contact for the ditch company (2003-present). The Diamond S Ditch was constructed in 1895, making it one of the newer Camp Verde area ditches. It is five miles long, and serves 82 users and irrigates 385 acres (Alam, 1997). It diverts from the east side of the Verde River 720603.55 E 1293638.14 N (Fig. 13), using a series of sluice gates to divert flow efficiently, with

Figure 11 - Location map of OK Ditch diversion and head gates, Camp Verde, central Arizona. First major spillway of ditch is above headgate control structure. Red arrow is diversion location, and yellow arrow is head gate location.

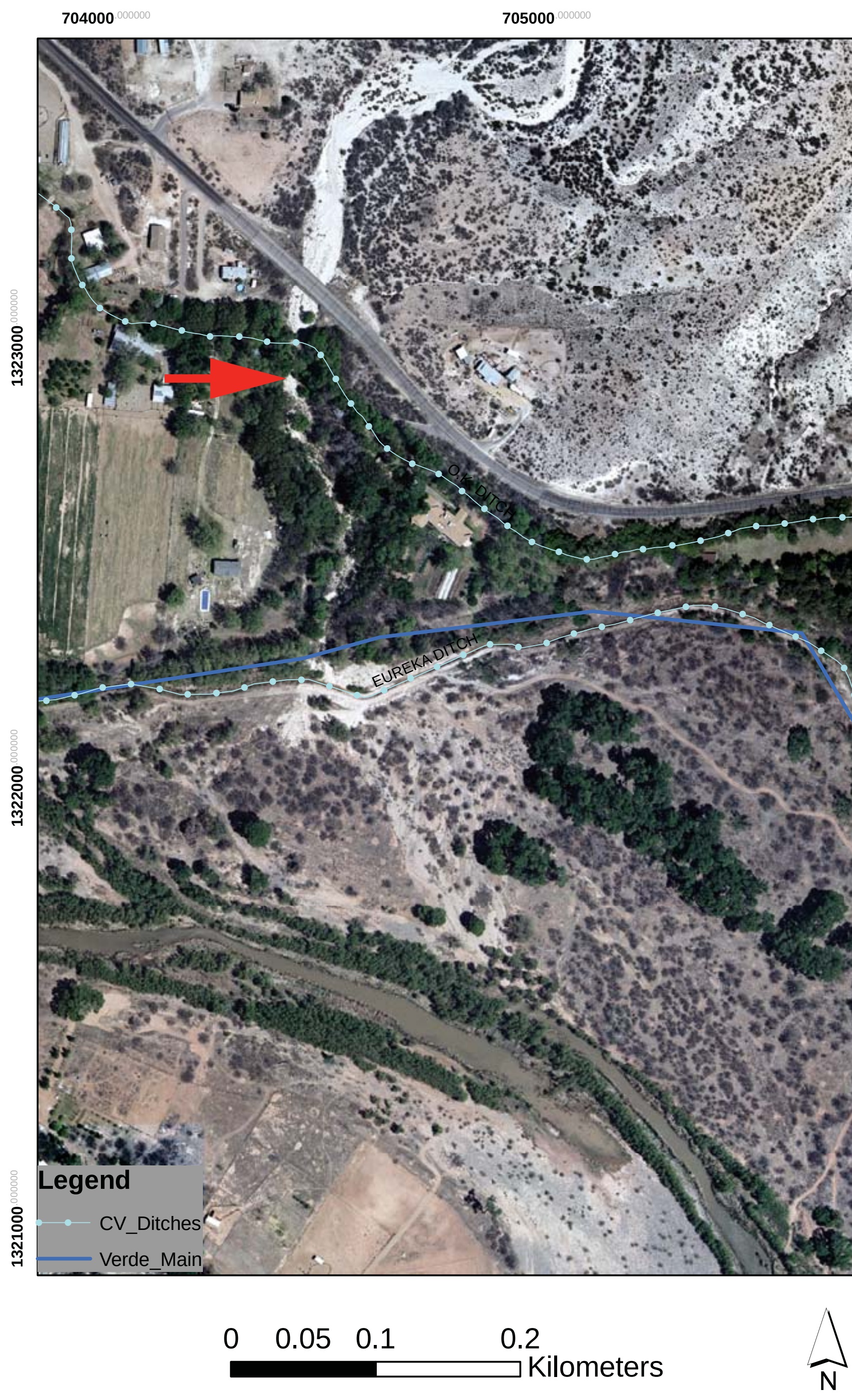

Figure 12 - Location map of OK Ditch return flow to Verde River, Camp Verde, central Arizona. Terminal spillway contributes discharge to Eureka Ditch system above first water user. Red Arrow is top of terminal spillway.

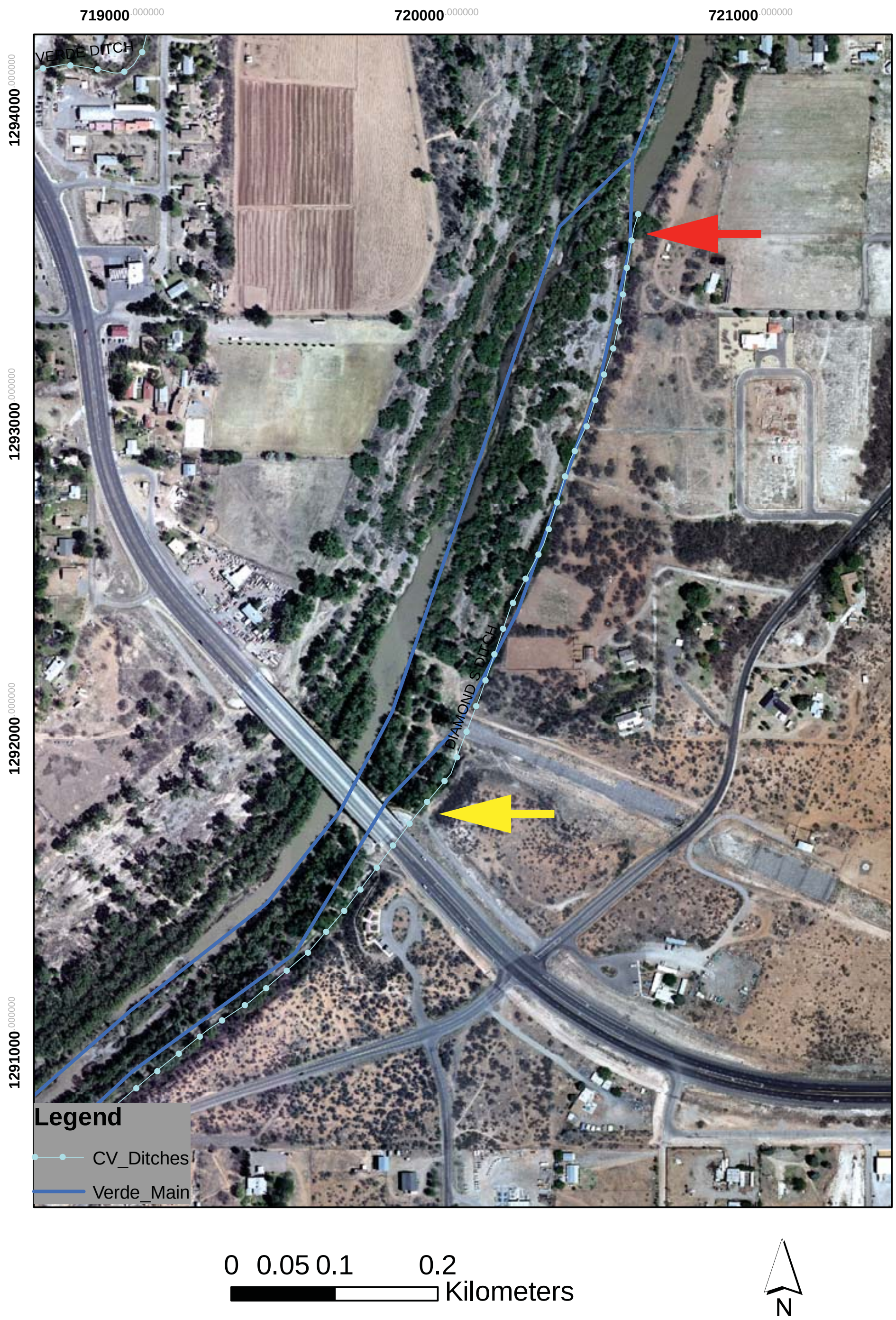

Figure 13 - Location of Diamond S Ditch diversion and head gates, Camp Verde, central Arizona. Red arrow is diversion structure, and yellow arrow is head gate structure. Initial spillway is directly above the head gates.

an average diversion of 21 ft^3/s. The diversion structure is roughly 300 feet long and nearly four feet high; it is generally stable due to a large rock/concrete foundation. The return flow for the ditch is located near a large stock pond southeast of Camp Verde 724752.04 E 1281847.68 N, where it returns to the Verde River (Fig. 14).

Verde Ditch

The Verde Ditch is the largest of the four Camp Verde area ditches, serving 1337 acres and 600 users over its 17-mile length (Alam, 1997). It is court-managed due to historical litigation involving users along its top portion (“new” or “upper Verde Ditch”) and the lower portion (“lower old Verde Ditch”). The ditch commissioner of the Verde Ditch is charged with distributing the water appropriately; this responsibility is shared among the board of commissioners. Al DePuoy is the current contact for the ditch (2009 – present). The Verde diversion is about 200 feet long and four feet high, and diverts from the west side of the Verde River 708185.4 E 1312924.84 E (Fig. 15). The Verde Ditch has a spillway at the head gate structure that returns large amounts of discharge to the river; the main stem of the Verde River drops temporarily to ten feet in width downstream of the diversion (Fig. 16). The Verde Ditch returns flow to the Verde River a considerable distance downstream from Camp Verde 730978.827 E 1265973.425 N (Fig. 17). The Verde Ditch has some unique management challenges compared to the other three ditches in the study area, mostly due to its length and the increase in urbanization around much of the ditch. Urban runoff can contribute large amounts of water during wet seasons, providing the need for multiple spillways (Alam, 1997).

Figure 14 - Location map of Diamond S Ditch return flow to Verde River, Camp Verde, central Arizona. Red arrow is return flow.

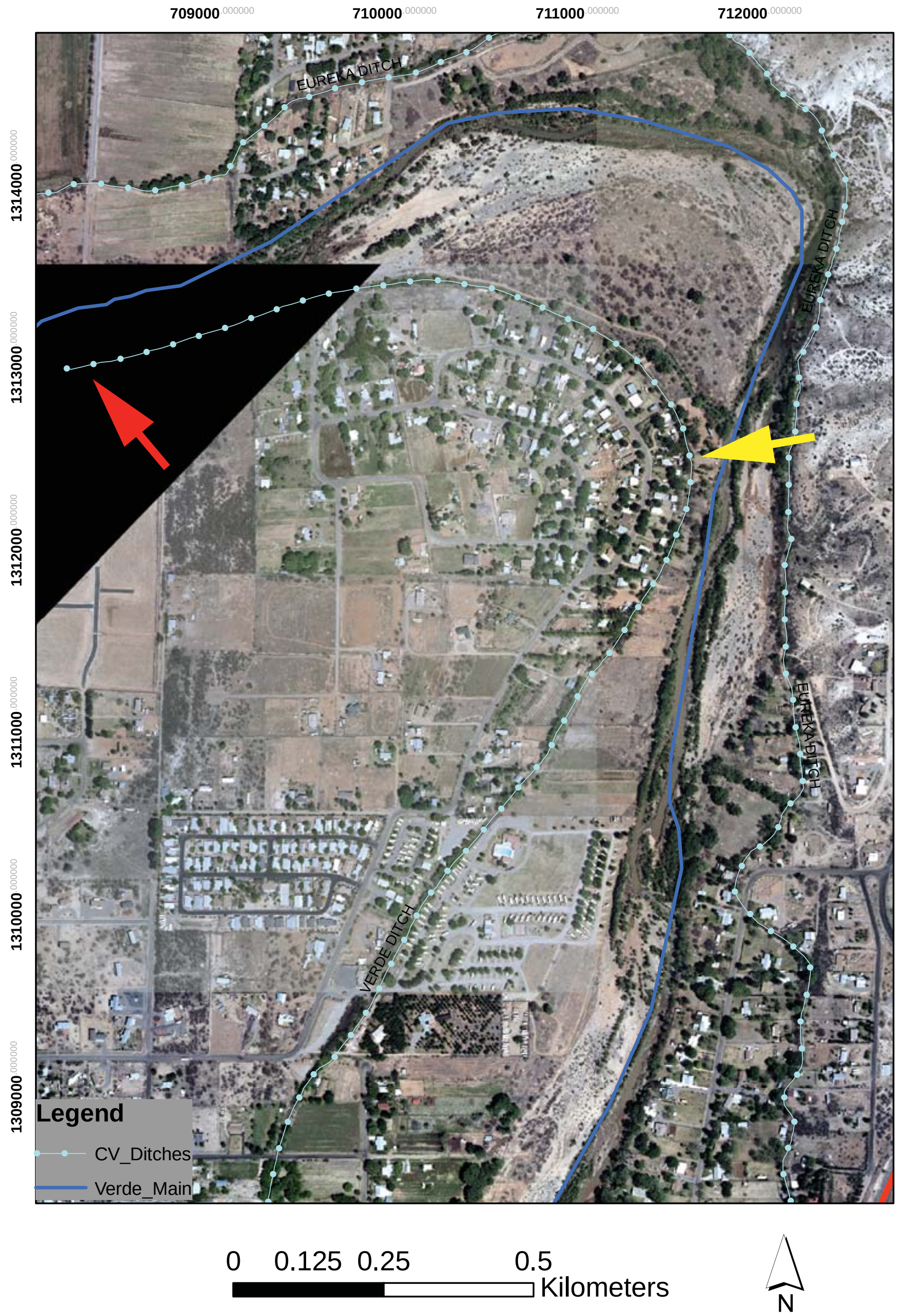

Figure 15 - Location map of the Verde Ditch diversion and head gates, Camp Verde, central Arizona. Red arrow is diversion structure, and yellow arrow is headgate. Large initial spillway is directly above head gate structure. Black triangle is gap in aerial photo coverage.

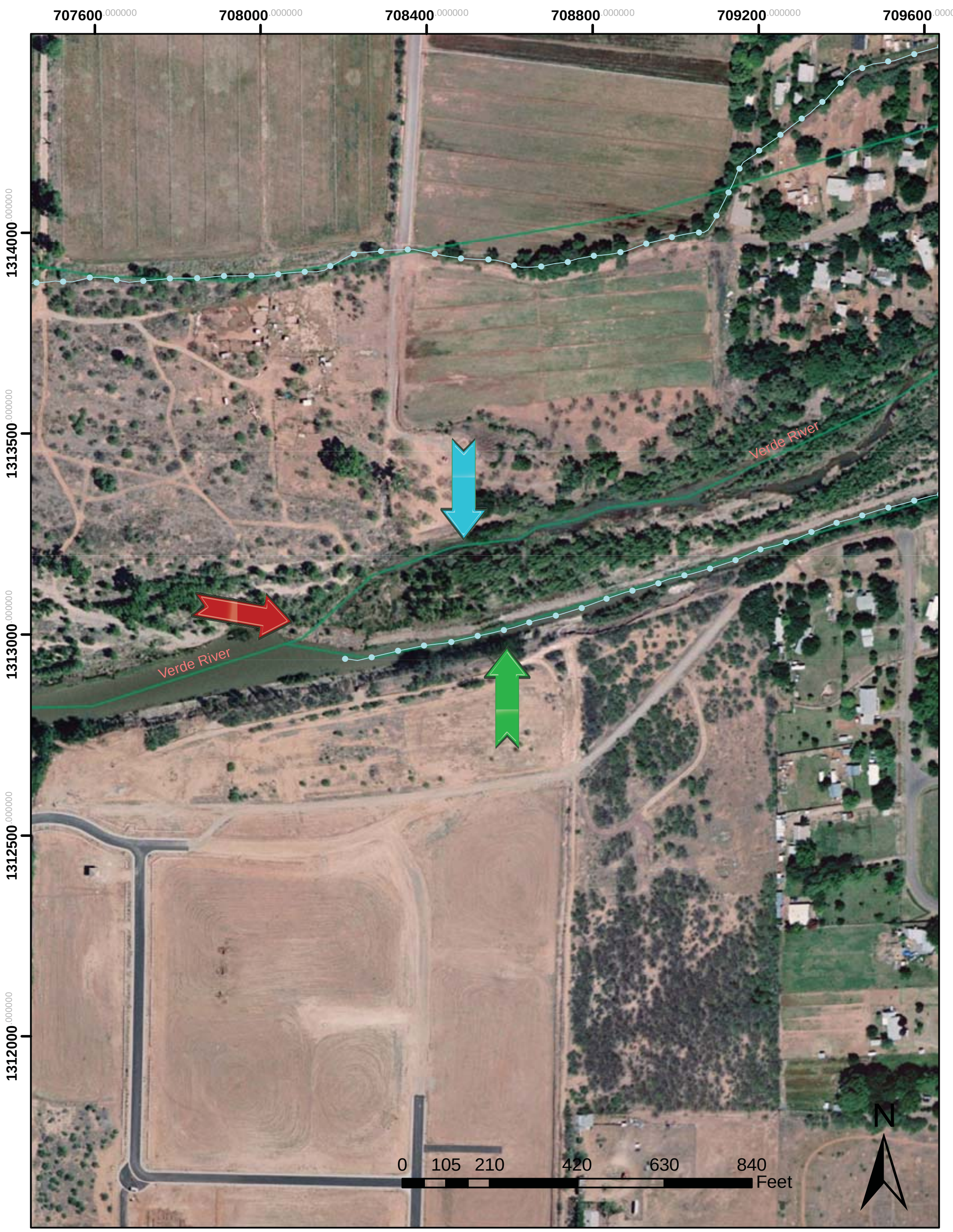

Figure 16 - Decrease in channel size and natural flow downstream of Verde Ditch diversion, Camp Verde, central Arizona. Red arrow shows diversion structure, green arrow is Verde Ditch, and blue arrow is Verde River after diversion. Note channel width of the Verde River decreases from near 30 meters to 3 meters after diversion. A series of spillways from the ditch return a large percentage of the diverted flow to the river over the next kilometer.

Figure 17 - Location map of Verde Ditch main return flow to Verde River, Camp Verde, central Arizona. Red arrow is main return flow.

Chapter 2 - Objectives and Methodology

2.1 Objectives

The purpose of this study is to organize and integrate previous and on-going studies to better describe the complex interactions of the various components of the Verde River system, as well as to provide previously non-existent data pertaining to the effects of irrigation ditch diversion from the Verde River. The following objectives will provide a description of the impacts of irrigation diversion on the river system:

- Map the features that pertain to the interaction of the river system and anthropogenic irrigation structures and compile into GIS
- Study the effects of diversion and recharge on the river system mechanics by instrumenting irrigation ditch stage at diversion and recharge points, and calculating discharge
- Quantify the effects of these interactions
- Create a database for future system analysis

2.2 Methods

The following is a comprehensive summary of the methods employed to achieve the above objectives:

2.2.1 Geographic Information System

A Geographic Information System (GIS) was used to graphically display all relevant data in a digital map format. GIS is a digital mapping system (e.g., ESRI ArcGIS, ENVI, ERDAS, etc.) that contains several types of data, including vector data, represented as points, polylines, and polygons, as well as raster data representing photographs, maps, and possibly elevation data (Fig. 18). These datasets contain embedded geographic, quantitative, and qualitative data, or attributes. Examples are length/area measurements, the names of property owners, and soil type/land use data (Fig. 19). These data were organized into a series of coverages and shapefiles, otherwise known as layers, using ESRI ArcGIS software (ESRI, Redlands, CA). A GIS relies on a projection system (UTM, StatePlane coordinates, etc.) to locate 3-D spatial features to a flat or 2D mapping surface (Fig. 20).

Data are organized into a "parent" system known as the geodatabase. Geodatabases can be in several formats, including personal or file geodatabases. The type of geodatabase used depends on the size and type of storage needed, as well as the planned network interfaces for the system. A file geodatabase is designed for very large datasets accessible to multiple users/editors over a network, while a personal geodatabase is generally used for databases managed and edited by one individual at a time. The geodatabase contains multiple coverages or shapefiles, and it utilizes a default projection for all data to support accurate 2-D presentation.

Several GIS datasets independently exist for the Verde Valley; the initial GIS work involved finding and examining all existing files. The Arizona Department of Water Resources (ADWR), Salt River Project (SRP), The Nature Conservancy (TNC), and Yavapai County were all sources of coverages representing irrigation ditches, ditch laterals, irrigated acreage, land ownership parcels, incorporated areas, groundwater monitoring wells, registered production wells, and the Verde River and its tributaries, among others (Table 5). Yavapai County Flood Control District and

Figure 18 - Sample GIS of the Verde Valley river and irrigation system, displaying vector and raster data. Aerial orthophoto base is raster data, while other displayed features are vector data.

Attributes of ditches

OBJECTID_1 *	Shape *	OBJECTID	DITCHNAME	WATER_SOUR	EST_ACRE	EST_USE	GEO_SOURCE	Shape_Leng	DITCHNAME2	CFS_HE	Shape_Le_1	Shape_Length
1	Polyline	25	DICKERSON DITCH	OAK CREEK	56	4	PROBABLY-SEC-VERDE.O	9827.428953		4	9826.255	9870.533935
2	Polyline	26	RED ROCK DITCH	OAK CREEK	50	42	PROBABLY-SEC-VERDE.O	6759.47632	SCHUERMAN DITCH	6.3	6761.031234	6288.937754
3	Polyline	27	POINT WILLOW DITCH	OAK CREEK	21	10	PROBABLY-SEC-VERDE.O	9714.15021		5.5	9716.293468	8715.026611
4	Polyline	28	LANGDON DITCH	BEAVER CREEK	9	0	PROBABLY-SEC-VERDE.O	7446.535807		0	7448.317936	7448.317936
6	Polyline	30	DUMAS DITCH	OAK CREEK	12	2	PROBABLY-SEC-VERDE.O	6516.563594	BALDWIN DITCH	2	6518.114489	6322.707377
7	Polyline	31	WINGFIELD #4	WEST CLEAR CREEK	149	1	PROBABLY-SEC-VERDE.O	10619.102741	SHILL DITCH	5	10621.621148	10737.269129
8	Polyline	32	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	13670.510381	WOODS DITCH	50	13670.822146	13631.512687
9	Polyline	33	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	2864.731662	WOODS DITCH	50	2865.400963	2950.826332
10	Polyline	34	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	10836.147932	WOODS DITCH	50	10838.690404	10900.373462
11	Polyline	35	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	8807.84476	WOODS DITCH	50	8809.861067	8920.065767
12	Polyline	36	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	3470.704244	WOODS DITCH	50	3471.487495	3524.126155
13	Polyline	37	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	6232.809747	WOODS DITCH	50	6234.224372	6477.605239
14	Polyline	38	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	2677.037169	WOODS DITCH	50	2677.655295	2368.235512
15	Polyline	39	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	7539.422009	WOODS DITCH	50	7541.208589	7503.887082
16	Polyline	40	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	10107.745574	WOODS DITCH	50	10110.151671	10305.912159
17	Polyline	41	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	1213.150545	WOODS DITCH	50	1213.442297	1235.852374
18	Polyline	42	VERDE DITCH	VERDE RIVER	1337	600	USGS-TOPO-DIG	10146.152484	WOODS DITCH	50	10148.585709	11033.44768
20	Polyline	44	COTTONWOOD DITCH	VERDE RIVER	672	200	USGS-TOPO-DIG	6075.690701		60	6076.934261	5976.52322
21	Polyline	45	COTTONWOOD DITCH	VERDE RIVER	672	200	USGS-TOPO-DIG	8975.755381		60	8977.570574	9343.09347
22	Polyline	46	COTTONWOOD DITCH	VERDE RIVER	672	200	USGS-TOPO-DIG	15611.625992		60	15646.334778	15815.716243
23	Polyline	47	COTTONWOOD DITCH	VERDE RIVER	672	200	USGS-TOPO-DIG	7915.825361		60	7917.424918	7387.35183
24	Polyline	48	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	3301.625423		15	3302.360449	6719.364264
25	Polyline	49	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	11878.646803		15	11881.302367	12538.597938
26	Polyline	1	DIAMOND S DITCH	VERDE RIVER	385	82	PROBABLY-SEC-VERDE.O	6443.503954	EAMON DITCH	21	6444.952049	6425.582921
27	Polyline	2	HART DITCH	OAK CREEK	18	0	PROBABLY-SEC-VERDE.O	4578.0208		0	4579.059323	5516.331323
28	Polyline	3	KINSEY DITCH	OAK CREEK	23	2	PROB.-SEC/MOD. ADWR	3490.523634	HIDDEN VALLEY DITCH	0	3491.291506	3645.462734
29	Polyline	4	PAGE #1 DITCH	OAK CREEK	6	0	SEC-VERDE	3745.605749		0	3746.469858	3475.547697
30	Polyline	5	JACK'S DITCH	OAK CREEK	74	3	PROBABLY-SEC-VERDE.O	6987.329948		4	6988.817929	7512.469521
31	Polyline	6	JACK'S DITCH	OAK CREEK	74	3	PROBABLY-SEC-VERDE.O	92.502231		4	92.521576	202.505886
32	Polyline	7	JOSEPHINE TUNNEL DITCH	MINE	10	0	PROBABLY-SEC-VERDE.O	4460.540339		0	4461.415081	4461.415081
34	Polyline	9	DUMAS DITCH	OAK CREEK	12	2	PROBABLY-SEC-VERDE.O	96.368948	BALDWIN DITCH	2	96.392108	1173.524988
36	Polyline	11	BACK DITCH	BEAVER CREEK	31	3	USGS-TOPO-DIG	8138.871248	MONTEZUMA WELL DITCH	3	8140.873301	8140.873301
37	Polyline	12	O.K. DITCH	VERDE RIVER	620	134	USGS-TOPO-DIG	5255.860354	MIDDLE VERDE CANAL	30	5257.040465	5165.768722
38	Polyline	13	FINNEY DITCH	BEAVER CREEK	0	0	PROBABLY-SEC-VERDE.O	1578.071049		0	1578.461966	1578.461966
39	Polyline	14	LANDER SPRING DITCH	SPRING	29	0	PROBABLY-SEC-VERDE.O	2394.699798	MAXWELL DITCH	0	2395.305225	2395.305225
40	Polyline	15	WINGFIELD #1 DITCH	WEST CLEAR CREEK	45	0	PROBABLY-SEC-VERDE.O	5293.629262		0	5295.002904	5295.002904
41	Polyline	16	OWENBY DITCH	OAK CREEK	100	40	PROBABLY-SEC-VERDE.O	3627.757304		1	3628.633013	5320.443638
42	Polyline	17	STAUDE-HART DITCH	OAK CREEK	15	0	PROBABLY-SEC-VERDE.O	2397.073732		0	2397.658598	3454.182637
43	Polyline	18	DIAMOND S DITCH	VERDE RIVER	385	82	PROBABLY-SEC-VERDE.O	12990.894686	EAMON DITCH	21	12995.297136	13085.435004
44	Polyline	19	PIONEER DITCH	West Clear Creek	360	30	PROBABLY-SEC-VERDE.O	9424.827093	MELVIN DITCH	10	9427.108718	9932.986058
45	Polyline	20	DUFF DITCH	VERDE RIVER	13	0	PROBABLY-SEC-VERDE.O	7154.301783		0	8634.647894	8634.647894
46	Polyline	21	E.L. JORDAN DITCH	VERDE RIVER	30	0	PROBABLY-SEC-VERDE.O	9721.781638	PERKINS DITCH	0	9417.522409	9417.522409
47	Polyline	22	SULLIVAN DITCH	VERDE RIVER	35	0	PROBABLY-SEC-VERDE.O	3187.553198		0	3638.635677	3639.443052
48	Polyline	23	ARMIJO DITCH	OAK CREEK	31	1	PROBABLY-SEC-VERDE.O	11473.650329		0	11476.302825	11452.283005
49	Polyline	24	DOWNING DITCH	OAK CREEK	37	0	PROBABLY-SEC-VERDE.O	6506.720513		0	6508.178544	7926.743715
50	Polyline	50	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	601.16269		15	601.298505	604.191898
51	Polyline	51	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	5910.911883		15	5912.24808	6052.342252
52	Polyline	52	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	5944.926895		15	5946.312669	6031.100392
53	Polyline	53	EUREKA DITCH	VERDE RIVER	421	180	USGS-TOPO-DIG	4889.966891		15	4891.074614	5068.451202
54	Polyline	54	OAK CREEK DITCH	OAK CREEK	300	70	USGS-TOPO-DIG	6472.204305	MASON LANE DITCH	20	6473.643402	6424.674772
55	Polyline	55	OAK CREEK DITCH	OAK CREEK	300	70	USGS-TOPO-DIG	8854.654743	MASON LANE DITCH	20	8856.600256	8878.128318
56	Polyline	56	OAK CREEK DITCH	OAK CREEK	300	70	USGS-TOPO-DIG	9785.546756	MASON LANE DITCH	20	9787.674248	12424.175555
58	Polyline	58	O.K. DITCH	VERDE RIVER	620	107	USGS-TOPO-DIG	14399.656257	MIDDLE VERDE CANAL	30	14402.788861	14415.862748
59	Polyline	59	O.K. DITCH	VERDE RIVER	620	107	USGS-TOPO-DIG	3056.42165	MIDDLE VERDE CANAL	30	3057.083576	3014.595347
60	Polyline	60	O.K. DITCH	VERDE RIVER	620	107	USGS-TOPO-DIG	8310.698564	MIDDLE VERDE CANAL	30	8312.553168	8471.613151
61	Polyline	61	CORNVILLE DITCH	OAK CREEK	168	55	USGS-TOPO-DIG	13281.033628		9	13283.902102	13718.258854
62	Polyline	62	CORNVILLE DITCH	OAK CREEK	168	55	USGS-TOPO-DIG	5978.337405		9	5979.629837	5900.415838
63	Polyline	63	PAGE SPRINGS DITCH	OAK CREEK	90	12	USGS-TOPO-DIG	7335.925166	PAGE #2 DITCH	4	7337.528609	8422.608018

Record: 1 Show: All Selected Records (0 out of 74 Selected) Options

Figure 19 - Example of attribute data embedded within GIS files.

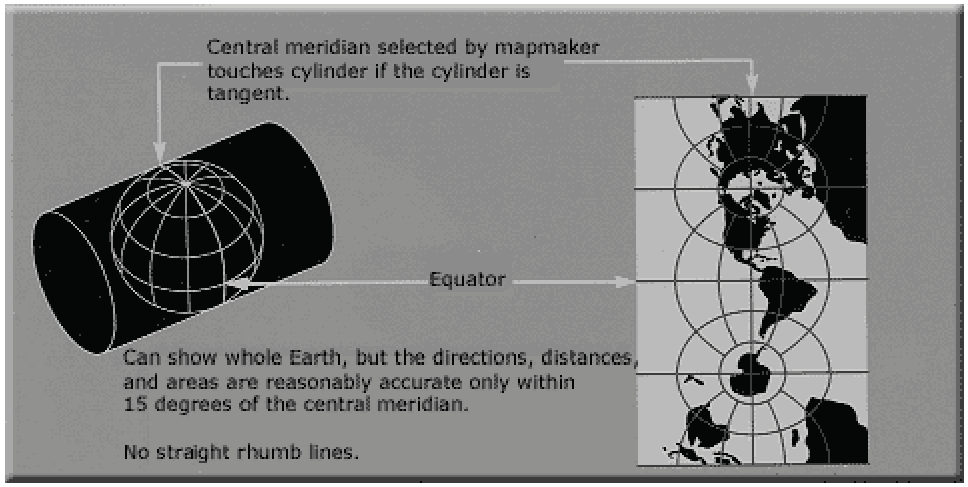

Figure 20 - Schematic of projection system used to correct 2-D map surface to earth surface curvature. Note that corrections are dependent upon distance from equator, leading to differentprojection systems for local/regional areas (from http://en.wikipedia.org/wiki/File:USGS_map_traverse_mercator.PNG).

Table 5 - GIS datasets for the middle Verde Valley, organized by type and source. Sources include Yavapai County GIS, Arizona Department of Water Resources (ADWR), Salt River Project (SRP), Then Nature Conservency (TNC), the Geospatial Research and Information Laboratory (GRAIL) at Northern Arizona University, and thesis research from this study and Masek-Lopez, 2001.

GIS Datasets for middle Verde Valley (Applicable to study)			
Feature Dataset	Feature Classes	Description	Source
County Data			
	00buildings	Building footprints	Yavapai County GIS
	04buildings	Building footprints	Yavapai County GIS
	parcels	Land parcels and ownership	Yavapai County GIS
Geology			
	Basin_Labels	Drainage basin labels	ADWR
	Basin_Outline	Drainage basin borders	ADWR
	Basin_polygon	Drainage basin coverage	ADWR
	faults	Faults	ADWR
	springs	Springs	ADWR
	verde_stream	Main channel of Verde River	GRAIL
Irrigation			
	ditches	Irrigation ditches	ADWR/SRP/TNC
	diversion_pt	Location of diversions	This study
	Diversions	Diversion polyline	This study
	GWSI_wells	groundwater surface inventory wells	ADWR/SRP/TNC
	irrigation	Irrigated acreage	ADWR/SRP/TNC
	laterals	partial coverage of irrigation laterals	ADWR/SRP/TNC
	outflow	Location of return flows	This study
	spillway	Partial coverage of major spillways	This study
	wells55	Registered wells	ADWR/SRP/TNC
Reference			
	az_city_pnt	Location of AZ cities	GRAIL
	city_poly	Coverages of spatial extent of AZ cities	GRAIL
	roads	Location of roadways	GRAIL
Vegetation			
	1940_mesq	vegetation coverages	Masek-Lopez, 2001
	1940_rip	vegetation coverages	Masek-Lopez, 2001
	1968_mesq	vegetation coverages	Masek-Lopez, 2001
	1968_rip	vegetation coverages	Masek-Lopez, 2001
	1995_mesq	vegetation coverages	Masek-Lopez, 2001
	1995_rip	vegetation coverages	Masek-Lopez, 2001
	Riparian_veg	vegetation coverages	Masek-Lopez, 2001
	mesquite	vegetation coverages	Masek-Lopez, 2001

PhotoMapper USA were sources of orthorectified aerial photographs (georeferenced to NAD 83 StatePlane, Arizona Central FIPS 202, international feet) with 2.5 foot and 1 meter resolution (pixel size). Individual coverages of the main stem of the Verde River and its tributaries, as well as I-17 were isolated and exported from waterway and road coverages from ADWR and the Geospatial Research and Information Laboratory (GRAIL) at NAU, respectively. The GIS with compiled data was loaded onto a ruggedized field tablet with ESRI ArcGIS and field checked for general accuracy (as time and resources allowed).

The compiled data were exported from ArcInfo to a personal geodatabase, with projection set to Arizona Stateplane Central Zone, NAD 83, international feet. All data were organized into primary data layers (operational data such as river and irrigation coverages), and secondary data (spatial/informational reference data such as land ownership, highways and roads, etc.). A common scale and tolerance of 1:750 is appropriate to the resolution of data relative to the size of the study area, as well as the available detail of the orthophotos. The data were grouped and simplified to fit the scale and scope of the model, with much of the simplification related to the polygons representing irrigated acreage (Fig. 21). The data were edited by overlaying the one-meter resolution orthophotos, with spatial data being matched to visible features on the photos (georeferenced to NAD 83 Stateplane) (Fig. 22).

Analysis of the edited layers yielded current and accurate irrigation ditch and delivery lateral lengths (Table 6), as well as better estimates of irrigated acreage served by each ditch. A local water table surface was created by contouring point data representing the groundwater levels in wells (Fig. 23). Coverages of riparian

A

B

Figure 21 - Example of irrigation data simplification from delivered state to data modified to meet model specifications. 21A is unedited data, while 21B is data edited overlaid to aerial orthophotos at 1:750 scale.

Figure 22 - Example of resolution of data overlain with aerial orthophotos. Note that data resolution of channel polyline is very high, due to quality of aerial photos and the relative size of the represenative shapefile, edited to 1:750 scale.

Table 6 - Corrected geospatial measurements of irrigation ditches.

Feature	Original Milage (Alam)	Updated Milage	Percent change
Verde Ditch	17	14.93	-0.14
Diamond S Ditch	4.9	3.695	-0.33
Eureka Ditch	7.6	7.01	-0.08
O.K. Ditch	5.5	5.882	0.06
Feature	**Alam diverted Q ft^3/s (ave)**	**Tinlin diverted Q ft^3/s (max)**	
Verde Ditch	50	58	
Diamond S Ditch	21	26	
Eureka Ditch	15	18	
O.K. Ditch	30	32	
Feature	**Measured Q ft^3/s (ave)**	**Measured Q ft^3/s (max)**	
Verde Ditch	26.35	88.32	
Diamond S Ditch	26.25	28.36	
Eureka Ditch	9.13	15.7	
O.K. Ditch	16.37	24.66	
Feature	**percent change (Alam)**	**percent change (Alam)**	
Verde Ditch	0.47	-0.77	
Diamond S Ditch	-0.25	-0.35	
Eureka Ditch	0.39	-0.05	
O.K. Ditch	0.45	0.18	
Feature	**percent change (Tinlin)**	**percent change (Tinlin)**	
Verde Ditch	-0.16	-0.52	
Diamond S Ditch	-0.24	-0.09	
Eureka Ditch	-0.20	0.13	
O.K. Ditch	-0.07	0.23	

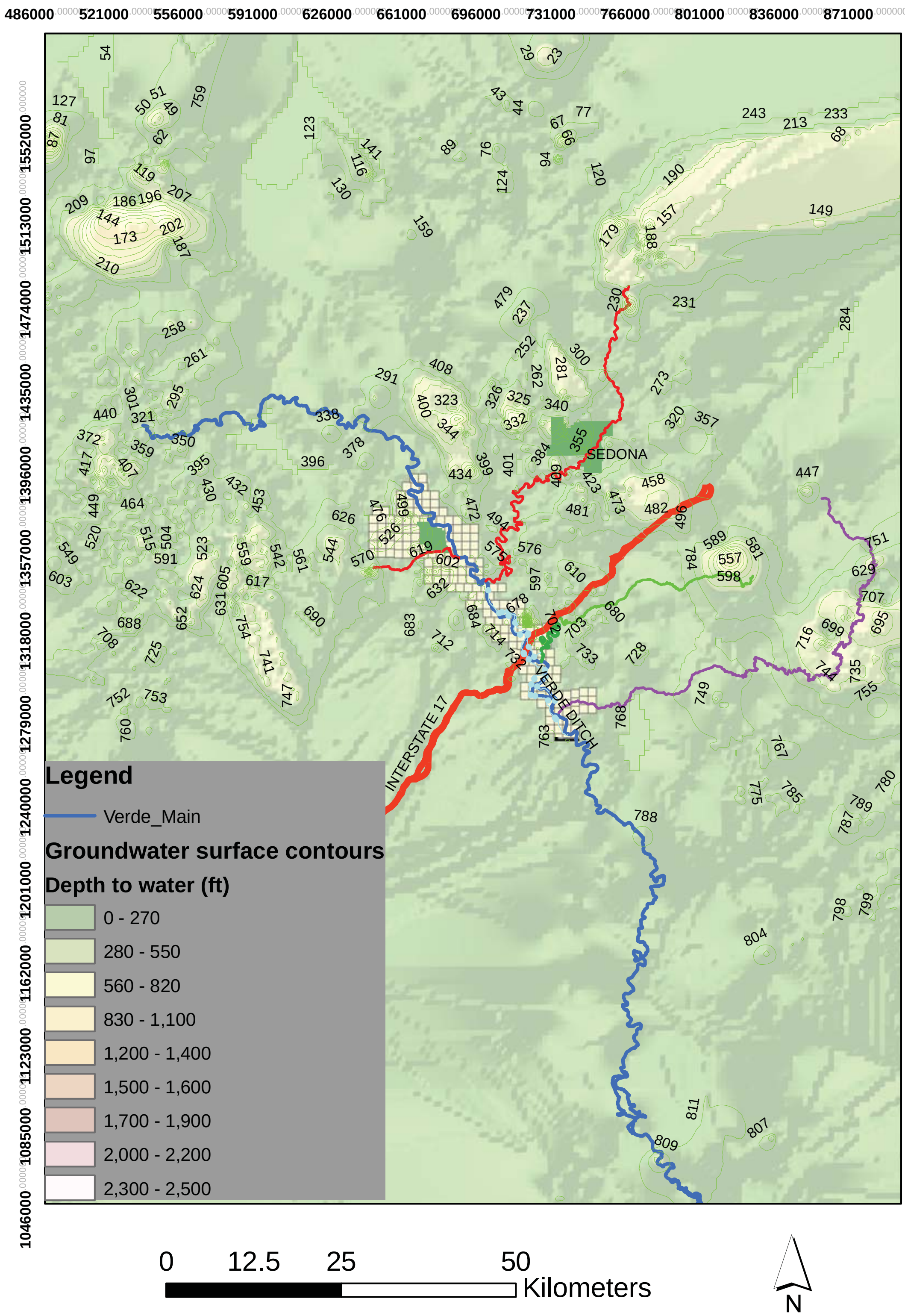

Figure 23 - Contoured water surface table of the middle Verde Valley, based from reported water level values reported by ADWR, 2000.

vegetation (Masek-Lopez, 2001) by type were used to help to estimate ET within the study reach and over the courses of the ditches (Fig. 24). Error margins for spatial editing of shapes, points, etc. are as small as less than one meter, and may be as great as five meters in certain areas of heavy vegetation (Table 7).

2.2.2 Channel survey

Supplemental survey work along the study reach from the Oak Creek/Verde River confluence to the return flow of the Verde Ditch yielded 142 bathymetric cross sections, with variable spacing dependent upon river characteristics. Width of transects ranges from 7 feet to 195 feet. Cross sections are closely grouped around changes in conveyance dictated by widening/narrowing of the channel, diversions and return of flow, and changes in slope or material properties (Manning's roughness coefficient), and are more widely spaced along reasonably straight sections of the river (Fig. 25). Cross-section ends were established with a hand-held GPS unit (Garmin ETrex, non-WAAS enabled), with inherent error ranging from two to fifteen feet, depending on signal reception. Topography such as cliffs, high terraces, and heavy vegetation increased systematic error of GPS-based positions. Level lines marked at five foot increments tied into rebar and a depth rod marked in decimal feet were used to develop bathymetry along each cross section. The period of the survey collection was between December 2008 and May 2009, with 142 cross sections gathered along the reach (Fig. 26).

2.2.3 Ditch flow instrumentation

The four irrigation ditches along the study reach were instrumented with vented-cable pressure transducers, which automatically correct for barometric

Figure 24 - Coverages of vegetation type, attributed with estimated ET for each mass vegetation type (from Masek-Lopez, 2001).

Table 7 - Error estimates of GIS data by individual file. Error listed as "unknown" was taken as-is from sources, and was not spatially edited, due to large datasets with limited field access.

GIS Datasets for middle Verde Valley (Applicable to study)				
Feature Dataset	Feature Classes	Description	Source	Error estimate
County Data				
	00buildings	Building footprints	Yavapai County GIS	unknown
	04buildings	Building footprints	Yavapai County GIS	unknown
	parcels	Land parcels and ownership	Yavapai County GIS	unknown
Geology				
	Basin_Labels	Drainage basin labels	ADWR	unknown
	Basin_Outline	Drainage basin borders	ADWR	unknown
	Basin_polygon	Drainage basin coverage	ADWR	unknown
	faults	Faults	ADWR	unknown
	springs	Springs	ADWR	unknown
	verde_stream	Main channel of Verde River	GRAIL	"+/- 2 meters
Irrigation				
	ditches	Irrigation ditches	ADWR/SRP/TNC	"+/- 0.5 meter
	diversion_pt	Location of diversions	This study	"+/- 1 meter
	Diversions	Diversion polyline	This study	"+/- 1 meter
	GWSI_wells	groundwater surface inventory wells	ADWR/SRP/TNC	unknown
	irrigation	Irrigated acreage	ADWR/SRP/TNC	"=/- 0.25 meter
	laterals	partial coverage of irrigation laterals	ADWR/SRP/TNC	unknown
	outflow	Location of return flows	This study	"+/- 0.5 meter
	spillway	Partial coverage of major spillways	This study	"+/- 0.5 meter
	wells55	Registered wells	ADWR/SRP/TNC	unknown
Reference				
	az_city_pnt	Location of AZ cities	GRAIL	unknown
	city_poly	Coverages of spatial extent of AZ cities	GRAIL	unknown
	roads	Location of roadways	GRAIL	unknown
Vegetation				
	1940_mesq	vegetation coverages	Masek-Lopez, 2001	unknown
	1940_rip	vegetation coverages	Masek-Lopez, 2001	unknown
	1968_mesq	vegetation coverages	Masek-Lopez, 2001	unknown
	1968_rip	vegetation coverages	Masek-Lopez, 2001	unknown
	1995_mesq	vegetation coverages	Masek-Lopez, 2001	unknown
	1995_rip	vegetation coverages	Masek-Lopez, 2001	unknown
	Riparian_veg	vegetation coverages	Masek-Lopez, 2001	unknown
	mesquite	vegetation coverages	Masek-Lopez, 2001	unknown

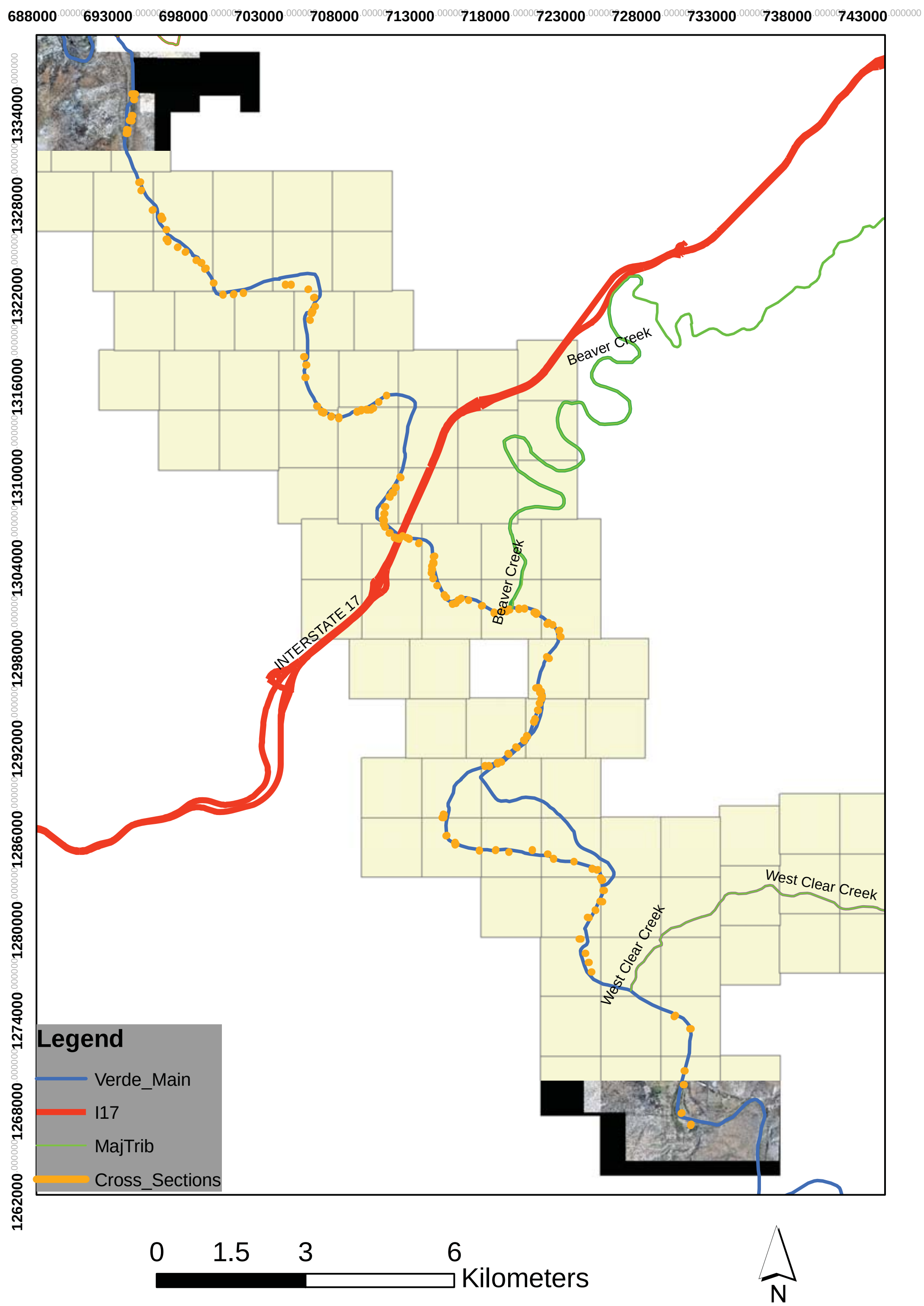

Figure 25 - Location of cross-section surveys of the Verde River, Camp Verde, central Arizona. Orange dashes represent cross-sections mapped into ArcGIS from field data.

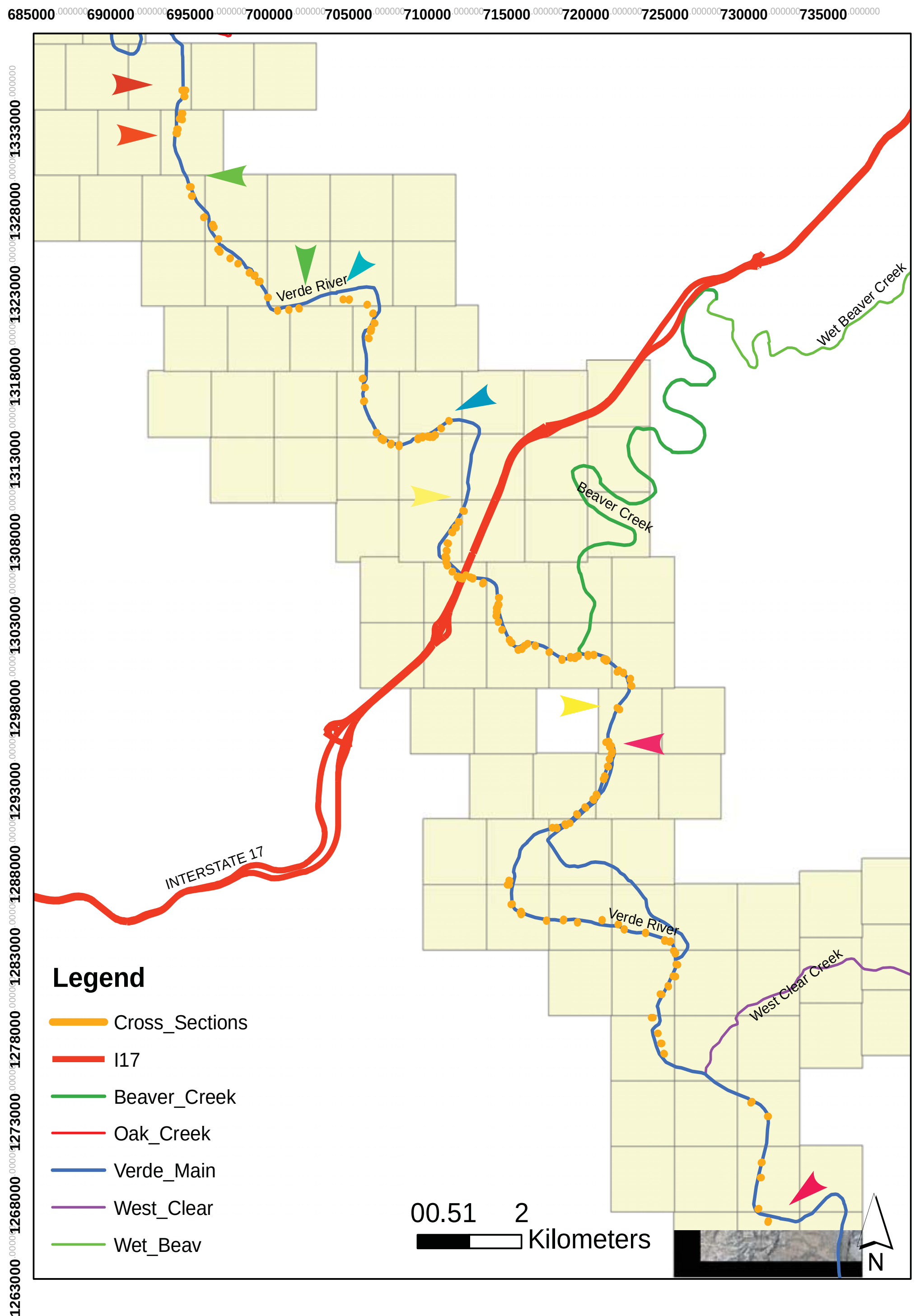

Figure 26 - Cross section surveys annotated by date of collection. Areas bracketed by red arrows were collected in December 2008, green arrows were collected in January 2009, blue arrows were collected in February 2009, yellow arrows were collected in March 2009, and pink arrows were collected in April 2010.

pressure, at or near the headgates and locations of return flow (Fig. 27). Transducers are deployed in 1.5-inch well casing with sand point tips, and are fixed to permanent structures such as concrete weirs, headgates, culverts, and fencing (Fig. 28). Transducers were programmed to measure and record stage every hour. Field tablet computers are used to download data, which were then exported to Microsoft Excel format (App. A).

The Eureka Ditch was instrumented beginning September 2008, the Diamond S Ditch in November 2008, the OK Ditch beginning March 2009, and the Verde Ditch in May 2009. All instruments remain in place at the completion of this study (12/2010). Data gaps exist in all ditches over periods of maintenance closure, with the Eureka having the longest closure period (generally late November through March). The transducers deployed (Table 8) are all manufactured by InSitu Inc. (Ft. Collins, CO), and are a mixture of older miniTroll units (deployed on the Eureka Ditch), and newer LevelTroll units (deployed on all other ditches). These units have pressure tolerances ranging from 5 to 15 pounds per square inch, or PSI, and provide conversion from pressure measurement to stage in feet. These units have a measurement uncertainty of 0.05 feet (InSitu, 2008), and may have additional uncertainty due to drift caused by water turbulence at the deployment site (e.g., just below Verde Ditch headgate) and/or turbidity created by high discharge events. Vegetative matter at or near the transducer may also factor into error. The transducers collect stage data every hour (App. A), and these stage data were converted to discharge by using rating curve equations (App. B). Stage data were corrected by rating curves at seven out of eight sites by comparing manually measured stage to the

Figure 27 - Example of pressure transducers deployed at headgates and return flows of Camp Verde area irrigation ditches. Model shown is Level Troll 900, InSitu LLC, Ft. Collins, CO.

Figure 28 - Example of pressure transducer deployed at head gate of the Eureka Ditch, Camp Verde, central Arizona. This deployment is down the ditch from the head gates, and is above the first water user. This site is located within a concrete weir, and the site is also utilized by Salt River Project (SRP) as a gauging station. Blue arrow indicates flow direction.

Table 8 - Summary of pressure transducer type, tolerance, interface software, serial number, and deployment location

Serial #	Unit designation	Location	Tolerance	Software
132535	Level Troll 500	Diamond S head	5 psi	WinSitu 5
134774	Level Troll 500	Diamond S return	5 psi	WinSitu 5
120789	Level Troll 700	OK head	30 psi	WinSitu 5
120797	Level Troll 700	OK return	30 psi	WinSitu 5
18532	miniTroll 900	Eureka head	15 psi	WinSitu 4
18432	miniTroll 900	Eureka weir	15 psi	WinSitu 4
18478	miniTroll 900	Eureka return	15 psi	WinSitu 4
136732	Level Troll 500	Verde head	5 psi	WinSitu 5
120802	Level Troll 700	Verde return	30 psi	WinSitu 5

stage reading from the instrument, with R^2 values ranging from 0.92 to 0.96. This correction generally bracketed the extreme high and low measurements, and provided corrected stage measurements in good agreement with observed stage (Table 9). Errors vary widely by site, and are greatest at instrumentation locations with high turbulence or water-borne debris.

The resulting stage measurements were converted into mean daily average values, to simplify the dataset, match USGS stream gage data, and to facilitate hydraulic modeling (App. C). Standard errors for these rating curves are R^2 values ranging from 0.98 to 0.92, depending on the sites (Table 10). The instantaneous flow was measured with a SonTek (YSI Inc., San Diego, CA) sonic flow meter, and the depth at the transducer was measured with a depth rod marked in increments of decimal feet. Depth measurement error is estimated at 0.05 feet. Errors for the flow measurements do not exceed 0.5% of measurement value (Table 11). Measuring flow and graphing it against the measured stage at the transducer produced the rating curves. Error compounded by calculations varies by instrument and site (Table 10). The resulting mean daily discharge is used as point discharge input for the hydraulic model.

2.2.4 Elevation model

Elevation models are in two basic formats, the digital elevation model (DEM) and the triangulated irregular network (TIN). In both cases, 3D point data consist of horizontal coordinates (x/y data; lat/long or UTM), with an associated elevation value for each point (z data). The DEM exists as a raster dataset, with evenly-spaced elevation nodes in a grid format. These nodes are connected by

Table 9 - Comparison of simulated stage to measured stage.

Site	Measurement date	Measured Stage (ft)	Calculated Stage (ft)	Percent difference
OK headgate	6/1/2009	1.75	1.580	0.10
	6/24/2009	1.55	1.580	(0.02)
	8/11/2009	1.8	1.820	(0.01)
	9/28/2009	1.7	2.130	(0.25)
	11/11/2009	2.41	2.820	(0.17)
Site Average		**1.84**	**1.99**	**(0.08)**
OK return	6/1/2009	1.5	1.300	0.13
	6/24/2009	1.21	1.210	0.00
	8/11/2009	1.27	1.210	0.05
	9/28/2009	0.8	0.970	(0.21)
	11/11/2009	1.52	1.440	0.05
Site Average		**1.26**	**1.23**	**0.03**
Eureka headgate	9/30/2008	1.134	1.134	0.00
	10/28/2008	1.144	1.144	0.00
	6/24/2009	1.226	1.230	(0.00)
	9/21/2009	1.457	1.457	0.00
	9/28/2009	1.361	1.361	0.00
	10/22/2009	1.338	1.338	0.00
Site Average		**1.28**	**1.28**	**(0.00)**
Eureka return	6/24/2009	0.9	1.009	(0.12)
	8/11/2009	0.85	1.070	(0.26)
	9/21/2009	1.4	1.290	0.08
	10/22/2009	1.36	1.400	(0.03)
	5/9/2010	1.59	1.501	0.06
Site Average		**1.22**	**1.25**	**(0.03)**
Diamond S headgate	11/25/2008	3.2	2.620	0.18
	6/1/2009	2.791	2.897	(0.04)
	9/28/2009	3	3.110	(0.04)
	10/22/2009	3.24	3.290	(0.02)
	5/9/2010	2.84	2.690	0.05
Site Average		**3.01**	**2.88**	**0.04**
Diamond S return	11/25/2008	1.2	1.730	(0.44)
	6/10/2009	1.3	1.520	(0.17)

Table 9, continued.

	9/21/2009	1.4	1.450	(0.04)
	10/22/2009	0.92	1.100	(0.20)
	5/9/2010	1.31	1.400	(0.07)
Site Average		**1.23**	**1.44**	**(0.17)**
Verde headgate	6/8/2009	2.6	2.360	0.09
	8/3/2009	1.8	1.807	(0.00)
	9/28/2009	1.8	1.737	0.03
	10/22/2009	1.4	1.490	(0.06)
	5/9/2010	2.1	1.936	0.08
Site Average		**1.94**	**1.87**	**0.04**
Verde return	6/8/2009	0.48	0.522	(0.09)
	8/3/2009	0	0.053	0.00
	8/12/2009	0.4	0.440	(0.10)
	9/21/2009	1.3	1.420	(0.09)
	10/22/2009	1.4	1.720	(0.23)
	5/9/2010	0.7	0.959	(0.37)
Site Average		**0.71**	**0.85**	**(0.19)**

Table 10 - Comparison of simulted discharge to measured discharge.

Site	Measurement date	Measured Discharge (ft3/s)	Calculated Discharge (ft3/s)	Mean calculated discharge (ft3/s)	Percent difference (instantaneous)	Percent difference (mean)
OK	6/1/2009	9.274	9.86	11.97	-0.06	-0.29
headgate	6/24/2009	21.217	13.37	13.23	0.37	0.38
	8/11/2009	11.57	12.3	13.64	-0.06	-0.18
	9/28/2009	9.231	15.77	11.02	-0.71	-0.19
	11/11/2009	19.54	21.24	21.26	-0.09	-0.09
	Site Average	**14.17**	**14.51**	**14.22**	**-0.11**	**-0.08**
OK	6/1/2009	6.31	5.99	5.77	0.05	0.09
return	6/24/2009	10.089	7.04	6.58	0.30	0.35
	8/11/2009	6.894	6.61	6.41	0.04	0.07
	9/28/2009	4.559	4.96	5.32	-0.09	-0.17
	11/11/2009	9.56	8.72	8.28	0.09	0.13
	Site Average	**7.48**	**6.66**	**6.47**	**0.08**	**0.09**
Eureka	10/28/2008	13.76	13.13	13.79	0.05	0.00
headgate	6/24/2009	11.901	11.75	11.75	0.01	0.01
	9/21/2009	14	13.8	13.71	0.01	0.02
	9/28/2009	12.25	12.52	12.53	-0.02	-0.02
	10/22/2009	12.37	12.36	12.35	0.00	0.00
	Site Average	**12.86**	**12.71**	**12.83**	**0.01**	**0.00**
Eureka	6/24/2009	1.812	2.62	2.6	-0.45	-0.43
return	8/11/2009	1.975	2.85	2.85	-0.44	-0.44
	9/21/2009	4.231	3.63	3.64	0.14	0.14
	10/22/2009	3.98	4.09	4.09	-0.03	-0.03
	5/9/2010	5.18	4.46	4.46	0.14	0.14
	Site Average	**3.44**	**3.53**	**3.53**	**-0.13**	**-0.13**
Diamond S	11/25/2008	21.25	20.5	20.46	0.04	0.04
headgate	6/1/2009	26.86	26.44	24.85	0.02	0.07
	9/28/2009	27.86	27.096	36.45	0.03	-0.31
	10/22/2009	30.24	30.08	34.51	0.01	-0.14
	5/9/2010	25.35	18.08	21.19	0.29	0.16
	Site Average	**27.04**	**26.79**	**26.71**	**0.07**	**-0.03**
Diamond S	11/25/2008	24.89	25.57	22.16	-0.03	0.11
return	6/10/2009	22.503	22.64	22.51	-0.01	0.00
	9/21/2009	20.461	21.47	20.48	-0.05	0.00
	10/22/2009	16.92	16.31	14	0.04	0.17
	5/9/2010	21.48	21.17	21.19	0.01	0.01
	Site Average	**21.25**	**21.43**	**19.49**	**-0.01**	**0.06**
Verde	6/8/2009	32.899	32.953	31.819	0.00	0.03
headgate	8/3/2009	30.756	29.64	29.51	0.04	0.04
	9/28/2009	29.202	28.77	29.06	0.01	0.00
	10/22/2009	23.56	24.04	24.02	-0.02	-0.02

Table 10 continued.

	5/9/2010	30.16	31.03	31.13	-0.03	-0.03
	Site Average	**29.32**	**29.29**	**29.11**	**0.00**	**0.01**
Verde	8/3/2009	0	0	0	0.00	0.00
return	8/12/2009	1.176	1.47	1.71	-0.25	-0.45
	9/21/2009	8.6697	8.27	6.94	0.05	0.20
	10/22/2009	9.61	10.36	10.385	-0.08	-0.08
	5/9/2010	6.514	6	6.02	0.08	0.08
	Site Average	**4.34**	**4.69**	**4.70**	**-0.04**	**-0.05**

Table 11 - Rating curve equations and R^2 error propagation.

Instrument location	Correction curve	R^2 error for correction curve
OK headgate	y=0.7196x+0.899	0.0825
OK return	y=2.2035x-1.371	0.0591
Eureka headgate	Null	0
Eureka return	y=x-9.099	0.0017
Diamond S headgate	y=0.8864x+0.4258	0.0147
Diamond S return	y=-0.2364x+(1.7591)	0.0009
Verde headgate	y=3.4188x-0.7974	0.0017
Verde return	y=0.8896x+0.0366	0.0298
	Rating curve	**R^2 error for discharge rating curve**
OK headgate	y=0.2238x-0.0298	0.0669
OK return	y=0.1756x-0.0234	0.0736
Eureka headgate	y=0.2667x	0.041085
Eureka return	y=0.1062x-0.0331	0.1137
Diamond S headgate	y=0.2521x	0.0051
Diamond S return	y=0.4201x-0.0005	0.0005
Verde headgate	y=0.448x+0.0113	0.0096
Verde return	y=6.2832x	0.0405
	Systemic error in instrument	**Propagated error**
OK headgate	0.05	0.1174
OK return	0.05	0.1068
Eureka headgate	0.05	0.0647
Eureka return	0.05	0.1242
Diamond S headgate	0.05	0.0524
Diamond S return	0.05	0.0500
Verde headgate	0.05	0.0509
Verde return	0.05	0.0709

breaklines connecting each nearest neighbor in a square representation (Fig. 29). The DEM is most useful in large scale models (watershed scale) used for hydrologic representation. The TIN represents elevation points in a vector dataset, with breaklines connecting point data that are not necessarily evenly spaced. Elevations at other locations are determined using an equation that fits each set of three points (Fig. 30). The TIN is very useful for high-resolution randomly-spaced data, as it will better represent local topography such as terraces, channel boundaries, etc., and is most commonly used for small-scale hydraulic modeling. Elevation data are generally collected either by aerial topographic survey techniques or by Light Detection and Ranging (LiDAR). LiDAR datasets are created by flying over a study area and emitting laser pulses. The time between the pulse and the detection of the reflected signal in conjunction with a geometric correction determines the elevation of the land surface. Currently, most LiDAR data are not precise over bodies of water, so supplementary bathymetric survey data are needed for channels. LiDAR generally also produces extremely dense ASCII pointfile datasets that are very unwieldy to manipulate. Yavapai County Flood Control District was able to provide contour shapefiles generated from the LiDAR data to enhance workability.

An elevation model was created as a base surface with latitude/longitude data points corresponding to elevation data for each point. LiDAR-based contours were used to create a TIN, which interpolates elevations between points by using probability breaklines. The LiDAR-based contour data from Yavapai County Flood Control were imported into ArcInfo, converted back to thinned point data by centroid conversion, and were used to create a TIN surface. The TIN surface provides an

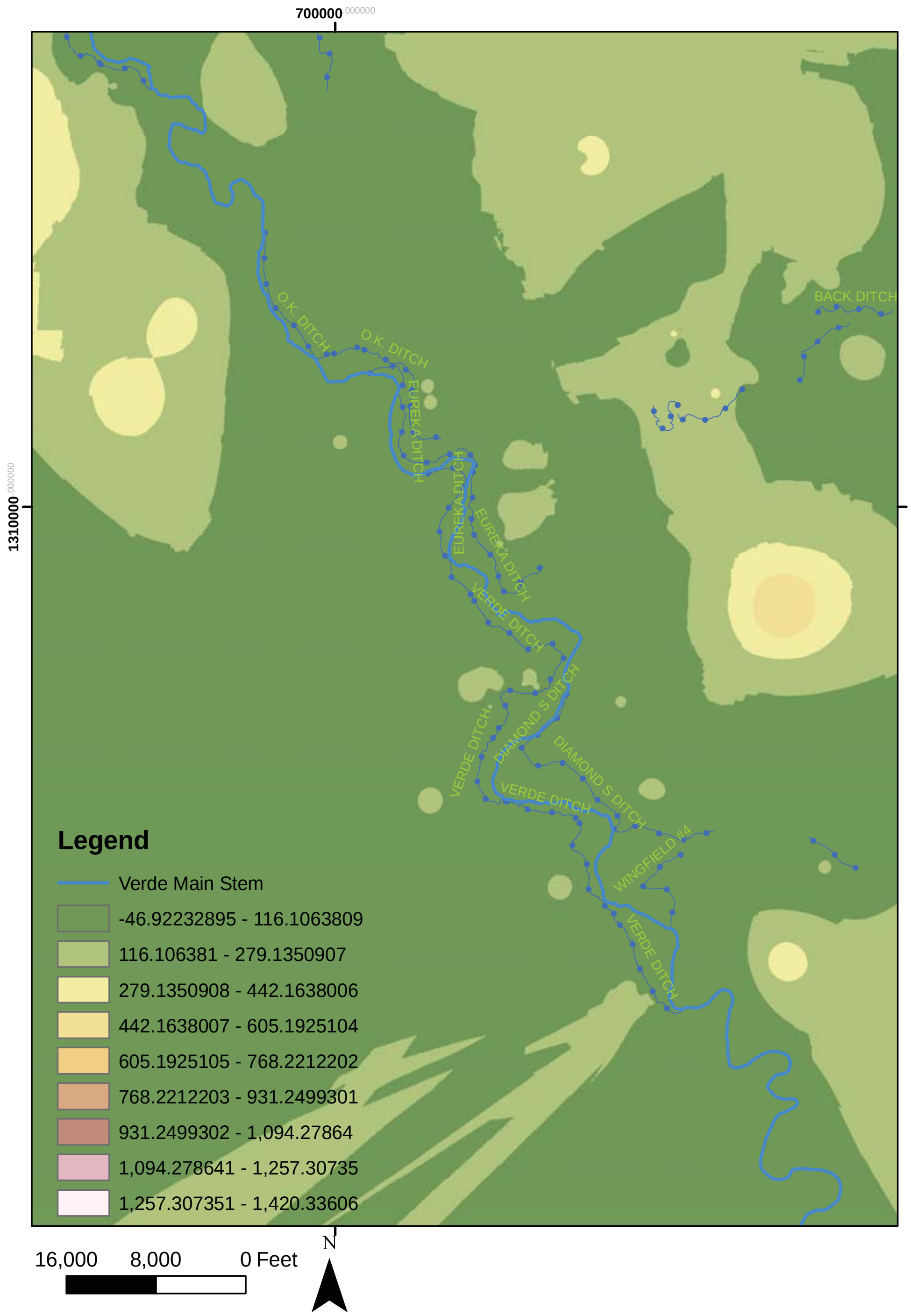

Figure 29 - Representation of digital elevation model (DEM) surface. DEMs create raster cells in a grid format, with each pixel having a representative elevation embedded within it. Interpolation can be problematic if elevation data is widely spaced.

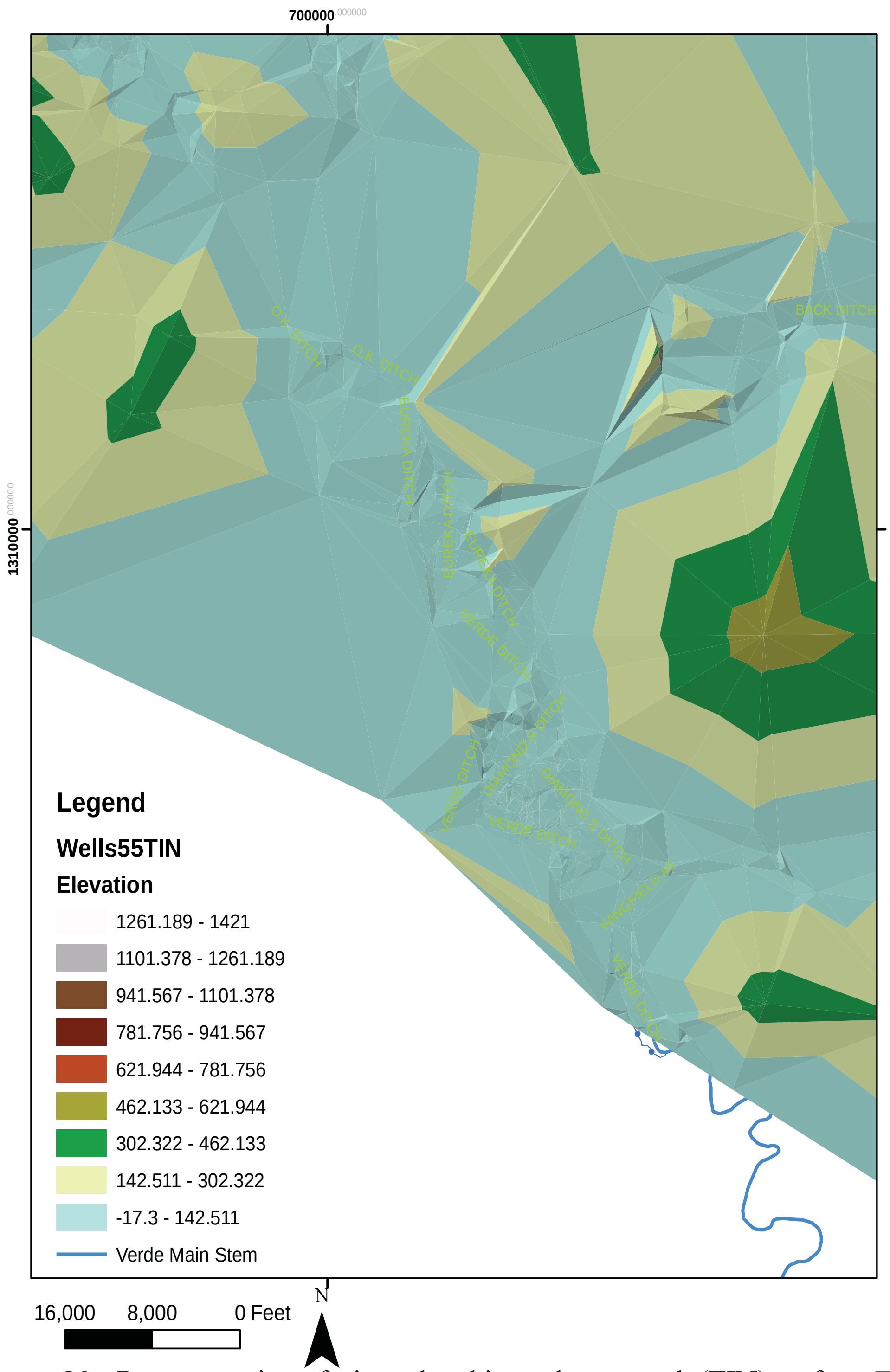

Figure 30 - Representation of triangulated irregular network (TIN) surface. TINs use a series of elevation points and breaklines to connect elevation points by triangulation to interpolate continuous elevation profiles. TINs are best suited to representing surfaces with irregular elevation data.

elevation base map for import into HEC-RAS hydraulic modeling software. Since LiDAR does not reliably penetrate water surface or heavy vegetation, supplemental elevation data from the channel bed were collected in a series of surveys along the river channel.

2.2.5 Hydraulic model

Two main types of models are applicable to the modeling process; hydrologic and hydraulic models. Hydrologic models are generally more appropriate to watershed-scale models used for runoff calculations, while hydraulic models are more applicable to in-channel water surface modeling. Hydraulic modeling was determined to be appropriate for the objectives of this study. Aquaveo's Watershed Modeling System (WMS) (Aquaveo, LLC, South Jordan, UT) was used to create a hydraulic flow model for the study reach under low-flow steady-state conditions. The model started with a known boundary condition (based on USGS stream gage data from Clarkdale and Oak Creek), and then determined water surface elevations at a series of cross sections given frictional loss parameters and channel geometry information. Cross sections were created from survey data (bathymetric profile across river channel), supplemented by a TIN elevation model. GIS coverages of the river channel, floodplain, terraces, and agricultural land were used as a basis for estimating Manning's roughness coefficient (n) in channel and floodplain areas. Data from ditch instrumentation serve to specify discharge/recharge at appropriate timed locations along the study reach.

WMS uses US Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) (citation) software as its hydraulic modeling engine. Elements necessary for a WMS HEC-RAS model include channel thalwag, boundary conditions (discharge at start of model reach, as well as input/output from irrigation ditches and tributaries), an outlet point (terminal discharge), materials properties for frictional loss (Manning's n), an elevation base (TIN format), cross sections for iteration, and optional channel boundaries (useful for ineffective flow zones). It also requires flow path lengths (measured in the GIS).

Many elements can be imported to WMS from GIS shapefiles (geometric data such as thalwag, banks, and cross sections), which are then mapped to WMS coverages. These coverages are then internally defined as centerline or cross section coverages. Elevation profiles on cross sections are edited with survey bathymetry, because available elevation data from LiDAR do not penetrate water surface. Boundary conditions are defined by USGS stream gages (initial discharge at top of study reach and tributary input) and irrigation ditch discharge measurements.

The model was calibrated by running a steady state low-flow scenario during a time of minimal ET (i.e., spring months with moderate temperature). Initial input is based on a period of reasonably consistent flow in the main stem of the Verde River and its tributaries, as well as reported moderate temperatures for the Verde Valley. Initial flow and measured values were used to calibrate the model by tuning its output to reasonable agreement with known discharge from the USGS stream gage near the terminus of the model reach. Variables used to calibrate were mainly roughness coefficient, slope, and expansion/contraction of no-flow channel areas along the boundaries. Once calibrated, the model was used to simulate flow in the system given different parameters.

2.2.6 Analysis and interpretation

The hydraulic model was used to simulate results from the steady-state low flow condition, and simulation results were compared to actual measured values of hydraulic parameters to estimate error. Once calibrated, I used the model to simulate flows under different boundary conditions, such as different scenarios in terms of diversion by irrigation ditches, and projected changes in agricultural and residential land use.

Chapter 3- Geographic Information System (GIS)

3.1 GIS software:

The GIS software platform chosen for this study is ESRI ArcGIS 9.3 (ESRI, Inc, 2009). This is the most commonly used GIS software, and was chosen for both its availability and sharing capabilities. ArcGIS allows for the creation of both personal and file geodatabases, depending on user needs. The file geodatabase is designed for network-based use by multiple users, as might be done with large projects involving a team of analysts. The personal geodatabase (used for this study) is a single-user access geodatabase, and it organizes data into a common projection/spatial reference scale (in this case, NAD 83, Arizona Stateplane Central Zone FIPS 202, international feet, was used). Data are imported from base sources into ArcGIS, and then exported into the user created and defined geodatabase as feature classes. The process both uniformly organizes the data, as well as makes the project highly portable, since it will self-reference the geodatabase as the data source for the layers within the project. Layers are individual shapefiles (point, polygon, polyline), elevation datasets and surfaces (rasters and TINs), and base maps and references such as aerial photos and topographic maps. The individual layer layout allows for viewing only layers of interest, as well as being able to edit the individual attributes or spatial data of each layer.

3.2 Data Compilation

Data exist for several components of the irrigation and riverine systems, including channel locations, irrigation ditches, delivery laterals, production and monitoring wells, and areas of historical irrigation. These data were collected over a long period by ADWR, with different methods, survey teams, and tolerances. The early data were collected on paper maps and digitized into early renditions of ArcGIS, as well as traced onto Mylar overlay placed on top of non-orthorectified aerial photographs. These methods involved a general degradation of spatial accuracy, especially towards the edges of the aerial photographs where the flat representation of a curved surface led to spatial distortion.

Data were gathered from other sources, such as Yavapai County GIS, the GRAIL at NAU, and Salt River Project and The Nature Conservancy. These data included incorporated city limits, roads and highways, land ownership parcels, and building footprints. Other data were needed for a complete informational database, including diversion structures, return flows, and survey cross-sections.

Other data needed to be extracted from complete layers, (i.e., main channel of the Verde River from streams coverage, I-17 from roads layer, irrigation areas for Camp Verde Ditches from irrigated areas coverage, etc). Data are organized by source (Table 5). The file geodatabase created for this project is internally organized into five feature datasets: Irrigation, Reference, County_Data, Geology, and Vegetation. Each of these feature datasets contains a series of feature classes for the riverine system.

3.3 Irrigation Feature Dataset

The GIS irrigation dataset contains layers/coverages (App. D) representing irrigation ditches, diversion structures, GWSI wells (ADWR monitoring wells), irrigated acreages, ditch laterals, return flows, spillways, and an inventory of production wells (Table 5).

The irrigation ditch coverage contains records representing all irrigation ditches in the Verde Valley. Each polyline record is attributed with ditch names, water source, estimated acres irrigated, estimated users, length of each ditch, and discharge measured at or near the headgates of the ditch (App. D). The diversion structure coverage contains records attributed with ditch name and structure width.

The GWSI (groundwater surface inventory) coverage records with attributes including site well id, UTM location coordinates, depth to water, active management area (AMA) code, source code, method code, and measurement date. Irrigated area records contain attributes indicating crop codes, water source, code sequence, and shape area.

Ditch laterals are a partial coverage of undocumented origin with attributes including conveyance type (generally canal or pipeline), name of associated ditch, and shape length.

The spillway and return flow coverages are user-created files, with attributes including spatial locations, feature lengths for spillways, and average discharge at return flow sites.

The production well coverage contains records attributed with ADWR registry id, county, watershed, sub basin, AMA, locations in both township/range and UTM coordinates, well type, water use, well depth, water level, casing type, casing depth, casing diameter, pump type, and ownership data (owner name or company name) (App. D).

3.4 Reference Feature Dataset

The reference dataset contains incorporated city boundaries, roads, and locations of transducers and survey cross-sections. The city boundaries coverage contains attributes including area, perimeter, and city name. The road coverage contains records with attribute data such as street name, shape length, and road number. The transducer coverage contains attributes including serial number, location, pressure tolerance, and date installed. The cross-section feature class contains records with UTM locations and section width attributed (App. D).

3.5 County Data Feature Dataset

The county data dataset contains three feature classes; building footprints from 2000, building footprints from 2004, and land ownership parcels. The building footprint coverages contain attributes such as area and perimeter of footprint, as well as building identification numbers and codes for both 2000 and 2004. The land ownership parcels cover the extent of the county, and contains area and perimeter, as well as name of owner, sub names of corporations, tax code, and parcel identification (App. D).

3.6 Geology Feature Dataset

The geology feature dataset contains four layers: faults, Verde_stream, main_channel, and springs. The faults coverage contains records attributed with length and fault id. The Verde_Stream coverage contains records displaying all rivers, washes, and waterways in the watershed, with attributes including river mile location, stream name, length, and identification. The main_channel coverage contains records exported from the Verde_Stream layer (same attributes), with the selection criteria based on the name equaling “Verde River”. The springs layer contains attributes with spring identification, name, and source (App. D).

3.7 Vegetation Feature Dataset

The vegetation dataset contains area and perimeter of riparian vegetation coverage, as well as riparian identification to describe majority foliage type (mesquite, cottonwood, tamarisk, etc.) (App. D).

3.8 Basemaps

Basemaps comprise one-meter pixel resolution orthorectified aerial imagery, and is in unsigned 8-bit integer raster format. The May 2007 imagery from PhotoMapper USA is corrected for accurate ground representation in a digital map format (i.e., the photos are merged and corrected to represent a curved surface). The photos are represented in Red-Green-Blue color scale. This type of photo base is essential for spatial editing of vector data (shapefiles, etc), as it shows the actual ground locations of features. The other component of the basemap is a one-meter scale USGS DEM obtained from ARIA (Arizona Regional Imagery Archive). This DEM is clipped to the study area, and each one-meter pixel contains an elevation datum for the corresponding area of ground surface.

3.9 Editing

After all spatial and attribute data were compiled into the geodatabase, they were analyzed for spatial accuracy, and updated to recent remote imagery. Many of the features were inaccurately placed, likely due to the limitations of early digitizing and lack of orthorectified aerial photo base. Described features were field checked with the GIS loaded onto a ruggedized tablet and a hand-held GPS unit, as well as compared to the orthophoto basemap. Significant differences existed between the represented and actual locations of several features such as river channel, irrigation ditches, and irrigated areas. Several of these features were also overly complicated for the scale of the model, and required consolidation/simplification (Fig. 21). This was accomplished through editing features overlaying the aerial photos base at a 1:750 map scale. This editing led to better measurements of length and area of the features, as well as reducing the number of polygons associated with irrigation and correcting their spatial extent. Several features of the GIS were not practical to edit, as they are secondary to the creation of a hydraulic flow model, and large numbers of record and land access issues made the verification and editing of these features beyond the scope of this investigation. The locations of springs, faults, and wells were among these features. The GIS was created and edited for all information pertaining to the Verde Valley, as well as outlying Yavapai County. The applicable data for the Camp Verde study area were isolated for model framework and identifying variable inputs.

3.10 Model Data

Several GIS layers were used for creation of the hydraulic model. These included: surveyed cross-sections; banks and thalwag of the Verde River; irrigation ditches; point locations of the tributaries of the Verde River; locations of diversions and return flows; irrigated areas and vegetation; and ditch lengths to assume primary ditch consumption. Most diverted flow not consumed by vegetation should return to the river system via spillways, return flows, and infiltration into the

Verde Formation. Also used for a secondary qualitative comparison was a contoured groundwater surface elevation derived from wells coverage data (Fig. 23).

Chapter 4 - Field Work

4. 1 Instrumentation and channel survey

In addition to model parameters existing in the GIS (thalwag and channel boundaries) and from USGS stream gage records (stage and discharge data for the Verde River and its tributaries), data were needed to define the effects of the irrigation ditches on river baseflows. Specifically, these data were needed for diversion and return flow of the ditches over the course of a year for conditions of low-flow, high-flow, and ditch closure during maintenance. Elevation data for the channel bed from USGS DEM and LiDAR-derived contours from Yavapai County Flood Control district were inadequate for creating profile cross sections. Physical surveys were needed to construct accurate cross sections for HEC-RAS model performance.

4.1.1 Instrumentation

The four ditches in the Camp Verde reach were each fitted with a pressure transducer at or near the headgates and near the location of return flow, beyond the terminal water user (Fig. 31). These pressure transducers are InSitu units, with two older miniTrolls and six newer Level Trolls of varying pressure tolerances (Table 8).

The Eureka Ditch was instrumented in September 2008 with the two miniTrolls (serial numbers 18432; 18478) at a concrete weir above the first water user and in a corrugated steel culvert at the terminal water user before it discharges to Beaver Creek. Both transducers were mounted in 1 ¼" well casing with sand point tips to allow flow-through. The casings are fixed to a chain link fence at the weir (Fig.

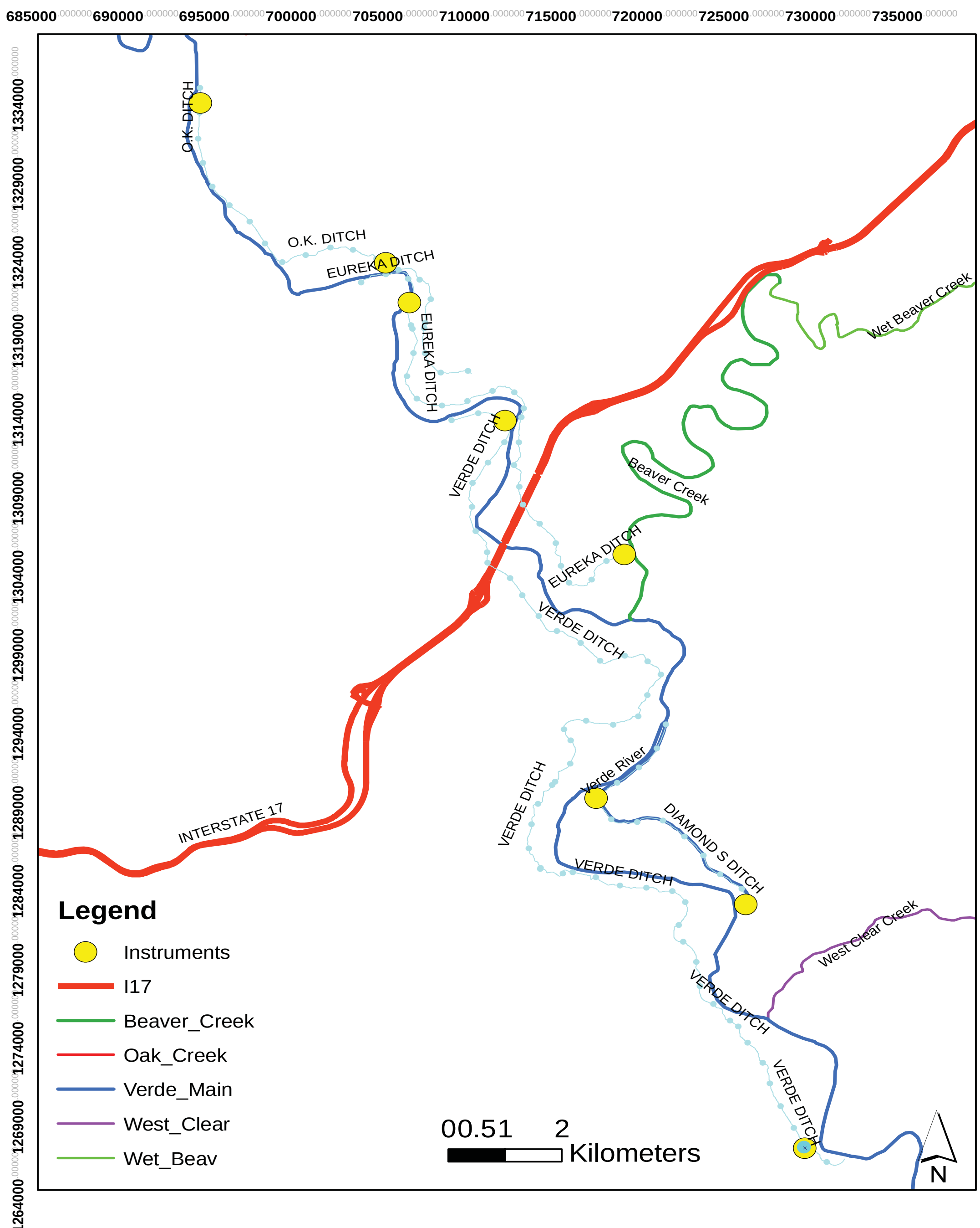

Figure 31 - Location map of transducers deployed in the Verde River hydraulic model study, Camp Verde, central Arizona. Yellow points indicate instrument placement, and coverages representing Interstate 17, Verde River, and tributaries are included for spatial reference.

28), and to a metal gate at the return flow (Fig. 32). Both transducers were programmed to read stage every hour, and to save the reading in an onboard data logger. Data were retrieved periodically with an InSitu Rugged Reader handheld field computer (serial number 132681), via a proprietary serial bus interface attached to the transducer (serial number 0097260).

The OK Ditch was instrumented in March 2009 with two Level Trolls (serial numbers 120789; 120797) at a concrete culvert upstream of the first water user and at a concrete pipe outlet downstream of the terminal water user (Fig. 31). The well casing was fixed to the concrete culvert structure with a fence post mount drilled into the concrete (Fig. 33). The well casing at the pipeline discharge was fixed to the concrete lining with a fence post mount drilled into the concrete (Fig. 34). Both transducers recorded hourly stage data, which were recovered using a ruggedized field tablet computer equipped with WinSitu software (v5, InSitu Inc., Ft. Collins, CO) with a proprietary InSitu interface connecting via a USB port and the transducer (serial number 137010).

The Diamond S Ditch was instrumented in November 2008 with two Level Trolls (serial numbers 132535; 134774) at the headgate structure and at a concrete culvert near the return flow, past the terminal water user (Fig. 31). The well casing at the headgate was fastened to steel pipe cross members with heavy gauge baling wire and cable ties (Fig. 35). The well casing at the concrete culvert near the return flow was fastened to exposed rebar from a broken portion of the culvert with heavy gauge baling wire and cable ties (Fig. 36). Hourly stage data were recorded and retrieved in the same manner as the OK Ditch system.

Figure 32 - Pressure transducer installed at Eureka Ditch return flow, Camp Verde, central Arizona. Shortly after this location, flow is returned to Beaver Creek.

Figure 33 - Pressure transducer installed at OK Ditch head gate, Camp Verde, central Arizona. This location is about 10 yards downstream of the initial major spillway returning flow to the Verde River. Blue arrow indicates flow direction.

Figure 34 - Pressure transducer installed at OK Ditch return flow, Camp Verde, central Arizona. This outlet is next to Grandpa Wash, which contributes some of the OK return flow to the Eureka Ditch.

Figure 35 - Pressure transducer installed at Diamond S Ditch headgate, Camp Verde, central Arizona. This concrete weir is directly at the headgates of the ditch, and is directly downstream of a major spillway returning significant flow to the Verde River.

Figure 36 - Pressure transducer installed at Diamond S Ditch return flow, Camp Verde, central Arizona. This culvert is directly downstream of the final flow diverted from the ditch into a storage tank. Blue arrow indicated flow direction.

The Verde Ditch was instrumented in April 2009 with two Level Trolls (serial numbers 136732; 120802) at the headgate structure and downstream of the terminal water user (Fig. 31). The well casing at the headgate was attached to a steel I-beam cross member with cable ties (Fig. 37); heavy flow during monsoon season displaced the instrument, and it was fastened to exposed rebar on the concrete wing of the structure in August 2009 (Fig. 38). The instrument at the return flow was attached to a chain link fence crossing the channel at the end of the downstream final water user's property boundary using baling wire and cable ties (Fig. 39). Hourly stage measurements were recorded and downloaded with the same equipment as described for the OK and Diamond S Ditches.

4.1.2 Rating curves

For each gauged ditch location, rating curves were used to constrain outlying stage measurements to agree with manual measurements, as well as to convert stage data to discharge data. In the case of stage data correction, numerous field measurements of depth were taken at the transducer location and compared with the transducer reading. For discharge, flow conditions calculated from velocity measurements were compared with the observed stage at the transducer. In both cases, equations relating observed to measured stage and stage to discharge were developed by means of linear regression.

4.1.3 Stage correction

Of the eight transducers deployed, one (Eureka weir) consistently displayed stage values coincident with field measurements of stage taken at the

Figure 37 - Pressure transducer installed at Verde Ditch head gate prior to high-flow displacement, Camp Verde, central Arizona. Instrument was recovered after August 2009 floods and relocated to river left side of structure. Blue arrow indicates flow direction.

Figure 38 - Pressure transducer installed at Verde Ditch head gate after high-flow displacement, Camp Verde, central Arizona. Current location of transducer (pictured) is on river left side of headgate structure. Blue arrow indicates flow direction.

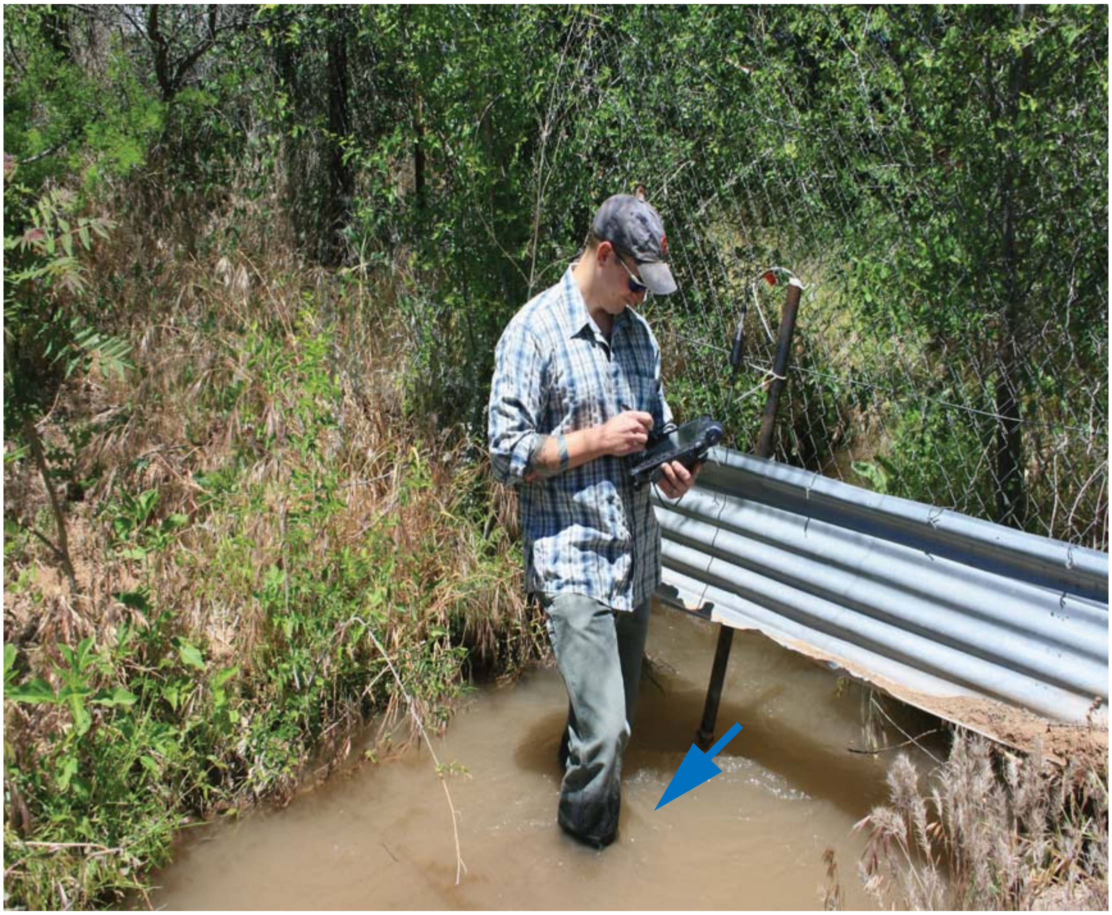

Figure 39 - Pressure transducer installed at Verde Ditch return flow, Camp Verde, central Arizona. Location is downstream of terminal water user. Blue arrow indicates flow direction.

transducer location. This transducer was mounted in a concrete flume, and was situated within laminar flow.

The other seven transducers were subject to water turbulence and debris collection, due to deployment in a less-than-ideal natural channel. Instrument sites needed an anchor spot, which in these types of channels is generally not in laminar flow in the channel center. Flow turbulence may have had a pressure effect within the well casings above the sand point tip, causing the indicated water level to be higher or lower than the actual water level outside of the instrument chamber. This flow turbulence led to inconsistent stage readings (App. A), but the data were corrected to reasonable values by manually measuring depth at the transducer, and comparing these direct stage measurements to the stage value indicated by the transducers.

The two sets of stage data (measured and indicated) were graphed against each other, and the equation of a linear regression trend line was determined (App. A). The equation of this trendline was then applied to indicated data, and the high and low extremes of the downloaded data were removed.

Currently, between four and seven relationships are included in the rating curve for each transducer. Corrected measurements of stage at or near the headgates were in good agreement with previously reported average and seasonal maximum values (Alam, 1997; Tinlin, 1977), and matched field measurements taken at known stages. RMS values of the accuracy of the linear regression curve relative to the compared field and indicated stage measurements vary between sites, and lie between 0.89 and 0.99 (Table 10).

4.1.4 Discharge estimation

The boundary condition data desired for the irrigation ditch/riverine system are discharge rates at known times at locations of diversion and return flows. To convert stage to discharge, a second rating curve was created for each instrumentation site. These rating curves relate discharge rates measured near the transducer with a SonTek sonic flow meter (serial number P2804) to observed stage at the transducer. The flow measurements were conducted by measuring at varying increments to obtain an average of 20 points across the channel, with each point taking a 40 second velocity measurement at 60 percent of depth (Fig. 40). The discharge was calculated by the SonTek onboard analysis program by deriving velocity per area increment and adding all flow derivations across the channel width. The SonTek was calibrated at each site using an onboard ping test to ensure quality data collection. For each site, between four and seven comparison measurements were made (App. B), with a 0/0 base point added for the linear regression analysis. Each rating curve yielded a linear regression equation, with RMS values ranging from 0.91 to 0.99 (Table 10). While an expanded rating curve for a wider range of flow variation would generally lend to an exponential fit, the limited range of discharge measurements created a linear best fit. The equation was then applied to corrected stage data for each transducer, yielding hourly discharge data in m^3/s and ft^3/s (App. B).

4.1.5 Data simplification

The length of deployment for pressure transducers collecting hourly stage data yielded large amounts of data (App. A). To reduce and simplify datasets,

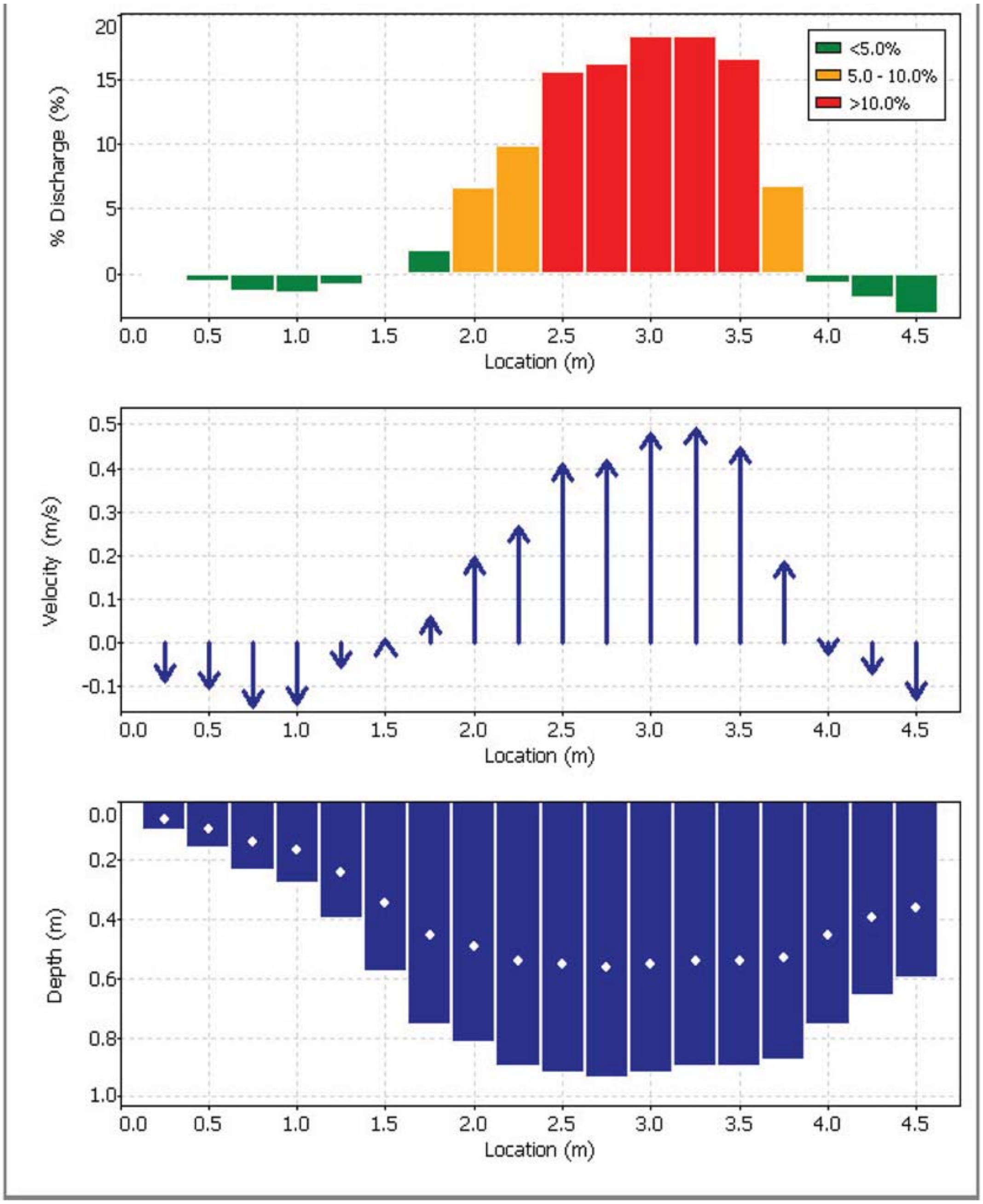

Figure 40 - Example cross section of velocity/area calculation of SonTek flowmeter. Measurement taken using 6/10 (60% depth) method at OK headgate.

and to provide meaningful parameters for the hydraulic model, the hourly discharge and stage data were reduced to mean daily averages (App. C). A PivotTable was created using the original date, corrected stage, and discharge in ft^3/s. The value reading of both stage and discharge was set to the average function, resulting in daily mean for each group of data associated with each date (App. C). The data match the format of the USGS stream gauge data for the Verde River and all tributaries, where mean daily discharge and stage are reported (App. E). The resulting data, much more manageable in number, provide better overall representations of the diversion and return flows of the ditches, and simplify graphical representations and data analysis for the YC WAC and for interested stakeholders and investigators.

4.2 Survey

Accurate channel cross-sections were needed for constructing the HEC-RAS model, and elevation data of the required resolution were not available through the DEM or LiDAR contour data. Verde River channel cross-sections were surveyed from the Oak Creek confluence to the point of the Verde Ditch return flow. A level string line marked in five-foot increments was set across the channel and fixed to rebar driven into each channel bank. The start station for each survey was marked with a Garmin ETrex handheld GPS unit, and depth from the water surface to channel bottom was measured with a depth staff marked in decimal feet at each five-foot increment. Cross-section lengths ranged from 10 to two hundred thirty feet, with average water depths of 5 feet. Survey data were recorded manually in the field, and were then processed using Microsoft Excel spreadsheets. Survey locations were chosen by river characteristics and accessibility. Changes in river conveyance such as width, depth, pool-riffle-run sequences, channel bed characteristics, and flow diversion/return needed cross sections bracketing these changes. Certain areas were not conducive to survey, due to lack of access points and deep sediment load in the river channel (Fig. 41). Surveys were conducted from December 2008 to May 2009, with 142 cross sectional profiles collected (Fig. 26).

The Verde River channel generally comprises a silty-clay substrate, with considerable rocks ranging in size from pebble/small cobble to large boulders, and ranging in shape from rounded to sub-angular to angular, depending on the local mechanisms depositing them (extended river transport and working vs. rockfall/landslide/debris flow from adjacent topographically higher features such as cliff faces. Vegetation ranges from heavy reed and grass growth to sparse channel-side riparian vegetation. Sediment load tends towards heavy silty bottom cover (several centimeters to meters thick) at shallow wide locations downstream from tributaries and return flows where overall velocity drops, to a thin layer (a few centimeters thick) at areas displaying narrowing channel boundaries, increased slope, and increased overall velocity. Bedrock channel was generally not observed within the study reach. Slope is variable over the course of the study reach, but is mostly very gentle, (averaging 0.0012 ft/ft). Manning's coefficient values vary for the area; an average value of 0.025 was used for sections of the river, depending on characteristics such as sinuosity, channel bed material, and velocity.

Cross section traces were drawn in ArcGIS using the GPS data coordinates for the start station of each cross section (Fig. 25), and orientation was determined by situating cross-sections approximately 90 degrees to the channel banks. The

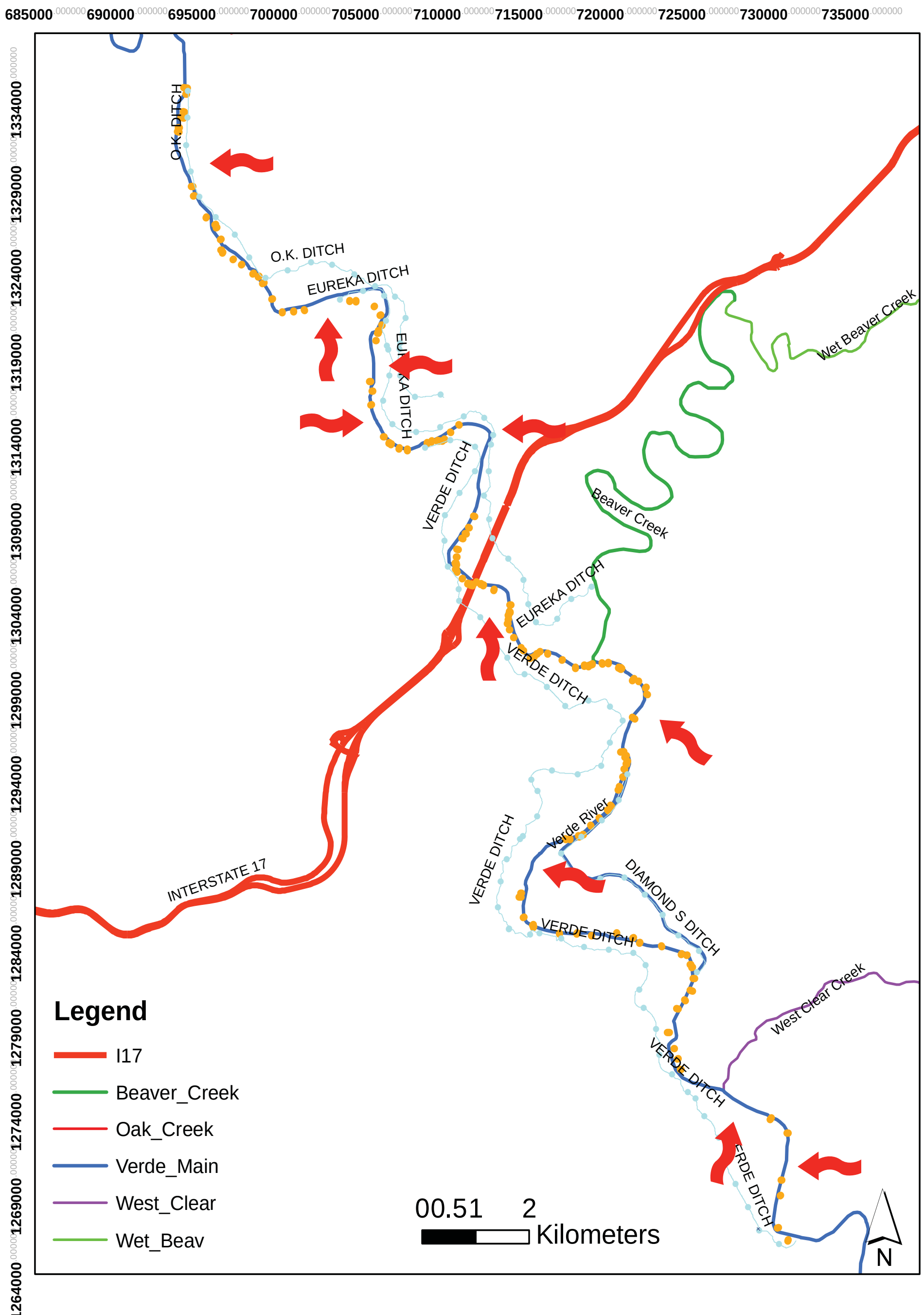

Figure 41 - Locations of data collection gaps for cross-section surveys due to accesibility issues. Most common was deep sediment in channel bottom over wide channel sections, where decreases in velocity increased sediment deposition. Narrow rapid sections also limited accessibility.

corresponding polyline shapefile of traces was exported to WMS software, and the traces were mapped to feature arcs within the WMS framework. The cross-sections were then extracted from base elevation data (Fig. 42), and the surveyed data were merged into the extracted cross sections (Fig. 43). Vertical registration along each trace was automated by matching the deepest point of survey data to the configured thalwag from the center channel line imported from ArcGIS to WMS. Qualitative error analysis from the systemic GPS error is between 1 to 15 feet, depending on the survey site.

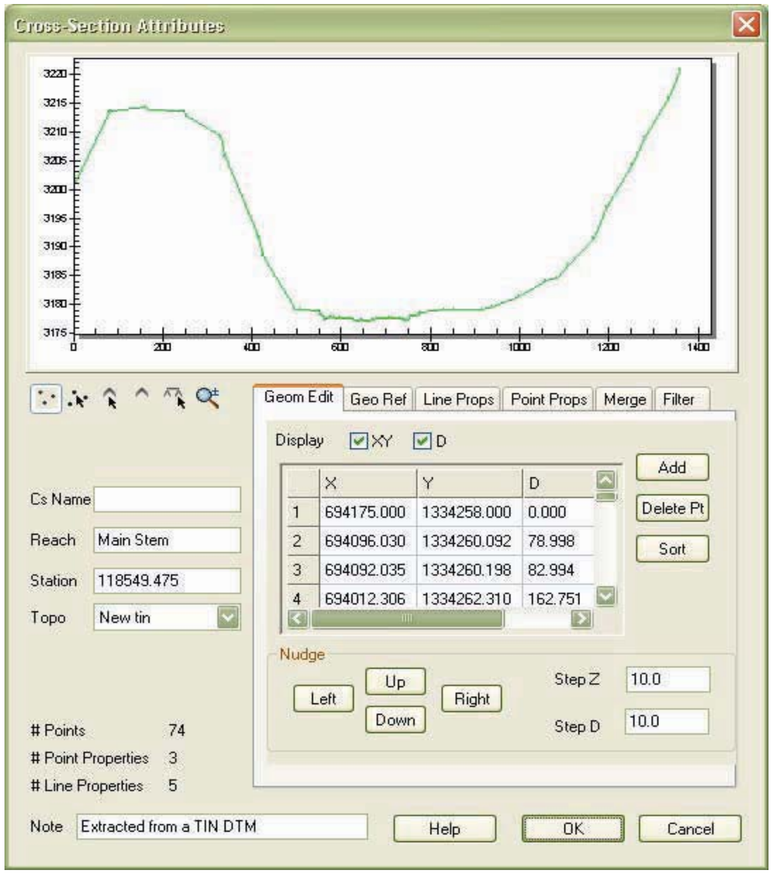

Figure 42 - Example cross-section extracted from elevation map of study area.

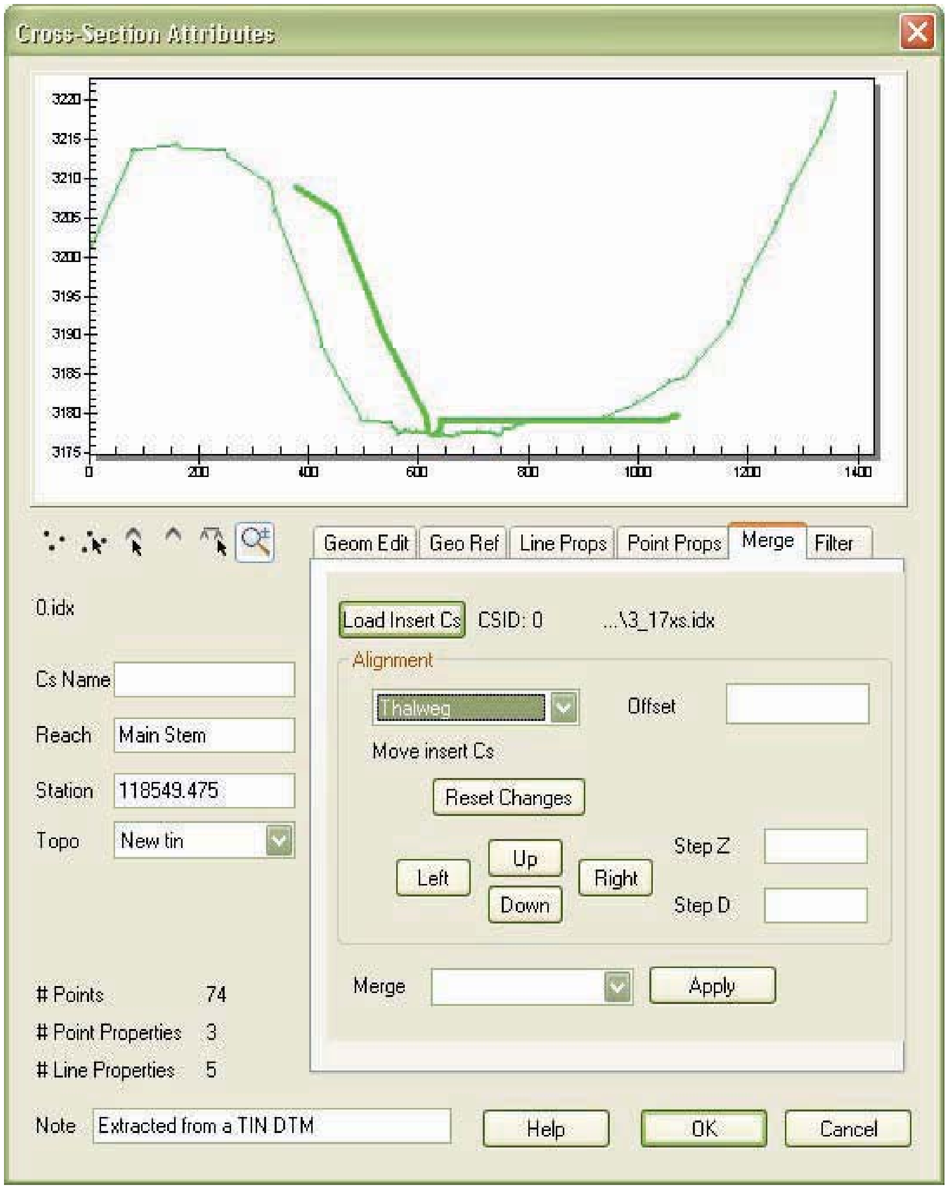

Figure 43 - Example cross-section merging survey data with TIN-extracted data.

Chapter 5 - Laboratory work

Several different options existed for developing an elevation model for the base of the hydraulic model framework, including USGS seamless DEMs, LiDAR flyover data from Yavapai County Flood Control District, and contours derived from the LiDAR data. The LiDAR data in its raw state as an ASCII point file was much too dense to process without dedicated workstations with terabyte scale memory, as well as difficult and cumbersome to transfer. A contour shapefile compatible with ArcGIS was delivered from Yavapai County Flood Control District, but the contour data lost resolution when converted into a point shapefile to be compatible with WMS. WMS has an automated "get data" tool that imported USGS DEM data (1/3 arc second resolution) within defined boundary coordinates. This tool provided the best resolution data with minimal processing, and provided a good land surface representation outside of the river channel. Bathymetric data for the Verde River are nonexistent, so detailed channel surveys were necessary for HEC-RAS cross-section profiles. The elevation data from the surveyed cross-sections were merged within WMS with the cross-section elevations extracted from the USGS seamless DEM surface. The survey profiles combined with the DEM data provide detailed cross-sections for the study reach both within the channel and the floodplain (Fig. 44).

5.1 Hydraulic model

The adopted hydraulic model was the US Army Corps of Engineers (USACE) Hydrologic Environmental Center River Analysis System (HEC-RAS), version 4.0 (USACE, 2009). Aquaveo Watershed Modeling System (WMS) (AquaVeo LLC, South Jordan, UT) was chosen as software that would facilitate data exchange

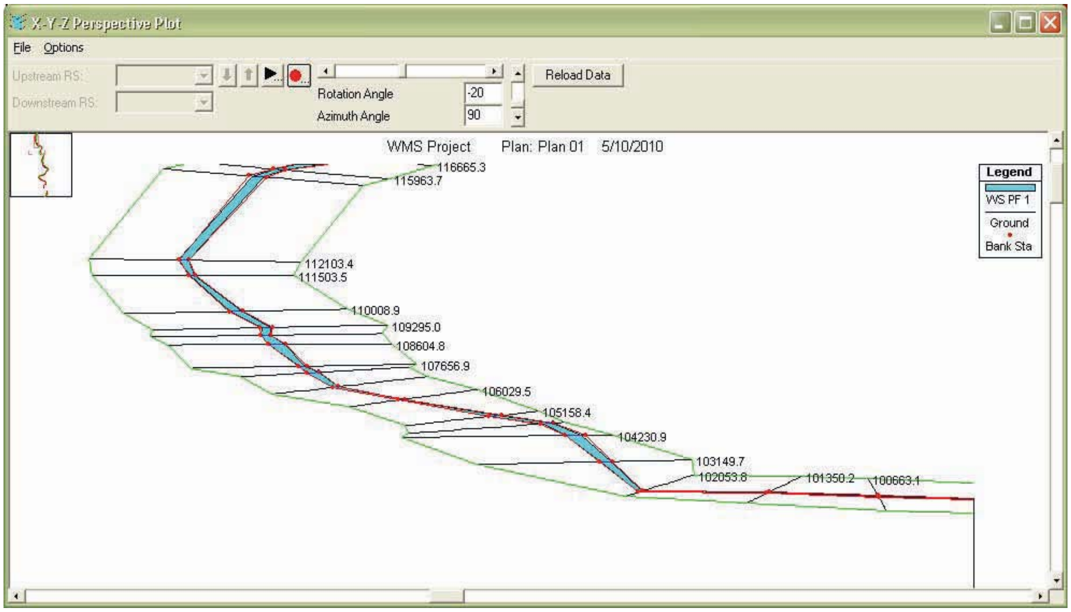

Figure 44 - Hydrologic environmental center river analysis system (HEC-RAS) output of channel detail in x-y-z profile plot for hydraulic model area.

between the project GIS and the HEC-RAS hydraulic simulation engine. Additional benefits of the WMS platform include: seamless future merging of the HEC-RAS model with other hydrologic, watershed, and drainage models. Aquaveo provides WMS upgrades that include HEC-RAS allowing water surface elevation profiling, point attributed flow change locations, enhanced GIS/HEC-RAS interoperability, and greater interaction in solution reading.

5.1.1 Hydraulic model framework

The WMS model base was created using Aquaveo's proprietary data search tool to retrieve a USGS DEM elevation model with 1/3 arc second resolution, along with TerraServer topographic and aerial orthophoto maps. The DEM model was converted into a TIN model, which is the elevation model compatible with WMS cross-section extraction.

A HEC-RAS model requires the following data: Thalwag, channel boundaries, cross-sections with elevation data, channel lengths along thalwag (right and left overbank distances) material property coverage (in this case Manning's roughness coefficient values), and boundary conditions (flow data and flow change locations due to flow diversion, return flow, and tributary input).

WMS uses a project explorer sidebar similar to the content index in ArcGIS, with organized layer tabs. These tabs include elevation data, coverages, images, hydrologic and hydraulic tree (operational schematics of system data), 2-D scatter points, and GIS features. Flows for boundary conditions were compiled from USGS/SRP stream gauge data (monitored at the Verde River at Clarkdale, below Camp Verde, at the Verde Falls low-flow gauge, Oak Creek near Cornville, Beaver

Creek near Montezuma Well, and West Clear Creek) (App. E), as well as discharge calculations at the diversions and return flows of the four irrigation ditches along the study reach (App. B).

HEC-RAS geometric input data including: thalwag, channel boundaries, model area, and cross-sections were developed in ArcGIS. Tributary and irrigation ditch spatial data were also used to specify flow change location stations in HEC-RAS. These geometric data were each made active and mapped to correlating feature coverages within WMS. In WMS, a series of feature coverages were created in the project explorer sidebar. These coverages were all given an appropriate coverage attribute, such as 1D-Hyd centerline, 1D-Hyd crossection, materials, or generic arc.

The river data were made into three centerline coverages; one each for thalwag, right bank, and left bank. These coverages are stored within WMS as feature arcs, the WMS format for a polyline file. In each case, the feature arcs were attributed with the corresponding data from the GIS coverages. The bank arcs and the centerline coverages were attributed as 1D-Hyd centerline feature arcs, with the sub-attribution of centerline and bank applied to each one as relevant.

The cross section coverage was initially mapped to the 1D-Hyd cross-section feature class, but a bug in the WMS program listed the arcs in a non-sequential order. In this case, the cross-sections were traced as feature arcs over the GIS coverage, and were expanded to ensure intersection of the cross sections with the bank and materials coverage. This ensured that the left and right overbank lengths automatically populated when exported to HEC-RAS.

The DEM downloaded via the data retrieval tool was converted to a TIN format using an internal command within WMS; evenly spaced point nodes were connected so that they would be recognized as triangulated by the river tools module. The GIS polygon bounding the study area was imported and mapped to the materials feature coverage. The outline of the model area was then appended with the channel boundaries, and the resulting feature arcs were then built into a polygon. Each area within the polygon was attributed with an appropriate land coverage type; river, floodplain, and agricultural. Each subdivided attribute was then associated with a general Manning's n value; 0.025, 0.15, and 0.05, respectively. The Manning's coefficient values were based on general published values (Chow, 1959) for the floodplain and agricultural areas, and on values specific to the Verde River (Yavapai County Flood Control District, 2010) for the river channel.

The river tools module for the cross section feature arcs was used to extract the cross sectional elevation data from the TIN dataset, as well as to order and georeference the channel stations. This extraction is done based off of the geometry of the thalwag of the channel, with bank location and materials properties also being embedded into the cross sections. A concern of hydraulic models vs. hydrologic models is to make sure that the channel computational direction along the centerline is from upstream to downstream, while in hydrologic models, the channel stationing is configured from downstream to upstream. The resulting cross section database was saved as an index file for reference and organization (xs3_24.idx) (App. F). The channel survey data were adjusted in Excel from depth to channel bottom to elevation of channel bottom, and were then saved as a series of text files in an index database (xs3_30.idx) (App. F) with cross section numbers corresponding to the cross section numbers within the first index file (xs3_24.idx).

The survey data were merged into the extracted cross section using the merge command tab within the edit cross-section database function within WMS. The survey cross-section was merged using the thalwag coverage as alignment (i.e., the thalwag of the survey was matched to the thalwag centerline coverage of the TIN extracted cross-section (Fig. 43). Point properties were individually verified and adjusted to accurately represent right and left channel banks, and channel thalwag (Fig. 45). Line properties were also examined to ensure appropriate distribution of roughness coefficient along the breadth of the cross-sections (Fig. 46). The materials list was selected in the project editor, and the values for the materials distribution properties were set to defaults matching the estimated roughness coefficients. The channel centerline was then made active in the project explorer, and a 1-D network schematic was created for the centerline, channel boundaries, and cross-sections (Fig. 47).

5.1.2 Schematic model and river reaches

The schematic model included three river reaches, separated by flow change locations at two tributary inputs into the main stem of the river (Beaver Creek and West Clear Creek) (Fig. 48). The resulting operational data were then exported as a HEC-GeoRAS file to HEC-RAS 4.0. The export from WMS automatically opens a HEC-RAS window on the computer, and creates a HEC-RAS model (Fig. 49). Cross-sectional locations corresponding to diversions, return flows, and tributaries were noted for development of flow change locations. This point-specific structure allowed

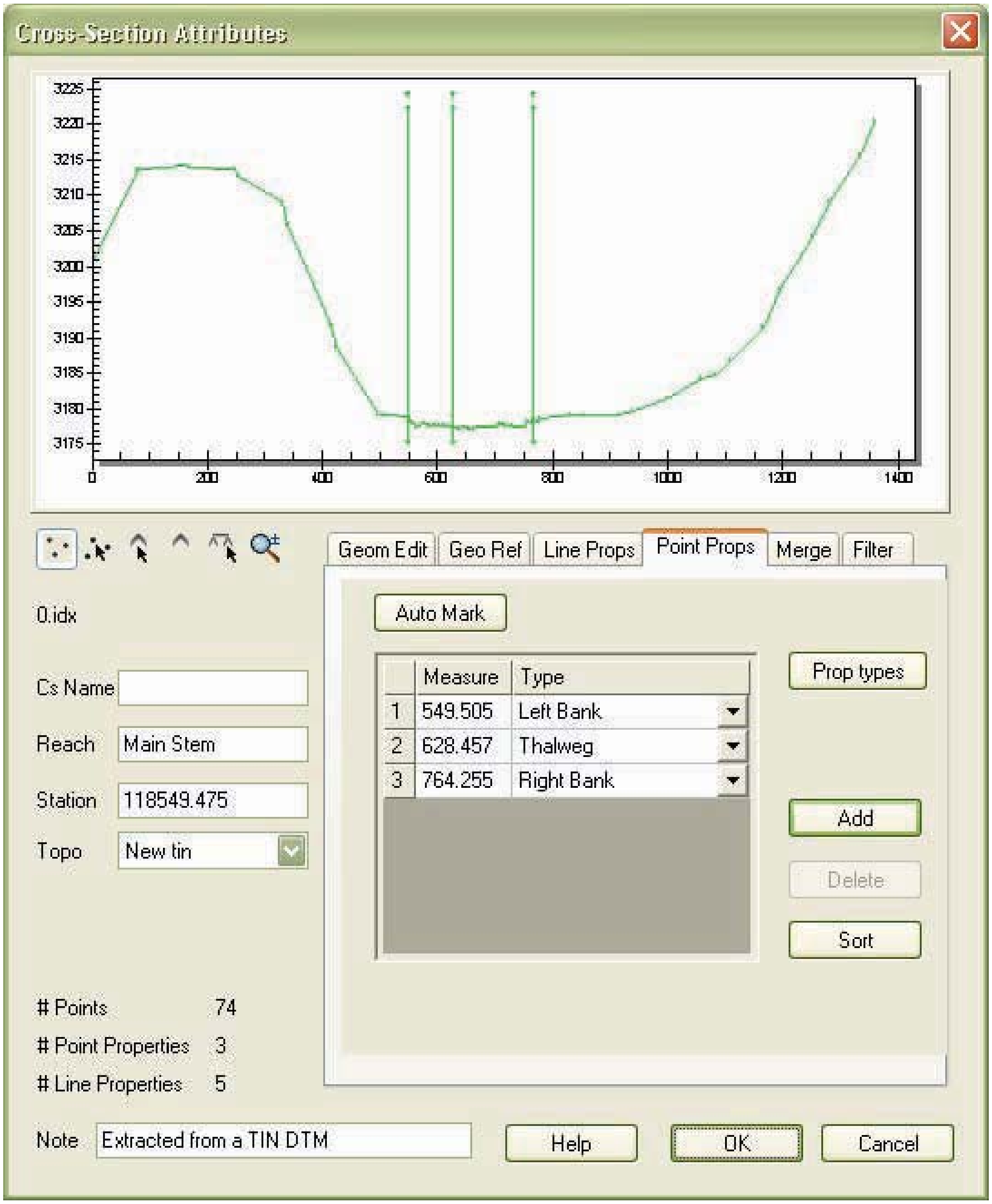

Figure 45 - Example cross-section showing point property adjustments for separation of frictional coefficients.

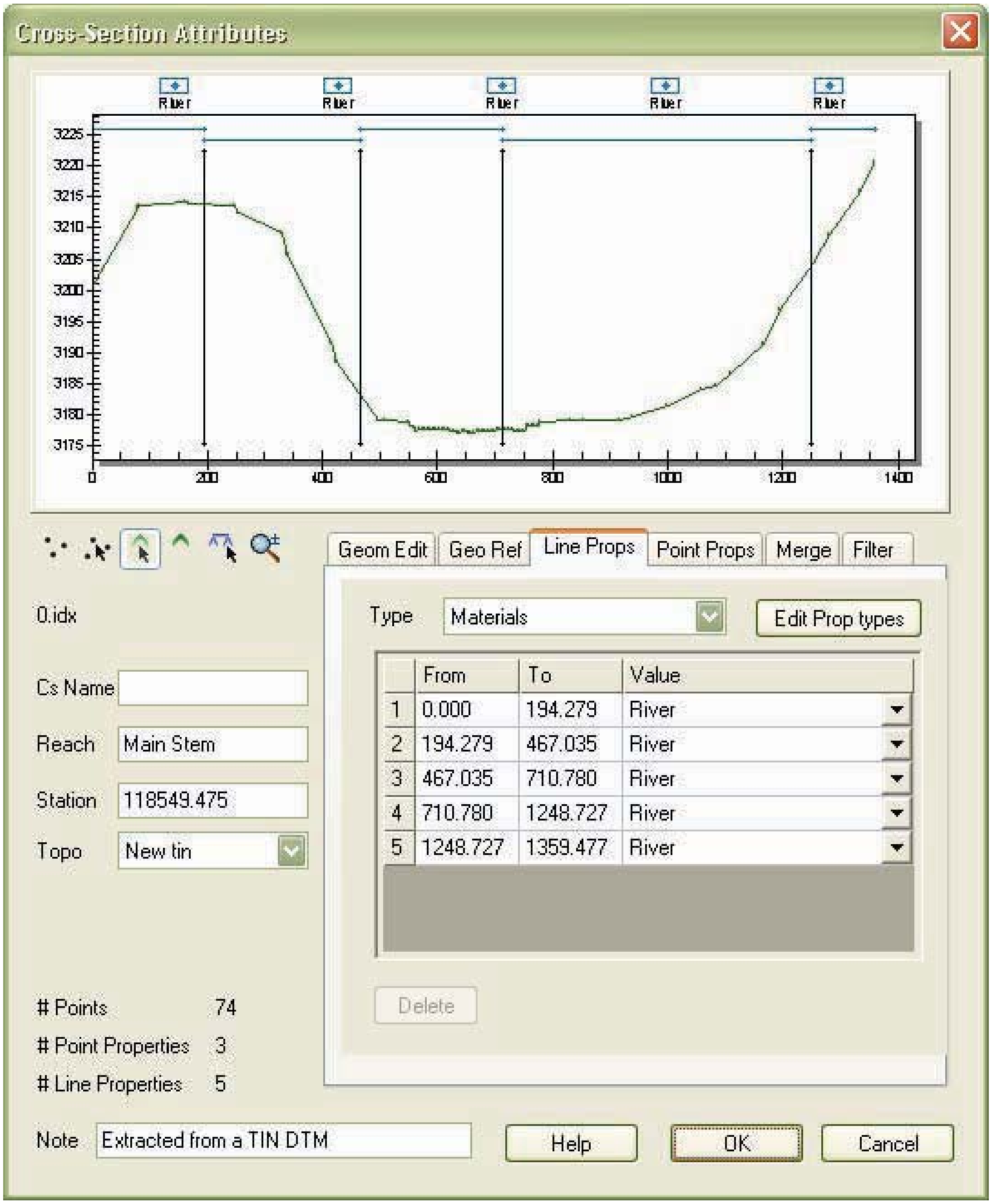

Figure 46 - Example cross-section showing line property adjustments for placement of channel properties such as thalwag and channel banks.

Figure 47 - One dimensional network schematic for operational data of HEC-RAS model.

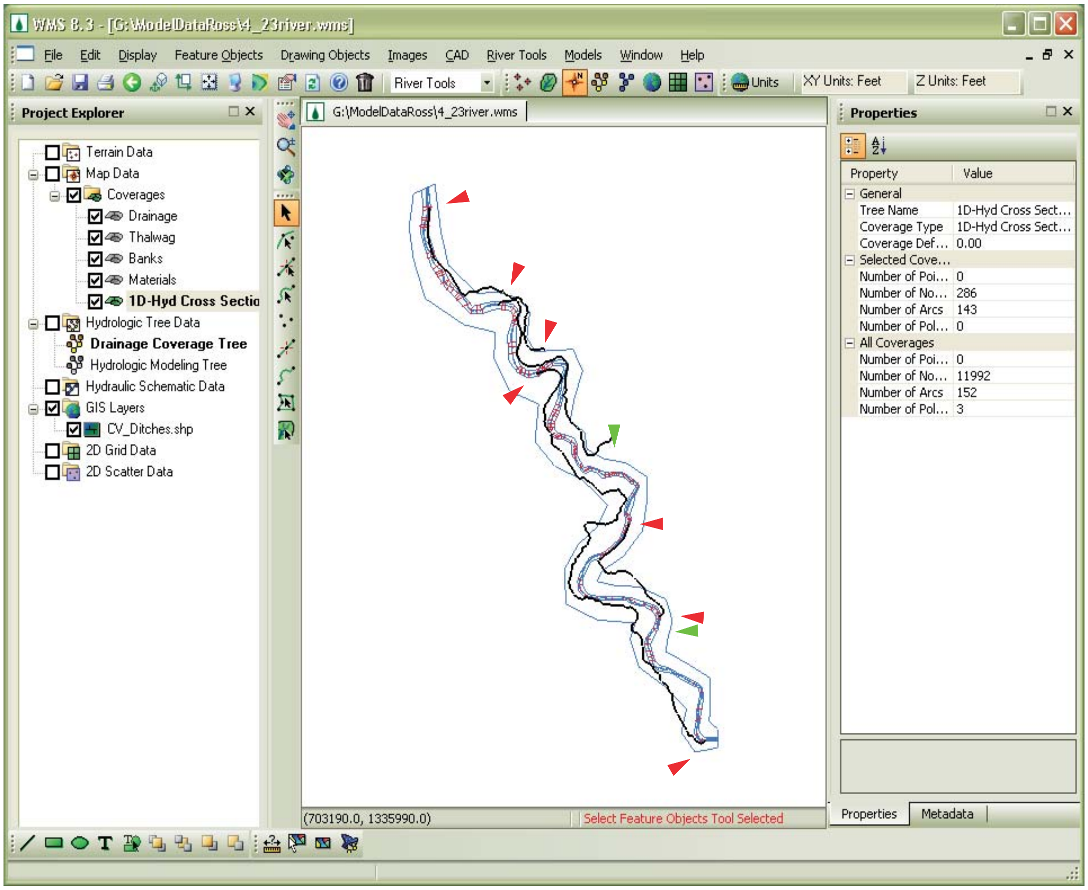

Figure 48 - Location of flow changes within one dimensional model coverage.
Red arrows indicate flow change due to ditch diversion and return flow,
and green arrows are flow change due to tributaries.

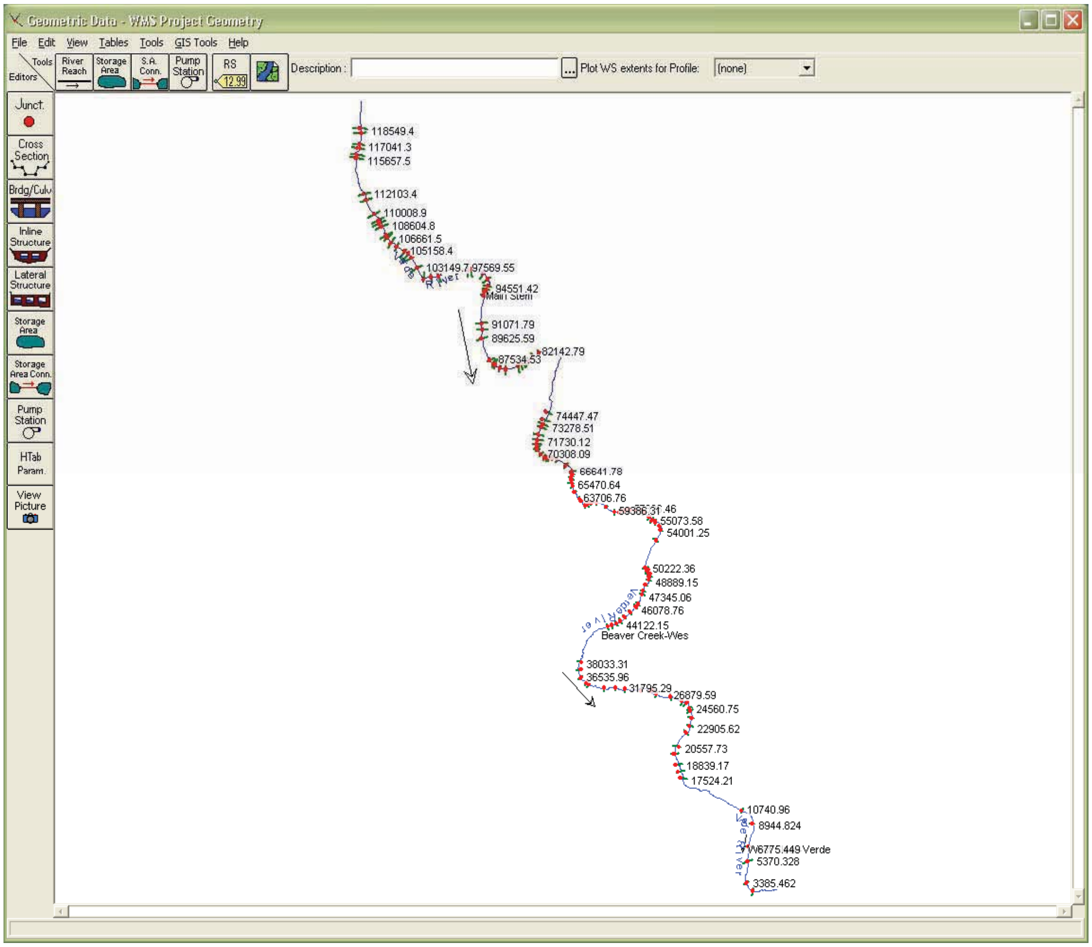

Figure 49 - Model geometry view of HEC-RAS model.

for one base model to be used for simulations of river flow with no diversions, one diversion at the top of the model area, and river flow including all diversion information.

5.1.3 HEC-RAS Model Construction

After data portage from WMS to HEC-RAS, the HEC-RAS model was arranged and optimized for different numerical solutions. Flow change locations existed in the HEC-RAS model at the three points of reach change, corresponding to tributary locations (Fig. 50). Flow change locations (Fig. 50) based on the location of irrigation diversions and return flows were added in the boundary condition editor within HEC-RAS. This can be done within WMS prior to portage, but arranging flow change locations within HEC-RAS adds flexibility to stipulate variable boundary conditions to examine different model objectives.

The HEC-RAS model was initially run at a steady-state condition with an arbitrary low-flow condition to flush out errors. Boundary conditions for flow were configured based on normal depths, with channel slope from the first two and last two cross-sections for each reach used to establish normal depths.

In some cases, the WMS porting to HEC-RAS duplicated a cross-sectional point, failed to populate an overbank distance, or failed to populate a material property. Bank station alignment was also sometimes misread by HEC-RAS. The initial run was done to flush out these types of problems. All errors were examined, and were addressed either in the base WMS framework, or corrected in HEC-RAS, depending on whether the error was due to a communication issue between the programs or an error in schematic construction. Lingering issues after making

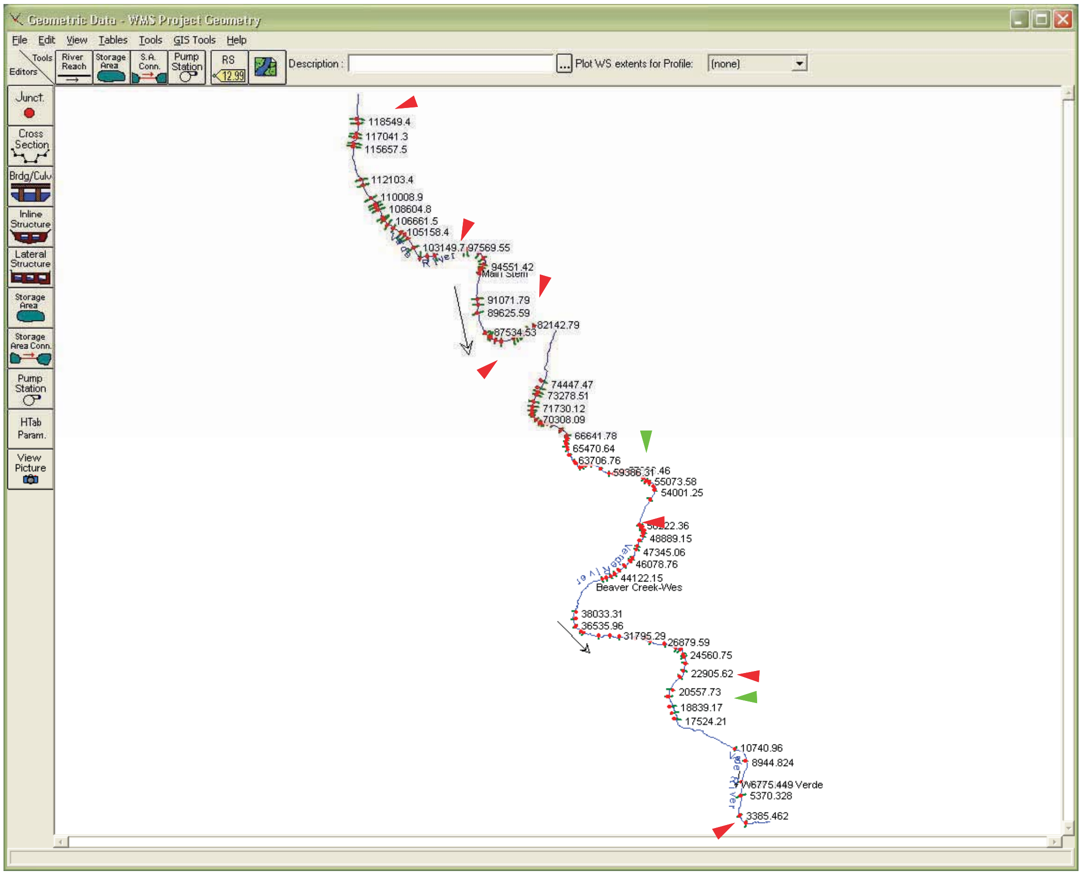

Figure 50 - Location of flow changes within HEC-RAS model. Red arrows indicate flow change due to ditch diversion and return flow, and green arrows are flow change due to tributaries.

corrections in WMS tended to involve duplicate points and overbank measurements (persistent errors consisted of two duplicate points and one missing overbank length over the model reach). The initial flow used for exposing errors was a low flow measurement based on USGS stream gauge data for the Verde River near Clarkdale and Oak Creek near Cornville (gauge numbers 09504000 and 09504500); the modeled channel should contain all flow at this discharge (82 cfs). Any cross-sections showing overbank discharges were reexamined and were adjusted in WMS for elevation and overbank extents.

Given that the field survey data were collected with a handheld GPS unit, the potential for elevation error was up to +/- 15 feet. In general, the cross-sections showing pooled or overbank flow were either lower than surrounding stations, or skewed by a cross-section upstream or downstream resulting in an interpretation of ponding where such an interpretation was not seen in the system (Fig. 51). All inconsistent cross-sections were examined relative to neighboring station data, and were adjusted up or down as appropriate to constrain the flow. In some cases, overbank elevations were raised to relegate flow to the channel as well. All elevation adjustments were within the range of reported GPS unit error. Initial model construction was deemed complete when flow behavior in the channel was entirely constrained and compared favorably to flow quantity observed during channel survey.

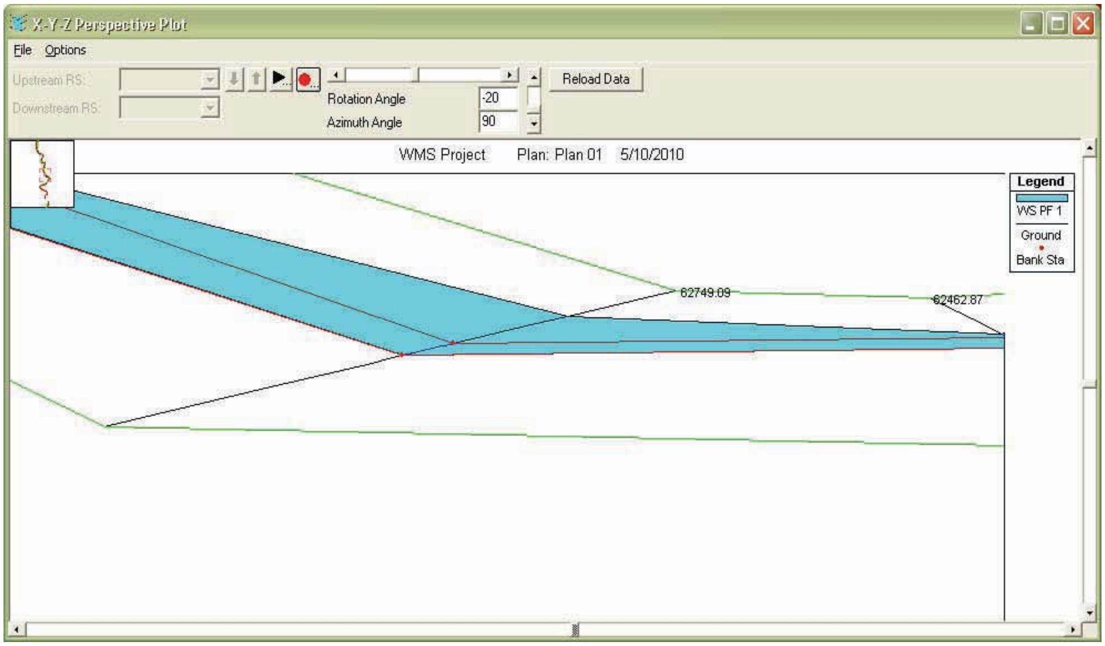

Figure 51 - Example of cross-section from HEC-RAS model showing overbank stage rather than low flow constrained by channel.

5.2 Analytical model calibration

5.2.1 Model application

The initial application of the model was to develop a numerical simulation of steady-state low-flow. Upstream and downstream boundary conditions were constrained at normal depth, and boundary flow was determined by the applicable stream gauge data and flow changes from ditch diversion and return flow. The data used for these boundary conditions were from June 22^{nd}-23^{rd}, 2009; this period was of sufficiently steady low-flow for the analysis.

Initial flow input to the system was determined to be 82 ft^3/s (combined discharge of the Verde River near Clarkdale and Oak Creek near Cornville), and the discharge was adjusted at each flow change location to account for ditch diversion, return flow, and tributary input. Calibration of the low-flow model consisted of running the model with calculated flow changes, and examining simulated discharge (Fig. 52) for value similar to observed discharge over reaches of relatively constant discharge (minimal deviation from defined flow), as well as examining top width and velocity variation over the study reaches. The calculated discharge at the terminal cross-section (at the end of the model reach downstream of the Verde return flow) was also compared to the USGS Verde Falls low-flow gauge with good agreement found. The observed discharge at very few locations deviated significantly from calculated discharge; all were within 0.5 ft^3/s of the calculated value. The steady-state model was then run through a series of 1000 random iterations (Monte Carlo simulation) to generate a measurement of systemic error, which is minimal (R^2 value of 0.99). All output was within 0.01% of output of other simulated runs.

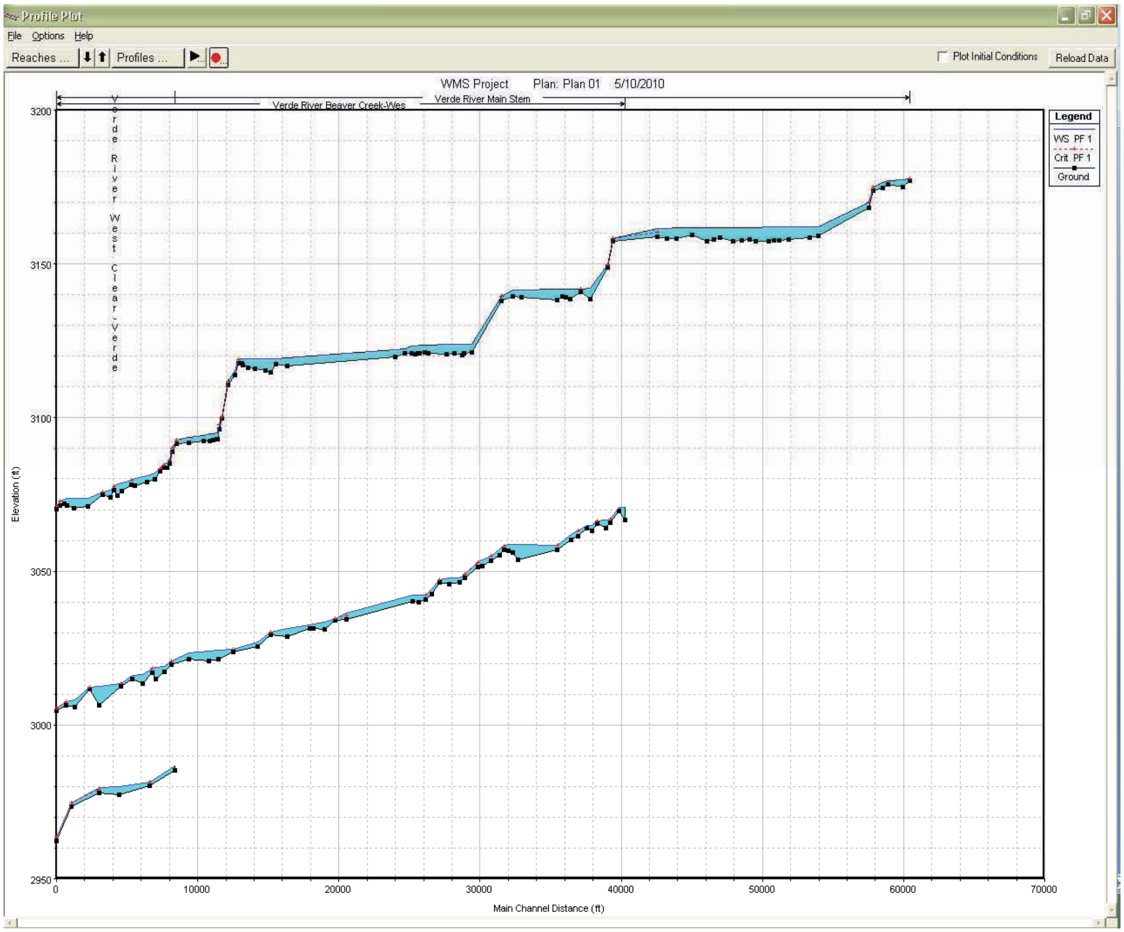

Figure 52 - Profile view of HEC-RAS steady-state model output for study reach of middle Verde River, Camp Verde, central Arizona.

5.2.2 Analytic model output and post-processing

The steady-state simulation results include discharge as well as hydraulic parameters such as velocity, flow area, channel area, top width, wetted parameter, and hydraulic radius. The water surface elevation is displayed for each cross-section, as well as interpolated between cross-sections for the water surface profile view of the study reach (Fig. 52). The steady-state low-flow model was arranged with no diversions, one diversion, and all diversions to show changes in river conveyance based on disruption by diversion structures. The effects of one diversion are important to examine the detailed change based on one individual variable, and the effects of all four irrigation ditches are required to simulate the overall structure, interactions, and attendant change of the system relative to the condition of no diversion.

The values of the hydraulic parameters (e.g., hydraulic radius, velocity, top width) delineate the manner of flow in the channel, and display differences based on the downstream effects of diversion (i.e., change in velocity and wetted area). Additional parameters such as the Froude number (gauging stream power) can possibly be used to identify locations of pool-riffle-run sequences within the channel. The HEC-RAS output data can be read back into WMS for post-processing, where water surface elevation, stage/discharge rating curves can be extracted, and the corresponding flood boundaries can be displayed in map form.

<u>Chapter 6</u> - Similar study areas

Irrigation ditch systems are common in the western US. Complex large-scale systems are well documented in Colorado, Utah, New Mexico, Nevada, and California, as well as in Arizona. Several of these systems have much in common with the Verde Valley system; most of these have been engineered and developed for better efficiency and to maximize associated river flows. The middle Rio Grande River Valley acequia systems of New Mexico have the greatest similarity to the Verde Valley. Here; I review specific solutions for maximizing diversion system efficiency in the Rio Grande river valley.

The following is from Gensler, et al. (2009) unless otherwise noted. The Middle Rio Grande Conservancy District (MRGCD) was officially founded in the 1920s, but was based on irrigation systems created by the Spanish in the 1600s. The district irrigates 22,300 ha of land, and the ditch system supports extensive riparian vegetation and helps with flood control by routing excess stormwater discharge downstream. The middle Rio Grande valley stretches north to south over 322 km from the Cochiti Reservoir to the Elephant Butte Reservoir, and includes Albuquerque as well as several smaller municipalities. Irrigation in the area peaked in the 1800s, and then declined as agricultural demand diminished. In the 1960s, demand increased due to rapid population growth. In 1996, the system experienced a drought crisis, and was evaluated for modernization. At the time, water was delivered by the manual opening of gates for scheduled intervals, and only 15 gauges (generally from weirs with physical measurements developed by stage/discharge relationships) were operating on 1,930 km of canals. The system was modernized by adding flow measurement structures, automated control structures, instrumentation, telemetry, and software. Gauges were initially added at diversion and return flow points, and the results showed areas within the system in need of more instrumentation. The Bureau of Reclamation's WINFLUME software was used to design site-specific flow gauging stations. Automated control structures are mostly Langemann overshot gates, with solar panels powering both gates and telemetry units. Flow is calculated with stage data measured with submersible pressure sensors or sonar sensors, depending on site characteristics. Telemetry uses FM frequency radio signals to transmit to and from MRGCD headquarters, with a dedicated computer used as a master data logger. Significant reductions in diversion necessary for irrigation have been seen since implementation of the modernized system, cutting diversion nearly in half (7.4×10^8 m^3/yr to 4.3×10^8 m^3/yr). This decrease in diversion has helped to maintain reservoir storage, decreasing the effects of drought in the Rio Grande river valley.

A decision support system (DSS) was developed by the MRGCD to optimize diversion for the area, and has met with some success. The following section draws directly from Oad et al. (2009). The DSS simulates water demands, the irrigation network, and the scheduling of irrigation. The DSS draws on engineering models, field data, a GIS, and graphical user interfaces. The purpose of the DSS is to define the best routing of water supply in the main channel to meet predicted/scheduled demand while minimizing diversion volume. Demand is calculated by examining acreage of irrigation, with specific demands of crop structure. Important parameters and variables are timing, duration, and interval of irrigation. Simulations indicate that diversion in the MRGCD system can be further reduced, while still providing necessary irrigation.

Chapter 7 - Results and Discussion

7.1 Results

7.1.1 Ditch instrumentation

All four irrigation ditches were monitored for differing time intervals (Table 8). For each instrument, hourly stage data were corrected to measured levels (App. B), and were then converted to discharge with a rating curve of measured stage to discharge (App. C). These data were then processed into mean daily flow (App. D). Values for flow conveyed past the headgates of the ditch were generally consistent, and average values are in good agreement with reported values from past measurements and reports (Table 6). Errors were calculated as percent deviation from mean values and measured values, and are reported as R^2 deviance from linear regression fitted to rating curves (Table 10). Error was propagated across calculations by taking the square root of the summation of all errors individually squared. Mean daily flow data for ditches reflects changes in seasonal ditch consumption and events such as closure for maintenance and rapid flows.

OK Ditch

The OK Ditch was monitored from March 2009 to May 2010. It was instrumented at a concrete weir near its headgates and at a siphon after its terminal water user. Average discharge at the head was 16.37 ft^3/s, and average discharge at the terminus was 6.22 ft^3/s. Maximum head and terminus values were 24.66 and 8.46 ft^3/s, respectively. The error propagated across R^2 values from the rating curve corrections and inherent instrument error was 0.50 at the head and 0.54 ft^3/s at the end, with respective deviations from mean of 3.8% and 8.6% (Table 10). The measured values of discharge at the OK headgate differ from instantaneous calculated values by 11%, and differ from the mean daily values for the dates of measurement by 8% (Table 11). Measured values at the OK return flow vary from instantaneous measurement by 8% and from mean daily calculated values by 9% (Table 11). The OK Ditch consumes a modest portion of the water it diverts, with a 10.15 ft^3/s drop between average values over the study period (Fig. 53).

Eureka Ditch

The Eureka Ditch was monitored from October 2008 to May 2010. It was instrumented at a concrete flume above its first water user and at a gate across a culvert at its terminal water user. Average flow diverted into the ditch was 9.13 ft^3/s; with an average return flow of 3.70 ft^3/s. Maximum discharge was 15.70 ft^3/s at the head and 6.22 ft^3/s at the return. Propagated error for the head and return was 0.07 and 0.45 ft^3/s, with deviations from mean of 0.7% and 12.1% (Table 10). Measured values at the Eureka head vary from instantaneous calculated values by 1% and from mean daily calculated values by less than 1%. Measured values at the Eureka return flow vary from calculated instantaneous and mean daily values by 13% (Table 11). The Eureka Ditch consumes a considerable amount of its diverted flow, with the difference between average values of 9.48 ft^3/s (Fig. 54).

Verde Ditch

The Verde Ditch was instrumented in May 2009, and has been recorded into May 2010. An instrument was placed on the headgate structure, but was later moved to a water wing nearby after being displaced by heavy flow. The return flow instrument was fixed to a chain link fence near the return flow, downstream of

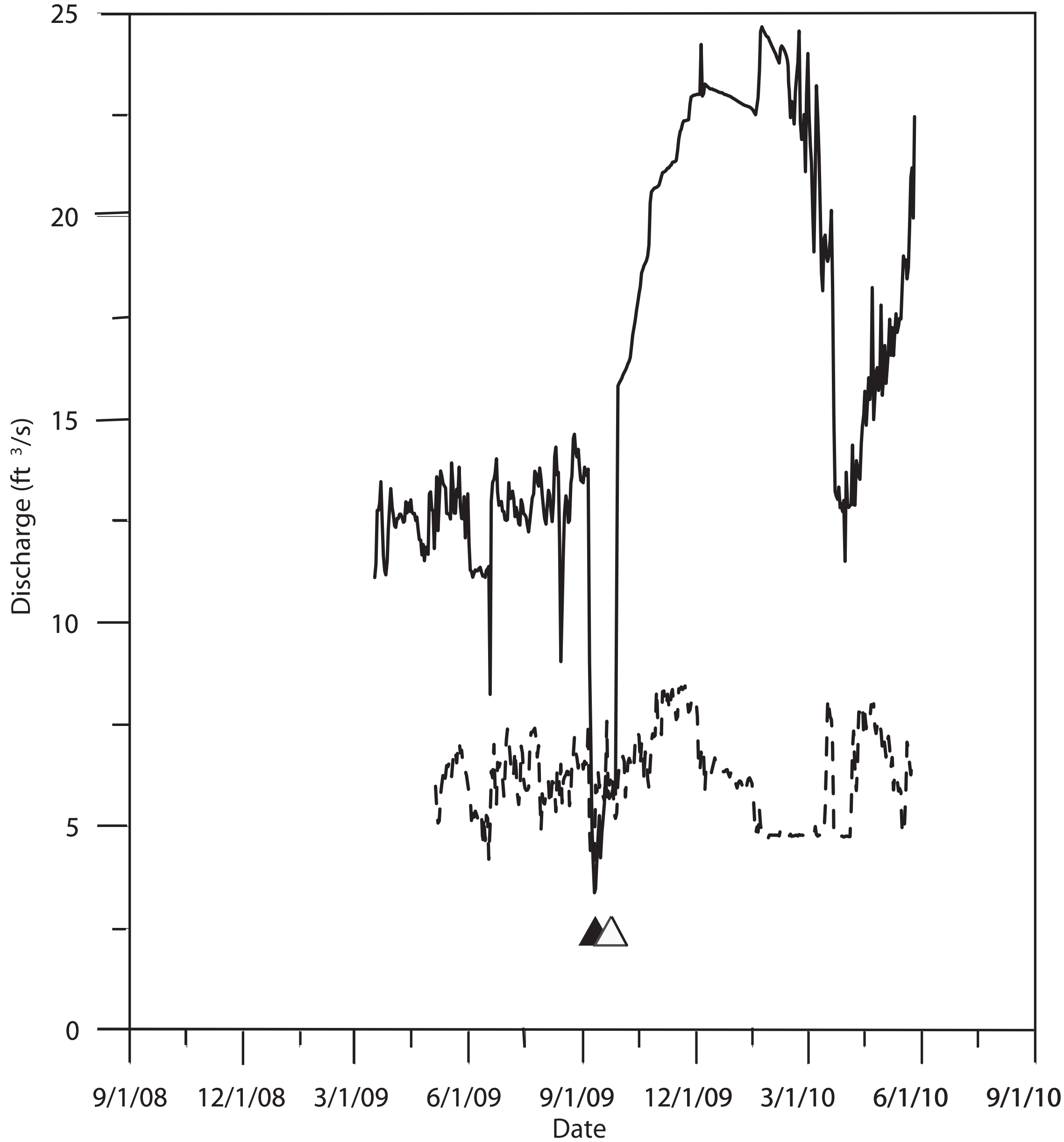

Figure 53 - Discharge and return flow of the OK Ditch, Camp Verde, central Arizona. Black arrow shows ditch closure, and white arrow shows resumption of operations. Solid black line is diverted flow, and dashed black line is returned flow.

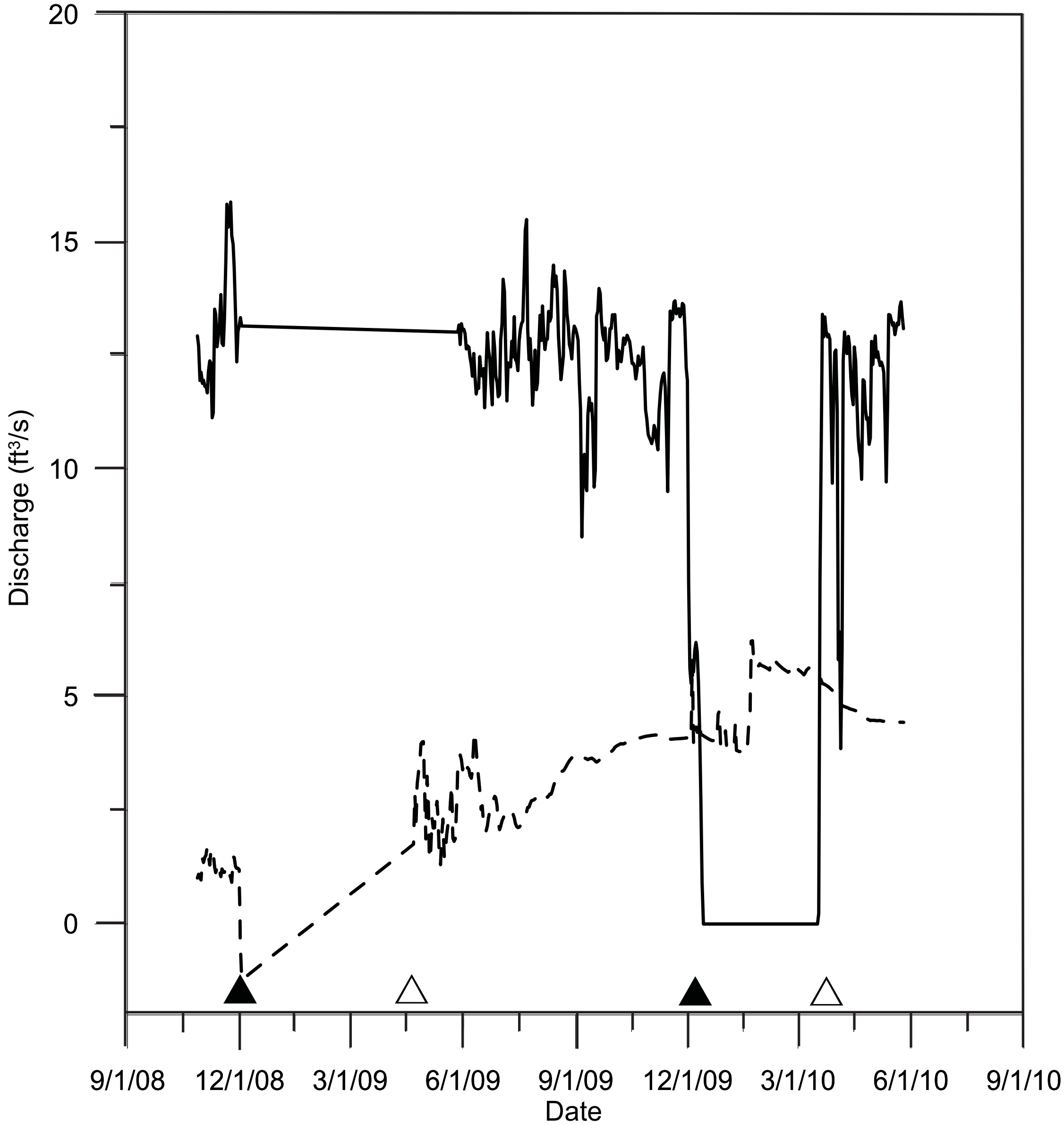

Figure 54 - Discharge and return flow of the Eureka Ditch, Camp Verde, central Arizona. Black arrows show ditch closure, and white arrows show resumption of operations. Solid black line is diverted flow, and dashed black line is returned flow.

the terminal water user. Average diversion was 26.35 ft^3/s; with an average return of 8.38 ft^3/s. Maximum flow at the headgate is 88.32 ft^3/s (likely a spike in the instrument from rapid drying), and maximum flow at the return is 16.94 ft^3/s. Propagated error for the headgate was 0.19 ft^3/s, with a deviation from mean value of 1%. Error for the return measurement was 1.18 ft^3/s, with a percent deviation from mean of 16.5%. This larger deviation is due to a measurement taken by SonTek meter that was at the low end of the instrument's tolerance; otherwise, mean deviation is less than 4% (Table 10). Measured values at the Verde headgate differ from instantaneous calculated values by less than 1% and from calculated mean daily values by 1% (Table 11). The Verde Ditch consumes much of its diverted flow, as it often runs dry at the terminus. Average consumption is 17.92 ft^3/s (Fig. 55).

Diamond S Ditch

The Diamond S Ditch has been instrumented from November 2008 to May 2010. The head transducer is installed above the headgate in a concrete weir, and is attached to a concrete culvert at the terminus. Average diversion at the head is 26.25 ft^3/s; with average return of 20.55 ft^3/s. Maximum diverted and returned flows are 28.36 and 29.02 ft^3/s, respectively. Error for the head gate and return flow is 0.09 ft^3/s (0.3% deviation from mean) and 0.11 ft^3/s (0.05% deviation from mean) (Table 10). Measured discharge varies from calculated instantaneous and mean daily discharge by 1% at the headgate. The deviations at the return flow are 1% for instantaneous calculated values, and 9% for mean daily calculated values (Table 11). Average consumption is 11.15 ft^3/s (Fig. 56).

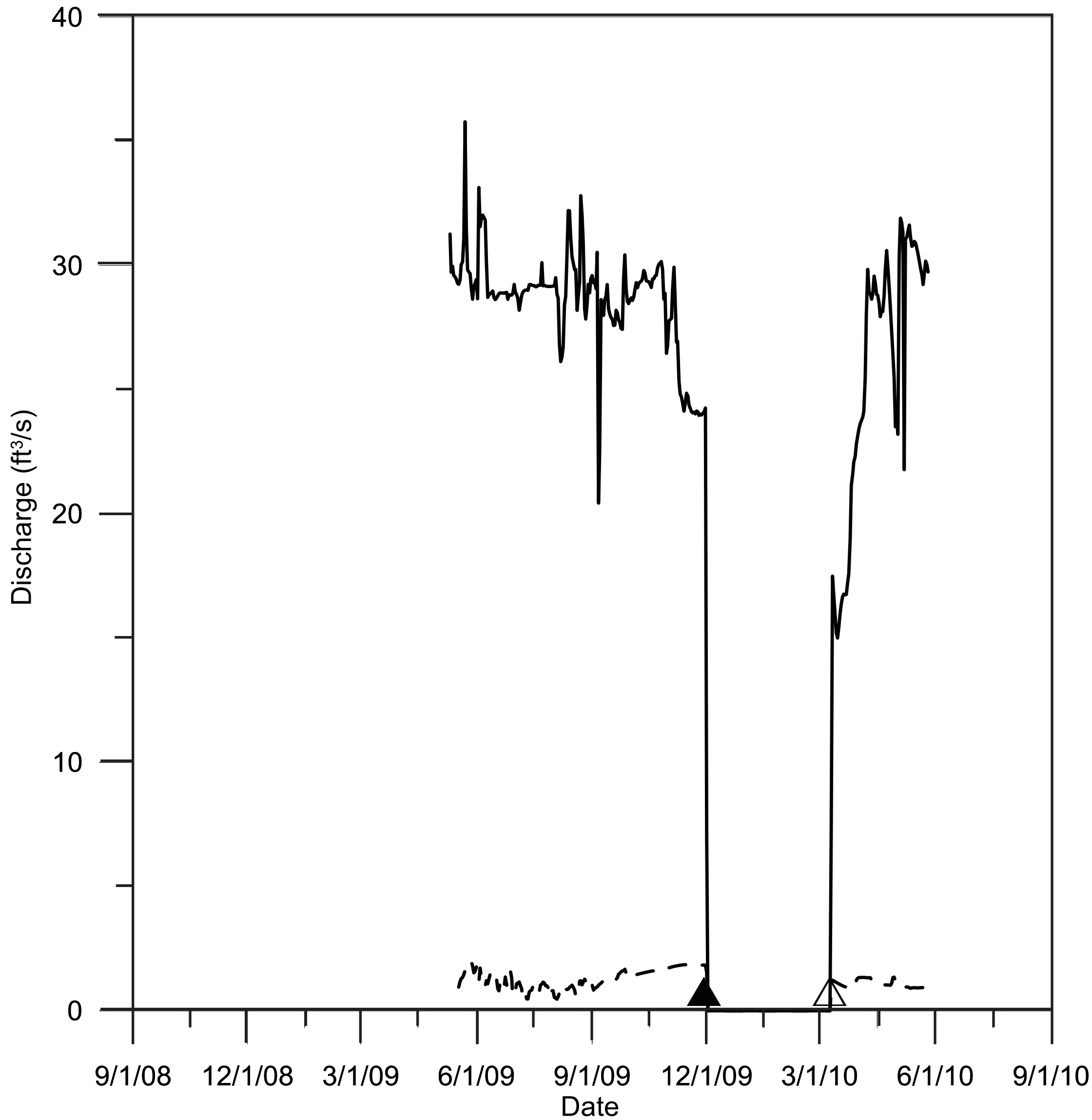

Figure 55 - Discharge and return flow of the Verde Ditch, Camp Verde, central Arizona. Black arrow shows ditch closure, and white arrow shows resumption of operations. Solid black line is diverted flow, and dashed black line is returned flow.

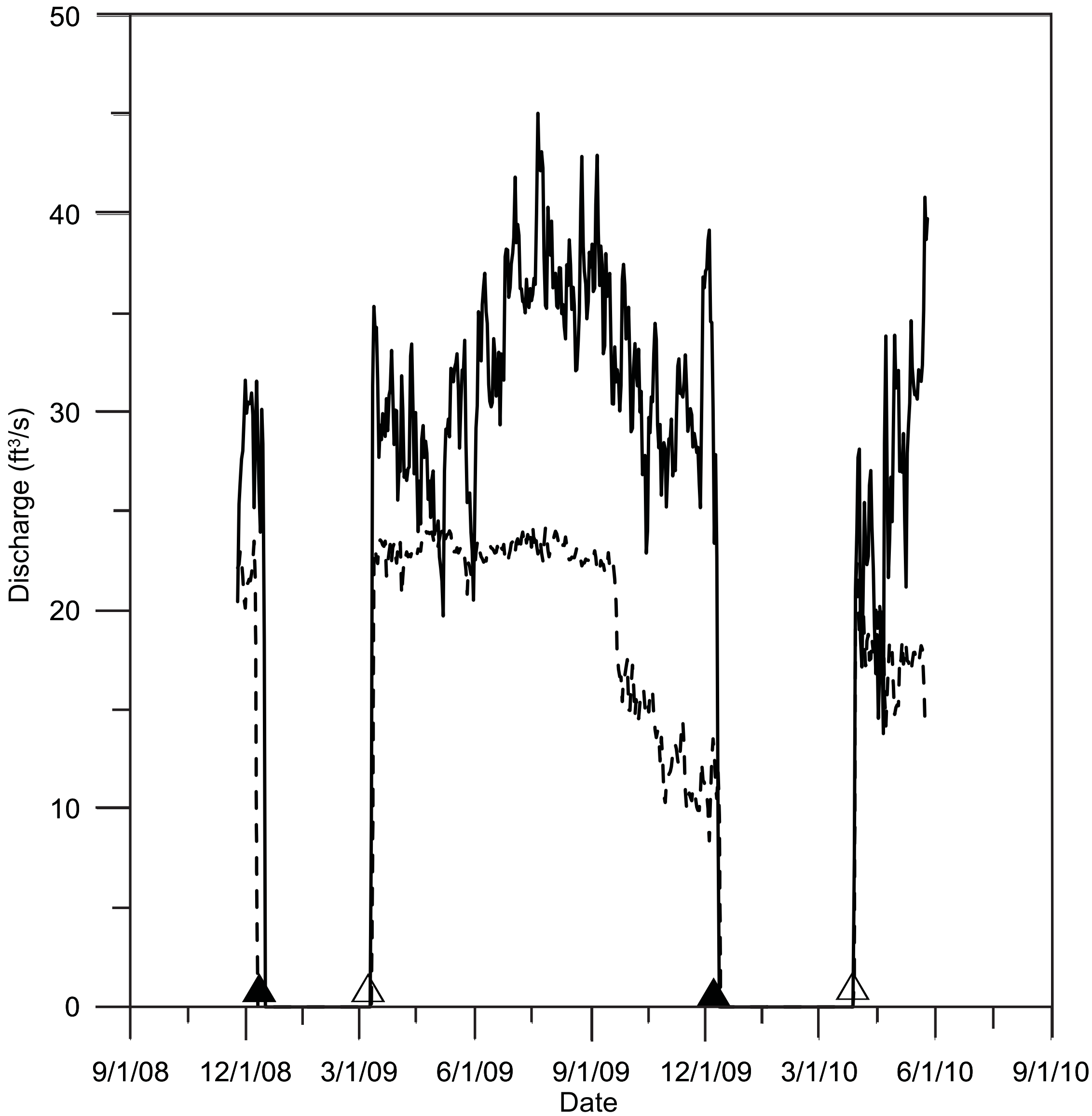

Figure 56 - Discharge and return flow of the Diamond S Ditch, Camp Verde, central Arizona. Black arrows show ditch closure, and white arrows show resumption of operations. Solid black line is diverted flow, and dashed black line is returned flow.

7.1.2 River and tributary flows

Flow and stage of the Verde River and its tributaries are measured by a series of USGS and SRP stream gauges; these measuring stations report discharge in all cases, and stage in some (App. E). Discharge reporting contains records of mean daily discharge in all cases, with maximum and minimum values intermittently reported at some sites. Flow varies widely at all gauges, with seasonal high values during summer monsoons occurring from June - August and winter storms centered during the months of January – March (App. E). Early June, prior to monsoon events, tends to yield the annual low values.

Verde River

Verde River data were collected at selected USGS gauging stations near Clarkdale (09504000), near Camp Verde (09506000), below Tangle Creek (09508500), and the seasonal Verde Falls low-flow gauge operated by SRP and the USGS (App. E). Note that the Verde Falls low-flow gauge is only operated during periods of seasonal low flow. The value of discharge at the Clarkdale gauge was used as a portion of the input flow for the HEC-RAS model along with flow data from the Oak Creek gauge. The sum of the two values was considered a close approximation to the total flow at the first model cross-section.

Oak Creek

Oak Creek is monitored at a gauging station near Cornville (9504500), which reports mean daily stage and discharge values (App. E). Discharge values range from around 20 ft^3/s at low flow to around 2000 ft^3/s during high flow events.

These data were used with measurements of the Verde River at Clarkdale to provide initial boundary conditions for the model.

Beaver Creek

Beaver Creek is monitored at a gauging station near Montezuma Well (09505400), which reports mean daily stage and discharge values (App. E). Discharge ranges from less than 1 ft^3/s at low flow to almost 10 ft^3/s during high flow events. Beaver Creek data are used for flow change input to the model at the separation between the first and second reaches.

West Clear Creek

West Clear Creek is monitored at a gauging station near Camp Verde (09505800), and reports mean daily stage and discharge, as well as maximum daily stage (App. E). Discharge ranges from around 15 ft^3/s at low flow to over 1000 ft^3/s during high flow events. West Clear Creek data are used as a basis for flow change data between the second and third model reaches.

7.1.3 Compilation of geospatial data

GIS data were compiled from several sources; where possible, data were edited to parameters available from remote sensing (aerial orthophotographs), and all data were organized into a common geodatabase in a common projection system. Several spatial statistics were updated, the most relevant of which was irrigation ditch attributes for ditch length and associated diverted flow (Table 6). Errors for these measurements are reported as possible visual variation from photo overlay; generally one meter to twenty centimeters (Table 7).

7.1.4 Model output

The steady-state model was configured with flow data collected on June 22nd and 23rd of 2009. This period was chosen because flow for the river, tributaries, and irrigation ditches was uniformly at a minimum, and stayed consistent for a period of a week or more. The steady-state simulations were run for the river system involving: undiverted flow, one diversion, and all diversions. Steady-state results included data for each cross-section along the reach, along with top width, channel area, flow area, velocity, hydraulic radius, flow area, etc.

Initial flow into the system was determined to be the sum of discharge of the Verde River at Camp Verde and the discharge of Oak Creek at Cornville. Irrigation ditch diversion and return flow and tributary input were added/subtracted from the running discharge total at each flow change location, with the final combined discharge value being in good agreement with the Verde Falls low-flow gauge (57 ft^3/s for the modeled value, 56 ft^3/s for the measured value). The model simulation was calibrated with known actual values of combined stream discharge by comparing simulated flow top width to observed cross-section survey top width (Fig. 57). In both simulations including either one or all diversions, simulated hydraulic parametric values such as velocity, top width, flow area, etc. decreased downstream of the diversion structures (Figs. 58, 59, 60, and 61). With all diversions simulated, hydraulic radius is reduced by 22%, flow is reduced by 47%, top width is reduced by 16%, velocity is reduced by 21%, and channel flow area is reduced by 34% relative to simulations with no diversions. Deviation of modeled data vs. measured data for the fully diverted model reach has an average value of 3%, which is statistically

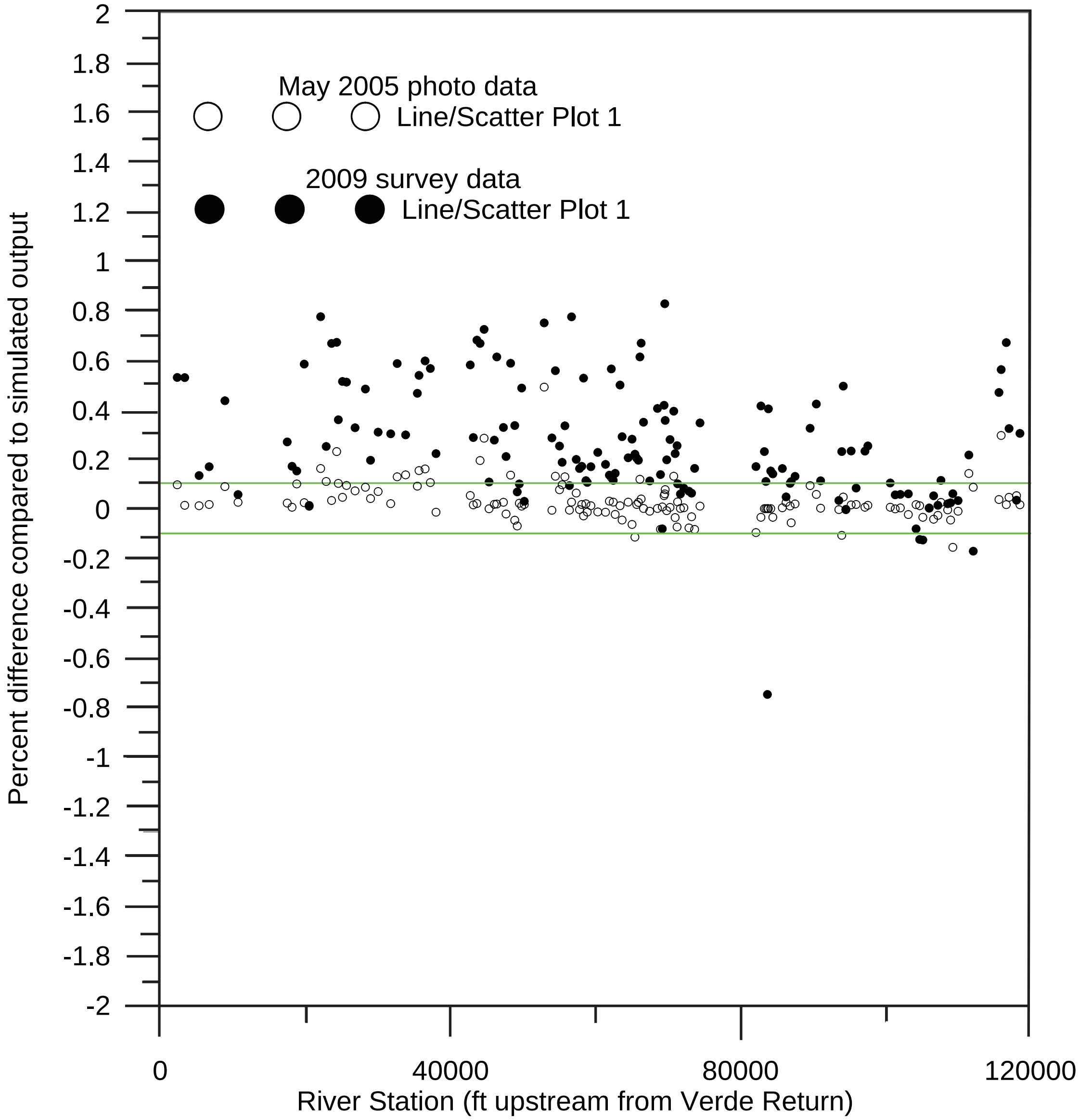

Figure 57 - Comparison of simulated channel top width to surveyed and remotely mapped top width. Reported values are percentage change between simulated and observed values. Green bars denote a ten percent error margin, with smaller differences observed from remotely mapped top widths photographed in May 2005, during low flow conditions.

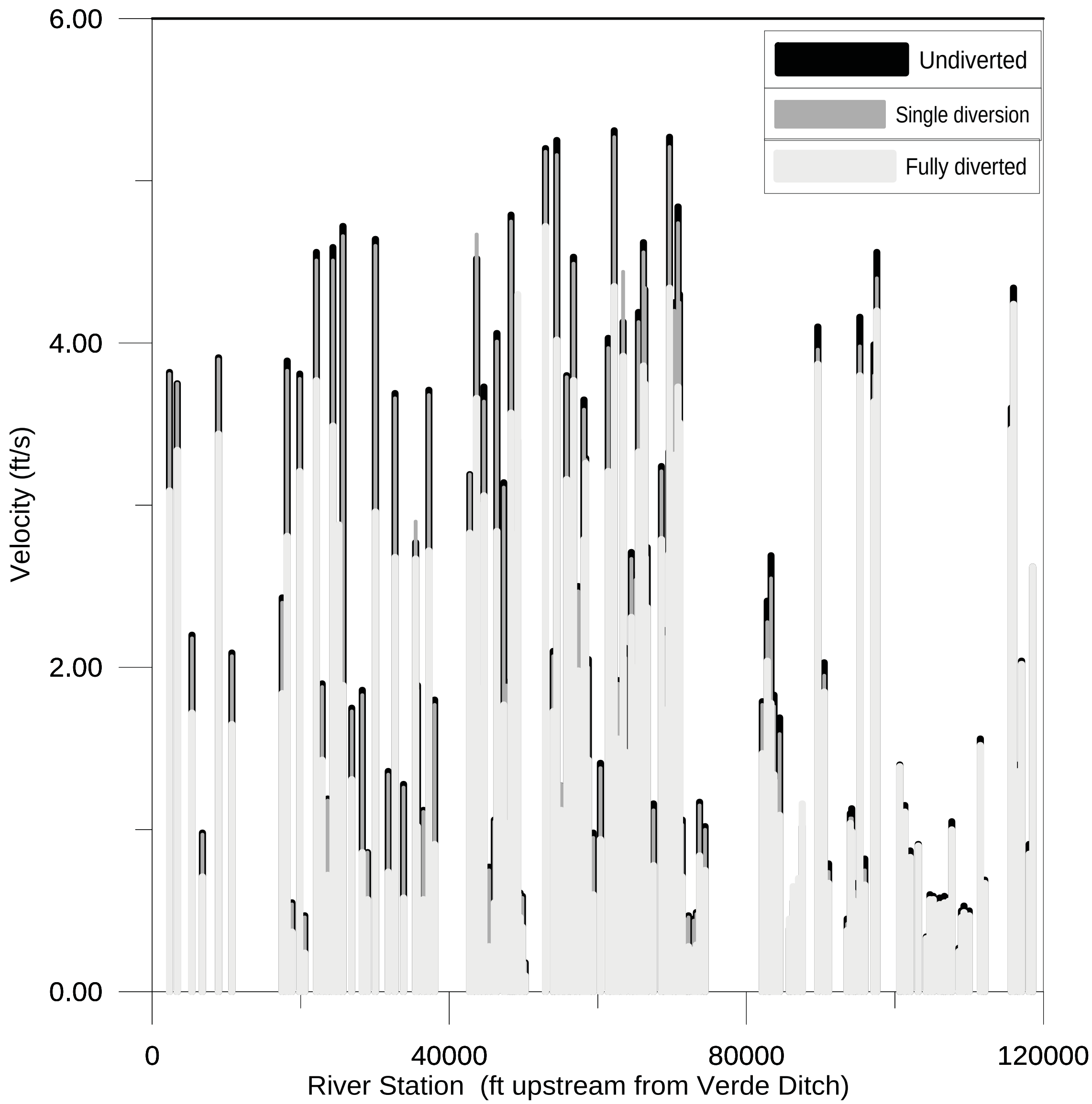

Figure 58 - Comparison of simulated velocity between modeling parameters consisting of no diversion, one diversion (OK Ditch), and all diversions.

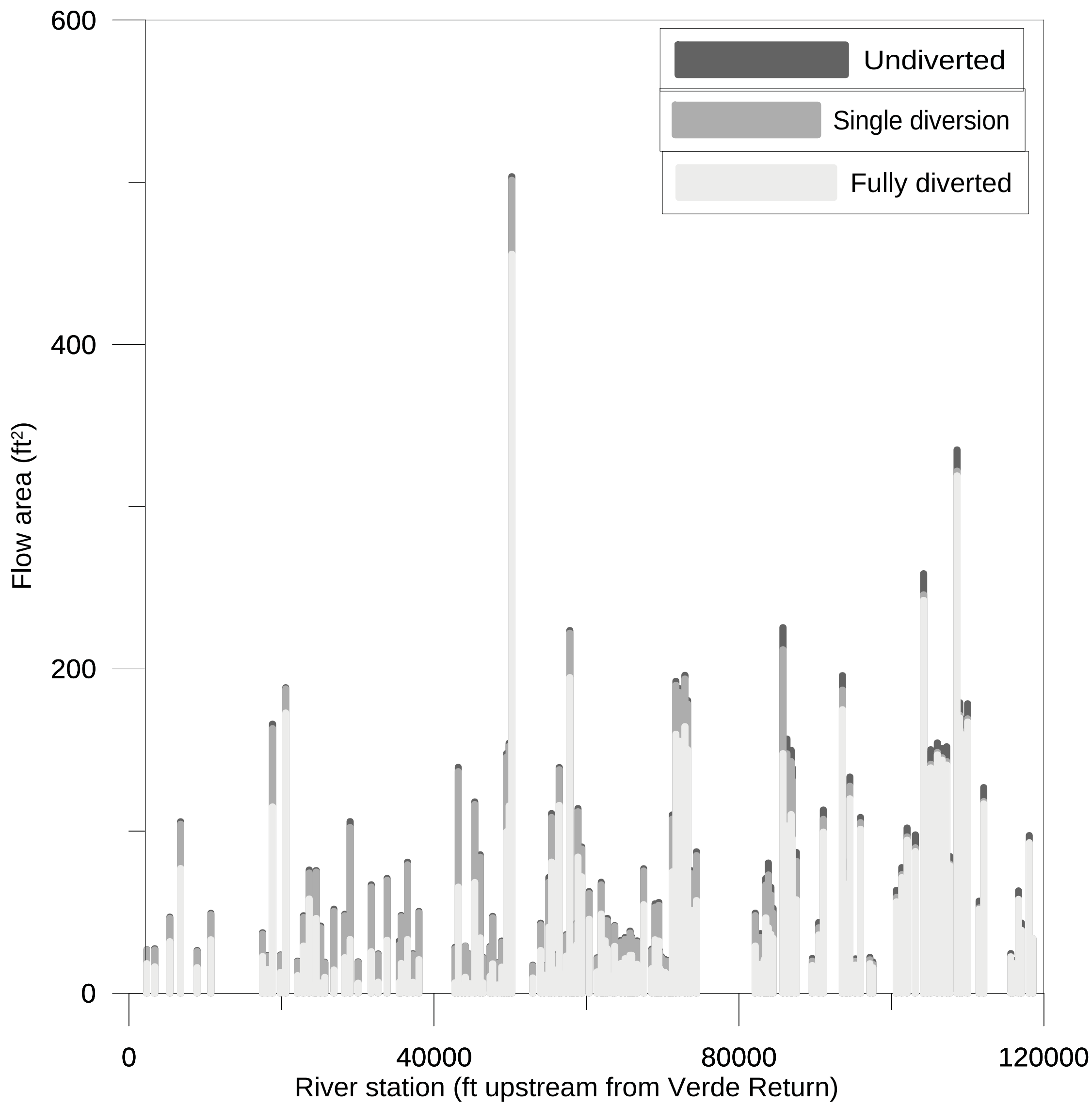

Figure 59 - Comparison of simulated flow area between modeling parameters consisting of no diversion, one diversion (OK Ditch), and all diversions.

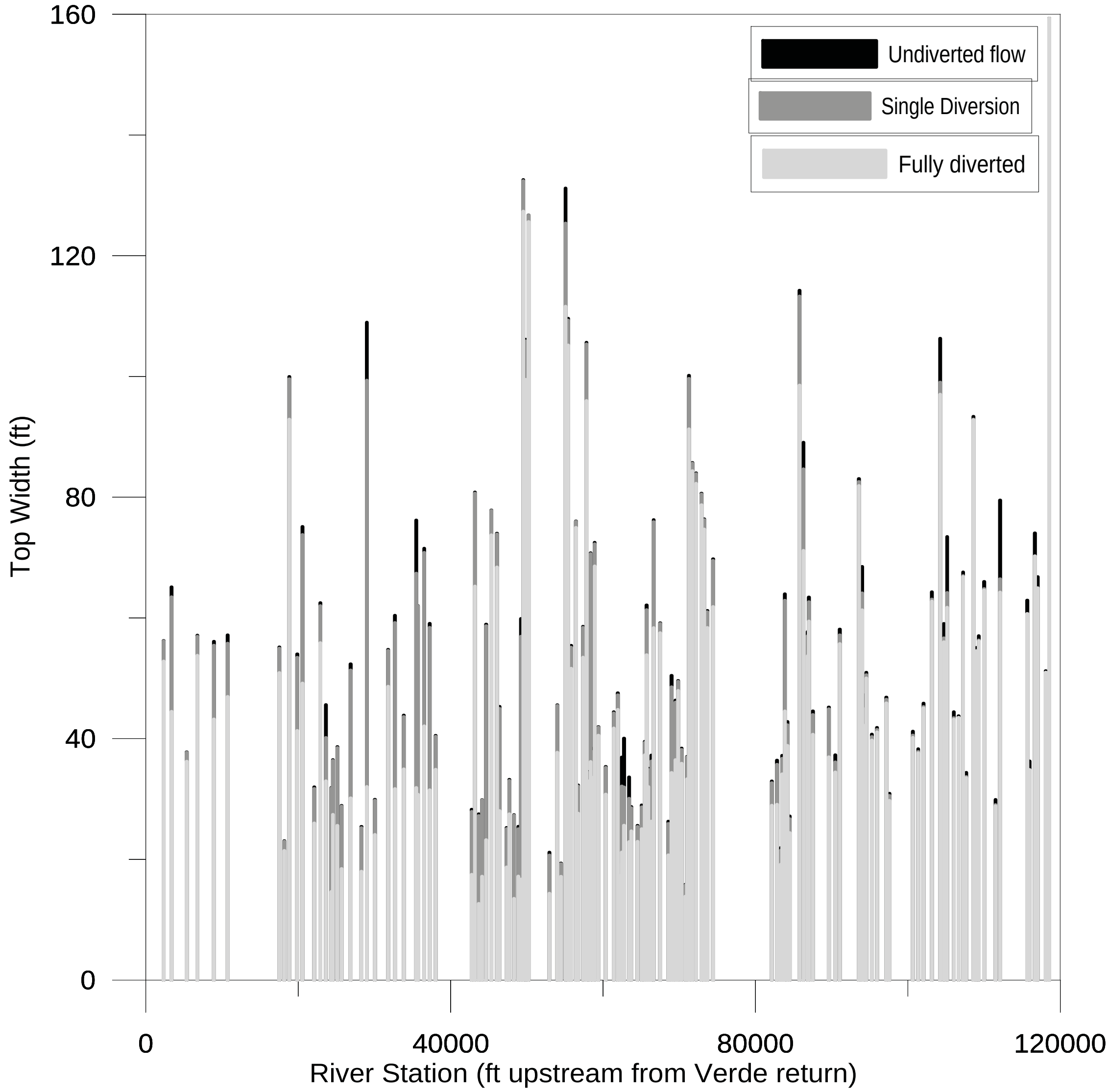

Figure 60 - Comparison of simulated top width between modeling parameters consisting of no diversion, one diversion (OK Ditch), and all diversions.

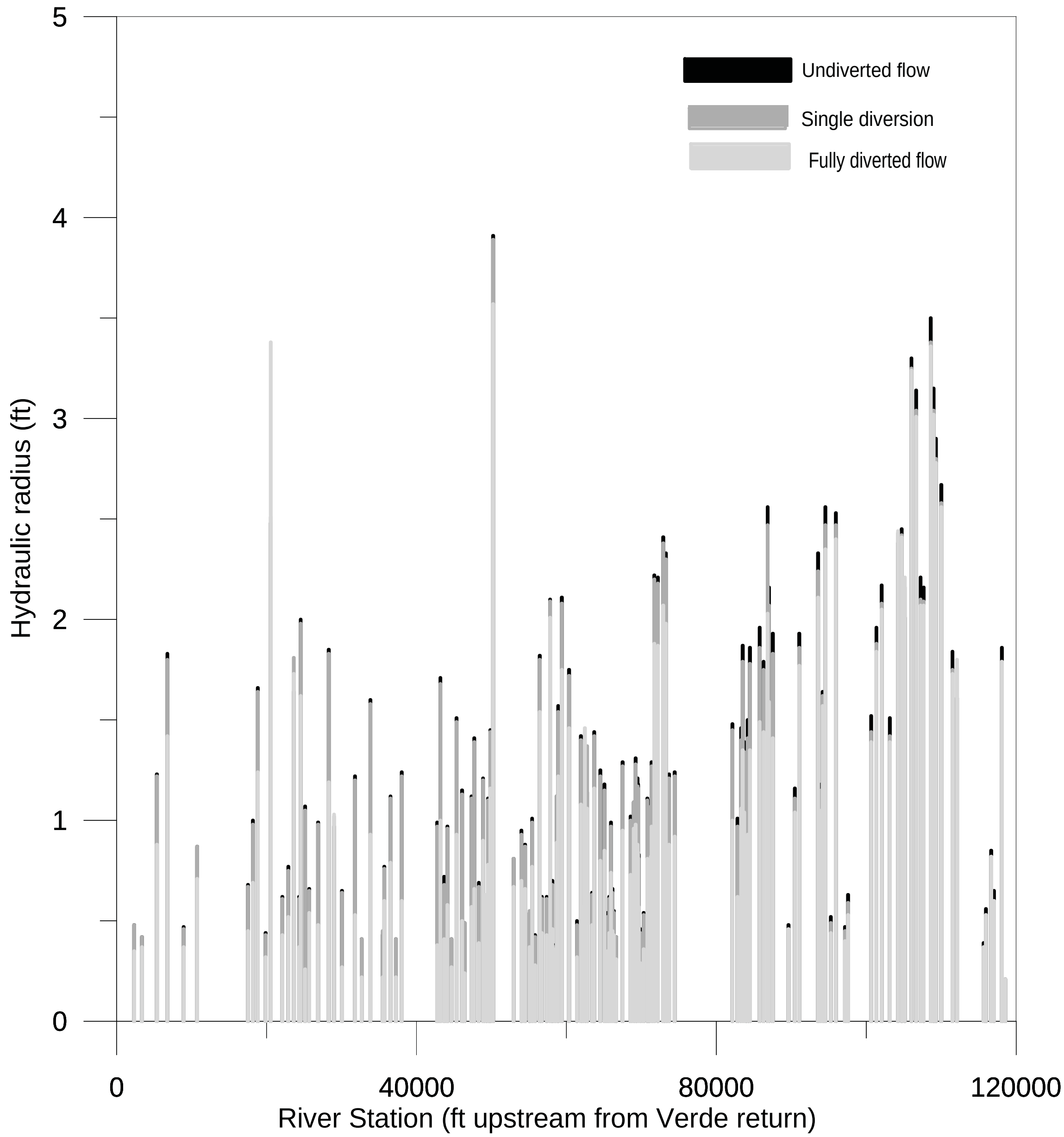

Figure 61 - Comparison of simulated hydraulic radius between modeling parameters consisting of no diversion, one diversion (OK Ditch), and all diversions.

insignificant compared to the magnitude of simulated differences between diverted and non-diverted river baseflows, as referenced above (Table 12).

7.2 Discussion

7.2.1 Implications of ditch instrumentation

Diversion structures for the irrigation ditches along the model reach are constructed solely to divert more flow than is necessary to ensure adequate delivery to the headgates of the ditches. Although more flow will be diverted at higher stages, a relatively constant amount of water is actually routed through the headgates of the ditches. In fact, at very high discharge periods, the headgates of some of the ditches are temporarily closed to prevent damage to the ditch system by flow greater than the conveyance capabilities of the ditch (F. Geminden, pers. comm., 2010). At very high discharge, it is likely that flow is not actually diverted by the diversion structure, but in fact flows directly into the ditch. These events often require repair of the diversion structures and conveyance systems leading to the headgates. It is likely that at lower flows, the small changes seen in the discharge entering the ditch headgates are reflective of the changes in river flow (Figs. 53, 54, 55, and 56).

7.2.2 Implications of model output

Discussion of changing management strategies

The irrigation ditches of Camp Verde are not efficient in their initial diversion of river flow. The simple diversion structures do not divert a set amount of water needed for the ditch operations; rather, they divert often twice the adequate flow to the headgates of the ditch, where large amounts of diverted flow are returned to the channel to ensure the proper amount of water entering the ditch. These

Table 12 - Error summary of steady state flow model, comparing top width values for simulated and measured flow.

Notes on reason for survey difference
G=gradual channel
D=diverted non-modeled flow
H=error due to higher flow during survey
S=within systematic error margin
N=ineffective flow margins

XS #	River Station	Reach	Top width (surveyed)	Top Width (May 2005)	TW (simulated w/all div)	% difference (survey/sim)	% difference (photo/sim)
0	118549.4	Main Stem	230	161.82	159.34	0.31	0.02
1	118084.4	Main Stem	53	53.76	50.98	0.04	0.05
2	117041.3	Main Stem	96.5	68.04	64.97	0.33	0.05
3	116665.3	Main Stem	215	71.36	70.23	0.67	0.02
4	115963.7	Main Stem	80	49.41	34.85	0.56	0.29
5	115657.5	Main Stem	115	62.99	60.69	0.47	0.04
6	112103.4	Main Stem	55	70.29	64.23	-0.17	0.09
7	111503.5	Main Stem	37	33.62	28.86	0.22	0.14
8	110008.9	Main Stem	67	63.91	64.59	0.04	-0.01
9	109295	Main Stem	60	48.59	56.17	0.06	-0.16
10	108980.3	Main Stem	56	52.06	54.47	0.03	-0.05
11	108604.8	Main Stem	95	92.32	92.8	0.02	-0.01
12	107656.9	Main Stem	38	34.36	33.52	0.12	0.02
13	107248.3	Main Stem	68	65.08	66.84	0.02	-0.03
14	106661.5	Main Stem	46	41.68	43.46	0.06	-0.04
15	106029.5	Main Stem	43.5	43.27	43.2	0.01	0.00
16	105158.4	Main Stem	55	59.61	61.73	-0.12	-0.04
17	104726.8	Main Stem	50	56.67	56.02	-0.12	0.01
18	104230.9	Main Stem	90	98.56	97.01	-0.08	0.02
19	103149.7	Main Stem	67	61.25	62.74	0.06	-0.02
20	102053.8	Main Stem	48	45.19	45.07	0.06	0.00
21	101350.2	Main Stem	40	37.58	37.64	0.06	0.00
22	100663.1	Main Stem	45	40.4	40.18	0.11	0.01
23	97569.55	Main Stem	40	30.13	29.73	0.26	0.01
24	97181.83	Main Stem	60	46.16	45.9	0.24	0.01
25	95948.03	Main Stem	45	41.8	41.1	0.09	0.02
26	95274.83	Main Stem	52	40.33	39.74	0.24	0.01

Table 12, continued.

27	94551.42	Main Stem	50		49.92	50.04	0.00	0.00
28	94184.05	Main Stem	84		44.25	42.18	0.50	0.05
29	93997.76	Main Stem	80		55.32	61.3	0.23	-0.11
30	93574.22	Main Stem	85		81.59	81.9	0.04	0.00
31	91071.79	Main Stem	63		55.78	55.7	0.12	0.00
32	90472.49	Main Stem	60		36.55	34.46	0.43	0.06
33	89625.59	Main Stem	55		40.73	36.95	0.33	0.09
34	87534.53	Main Stem	47		41.45	40.69	0.13	0.02
35	87007.26	Main Stem	67		56.23	59.45	0.11	-0.06
36	86846.58	Main Stem	60		54.27	53.7	0.11	0.01
37	86306.31	Main Stem	75		72.98	71.16	0.05	0.02
38	85774.25	Main Stem	118		98.84	98.52	0.17	0.00
39	84479.85	Main Stem	28.5		23.56	24.4	0.14	-0.04
40	84194.19	Main Stem	46	null		38.86	0.16	0.00
41	83858.5	Main Stem	75	null		44.57	0.41	0.00
42	83720.1	Main Stem	15	null		26.18	-0.75	0.00
43	83524.02	Main Stem	38.5	null		34.14	0.11	0.00
44	83318	Main Stem	25	null		19.15	0.23	0.00
45	82825	Main Stem	50		28.09	29.09	0.42	-0.04
46	82142.79	Main Stem	35		26.39	28.94	0.17	-0.10
47	74447.47	Main Stem	95		62.45	61.83	0.35	0.01
48	73695.19	Main Stem	70		53.84	58.37	0.17	-0.08
49	73278.51	Main Stem	80		72.36	74.7	0.07	-0.03
50	72919.93	Main Stem	85		73.02	78.72	0.07	-0.08
51	72204.45	Main Stem	90		82.54	82.26	0.09	0.00
52	71730.12	Main Stem	90		84.41	84.34	0.06	0.00
53	71357.29	Main Stem	70		64.48	62.71	0.10	0.03
54	71274.43	Main Stem	123		85.01	91.28	0.26	-0.07
55	71014.34	Main Stem	43		32.16	33.31	0.23	-0.04
56	70802.31	Main Stem	23		15.96	13.87	0.40	0.13
57	70308.09	Main Stem	50		36.06	35.9	0.28	0.00
58	69848.47	Main Stem	60		47.53	47.95	0.20	-0.01
59	69650.2	Main Stem	27		18.74	17.3	0.36	0.08
60	69568.76	Main Stem	109		19.73	18.56	0.83	0.06

Table 12, continued.

61	69495.2	Main Stem	63	38.47	36.48	0.42	0.05
62	69242.92	Main Stem	23	24.96	24.8	-0.08	0.01
63	68989.07	Main Stem	40	31.69	34.34	0.14	-0.08
64	68568.73	Main Stem	35	20.73	20.71	0.41	0.00
65	67507.01	Main Stem	65	56.89	57.51	0.12	-0.01
66	66641.78	Main Stem	90	58.39	58.35	0.35	0.00
67	66331.51	Main Stem	80	27.36	26.31	0.67	0.04
68	66148.47	Main Stem	64	27.9	24.61	0.62	0.12
69	65949.54	Main Stem	40	32.85	32.04	0.20	0.02
70	65717.64	Main Stem	68	54.78	53.88	0.21	0.02
71	65470.64	Main Stem	48	33.43	37.29	0.22	-0.12
72	65073.94	Main Stem	35	23.54	25.05	0.28	-0.06
73	64527.73	Main Stem	29	23.56	22.95	0.21	0.03
74	63706.76	Main Stem	35	23.62	24.7	0.29	-0.05
75	63415.15	Main Stem	46	23.17	22.91	0.50	0.01
76	62749.09	Main Stem	30	25.03	25.62	0.15	-0.02
77	62462.87	Main Stem	24	21.73	21.17	0.12	0.03
78	62208.65	Main Stem	40	19.79	17.31	0.57	0.13
79	61941.56	Main Stem	52	46.2	44.8	0.14	0.03
80	61411.07	Main Stem	51	41.14	41.73	0.18	-0.01
81	60352.37	Main Stem	40	30.38	30.78	0.23	-0.01
82	59386.31	Main Stem	49	41.01	40.54	0.17	0.01
83	58893.16	Main Stem	77	67.63	68.59	0.11	-0.01
84	58707.67	Main Stem	38	34.24	33.57	0.12	0.02
85	58368.49	Main Stem	77	35.16	36.18	0.53	-0.03
86	58134.37	Main Stem	40	33.55	33	0.18	0.02
87	57826.46	Beaver Creek-Wes	115	95.58	95.97	0.17	0.00
88	57365.43	Beaver Creek-Wes	67	57.05	53.48	0.20	0.06
89	56732.37	Beaver Creek-Wes	124	28.36	27.62	0.78	0.03
90	56444.7	Beaver Creek-Wes	83	74.49	74.95	0.10	-0.01
91	55818.1	Beaver Creek-Wes	78	59.21	51.62	0.34	0.13
92	55426.15	Beaver Creek-Wes	130	116.35	105.17	0.19	0.10
93	55073.58	Beaver Creek-Wes	150	120.79	111.61	0.26	0.08
94	54480.31	Beaver Creek-Wes	39	19.73	17.15	0.56	0.13

Table 12, continued.

95	54001.25	Beaver Creek-Wes	53	37.45	37.7	0.29	-0.01
96	52961.8	Beaver Creek-Wes	58	28.17	14.36	0.75	0.49
97	50222.36	Beaver Creek-Wes	130	127.76	125.63	0.03	0.02
98	49850.35	Beaver Creek-Wes	195	100.48	99.5	0.49	0.01
99	49538.91	Beaver Creek-Wes	142	130.15	127.35	0.10	0.02
100	49234.02	Beaver Creek-Wes	18	15.63	16.72	0.07	-0.07
101	48889.15	Beaver Creek-Wes	26	16.42	17.19	0.34	-0.05
102	48321.75	Beaver Creek-Wes	33	15.63	13.53	0.59	0.13
103	47701.5	Beaver Creek-Wes	35	26.92	27.51	0.21	-0.02
104	47345.06	Beaver Creek-Wes	28	19.2	18.72	0.33	0.03
105	46421.59	Beaver Creek-Wes	73	28.58	28.06	0.62	0.02
106	46078.76	Beaver Creek-Wes	95	69.6	68.39	0.28	0.02
107	45352.61	Beaver Creek-Wes	83	73.71	73.74	0.11	0.00
108	44664.84	Beaver Creek-Wes	85	32.45	23.24	0.73	0.28
109	44122.15	Beaver Creek-Wes	52	21.3	17.17	0.67	0.19
110	43687.64	Beaver Creek-Wes	40	12.93	12.66	0.68	0.02
111	43184.35	Beaver Creek-Wes	92	66.24	65.26	0.29	0.01
112	42762.62	Beaver Creek-Wes	42	18.47	17.5	0.58	0.05
113	38033.31	Beaver Creek-Wes	45	34.36	34.87	0.23	-0.01
114	37252.7	Beaver Creek-Wes	73	35.16	31.49	0.57	0.10
115	36535.96	Beaver Creek-Wes	105	50.11	42.09	0.60	0.16
116	35707.88	Beaver Creek-Wes	67	36.32	30.74	0.54	0.15
117	35483.83	Beaver Creek-Wes	60	35.04	31.87	0.47	0.09
118	33856.76	Beaver Creek-Wes	50	40.46	34.95	0.30	0.14
119	32694.42	Beaver Creek-Wes	77	36.32	31.68	0.59	0.13
120	31795.29	Beaver Creek-Wes	70	49.63	48.63	0.31	0.02
121	30064.65	Beaver Creek-Wes	35	25.85	24.07	0.31	0.07
122	29010.56	Beaver Creek-Wes	40	33.43	32.06	0.20	0.04
123	28301.37	Beaver Creek-Wes	35	19.7	18	0.49	0.09
124	26879.59	Beaver Creek-Wes	45	32.48	30.16	0.33	0.07
125	25690.62	Beaver Creek-Wes	38	20.36	18.46	0.51	0.09
126	25150.23	Beaver Creek-Wes	53	26.83	25.61	0.52	0.05
127	24560.75	Beaver Creek-Wes	43	30.51	27.42	0.36	0.10
128	24338.5	Beaver Creek-Wes	45	19.02	14.64	0.67	0.23

Table 12, continued.

129	23644.18	Beaver Creek-Wes	100	34.09	32.98	0.67	0.03
130	22905.62	Beaver Creek-Wes	75	62.75	55.88	0.25	0.11
131	22115.25	Beaver Creek-Wes	117	30.98	25.99	0.78	0.16
132	20557.73	Beaver Creek-Wes	50	49.62	49.17	0.02	0.01
133	19873.56	Beaver Creek-Wes	100	42.34	41.31	0.59	0.02
134	18839.17	Beaver Creek-Wes	110	103.13	92.89	0.16	0.10
135	18188.43	Beaver Creek-Wes	26	21.57	21.45	0.18	0.01
136	17524.21	Beaver Creek-Wes	70	52.06	50.91	0.27	0.02
137	10740.96	West Clear-Verde	50	48.2	46.97	0.06	0.03
138	8944.824	West Clear-Verde	77	47.44	43.22	0.44	0.09
139	6775.449	West Clear-Verde	65	54.7	53.79	0.17	0.02
140	5370.328	West Clear-Verde	42	36.63	36.22	0.14	0.01
141	3385.462	West Clear-Verde	95	45.09	44.49	0.53	0.01
142	2344.045	West Clear-Verde	113	58.41	52.82	0.53	0.10

large amounts of diverted flow cause an unnecessary decrease in wetted area within the main stem of the river channel temporarily, and create lasting decreases in hydraulic parameter values (e.g., velocity, flow area, top width, etc.) for significant distances downstream. This can be seen in the steady-state simulation with just the OK Ditch diversion; parameters do not return to those of the undiverted simulation until the last three cross-sections of the model (Fig. 62).

Effects of ditches on river flows

The calibrated simulation results indicate that irrigation ditch diversions impact downstream flows by reducing velocity, hydraulic radius, and discharge, among others (Figs. 58, 59, 60, and 61). While the ditches do not consume the full amount of water diverted, they do decrease the in-channel flow downstream of diversion, and reduce flows significantly over large reaches of the river system. Ditch operations most likely expand the Verde River riparian ecosystem spatially, and have possibly created unique ditch ecosystems, although this is speculation based on general observations, and not currently a defendable hypothesis. Given the amount of water returned to the channel after initial diversion and before flow through the headgates, as well as the large amount of water returned by two of the four ditches (Diamond S and OK Ditches) at the return flow sites, it is likely that more modern management practices including engineered diversion structures or pumps, permanent flow monitoring, and scheduled, metered delivery would provide the necessary amount of water to the water users, maintain baseflow necessary for riparian vegetation, and maximize the flow left in the main stem. The major issues in implementation of these practices include the time and expense of procuring new

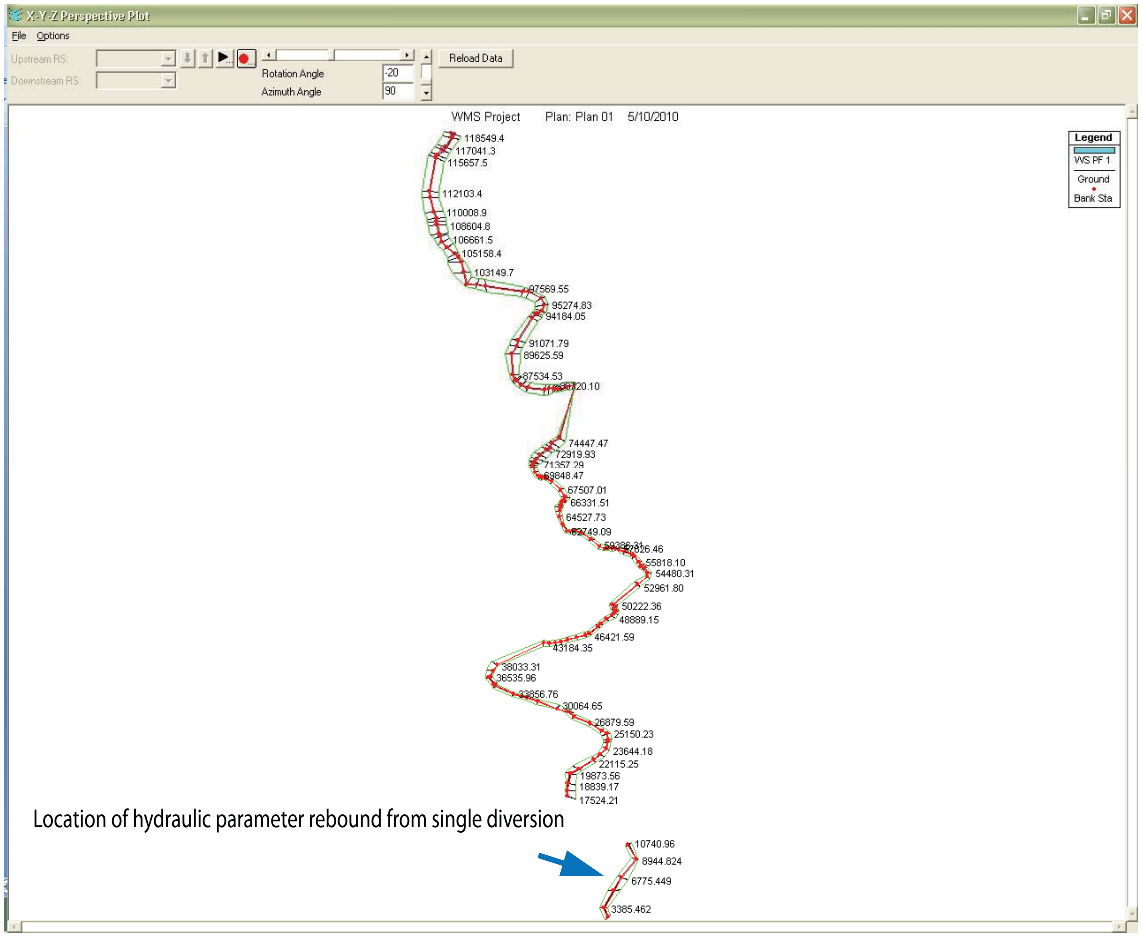

Figure 62 - Location of return to undiverted hydraulic parameter values after modeling a single diversion (OK Ditch).

Clean Water Act Section 404 permits. Presently, the ditches currently operate without conformation to permitting due to the dates of their establishment. The expense of constructing and maintaining these types of management practices are significant. A possible solution would be to solicit the services of parties with experience in these practices to assist those irrigation ditch companies that are interested in increasing their operational efficiency. It has been shown in the middle Rio Grande Conservancy District that modernization of diversion and delivery systems can greatly increase the amount of water retained by the main stem of a river, while still providing necessary irrigation resources (Oad et al., 2009; Gensler et al., 2009).

7.2.3 Suggestions to future authors

Irrigation ditch management companies may be interested in developing their own resources for flow and delivery monitoring. The Verde Ditch has expressed interest in developing a permanent instrumentation system for their ditch, to better manage diversion and delivery. A more advanced and comprehensive system could be designed to accurately monitor: flow at headgates; return flow; main lateral discharges; and spillway flow. Data from this monitoring could also be helpful to the companies for reducing the costs by constraining and guiding engineering and design of improvements. Conducting a better bathymetric survey of the entire river channel, as well as studying seepage loss from return flows and spillways would better constrain the model framework.

The model, while useful as a stand-alone resource, can be used to generate simulation results that constrain conditions in local and regional groundwater flow models, such as the USGS regional MODFLOW framework.

Further work in this area will help define interactions between Verde Valley groundwater and surface water systems.

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